# DRAFT

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# Final Report to the U.S. Army Corps of Engineers concerning the oyster restoration efforts in Town Pond (Portsmouth, RI)

Submitted by:

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**Statement of Work for**
**Town Pond Restoration Area**
**Oyster Establishment**
**May 28, 2008**

**Project Requirement:** The Contractor shall establish a viable population of eastern oysters (*Crassostrea virginica*) along the east side entrance to the newly opened Town Pond in Portsmouth, Rhode Island (Figure 1).

**Criteria for site preparation and seeding:** The oyster restoration site is located on the east bank of the pond just inland of the railroad bridge and measures approximately 85 ft along the shore by 80 ft from mid-intertidal to subtidal, which translates to 0.16 acres (~7,000 $ft^2$) (Figure 2). The Contractor shall fully prepare the site with cultch in the first year and seed it each year for two years (2008 and 2009).

- Preparation of the restoration area shall be conducted with aged shell at an application rate of 2,000 bushels of cultch per acre. The estimated volume of cultch for this project (0.16 acres) is 320 bushels of aged shell.
- Each spring, the contractor hatchery shall produce oyster larvae for this project using locally collected oysters for broodstock. The broodstock must be from Narragansett Bay, and the batch oysters produced shall require Coastal Resources Management Council (CRMC) Biosecurity Board certification prior to being moved to the restoration site if transported from outside the immediate vicinity of deployment.
- All work must be conducted in accordance with current Rhode Island Department of Environmental Management (DEM), CRMC, and CRMC Biosecurity Board requirements.

**Oyster Growth and Seeding:** Oyster larvae shall be "set" onto bagged cultch material in tanks and maintained in the hatchery until transferred to field nursery sites. The oysters will be grown over the summer until reaching a predator-resistant size suitable for planting in Town Pond. The shell length at the time of planting must be 1 inch to maximize the likelihood of survival. The target planting density for this project is 200 oysters per square meter, thus this project will require the planting of approximately 155,000 juvenile oysters on cultch each year for two years. An estimated 125 bags of oysters set on cultch is required for production each year.

**Period of Service:** The Contractor shall complete all work and invoicing by December 31, 2009.

**Material to Be Provided By the Government:** The Contractor shall furnish all material and supplies required for this work.

**Coordination with the Contract Manager:** David Larsen, Project Planning Section, New England District, Corps of Engineers (978-318-8113) shall be the Contract Manager and shall be contacted to answer any questions about this work.

The oyster restoration effort at Town Pond (Portsmouth, RI, in the vicinity of 41°38'14.31"N / 71°14'39.81"W) was initiated on 5 June 2008 with a survey of the Town Pond area and a preliminary determination of locations for the oyster restoration efforts. A timeline of the activities undertaken by RWU Center for Economic and Environmental Development (CEED) and the Rhode Island Oyster Gardening for Restoration and Enhancement (RI-OGRE) summarizes the general activities associated with this project in Table 1.

| Town Pond Timeline | |
|---|---|
| **Date** | **Action** |
| 21-Sep-07 | open channel for tidal circulation |
| 5-Jun-08 | initial survey of site |
| 25-Jun-08 | visit to site to plan restoration experiment |
| 2-Jul-08 | delineate experimental plots |
| 24-Jul-08 | stake initial plots at 25' x 25' |
| 28-Jul-08 | expand plots to 25' x 75' |
| 16-Sep-08 | start cultching sites (finish on 30-Jun-09) |
| 10-Oct-08 | plant 6 totes spat-on-shell (~45,000 oysters) in Plots 1 & 3 |
| 6-Dec-08 | OGRE-fest at RWU |
| 6-Dec-08 | plant 5 totes spat-on-shell (~37,500) in Plot 4 and 10 totes(~75,000) in Plot 3 |
| ??-Dec-08 | plant 4 totes spat-on-shell (~30,000) in Plot 1 |
| ??-Jan-09 | plant 2 totes spat-on-shell (~15,000) in Plot 5 |
| 22-May-09 | sample oysters in Plots 3 & 4 intertidal |
| 26-May-09 | sample oysters in Plot 1 intertidal & subtidal; & 5 subtidal |
| 1-Jun-09 | sample oysters in Plot 3 & 4 subtidal |
| 6-Aug-09 | sample oysters in all Plots |
| 21-Nov-09 | plant 14 totes spat-on-shell (~80,000) on Plots 1 & 2 |
| 11-Dec-09 | plant 18 totes spat-on-shell (~100,000) on Plots 3 & 4 |
| 8-Jun-10 | deploy spat collectors |
| 21-Jun-10 | sample intertidal oysters in all Plots |
| 24-Jun-10 | sample subtidal oysters in all Plots |
| 20-Sep-10 | plant 10 totes spat-on-shell (~60,000) in Plots 1 & 2 |
| 20-Sep-10 | plant 10 totes spat-on-shell (~60,000) in Plot 6 |
| 15-Nov-10 | plant 13 totes spat-on-shell (~78,000) in Plot 6 |
| 6-Dec-10 | retrieve spat collectors |
| 6-Jan-11 | plant 6 totes spat-on-shell (~36,000) in Plot 6 |
| 3-Jun-11 | measure all plot areas - sample oysters in Plot 1 |
| 13-Jun-11 | sample oysters in Plots 2, 3, & 4 |
| 20-Jun-11 | sample oysters in Plot 6 |
| 6-Jul-11 | sample oysters in Plot 5 |

Table 1: A timeline of oyster restoration activities in Town Pond (Portsmouth, RI) between 2008 and 2011.

During the first summer (June through July 2008), Plots 1 to 4 were laid out and demarcated (Figures 1 & 2; photo-documented in Appendix A). Following delineation of the sites, an effort was undertaken to cultch Plots 1 through 4 using bivalve shells (surf clam *Spisula solidissima* and mahogany quahog *Arctica islandica*) donated by a local shellfish processing plant (Blount Seafood, Warren, RI). The actual deployments of shell and the total cultch additions are summarized in Table 2. Twenty trips from seafood plant to Town Pond were completed, with each trip consisting of approximately four hours of effort to load totes, drive to site and deploy cultch from a small aluminum skiff in Town Pond, using a team of 4 to 8 RWU students and investigators. Photographs of the cultching effort are included in Appendix A. The final volume of cultch applied to the plots in Town Pond was 1,134 bushels, far in excess of the 320 bushels stipulated in the USACE Work Agreement.

Table 2: Summary of cultch additions to Plots 1 through 4 in Town Pond during the first season of oyster restoration (2008-2009).

| Date | # totes | plot | tidal height* |
|---|---|---|---|
| 16-Sep-08 | 18 | 1 | i |
| 18-Sep-08 | 25 | 1 | i |
| 17-Jun-09 | 2 | 1 | s |
| 22-Jun-09 | 26 | 1 | s |
| 30-Jun-09 | 26 | 1 | s |
| 23-Sep-08 | 25 | 2 | i |
| 23-Oct-08 | 34 | 2 | i/s |
| 30-Oct-08 | 34 | 2 | s |
| 15-Jun-09 | 25 | 2 | s |
| 17-Jun-09 | 23 | 2 | s |
| 12-Nov-08 | 34 | 2 | s |
| 10-Oct-08 | 90 | 3 | i |
| 16-Oct-08 | 66 | 3 | s |
| 23-Oct-08 | 33 | 3 | s |
| 20-Oct-08 | 33 | 4 | i |
| 7-Oct-08 | 66 | 4 | i/s |
| 9-Oct-08 | 7 | 4 | i/s |

| Plot | total cultch added** | area (ft$^2$) |
|---|---|---|
| 1 | 194 bu | 1,946 |
| 2 | 350 bu | 1,807 |
| 3 | 378 bu | 2,211 |
| 4 | 212 bu | 1,674 |
| total | 1,134 bu | 7,638 |

* i - intertidal; s - subtidal
** assume 2 bu per tote

In addition to the clutched plots (1 - 4), a fifth plot was established at the end of the 2008 oyster planting season (Plot 5 - Figures 1 & 2). This plot was established to evaluate the necessity of cultching the plots in Town Pond by directly planting spat-on-shell on uncultched substrate adjacent to the clutched plots.

Lastly, as a follow-up to the initial oyster plantings (supported by the USACE), a sixth plot was established; separate from the initial site on the opposite shore across the Town Pond channel (Plot 6 - Figures 1 & 2). This site along with Plots 1 & 2 were planted with spat-on-shell in 2010, with funds provided by the NOAA Community Restoration Program.

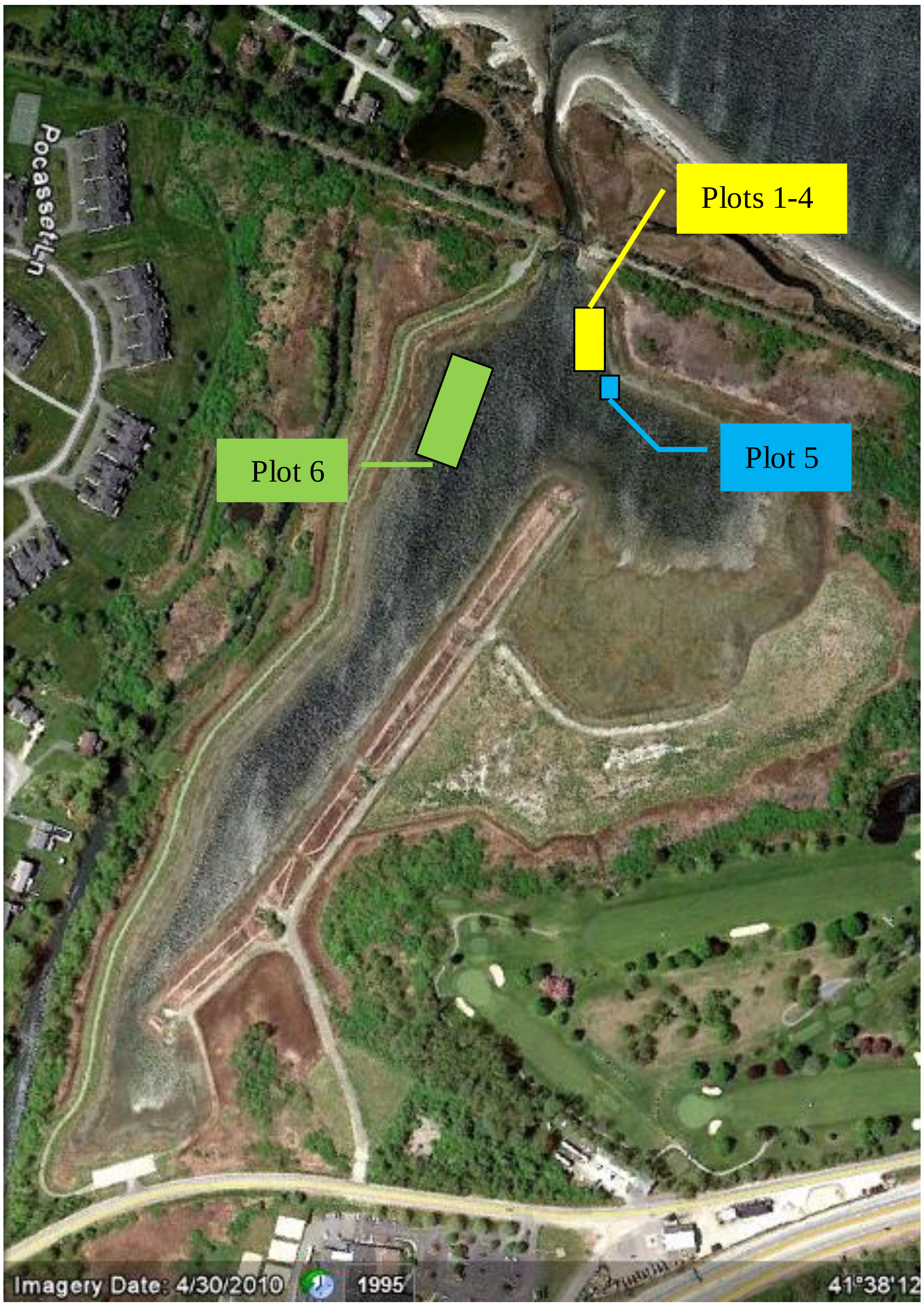



Figure 1: Aerial photo of Town Pond (Portsmouth, RI) with oyster restoration plot areas demarcated (not to scale).

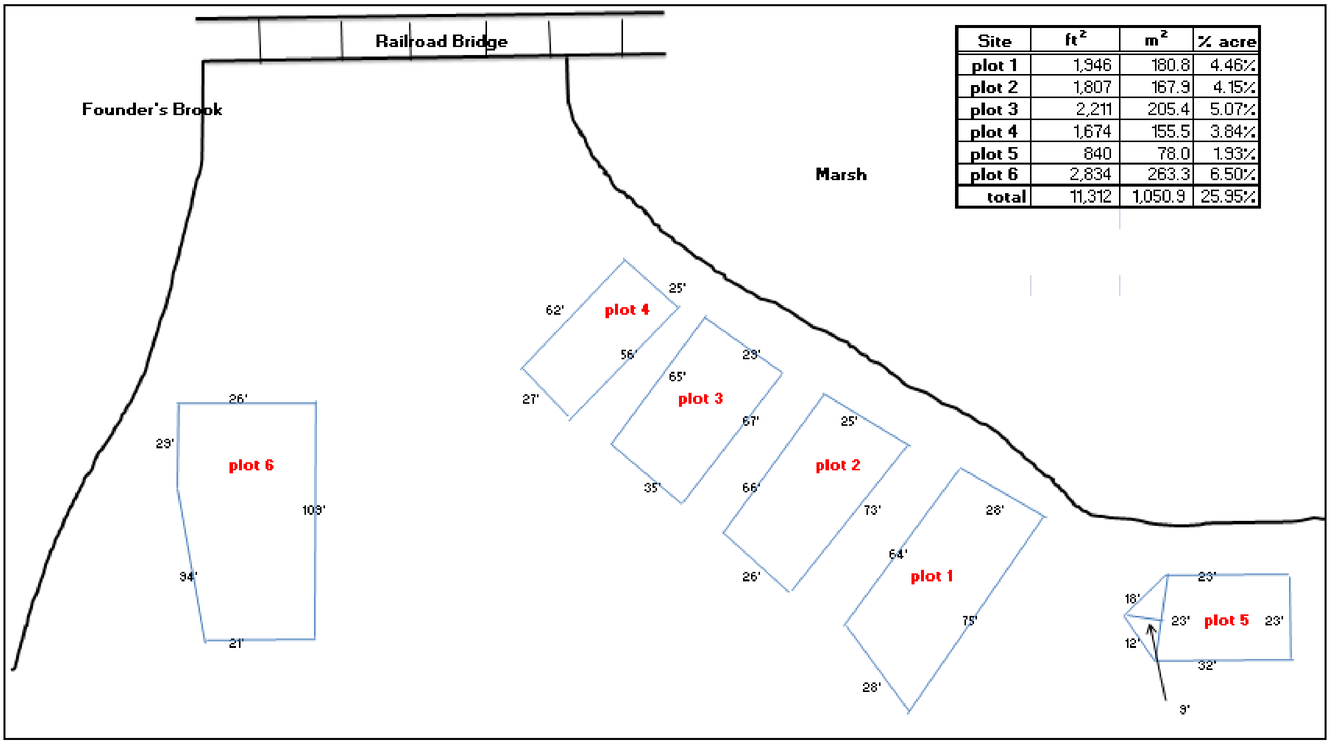



Figure 2: Schematic diagram of the placement and area of the oyster restoration plots in Town Pond.

Plots 1 – 4 represent a combined surface area of 7,638 ft$^2$ (0.175 acre), meeting the stipulated area (~7,000 ft$^2$) in the USACE Work Agreement. In addition, Plots 5 and 6 provide an additional 3,674 ft$^2$ (0.084 acres) resulting in a total area of restored oyster bed as 11,312 ft$^2$ (0.259 acres.)

Following the set-up of the clutched and uncultched plots, oyster spat-on-shell were produced for deployment on the site. Spat-on-shell are produced through the activities of the Rhode Island OGRE Program, where competent oyster larvae are set on aged shell contained within plastic mesh bags at the RWU Shellfish Hatchery. The bagged spat-on-shell are nursery cultured by volunteer gardeners throughout Rhode Island until they grow to a size where they have a higher probability of survival when released onto restoration sites. When the individual oysters have achieved a size of >25 mm, they are ready for planting on the restoration site.

The timing for oyster restoration planting starts in the fall and can extend into the winter, depending on the scheduling of oyster returns from the OGRE gardeners. As summarized in

Table 3: Summary of spat-on-shell plantings in Town Pond between 2008-2010.

| | | | | |
|---|---|---|---|---|
| 2008 | 1 tote = 6 shell bags @ 1,667 spat per bag =10,000 spat/tote | | | |
| 2009 | 1 tote = 5 shell bags @ 1,000 spat per bag = ~5,000 spat/tote | | | |
| 2010 | 1 tote = 5 shell bags @ 1,200 spat per bag = ~6,000 spat/tote | | | |
| **Date** | **Plot(s)** | **# Totes** | **app. # oysters** | **Yr Total** |
| **10-Oct-08** | 4 | 6 | 60,000 | |
| **6-Dec-08** | 4 | 5 | 50,000 | |
| | 3 | 10 | 100,000 | |
| **??-Dec-08** | 1 | 4 | 40,000 | |
| **13-Jan-09** | 5 | 4 | 40,000 | 290,000 |
| **21-Nov-09** | 1 | 7 | 35,000 | |
| | 2 | 7 | 35,000 | |
| **11-Dec-09** | 4 | 9 | 45,000 | |
| | 3 | 9 | 45,000 | 160,000 |
| **20-Sep-10** | 1 | 5 | 30,000 | |
| | 2 | 5 | 30,000 | |
| | 3 | 5 | 30,000 | |
| | 4 | 5 | 30,000 | |
| **13-Nov-10** | 6 | 13 | 78,000 | |
| **6-Jan-11** | 6 | 6 | 36,000 | 234,000 |
| **Subtotals** | 1-5 | | | 510,000 |
| | 6 | | | 114,000 |
| **Grand Total** | | | | 684,000 |

Table 3, the plantings in Town Pond over the time interval between 2008 and 2010 occurred within the time frame of late September to early January of each year. Town Pond plots received an average annual planting of 228,000 oysters as spat-on-shell between 1998 and 2010. This represents an average of 172 bags of remote set oysters per year. Based on the requirements of the USACE Work Agreement that states we will plant 155,000 juvenile oysters in an estimated 125 bags of cultch per year, we have met the stipulations of the funded project.

To assess the efficacy of oyster restoration in Town Pond, we implemented a monitoring program to evaluate various production parameters, including oyster growth, oyster survival, spat production, and habitat enhancement. The Town Pond site was visited a minimum of once per year, in the early summer, where basic measurements were made on oysters retrieved within replicated random quadrats sampled within each plot. Sampling times and locations are outlined in the timeline (Table 1). In addition, a habitat assessment study of restored oyster bottom in Town Pond was conducted as an RWU Undergraduate Research Senior Thesis by Todd Massari (B.S. 2010) with funding provided by an USEPA Undergraduate Training Fellowship. The Senior Thesis is included as Appendix B.

The overall method for field sampling of the restored oyster beds consisted of randomly placing 0.25 $m^2$ quadrats within each plot and removing all shell material from within the quadrat. The total number of live oysters as well as oyster boxes (paired empty oyster valves, assumed to be a recent mortality, within the past year, due to the persistence of the articulation of the two shells) was counted within each quadrat. In addition, the size (to the nearest 1 mm) of a minimum of 25 live oysters from each quadrat was measured across the longest axis (umbo to ventral margin) using Vernier calipers.

Variations to this basic protocol occurred in 2009 when quadrats were sampled to differentiate intertidal deployments from subtidal deployments, based on a perception of variable survival between the two conditions. In addition, the quadrat size was increased to 1 $m^2$ in 2010 as we attempt to standardize our sampling protocols across all oyster restoration activities in RI.

As an additional assessment of success in the restoration of oysters in Town Pond, we deployed net bags of clean cultch (identical to the bags used in the remote set of the OGRE oysters) as spat collectors suspended from buoys at random sites throughout Town Pond during the summer of 2010. The spat collectors were placed in the field in June and were collected back in December (Table 1). The total number of live oyster spat recruited to the collectors was counted and the lengths measured upon retrieval.

**Results & Discussion:**

**Overall Survival**

Survival was measured as the number of living oysters collected within replicated quadrats sampled in each plot during the early summer (May-June) compared with the number of living oysters measured the year before combined with any new spat-on-shell planted within the plot in December. Overall annual survival averaged 33.7% ($\pm$27.0% S.D.) with considerable variability both between years and among plots (Table 4). Because this estimate of overall survival represents a highly mixed population of oysters ranging from young of the year to two-year old oysters, it is difficult to make any judgment as to the efficacy of oyster restoration in Town Pond. Therefore, the survival data can be teased apart to look at survival for the following situations:

- young of the year,
- adults,
- a single plot over the three year interval,
- location within the tidal range, and
- placement on clutched or non-cultched bottom.

Table 4: Summary of annual survival from a mixed population of oysters planted in Town Pond.

| Site | Live in December | Live in May | % Survival |
|---|---|---|---|
| **2008-2009** | | | |
| Plot 1 | 40,000 | 31,098 | 77.7% |
| Plot 2 | | | |
| Plot 3 | 100,000 | 63,469 | 63.5% |
| Plot 4 | 110,000 | 23,792 | 21.6% |
| Plot 5 | 40,000 | 37,284 | 93.2% |
| Plot 6 | | | |
| | | avg | 64.0% |
| | | stdev | 30.8% |
| **2009-2010** | | | |
| Plot 1 | 66,098 | 9,123 | 13.8% |
| Plot 2 | 35,000 | 19,489 | 55.7% |
| Plot 3 | 108,469 | 10,574 | 9.7% |
| Plot 4 | 68,792 | 16,587 | 24.1% |
| Plot 5 | 37,284 | 15,550 | 41.7% |
| Plot 6 | | | |
| | | avg | 29.0% |
| | | stdev | 19.4% |
| **2010-2011** | | | |
| Plot 1 | 39,123 | 8,941 | 22.9% |
| Plot 2 | 49,489 | 6,278 | 12.7% |
| Plot 3 | 40,574 | 14,073 | 34.7% |
| Plot 4 | 46,587 | 7,697 | 16.5% |
| Plot 5 | 15,550 | 2,208 | 14.2% |
| Plot 6 | 114,000 | 4,609 | 4.0% |
| | | avg | 17.5% |
| | | stdev | 10.4% |
| **2008-2011** | | overall avg | 33.7% |
| | | stdev | 27.0% |

## Young of the Year Survival:

Table 5: Survival of first-year oyster spat-on-shell at Town Pond compared to other RI sites stocked during the North Cape Oil Spill remediation effort.

| Site | Total Seeded | Est. No. Alive | % Survival |
|---|---|---|---|
| **Town Pond** | | | |
| 2008 - Plot 1 | 40,000 | 31,098 | 77.7% |
| 2008 - Plot 3 | 100,000 | 63,469 | 63.5% |
| 2008 - Plot 4 | 110,000 | 23,792 | 21.6% |
| 2008 - Plot 5 | 40,000 | 37,284 | 93.2% |
| 2009 - Plot 2 | 35,000 | 19,489 | 55.7% |
| 2010 - Plot 6 | 114,000 | 4,609 | 4.0% |
| | | average | 52.6% |
| | | stdev | 33.8% |
| **North Cape (2003 - 2004)** | | | |
| Smelt Brook | 114,432 | 8,900 | 7.8% |
| Saugatucket | 80,000 | 13,000 | 16.3% |
| Bissel | 112,416 | 5,000 | 4.4% |
| Spectacle | 96,600 | 7,100 | 7.3% |
| Potter | 140,792 | 23,300 | 16.5% |
| | | average | 10.5% |
| | | stdev | 5.6% |

In those plots where we were able to specifically sample young of the year spat-on-shell planted in Town Pond, the survival following the first six months of existence in the field averaged 52.6% (±33.8% stdev; Table 5). The young of the year survival in Town Pond exceeds that reported in other Rhode Island sites that were seeded during the remediation effort for the North Cape Oil Spill, where the North Cape oysters survived at a rate of 10.5% (±5.6%; Table 5). The difference may be attributable to the form in which the oysters were released. The Town Pond releases were oyster spat-on-shell, clusters of living oysters set on large pieces of cultch, while those of North Cape were for single oysters set on microcultch. Clusters of oysters on cultch provide a more complex substrate that interferes with the predatory activity of many benthic consumers of oysters. Single oysters have been demonstrated to be more susceptible to predation when compared to spat-on-shell. In 2008, the spat-on-shell oysters generated by the RI OGRE Program averaged 10.9 (±12.1) live oyster spat per shell at the time of initial field planting.

## Adult Survival:

It has been demonstrated that the first year of existence for a bivalve mollusk is the period of highest risk in terms of predation mortality. As the mollusk grows it surpasses a size threshold where predators have less success in opening and consuming the bivalve. To investigate the long-term survival of post-

Year 1 oysters, we identified one plot (Plot 5) where the oysters' survival could be measured for more than the first year without the added introduction of new year classes of spat-on-shell to the plot. During the interval from initial planting (2008) to the most recent sampling (2011) the population density dropped from the initial 40,000 oysters to a final population of 2,208, a reduction to 5.5% of the original planting (Table 6). In comparison, the North Cape oyster populations were reduced to 1.3% (±0.5%) of their original density over a time interval of 5 years (2003-2008; Table 6). One important difference in comparing these data is that the time interval between the Town Pond deployments (3 years) is two years less than that measured for the North Cape sites (5 years). The etiology of two significant oyster diseases (MSX and dermo) is such that these slowly developing diseases often take more than one year to infect the oyster to the point of causing mortality. Therefore, based on our knowledge of local oyster diseases, two additional years may be a significant contributor to the reduced survival of the North Cape adults due to increased disease severity. We plan to continue to monitor the Town Pond plots to compare the performance of Town Pond in sustaining a viable oyster population relative to anticipated long-term mortality.

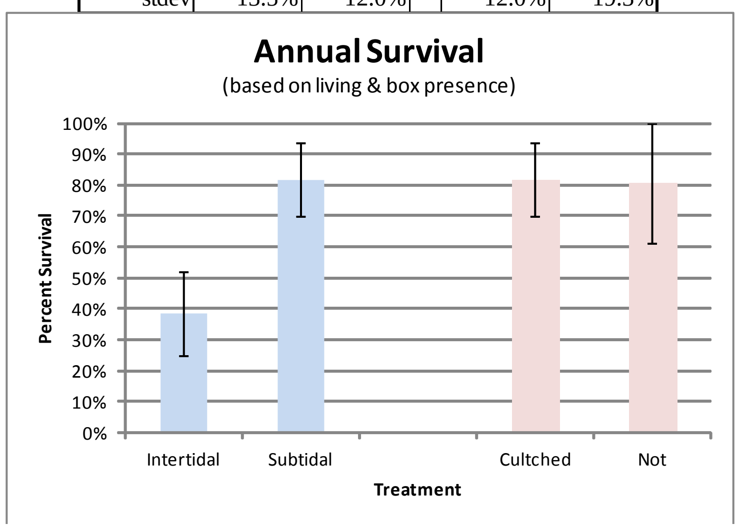
Table 6: Long-term survival of adult oysters at Town Pond compared to other RI sites stocked during the North Cape Oil Spill remediation effort.

| Site | Total Seeded | Est No. Alive | % survival |
|---|---|---|---|
| **Town Pond (2008-2011)** | | | |
| Plot 5 | 40,000 | 2,208 | 5.5% |
| **North Cape (2003 - 2008)** | | | |
| Saugautuck River | 1,310,657 | 8,192 | 0.6% |
| Smelt Brook Cove | 1,275,915 | 18,991 | 1.5% |
| Spectacle Cove | 680,189 | 12,671 | 1.9% |
| Prudence/Potter Cove | 800,089 | 10,311 | 1.3% |
| | | average | 1.3% |
| | | stdev | 0.5% |

In addition to predation and disease, other environmental factors may play a role in the successful planting of oysters in Town Pond. For example, following our original planting of spat-on-shell in Plots 1, 3, & 4 in 2008, we suspected that the intertidal plantings were impacted more severely by the winter of 2008-2009 than the subtidal plantings. An analysis of the oyster densities in intertidal and subtidal zones within each planted plot demonstrated that there was a significant difference in survival between the two environments (Table 7 and Figure 3). Survival of the subtidal oysters during their first winter was 81.8% (±13.5%), based on the proportion of boxes to live oysters in the May samples, while the intertidal oysters survived at a level of 38.3% (±12.0%). The intertidal plantings produced less than half of the Year 1 spat-on-shell than the subtidal environment.

Table 7 & Figure 3: Overwinter survival of young of the year spat-on-shell when planted at two levels in the tidal zone or planted with or without a cultch base.

| **Annual Survival** | | | | | |
|---|---|---|---|---|---|
| 2008-2009 | Intertidal | Subtidal | | Cultched | Not |
| avg | 38.3% | 81.8% | | 81.8% | 80.7% |
| stdev | 13.5% | 12.0% | | 12.0% | 19.3% |



Another variable that we investigated was the requirement for cultch in the semi-soft substrate of Town Pond. Cultching turned out to be a very large commitment of time and effort to complete and it was not immediately evident as to whether this initial step was required for planting oysters in Town Pond. By comparing the overwinter survival of planted oysters in the subtidal component of Plots 1, 3 & 4 (cultched) compared to Plot 5 (non-cultched) we could evaluate the need for cultch on Town Pond restoration sites. Survival of the oysters in the subtidal sections of Plots 1, 3, & 4 (81.8% ±12.0%) was no different than that for Plot 5 (80.7% ± 19.3%), the non-cultched site that was entirely subtidal. Therefore, we concluded that we could continue to expand the Town Pond restoration sites without additional cultch additions prior to planting.

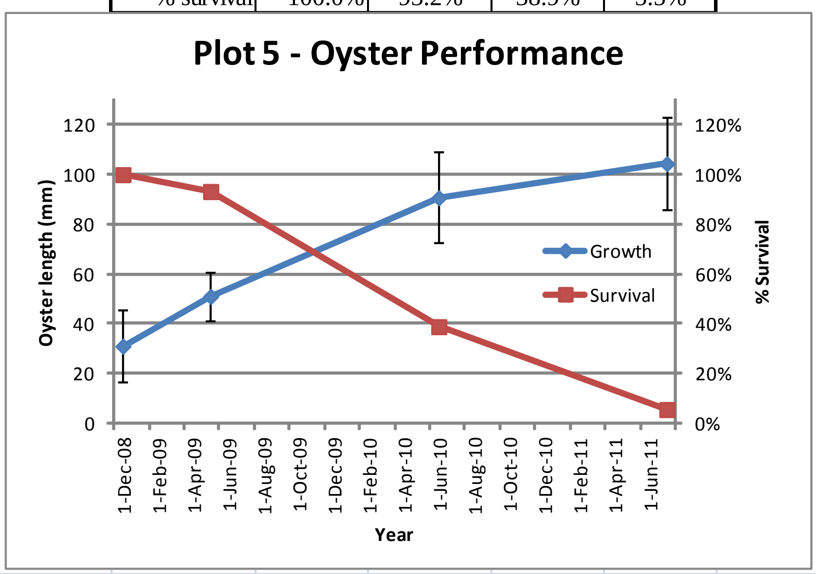
**Growth:**

An important component to evaluate the success of oyster restoration is the growth rate of oysters within the restored population. The size and rate of growth dictates their reproductive contribution to the continuation of the population as well as their probability of survival, primarily against predation. For the most part, measuring the rate of growth for the mixed populations in Town Pond have been confused because of the three year classes planted within the same restoration area. Differentiating specific year classes of oysters can be problematic due to the highly variable nature of their growth and the overlay of one age class on another. However, there are two planting situations that allow us to approximate the size class distribution for the 2008 and the 2010 plantings.

The first estimate of overall oyster growth in Town Pond can be measured for the 2008 year class by following the size of the individual oysters in Plot 5. This plot was planted only in 2008 and therefore only has members of that year class. The average length of oysters in Plot 5 was initially 31.0 mm (±14.5) when planted on 6 December 2008 and they grew to an average length of 104.4 mm (±18.4) by 6 July 2011 (Table 8 and Figure 4). Over the same elapsed time, the population size dropped to 5.5% of the initial planting by 2011 (as described above and in Table 8 and Figure 4).

Table 8 & Figure 4: Analysis of the growth and survival performance of a single cohort of oyster spat-on-shell planted on Plot 5 in Town Pond.

| **Growth & Survival** | | | | |
|---|---|---|---|---|
| Plot 5 (no cultch) | | | | |
| | 6-Dec-08 | 26-May-09 | 24-Jun-10 | 6-Jul-11 |
| avg size (mm) | 31.0 | 51.0 | 90.7 | 104.4 |
| stdev | 14.5 | 9.9 | 18.3 | 18.4 |
| % survival | 100.0% | 93.2% | 38.9% | 5.5% |




The overall size structure of the Plot 5 population, when sampled on 6 July 2011, is represented in Figures 5a & b. Through the use of Magic Plot® software, the size frequency distribution curve was smoothed and approximately fitted by eye (Figure 5b) to the real distribution, as represented in Figure 5a. The line in Figure 5a is

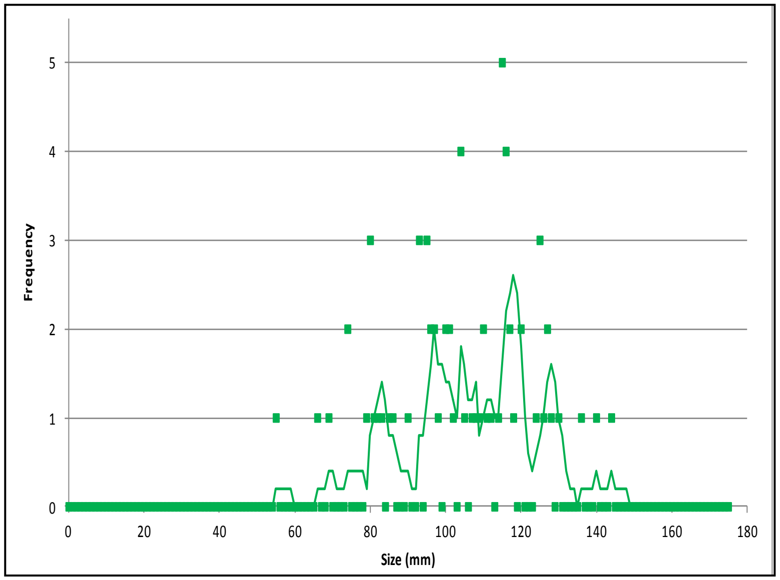


Figure 5a: The size frequency distribution of oyster lengths measured from the population of oysters located in Plot 5 in Town Pond. The solid line represents a 5-point moving average of the data.

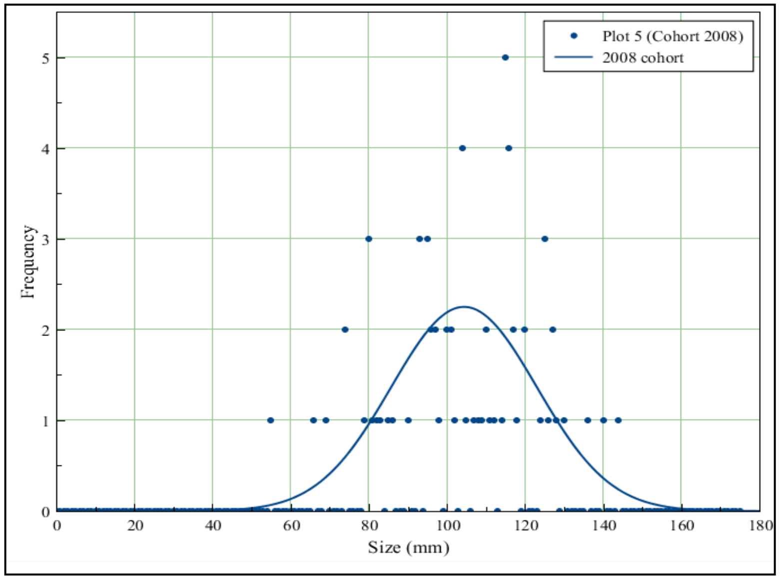


Figure 5b: An estimate of the size distribution of oysters in Plot 5 of Town Pond, where the size frequency curve has been smoothed through the application of Magic Plot® curve fitting software.

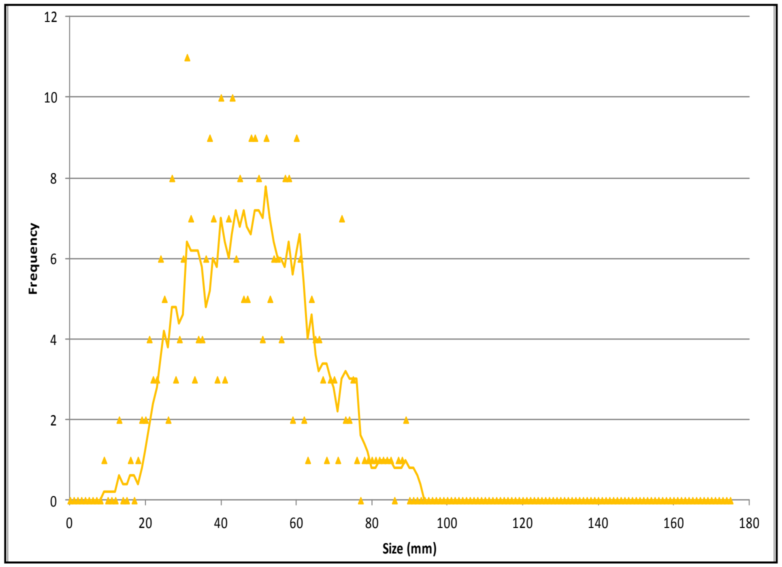


Figure 6a: The size frequency distribution of oyster lengths measured from the population of oysters located in Plot 6 in Town Pond. The solid line represents a 5-point moving average of the data.

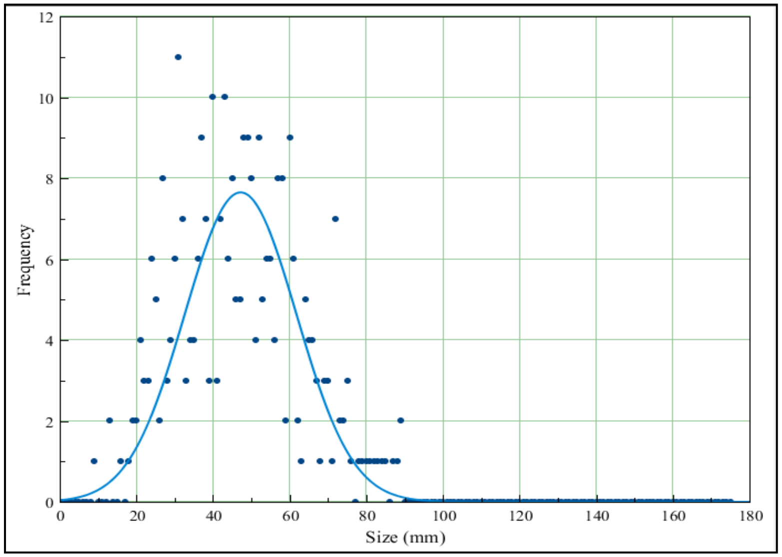


Figure 6b: An estimate of the size distribution of oysters in Plot 6 of Town Pond, where the size frequency curve has been smoothed through the application of Magic Plot® curve fitting software.

a 5-point moving average to initially smooth the line for visualization.

A similar determination of the size of a second specific year-class of planted oysters (2010 planting) can be generated by analyzing the size frequency distribution of those oysters planted in Plot 6 (Figures 6a and b). Only the 2010 year class was planted on Plot 6 and these oysters were placed on the site on September through December of 2010. They were subsequently sampled in July 2011 and the average size of this group of oysters was 47.2 mm ($\pm$17.0) when sampled.

Armed with this information, we can estimate the size frequency distribution of the three year-classes of oysters planted on Plots 1-4 and the proportion of each age-class to the total population. The size frequency distribution of the entire oyster population in Plots 1-4 are depicted in Figure 7a. The shape of the 5-point moving average was duplicated by manipulating the individual year-class contributions in Figure 7b, through the use of Magic Plot® curve fitting software, by eye to fit the moving average.

The resulting plots of each individual year class allows one to determine the overall contribution of that year class to the entire population. Overall, the 2009 year class is the predominant year-class in Plots 1-4 (70.9% of total oysters) followed by the 2008 year class (21.6%) and the 2010 cohort (7.4%) (Table 9). These contributions translate to densities of each cohort equal to 42.2, 12.9, and 4.4 individuals per square meter, respectively (Table 9)

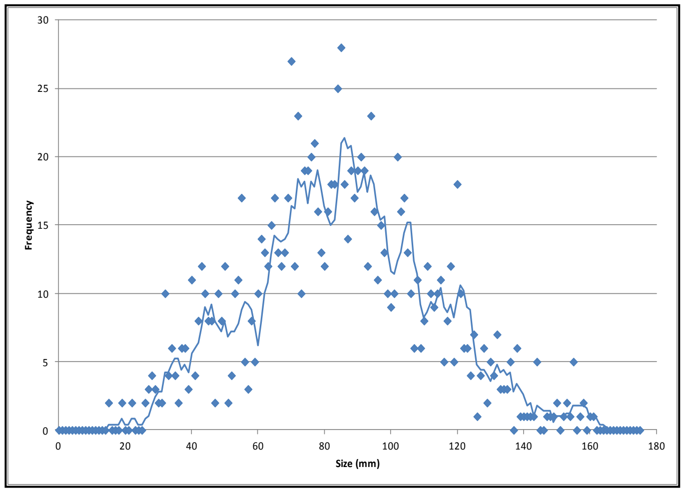



Figure 7a: The size frequency distribution of oyster lengths measured from the population of oysters located in Plots 1-4 in Town Pond.

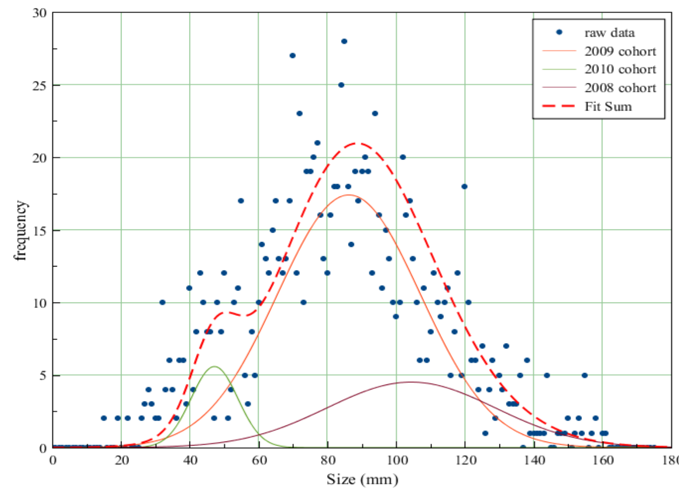



Figure 7b: An estimate of the size distribution of oysters in Plots 1-4 of Town Pond, where the size frequency curve has been broken down into the three constituent annual populations (by eye) and smoothed through the application of Magic Plot® curve fitting software.

Table 9: Summary of the contribution of each year class to total population of oysters in Plots 1-4.

| Plots 1-4 (mixed year class) | 2010 cohort | 2009 cohort | 2008 cohort |
|---|---|---|---|
| mean size (mm) | 47.2 | 86.3 | 104.4 |
| % of total population | 7.44% | 70.94% | 21.61% |
| density of live oysters (ind/$m^2$) | 4.4 | 42.2 | 12.9 |

The delineation of the three year classes demonstrated in Figures 7a & b and Table 9, provides a second method to measure the overall growth rate of oysters planted in town pond. Rather than follow a single cohort over multiple years (Table 8 and Figure 4), one can measure three consecutive year classes planted at the same site. The result of this analysis suggests that the two methods of measuring individual growth rate are very similar and would provide equivalent estimates of oyster growth (Figure 8). Using the single cohort method, oysters planted in Plots 1 – 4 of Town

Pond grew at an average rate of 0.078 mm/d while using the multiple cohort method estimates growth rate at 0.074mm/d.

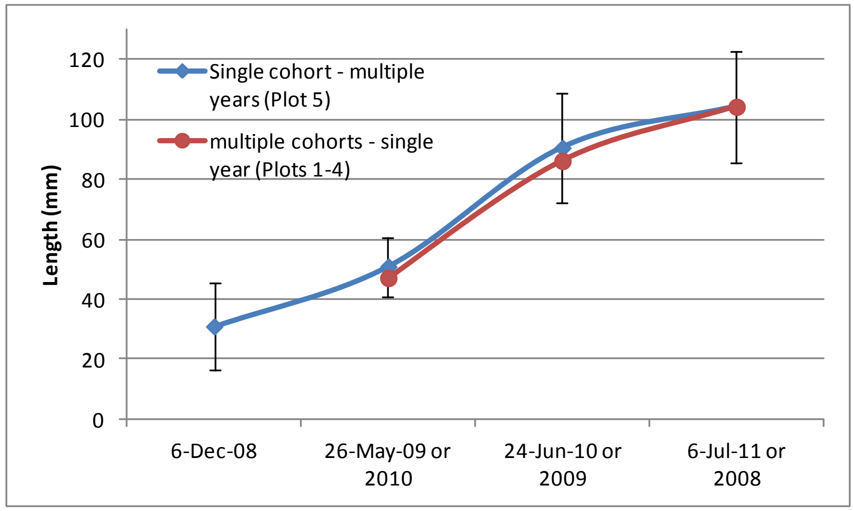


Figure 8: Two methods for measuring oyster growth rate at Town Pond, either a single cohort monitored over a three year period or three year classes measured at one point in time.

**Recruitment:**
The ultimate success of oyster restoration in Town Pond rests on the ability of the restored population to reproduce and sustain itself. Following the first two years of restoration, the individual oysters planted in Plots 1-5 had gained a size and age that allows for the production of eggs and sperm. To measure the reproductive success of the planted oysters and larval retention in Town Pond, during the early summer of 2010 (8 June), a series of spat collectors were placed at random locations throughout Town Pond (Figure 9).

Figure 9: Locations of spat collectors deployed in Town Pond during the early summer of 2010.

Spat collectors consisted of four plastic mesh bags filled with aged surf clam shell that were suspended from a surface buoy and anchored to the location. The collectors were deployed on 8 June 2010 and allowed to remain on site until 6 December 2010. Through that time interval, larval oysters would have a chance to set on the shell material and grow to a size that would allow easy determination of setting frequency and density.

Table 10: Results of spat bag deployments in Town Pond during the summer of 2010.

| Float # | shells/bag | # spat | spat/bag | spat/shell |
|---|---|---|---|---|
| 1 | 164 | on bottom at low tide - predation | | |
| 2 | 145 | 11 | 2.8 | 0.019 |
| 3 | 149 | 17 | 4.3 | 0.028 |
| 4 | lost array | | | |
| 5 | 134 | 33 | 8.3 | 0.062 |
| 6 | 160 | 47 | 11.8 | 0.073 |
| 7 | 99 | 28 | 7.0 | 0.071 |
| 8 | 135 | 36 | 9.0 | 0.067 |
| 9 | 135 | 39 | 9.8 | 0.072 |
| 10 | 141 | 24 | 6.0 | 0.043 |
| mean | 140 | 29.4 | 7.3 | 0.054 |
| stdev | 19 | 11.8 | 3.0 | 0.021 |

Overall, there was oyster spat settlement on the collectors in Town Pond during the summer of 2010. An average of 29.4 ($\pm$ 11.8) juvenile oysters was measured at each spat location and that was equivalent to one oyster spat on approximately every 20 shells placed in the Town Pond environment (Table 10). The average length of the natural occurring 2010 year class settled in Town Pond and measured in December was 39.2 mm ($\pm$ 6.8).

A closer analysis of the size frequency distribution of the wild spat collected in Town Pond during the summer of 2010 (Figure 10a) allows us to further delineate the spat settlement pattern during that reproductive season. Through the application of Magic Plot® software, the 3-point moving average of the size frequency distribution (Figure 10a) can be duplicated by a combination of four distinct cohorts of juvenile oysters (Figure 10b), suggesting four independent spatfalls occurred during the reproductive season (summer 2010). The four cohorts had average lengths of 61.3mm, 44.4mm, 32.8mm, and 21.3mm (Table 11) based on the four peaks identified in Figure 10b.

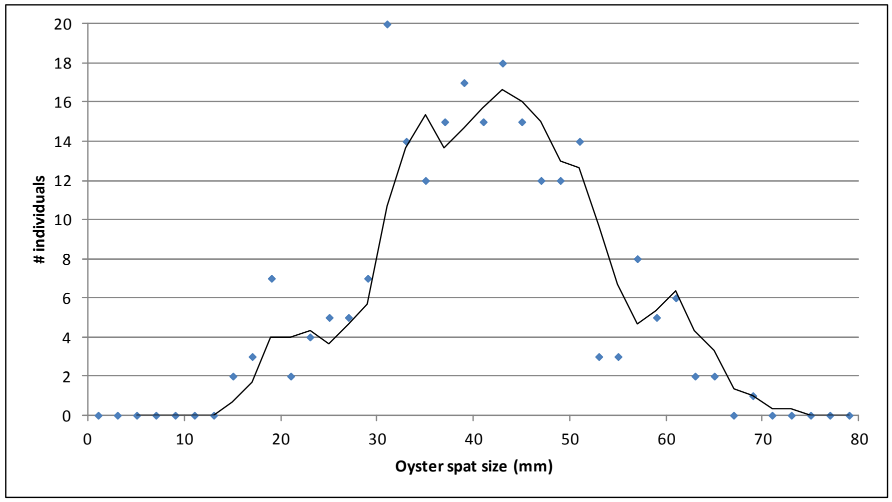



Figure 10a: The size frequency distribution of wild oyster spat settled on collectors in Town Pond during the summer of 2010 and measured on 6 December. The solid line represents a three-point moving average.

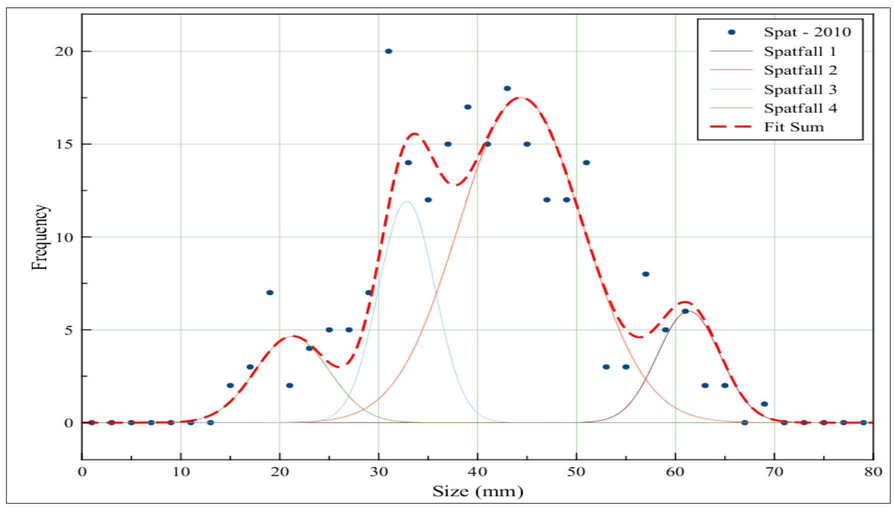



Figure 10b: An estimate of the size distribution of wild oyster spat settled on collectors in Town Pond during the summer of 2010, where the size frequency curve has been broken down into the four constituent settlement events (by eye) and smoothed through the application of Magic Plot® curve fitting software.

Based on the relative size of each peak and the area integrated under each curve, it is possible to assign a relative level of contribution of each spawning event to the overall recruitment for the reproductive season (Table 11). In Town Pond during the summer of 2010, the second wave of larval settlement contributed the largest amount of the recruited juvenile oysters (61.0%) with the third wave providing 18.9% of the total recruits. These are followed by approximately equal contributions from the first and fourth waves (10.6% and 9.6% respectively).

Table 11: Calculation of average size and level of contribution of each spat settlement event to total spatfall, derived from Figure 11b.

| Spat fall event | Area | % of total | Size (mm) | stdev |
|---|---|---|---|---|
| 1 | 47.8 | 10.6% | 61.3 | 6.0 |
| 2 | 275.9 | 61.0% | 44.4 | 17.5 |
| 3 | 85.3 | 18.9% | 32.8 | 11.9 |
| 4 | 43.3 | 9.6% | 21.3 | 4.6 |
| Total | 452.3 | 100.0% | | |

If we match the size of the juveniles in December to those originating from the OGRE Program, the third wave of wild spat recruitment is approximately equivalent to the size of the OGRE spat, which was settled in late June in the RWU Hatchery. This suggests that the primary larval production of oyster spat in Town Pond (second wave) most likely occurred during early to mid-June, with the earliest happening in late May to early June and the latest occurring probably in late July.

**Habitat Enhancement:**
Evaluation of the role that restored oyster sites may play in the overall structure of the ecosystem was completed as an undergraduate Senior Thesis for 2010 RWU graduate Todd Massari. The following presentation of Todd's thesis summarizes his findings without providing any of the detail of his methods or results. For a complete discussion of this work, Todd's thesis is included in Appendix B, attached to this document.

In addition to the economic benefit of oyster beds in Narragansett Bay, it is a well-established concept that oysters provide a series of ecosystem services that enhance the quality of the environment where they occur. To evaluate the services provided by oysters restored to Town Pond, a number of environmental parameters were evaluated, including sediment carbon and nitrogen content along with density and diversity of infaunal invertebrates, epifaunal invertebrates and epifaunal finfish. Town Pond oyster restoration site were measured for these variables and compared to a non-oyster site within Town Pond as well as both restored and non-oyster sites at two other locations in Rhode Island, Bissel Cove in Narragansett Bay (North Kingston, RI), and Smelt Brook Cove in Point Judith Pond (Wakefield, RI).

Based on sediment carbon and nitrogen content, Town Pond was intermediate between the highest (Bissel Cove) and the lowest (Smelt Brook Cove) with an average sediment carbon content of 1.47% and nitrogen content of 0.12% and with no differences detected between the restored oyster bottom and non-oyster bottom. However differences were significant between restored oyster bottom and non-oyster bottom when the mean abundance of infaunal invertebrates in Town Pond was considered. Restored oyster bottom supported a significantly higher total infaunal invertebrate abundance of 0.13 individuals per $cm^3$ ($\pm$0.03) compared to non-oyster bottom (0.04 $\pm$0.008). In addition, Town Pond restored oyster bottom supported a higher infaunal invertebrate abundance than was observed at the other two oyster restoration sites (Figure 12). Similar observations were made on species richness of infaunal invertebrates between sites and among locations.

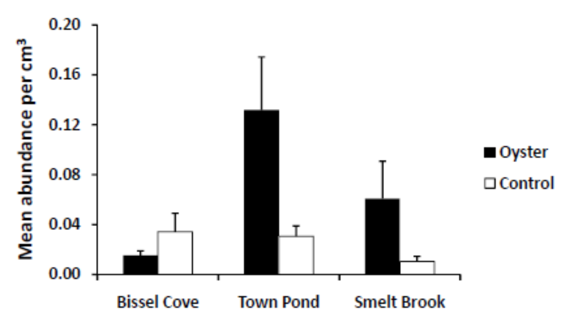



Figure 12: Comparison of infaunal invertebrate abundance between restored and non-oyster sites among three locations in Rhode Island.

The results from measurements of epifaunal invertebrate and vertebrate use of the restored oyster sites was less clear, most likely due to the biased sampling resulting from using baited traps to assess these abundances. Overall, the only differences noted between restored oyster bottom and non-oyster bottom was in species richness between the two sites at all locations and the species diversity when the results were pooled.

In conclusion, Todd summarized his overall study on the effects of restored oyster beds on ecosystems with the following paragraph:

"*This study demonstrated that restored oyster beds in Narragansett Bay have the potential to impact the community structure of marine benthos and macrofauna. Although the OB* [restored oyster bed] *sites did not appear to impact the levels of sedimentary organic compounds based on the data, this may have been a result of the increased attraction to the OB sites by infaunal invertebrates. Therefore, it is possible that these organisms masked the impact of oysters on the benthic sediments. The data for the infauna supported the initial hypotheses for this research because oysters did appear to increase their presence. This also appeared to impact the community structure of finfish with regards to the number of species present. With several different explanations as to why finfish would be more attracted to the OB sites, the food resources provided by a thriving benthic infaunal community seems like a major driving force. The insignificance between OB and NOB* [non-oyster bed] *sites for epifaunal invertebrate data and finfish abundance is most likely due to the bias created by sampling gear and lack of distance separating the two sites from one another at each field location. Restoration oyster beds have the potential to enhance the ecology of coastal habitats in Narragansett Bay, but a longer term study with sound sampling methods is necessary to examine their overall impacts."*

**Results Summary:**
The gauge of success of an oyster restoration program is dependent on establishing a viable oyster population that is capable of sustaining itself and (hopefully) expanding due to its inherent reproductive capacity. Overall, the restoration of oysters to Town Pond has been an unarguable success. The oyster spat planted in the Pond has survived, grown, reproduced and supported recruitment of new oysters into the existing population. While expansion of the population has not been documented, due to lack of funding to survey for new recruits throughout the entire Pond and surrounds, the presence of viable spat on the collectors in the Pond indicates that the potential for expansion is present, provided adequate substrate is available to support new oyster recruits. Through the concerted efforts of Roger Williams University, the US Army Corp of Engineers, the NOAA Community Restoration Program and the RI Department of Environmental Management, the restoration of Town Pond has been enhanced with the successful introduction of native oysters to the ecosystem.

**Future Plans:**
While the initiation of the restoration of oysters into Town Pond has been successfully completed, we propose to continue our work in the Pond, contingent on the acquisition of new funding to support our efforts. A continuing plan for the restoration of oysters in Town Pond and throughout the Mount Hope Bay/Narragansett Bay system would include the following aspects:

- Oyster Restoration, in general:
    - Continue to generate spat on shell for oyster restoration through supporting and expanding the RI Oyster Gardening for Restoration and Enhancement Program;
    - Identify, establish and stock old and new oyster restoration areas within the system;
    - Expand our monitoring efforts to document the successes and failures of oyster restoration in Rhode Island and to fine tune our capacity to identify viable restoration areas;
- Town Pond, specifically:
    - Continue to expand the restored areas by the addition of new oysters generated by the OGRE Program;

- Continue to monitor the existing stocks and expand our database documenting the successes and failures of oyster plantings in Town Pond;
- Deploy new cultched areas in late May to early July to assess the potential for new oyster recruits generated by the existing restored populations and evaluate the potential for lack of suitable habitat to limit the expansion of new or larger oyster areas;

**Appendix A:** Photo journal of oyster restoration in Town Pond (Portsmouth, RI).

Figure A-1: Laying out the oyster restoration grid in Town Pond (summer 2080).


Figure A-2: Relaying cultch to Plots 1 – 4 in Town Pond (summer 2008).


Figure A-3: Cultched Plots 1 (foreground) through 4 (adjacent to Railroad Trestle in background) ready to receive spat-on-shell (winter 2008-9).

Figure A-4: Spat on shell oysters generated by the RI OGRE Program and ready for planting on the cultch beds in Town Pond (fall 2008).

Figure A-5: Distributing oyster spat-on-shell from totes onto cultched plots in Town Pond (fall 2008).

Figure A-6: Planted oysters on Plots 1-4 in Town Pond, one year following initial planting (fall 2009).

Figure A-7: Close-up of one-year old oysters retrieved from the planted plots in Town Pond (fall 2009).

**Appendix B:** The Senior Thesis of Todd Massari (RWU - B.S. 2010), including studies of the habitat value of restored oyster bottom in Town Pond and at other sites within Rhode Island.

# Effects of biogenic oyster beds on benthic sediments and infaunal and epifaunal community structure in Narragansett Bay, Rhode Island

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May 2010

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# ABSTRACT

The Eastern oyster (*Crassotrea virginica*) is an ecologically important species that provides multiple ecosystem services, including the potential to increase complex habitat for resident marine fauna. The objective of this study was to determine if the presence of restored oyster beds in the Narragansett Bay (RI, USA) had significant effects on: (1) sediment nitrogen and carbon levels, and (2) the abundance, richness and diversity of benthic infaunal invertebrates, mobile epifaunal invertebrates, and finfish. During the summer of 2009, oyster bed sites (OB) and non-oyster bed control sites (NOB) at Bissel Cove (Narragansett Bay, RI), Town Pond (Mount Hope Bay, RI) and Smelt Brook Cove (Point Judith Pond, RI) were sampled fortnightly using a combination of benthic core samples and baited traps. There was no difference in the percent sediment nitrogen and carbon between OB and NOB sites ($p$=0.11 and 0.39, respectively). Relative to NOB sites, total abundance of infaunal invertebrates was greater at the Town Pond and Smelt Brook Cove OB sites ($p$<0.05), while species richness was greater at OB across all study sites ($p$<0.0001). Species diversity of infaunal invertebrates was roughly the same for OB and NOB sites (Simpson's Index: OB=5.18, NOB=5.19; Shannon Index: OB=0.85, NOB=0.83). Total abundance and species richness did not differ between OB and NOB sites for epifaunal invertebrates ($p$=0.88 and 0.82, respectively). Again, the species diversity of epifaunal invertebrates was the same between sites (Simpson: OB=2.49, NOB=2.48; Shannon: OB=0.47, NOB=0.46). Similarly, the total abundance of finfish did not differ between OB and NOB sites ($p$=0.88), but species richness was greater at OB sites ($p$<0.001). The species diversity of finfish did appear to be greater at the OB compared to the NOB sites (Simpson: OB=2.11, NOB=1.45; Shannon: OB=0.48, NOB=0.31). This study demonstrated that the

presence of oysters can significantly affect the community structure of certain marine organisms across multiple trophic levels.

# BACKGROUND INFORMATION

Oysters, including the Eastern oyster (*Crassostrea virginica*), are filter feeding bivalves that use coastal ecosystems as suitable habitat for settlement and survival (Reeb & Avise 1990; Hargis, Jr. & Haven 1999). *C. virginica* can be found along the Atlantic coast of North America, ranging from the Gulf of St. Lawrence (Canada) to the Yucatan Peninsula (Mexico), and potentially as far south as Brazil (Buroker 1983). This latitudinal range of approximately 9000 km would suggest that *C. virginica* is well adapted to survive in a broad range of environmental and ecological conditions. It is a euryhaline species (surviving in salinities as high as 35 ppt), but it typically reproduces in waters with salinities that are fairly low (Buroker 1983; Newell 1988). Along the eastern United States, two major estuarine habitats historically rich in wild *C. virginica* populations were Chesapeake Bay (Maryland/Virginia) and Narragansett Bay (Rhode Island) (Ulanowicz & Tuttle 1992; Hargis, Jr. & Haven 1999; Kirby 2004).

The oyster beds of the Chesapeake Bay developed between 6000-7000 years ago during the Holocene, and until the last 200 years, these beds were able to sufficiently maintain and replenish themselves (Hargis, Jr. & Haven 1999; Kirby 2004). The history of the Chesapeake Bay region and *C. virginica* can be traced back at least as far back as the early colonists in Jamestown, Virginia (Hargis, Jr. & Haven 1999). *C. virginica* remains the single most valuable seafood item extracted from a region that has come to rely heavily on this estuary, totaling over $5 million for 2008 (Fig. 1.2A) (Kennedy & Breisch 2001; NOAA Commercial Fisheries Annual Landings data).

Since the 1800's, wild populations of *C. virginica* in the Chesapeake Bay have declined precipitously (Newell 1988). Wild harvests averaged about 10 million bushels of oysters per year during the late 19$^{th}$ century, compared to about 2 to 3 million bushels per year during the

20th century (Fig. 1.1) (Kennedy & Breisch 2001). The harvests from the late 19th century comprised a large percentage of the world production of oysters, peaking at 615,000 metric tons in 1884-1885 (Rothschild et al. 1991). The decline of *C. virginica* in the Chesapeake Bay can be attributed to several factors, including historical overharvesting by humans (Hargis, Jr. & Haven 1999; Kennedy & Breisch 2001), and the recent introduction of lethal shellfish pathogens during the last few decades (Andrews & Hewatt 1957; Fayer et al. 1998).

Recent harvests have shifted from those dominated by the natural cycles of reef replenishment to one of put-and-take methods controlled by human efforts (Kennedy & Breisch 2001). Overharvesting and decimation of natural *C. virginica* populations have had other profound impacts on the Chesapeake Bay (Fig. 1.1), leading to a drastic reduction in the overall fecundity of broodstock oysters and the genetic diversity of individual populations (Hargis, Jr. & Haven 1999). The loss of oysters as biofilters may be leading to an increase in anoxic episodes during the summer phytoplankton blooms and in coastal eutrophication (Newell 1988; Cerco & Noel 2007).

One of the most prevalent diseases to have affected oysters in the Chesapeake Bay has been *Perkinsus marinus*, more commonly known as *Dermo* (Andrews & Hewatt 1957). This fungus does not harm humans but causes mass mortalities among shellfish. It has been studied along the Atlantic coast and has increased its range from the Delaware Bay region up into New England waters since it was studied during the 1950s (Andrews & Hewatt 1957). Another deadly parasite that is of human concern is *Cryptosporidium parvum*, which accumulates in oyster tissue and then can be consumed by humans (Fayer et al. 1998).

Narragansett Bay is one of the largest estuaries in New England and historically maintained thriving natural populations of *C. virginica* (Kirby 2004; Calabretta & Oviatt 2008).

While the Narragansett Bay/Long Island Sound coastal region did not rival the Chesapeake Bay in historical annual production, it still provided oysters as a valuable seafood product as a result of shellfish aquacultural practices (Loosanoff et al. 1939). In 1950, the Rhode Island oyster industry was worth $429,240. Even in 2007, the annual landings were quite high, valued at $1,608,892 (Fig. 1.2B) (NOAA Commercial Fisheries Annual Landings data). Currently, native populations of *C. virginica* in the Narragansett Bay only exist in sparse, isolated locations throughout the estuary (DeAngelis et al. 2009). The annual landing for 2008 was only about .5 metric tons of oysters and the industry was valued at $5,034 (Fig. 1.2B) (NOAA Commercial Fisheries Annual Landings data). The reasons for the decline include overharvesting and shellfish pathogens. The historical patterns of oyster production and decline are not as extensively documented as they are for the Chesapeake Bay region (Newell 1988; Rothschild et al. 1991; Ulanowicz & Tuttle 1992; Hargis, Jr. & Haven 1999; Kennedy & Breisch 2001; Cerco & Noel 2007).

With the recent decline of *C. virginica* in the Chesapeake Bay, Narragansett Bay, and other estuaries along the eastern United States, it has become increasingly important to begin implementing oyster restoration (Coen & Luckenbach 2000). In Maryland, legislation (MD DNR 2004) was recently passed for restoration measures that include habitat reconstruction, establishment of coastal marine sanctuaries, and strictly managing the maximum harvest levels (Paolisso et al. 2006). The goal of shellfish habitat restoration is very different and challenging compared to that of seagrass, mangrove or other coastal habitats. This is because oysters are harvested as a resource so the habitat itself will ultimately be removed to some extent (Coen & Luckenbach 2000). The Chesapeake Bay experienced some success during the 1960s through means of shell and seed planting. The annual harvest during the early part of the decade averaged about 1.6 million bushels, but increased to 2.6 million from 1966-1975 (Kennedy & Breisch 2001). Within Narragansett Bay, oysters are being grown through the use of aquaculture methods such as floating upweller systems (FLUPSY) and oyster gardening programs (D. Leavitt, personal communication). Once the juvenile oysters reach the desired size to safely release them, they are scattered throughout the bay at carefully established permanent oyster restoration sites (DeAngelis et al. 2009). This has occurred regularly since 2003 in Rhode Island.

Restoration of *C. virginica* still has many obstacles to overcome in upcoming years. There is still the ever present danger of people moving into the restoration sites and taking oysters despite legislation guarding against this. There is also the issue concerning the ability of oyster beds to begin naturally reproducing and replenishing themselves. Oyster sites in the Narragansett Bay have been monitored for gonad development as well as spawning and recruitment (DeAngelis et al. 2009). One method to sample for oyster larvae has been through the use of spat collectors, which provide solid substrate for the larvae to settle (DeAngelis et al. 2009). Thus far, spat have not been documented in any significant numbers at these sites. Therefore, it is important in the coming years to dedicate more research and restoration efforts to replenishing natural populations of *C. virginica* and to monitor them closely to ensure future survival.

The goal of oyster restoration was traditionally to replenish the population of natural oysters in the environment for harvesting and consumption purposes (Coen & Luckenbach 2000). There are many secondary benefits of restoration oyster bed habitats, including their potential to create structured habitats for a variety of marine fauna (Lehnert & Allen 2002; Henderson & O'Neil 2003). As scientific research begins to shift towards an ecosystem based approach to oyster restoration and management, it is becoming increasingly harder to balance the needs of the seafood industry with those of the coastal marine environments (Coen & Luckenbach 2000). There is now an increased need to incorporate both science and business into the practice of oyster restoration (Soniat & Brody 1988; Coen & Luckenbach 2000).

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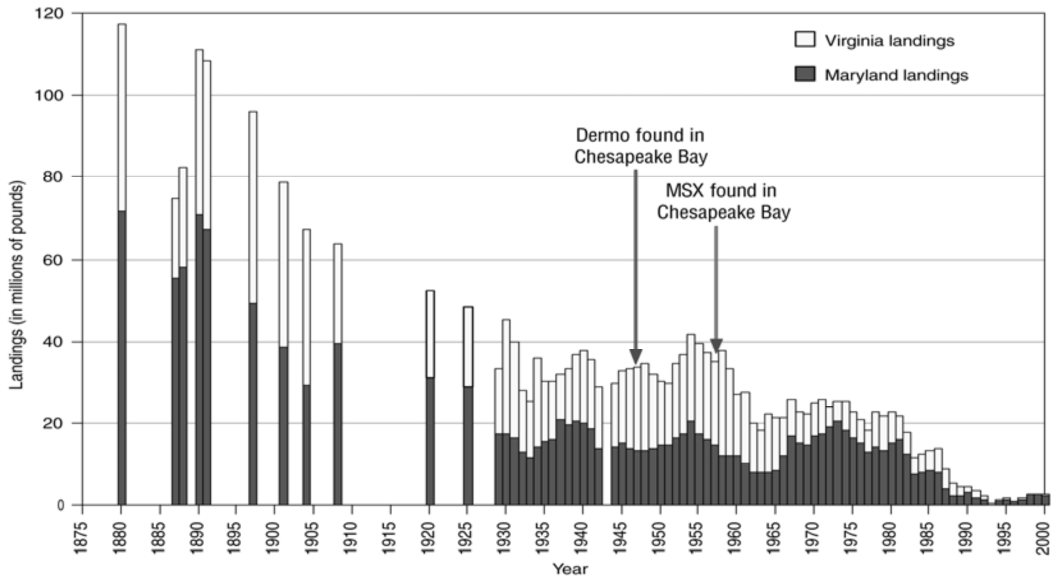
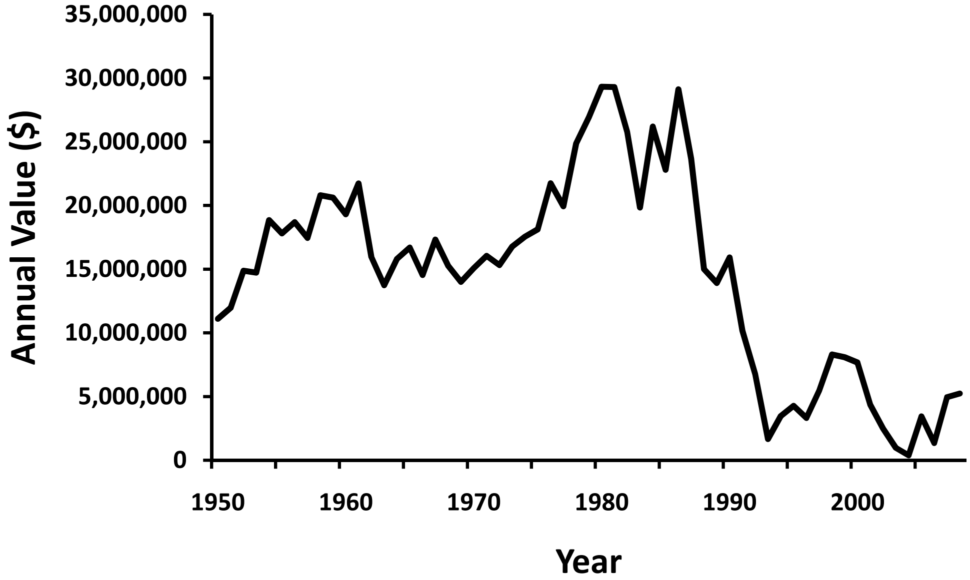



**Figure 1.1.** Annual commercial oyster landings (5 year increments) in the Chesapeake Bay for Maryland and Virginia since 1875. The first traces of *Dermo* and MSX in oysters are also highlighted. (http://dels.nas.edu/oceans/marine_ecosystems_part_2.shtml)

A.




B.

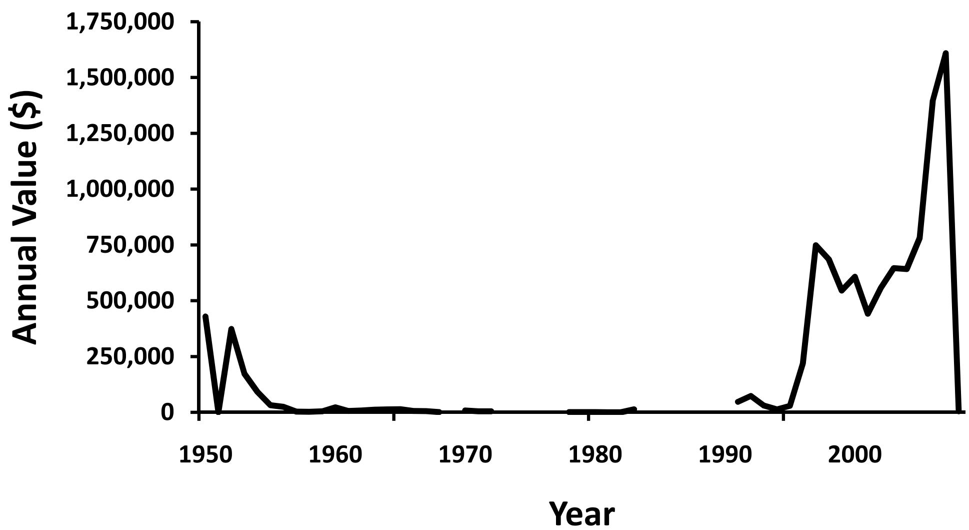



**Figure 1.2:** Annual value ($) of *C. virginica* industry in **(A)** Chesapeake Bay (Maryland and Virginia combined) and **(B)** Rhode Island from 1950 to 2008 (10 year increments).

# INTRODUCTION

The Eastern oyster (*Crassostrea virginica*) is an economically and environmentally important native shellfish species along the Atlantic and Gulf coasts of the United States (Henderson & O'Neil 2003; Grizzle at al. 2005; Grabowski & Peterson 2007). Recent declines in the wild oyster populations have prompted the need for restoration efforts (Newell 1988; DeAngelis et al. 2009). Oysters are biologically important because their filter-feeding removes suspended particulate matter to improve overall water quality and promote the cycling of nutrients in a habitat (Meyer & Townsend 2000; Lehnert & Allen 2002). The three-dimensional biogenic oyster beds improve habitat complexity, diversity and water quality by increasing finfish and invertebrate diversity (Lehnert & Allen 2002; Henderson & O'Neil 2003; Peterson et al. 2003; Grabowski & Powers 2004; Piazza et al. 2005; Plunket & La Peyre 2005; Tolley & Volety 2005; Grabowski & Peterson 2007), production of natural oyster populations (Coen et al. 2007; Grabowski & Peterson 2007), filtration and clarification of the water column (Meyer & Townsend 2000; Nelson et al. 2004; Grabowski & Peterson 2007), coastal protection against erosion and hydrodynamic dampening (Henderson & O'Neil 2003; Grabowski & Peterson 2007), and overall habitat complexity within coastal marine environments (Meyer & Townsend 2000; Lehnert & Allen 2002).

The role of oyster beds as habitat for invertebrates and finfish is now well documented (Lenihan et al. 2001), and is best understood through a cause-and-effect process that begins with filter-feeding. As they filter the water, oysters, such as *C. virginica*, produce feces and pseudofeces that are are incorporated into the benthic sediment (Grabowski & Peterson 2007). As a result, there is an increase in the concentration of benthic nitrogen on an oyster bed. In addition, filter-feeding decreases phytoplankton abundance, which leads to an increase in light penetration and an increase in the presence of submerged aquatic vegetation (Grabowski & Peterson 2007). As the oyster bed habitat increases in size and complexity, a greater diversity of invertebrates occupies the space (Lehnert & Allen 2002; Henderson & O'Neil 2003; Grabowski & Powers 2004; Tolley & Volety 2005). Once the population of benthic invertebrates increases, finfish are attracted to the bed because of increased food resources (Meyer & Townsend 2000; Peterson et al. 2003; Plunket & La Peyre 2005; Grabowski & Peterson 2007). Oyster habitat may also serve as critical nursery for juvenile finfish, providing refugia from predation (Heck Jr. et al. 1995; Beck et al. 2001).

Numerous studies have been conducted on the role of oyster beds in structuring particular aspects of coastal marine ecosystems. However, in general these do not provide a synoptic examination of the effect of oyster beds on localized habitat. The purpose of this study is to investigate the impact of three-dimensional oyster beds on community structure of local marine fauna. To better understand the effects of oysters on marine fauna, the direct functional role of oysters was examined. The effect of oysters on sediment nitrogen and carbon concentrations was assessed. Following this, a biotic survey was conducted to sample the abundance, richness and diversity of invertebrate species and finfish that use the oyster bed as a habitat. This helped to determine if there was a connection between the nitrogen/carbon levels and overall invertebrate/finfish community structure (Lehnert & Allen 2002; Henderson & O'Neil 2003; Grabowski & Powers 2004; Tolley & Volety 2005). By studying multiple trophic levels, the impact of oyster beds on community structure of marine fauna could be better understood.

## MATERIALS AND METHODS

### *Sampling Sites*

Three field locations were monitored in major water bodies within Narragansett Bay, RI: Town Pond (Portsmouth, RI), Bissel Cove (North Kingstown, RI) and Smelt Brook Cove (Point Judith Pond, Wakefield, RI) (Fig. 2.1). Water temperature (°C), dissolved oxygen (mg/L) and salinity (ppt) were measured during each sampling time using a handheld YSI instrument (Table 2.1). At each of these locations, there was one OB site and one NOB site, with each site sampled fortnightly between late May and early August 2009. There were four sampling dates at Town Pond and Bissel Cove, and three complete dates at Smelt Brook Cove. An initial site assessment of each OB was conducted prior to the sampling period. At each OB site, the density of oysters per square meter was measured through the use of 10-15 0.25 $m^2$ quadrats. In addition, randomly (random number generator) selected 0.25 $m^2$ quadrats were used to collect all individual oysters and shell height (mm) was measured with Vernier Calipers. The total area ($m^2$) of the oyster bed was estimated using geographic information system (GIS) software (Table 2.2).

### *Sediment Nitrogen/Carbon Analysis*

Sedimentary nitrogen and carbon were measured at OB and NOB sites for the solid phase of the sediment. Sediments were collected using plastic coring tubes (14.5 cm length x 7 cm diameter; n=4 per OB and NOB sites) (Seitzinger 1987). In the laboratory, samples were frozen at -20°C until prepared and analyzed using a CHN analyzer (Thermo Flash EA1112 CHNS/O Analyzer). Samples were thawed and homogenized (stirred with metal spatula), and then a spatula sized sample was taken and placed in a tin foil weigh boat. Samples were then placed in a drying oven at 75°C for 24-48 hrs, ground into a fine powder with the spatula, and stored in scintillation vials (30 $cm^3$). To run the CHN analysis, approximately 5 mg of each sample were weighed and folded into small foil packets for analysis. The total percent dry mass of sedimentary nitrogen and carbon were reported, and a three-way analysis of variance (ANOVA) model was used to test these levels as a function of site (OB and NOB), time, and location.

***Infaunal Invertebrate Analysis***

Benthic invertebrate abundance (# per $cm^3$) and richness were sampled using the same coring procedure described for nitrogen and carbon analysis. Core samples were taken at each oyster and control site (n=4 at each OB and NOB site). Sediment samples were sieved (mesh size = 500 μm) into storage jars in the laboratory and preserved with 10% formalin and Rose Bengal. Later, the invertebrates were extracted from the sediment and restored in vials with 10% formalin. These samples were examined under a stereomicroscope and classified quantitatively to the lowest possible taxa. Total abundance, total richness (# of species), and abundance of specific taxa (polychaetes, crustaceans and gastropods) were analyzed with a three-way ANOVA model using site, time, and location as fixed factors. If the ANOVA were significant, the mean values of infaunal abundance and richness across four levels of time and three levels of location were contrasted with Ryan-Einot-Gabriel-Welsch (Ryan's Q) comparison tests.

To determine the index of infaunal invertebrate species diversity, the Simpson's Index:

$$D = \frac{\Sigma n(n-1)}{N(N-1)}$$

where n is the number of species and N is the total number of organisms documented, and the Shannon Weiner Index:

$$H = \Sigma pi(\ln pi)$$

where $p_i$ is the relative abundance of each species, were both determined.

### *Epifaunal Invertebrate and Finfish Analysis*

To sample the epifaunal invertebrates and finfish, baited traps (clam bellies used as bait) were placed at the field locations. At each OB and NOB site, four Gee Minnow wire mesh traps (length=45 cm, mesh=0.64 $cm^2$) and two rectangular wire mesh traps (33 cm x 46 cm x 91 cm, 45 cm x 4.5 cm "V" opening, 0.6 $cm^2$ mesh) were randomly deployed at high tide ±1 hour. The traps were then removed from the water, fish and invertebrates were enumerated, and lengths were measured as follows: carapace length for crabs (mm), rostrum length for shrimp (mm) and total length (mm) for finfish. Following classification and measurement, all individuals were returned to their place of capture. A two-way ANOVA was used to analyze the total abundance and species richness of epifaunal invertebrates and finfish as a function of site and time. The experimental unit being tested in this methodology was the field location. To determine the index for epifaunal invertebrate and finfish species diversity, the Simpson's Index and the Shannon-Weiner Index were both determined.

## RESULTS

### *Sediment Analysis*

Mean percent total sedimentary nitrogen differed significantly as a function of field location, but not site or time (Fig. 2.2A, Table 2.3). Bissel Cove experienced the greatest percent total nitrogen (OB=0.14% ± 0.01, NOB=0.19% ± 0.03), ranging from 0.01 to 0.30% across the OB and NOB sites. The Town Pond nitrogen was roughly equal between the two sites (OB & NOB=0.12% ± 0.02), while the level of nitrogen was also greater on the NOB site at Smelt Brook Cove (OB=0.05% ± 0.01, NOB=0.08% ± 0.02). The interaction effects for total nitrogen (location-time, site-location, time-site) did not yield any significant differences. The range of nitrogen levels over time ranged from 0.09% during the first sampling period (June 16-18, 2009) to 0.13% during the second (June 30-July 6, 2009) and fourth (July 27-29, 2009) sampling periods.

The analysis for percent total sedimentary carbon yielded similar results to that of nitrogen, with the levels of carbon significantly greater at Bissel Cove (1.62%) and Town Pond (1.47%) than Smelt Brook Cove (0.65%) (Fig. 2.2B, Table 2.3). While carbon did not differ between OB and NOB sites, the range of total carbon levels was broader on the NOB sites at Bissel Cove (OB=0.71-2.06%, NOB=0.23-3.62%) and Smelt Brook Cove (OB=0.23-1.59%, NOB=0.21-2.26%). Time was a not a significant factor in the carbon analysis, ranging from 1.12% during the first sampling period to 1.39 % during the second sampling period. Total percent carbon data did not yield any significant differences in any of the interaction effects analyzed.

***Infaunal Invertebrate Analysis***

The mean abundance per $cm^3$ of total infaunal invertebrates, polychaetes and crustaceans was significantly different with regards to field location, time series, and site (Fig. 2.3A, 2.4A, 2.4B, Tables 2.3, 2.4). For the total invertebrates, polychaetes and crustaceans, Town Pond (0.09, 0.07, and 0.01 individuals per $cm^3$, respectively) had a greater abundance compared to Bissel Cove (0.03, 0.02, and 0.002 per $cm^3$, respectively) and Smelt Brook Cove (0.05, 0.04, and 0.001 per $cm^3$, respectively). Town Pond and Smelt Brook Cove experienced a greater abundance of infauna on the OB site for total abundance (TP: OB=0.13 ± 0.03, NOB=0.04 ± 0.008; SBC: OB=0.60 ± 0.01, NOB=0.03 ± 0.004 invertebrates per $cm^3$) and polychaetes (TP: OB=0.11 ± 0.03, NOB=0.04 ± 0.008; SBC: OB=0.48 ± 0.01, NOB=0.02, 0.004 invertebrates per $cm^3$) than Bissel Cove. The interaction of site-location was significant for the total abundance and polychaete abundance (Table 2.4), with Town Pond demonstrating increased abundance as a location and on its OB site. For the crustacean abundance, the time-location interaction revealed that Bissel Cove had the greatest abundance during the earliest sampling period (0.008 per $cm^3$) and Town Pond during the final sampling period (0.02 per $cm^3$). In the analysis of gastropod abundance per $cm^3$, Smelt Brook Cove had a significantly greater abundance (0.006 per $cm^3$) than Bissel Cove (0.003 per $cm^3$) and Town Pond (0.00 per $cm^3$) (Fig. 2.4C, Table 2.4). Gastropod abundance did not differ at any of the three locations between the OB and NOB sites.

The species richness per $cm^3$ increased on the OB sites versus the NOB sites at Town Pond (OB=0.012 ± 0.01, NOB=0.007 ± 0.0007 per $cm^3$), Smelt Brook Cove (OB=0.014 ± 0.0014, NOB=0.006 ± 0.0006 per $cm^3$) and Bissel Cove (OB=0.008 ± 0.002, NOB=0.004 ± 0.002 per $cm^3$) (Fig. 2.3B, Table 2.5). Smelt Brook Cove (0.01 per $cm^3$) and Town Pond (0.01 per $cm^3$) as field locations experienced a significantly greater richness compared to Bissel Cove (0.006 per $cm^3$). The species richness was variable as a function of time, with the first period (0.01 per $cm^3$) greater than the second (0.005 per $cm^3$) and fourth (0.008 per $cm^3$) sampling dates, and the third period (0.009 per $cm^3$) greater than the second. Patterns in two analyses of species diversity yielded similar results for the three field locations. Bissel Cove appeared to have a greater diversity of infauna on the OB site (Simpson: OB=6.84, NOB=2.85; Shannon: OB=0.96, NOB=0.67) (Table 2.6). This was the same trend experienced at Smelt Brook Cove as well (Simpson: OB=4.71, NOB=4.48; Shannon: OB=0.81, NOB=0.75). At Town Pond, the species diversity was greater on the NOB site (Simpson: OB=3.45, NOB=5.71; Shannon: OB=0.69, NOB=0.81). The species diversity for the combination of the three field locations resulted in similar results for OB and NOB sites (Simpson: OB=5.18, NOB=5.19; Shannon: OB=0.85, NOB=0.83).

### *Epifaunal Invertebrate and Finfish Analysis*

The mean abundance of epifaunal invertebrates revealed no significant difference between the OB and NOB sites (Fig. 2.5A, Table 2.3). The data ranged from 2.02-34.1 invertebrates per trap at OB sites and 1.88-28.7 invertebrates per trap at NOB sites. Although the abundance did not differ over time, there was a broad range between the abundance on the second (3.04 invertebrates per trap) and fourth (27.85 invertebrates per trap) sampling dates. The site-time interaction did not reveal any difference in the abundance of epifaunal invertebrates. Mean species richness per trap of invertebrates was roughly the same between the OB and NOB sites (Fig. 2.5B, Table 2.5). The richness ranged from 0.44-1.67 invertebrates per trap at OB sites and 0.67-1.56 invertebrates per trap at NOB sites. The species richness was relatively stable for epifaunal invertebrates across the four sampling periods (0.96-1.21 invertebrates per trap). Species diversity was roughly equal between OB and NOB sites for the three field locations (Table 2.6). The Simpson Index was 2.49 on OB sites and 2.48 on NOB sites, while the Shannon Index was 0.47 and 0.46 for OB and NOB sites, respectively.

Similar to epifaunal abundance, the mean abundance per trap of finfish did not differ as a function of site (Fig. 2.6A, Table 2.3). Mean abundance ranged from 0.89-3.28 fish per trap at OB sites and 0.28-3.39 fish per trap at NOB sites. Although the finfish abundance was higher during the second sampling period (4.17 fish per trap), it was not significant compared to the first, third and fourth periods (1.17-2.70 fish per trap). The time-site interaction did not reveal any distinct differences in the mean abundance of finfish as well. The mean species richness per trap of finfish was greater on the OB sites at Bissel Cove (OB=0.63 ± 0.06, NOB=0.17 ± 0.03 fish per trap), Town Pond (OB=0.75 ± 0.07, NOB=0.18 ± 0.05 fish per trap) and Smelt Brook

Cove (OB=0.61 ± 0.06, NOB=0.39 ± 0.05 fish per trap) (Fig. 2.6B, Table 2.5). This analysis was one of the only in which the data for the OB was greater than the NOB at all three field locations. There was not a dramatic difference in the finfish richness across the sampling dates (0.39-0.59 fish per trap). The time-site interaction, much like that of the epifaunal invertebrates, was insignificant for finfish species richness (Table 2.5). The species diversity of finfish for the combination of the field locations appeared greater on the OB than the NOB sites (Table 2.6). The Simpson Index yielded a diversity of 2.11 on OB sites and 1.45 on NOB sites, while the Shannon Index was 0.48 on OB and 0.31 on NOB sites.

## DISCUSSION

This study determined the impact of restoration oyster beds on sedimentary nitrogen and carbon, and infaunal/epifaunal invertebrate and finfish abundance, species richness and species diversity. The presence of oysters was found to significantly impact several of the variables being studied, namely: (1) abundance and species richness of total infaunal invertebrates, (2) abundances of infaunal polychaetes and crustaceans, and (3) species richness of finfish. Other variables differed as a function of time, field location, or one or more of the interaction effects of these variables. This suggests that OB-NOB differences are present in certain aspects of the data but these site differences are not the only factors driving oyster bed community structure.

Denitrification is one process that removes organic nitrogen from sediments and converts it to a gaseous state, and it typically occurs when increased levels of oxygen are consumed within a marine system (Seitzinger 1987). The mean dissolved oxygen during the summer of 2009 was lower at the OB sites for all three of the field locations. This may suggest that the higher consumption of oxygen on OB sites limited the levels of sediment nitrogen compared to the NOB sites, accounting for no difference between the sites (Hopkinson & Wetzel 1982; Nielsen & Glud 1996). Similarly, the level of oxygen in a marine environment has been shown to impact the levels of sedimentary carbon (Wenzhofer & Glud 2002). An increased availability of oxygen makes it possible for organic carbon to mineralize in sediments (Wenzhofer and Glud 2002). This may account for the lack of significance between carbon levels of OB and NOB sites.

One unexpected result was that the levels of nitrogen and carbon did not differ over time because the levels of sedimentary organic compounds are known to be both higher and fluctuate more during the summer months (Boucher & Boucher-Rodoni 1988). Boucher & Boucher-Rodoni (1988) suggest that temporal variation is one of the factors influencing nitrogen levels, in particular at oyster habitats. The differences in nitrogen and carbon levels as a function of field location may be due to the differences in oyster density and size, as well as unsampled variables such as sediment grain size (Dale 1974) and phytoplankton biomass (Seitzinger 1987; Lewitus et al. 1998). The oyster bed measurements (size & density) would impact the relative filter-feeding capabilities at each location (Seitzinger 1987). Moreover, with respect to grain size, finer sediments often have a greater surface area than coarser sediments, which could allow for a greater organic content (Dale 1974). Phytoplankton biomasses thrive in high nitrogen regions and those locations with greater relative levels of nitrogen would most likely have reduced biomasses of phytoplankton (Seitzinger 1987).

Infaunal invertebrates, including polychaetes, crustaceans and gastropods, may be attracted to the sediments of OB habitats because there are higher levels of nitrogen, carbon and other organic compounds present from filter-feeding and pseudofeces (Meyer & Townsend 2000; Lehnert & Allen 2002). This would suggest that initially OB sites had greater levels of organic compounds in their sediments compared to NOB sites. Therefore, the abundance of infaunal invertebrates may be greater at OB sites because the organisms are attracted by increased organic matter on which to feed (Oakden 1984; Rudnick et al. 1985; Meyer & Townsend 2000). However, the presence of increased levels of infaunal invertebrates means that there are more living organisms that must consume oxygen to survive (Riedel et al. 1997). This removal of oxygen from the marine system helps lead to the denitrification that results in a removal of organic nitrogen and the demineralization that leads to the removal of organic carbon (Seitzinger 1987; Wenzhofer & Glud 2002). The increase in abundance and species richness of infaunal invertebrates as a result of increased food resources on the OB sites suggests that there would be also be an increase in the abundance and species richness of epifaunal invertebrates and finfish that occupy the space in and above the OB sites (Meyer 1994; Meng & Powell 1999; Peterson et al. 2003).

Increased finfish species richness on OB sites was most likely a result of multiple factors acting together. One of the most likely scenarios for the initial attraction of finfish to OB sites would be the increased structure and refuge they offer, particularly for small juveniles (Keller et al. 1999; Meng et al. 2000; Lenihan et al. 2001; Lehnert & Allen 2002; Peterson et al. 2003; Kimbro & Grosholz 2006). Many species of finfish, such as the winter flounder (*Pseudopleuronectes americancus*) and mummichog (*Fundulus heteroclitus*) utilize coastal habitats such as OB sites in Narragansett Bay as sheltered spawning grounds for their offspring (Meng et al. 2000; McMahon et al. 2005). It is also necessary to consider the abundance and species richness of infaunal invertebrates as a potential impact on the species richness of finfish on OB sites. These invertebrates, especially polychaetes and crustaceans, provide sufficient food resources for the resident finfish species that would attract a more diverse range of species to the

OB sites (Jeffries & Terceiro 1985; Allen et al. 1994; Meng & Powell 1999; Claudet & Pelletier 2004; McMahon et al. 2005). The fact that there is also a greater number of infaunal invertebrates on OB sites suggests that an increase in species richness of finfish is due to the opportunities for more abundance and diverse food resources.

There are several possible explanations for the lack of significance in the abundance and richness of epifaunal invertebrates and abundance of finfish between the OB and NOB sites. Species richness of epifaunal invertebrates was most likely biased from the particular traps that were used for sampling. Minnow traps are effective at sampling certain small estuarine invertebrates such as shrimp and mud snails because they can fit through the small openings in the trap (Layman & Smith 2001). The rectangular collapsible traps are effective at retaining larger, mobile species such as green crabs (*Carcinus maenas*), but smaller organisms can easily slip through the larger mesh. One intermediate sized species that may have been under-represented in the study was the mud crab (Xanthidae), which has been well documented at OB habitats (Meyer 1994). Mud crabs (typically 10-45 mm) can be too large to fit in the minnow traps and too small to retain in the rectangular traps (Whetstone & Eversole 1981). They are also a more cryptic species that is often found within the structured oyster habitat, while the sampling traps were placed over the beds and may not have targeted them as effectively (Bohnsack & Bannerot 1986; Meyer 1994). The abundance of finfish most likely did not differ between OB and NOB sites because of their relative proximity to one another and the ease at which a fish could swim between the two sites (Keller et al. 1999). The baited traps were deployed randomly in the field, and the likelihood of a baited trap at the corner of the NOB site being closer to a finfish on the OB than the closest OB site trap is fairly high.

This study demonstrated that restored oyster beds in Narragansett Bay have the potential to impact the community structure of marine benthos and macrofauna. Although the OB sites did not appear to impact the levels of sedimentary organic compounds based on the data, this may have been a result of the increased attraction to the OB sites by infaunal invertebrates. Therefore, it is possible that these organisms masked the impact of oysters on the benthic sediments. The data for the infauna supported the initial hypotheses for this research because oysters did appear to increase their presence. This also appeared to impact the community structure of finfish with regards to the number of species present. With several different explanations as to why finfish would be more attracted to the OB sites, the food resources provided by a thriving benthic infaunal community seems like a major driving force. The insignificance between OB and NOB sites for epifaunal invertebrate data and finfish abundance is most likely due to the bias created by sampling gear and lack of distance separating the two sites from one another at each field location. Restoration oyster beds have the potential to enhance the ecology of coastal habitats in Narragansett Bay, but a longer term study with sound sampling methods is necessary to examine their overall impacts.

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**Table 2.1.** Mean water quality readings from field sampling dates during summer 2009 at Bissel Cove, Town Pond and Smelt Brook Cove. Data indicates temperature (°C), dissolved oxygen (mg/L) and salinity (ppt) at both oyster bed and non-oysters sites.

| Site | Location | Temperature | Dissolved oxygen | Salinity |
|---|---|---|---|---|
| Oyster | | | | |
| | Bissel Cove | 21.0 | 7.82 | 24.9 |
| | Town Pond | 23.0 | 7.28 | 25.7 |
| | Smelt Brook | 23.1 | 8.02 | 19.0 |
| Non-oyster | | | | |
| | Bissel Cove | 20.9 | 8.06 | 24.9 |
| | Town Pond | 22.2 | 7.52 | 26.5 |
| | Smelt Brook | 23.6 | 9.72 | 20.2 |

**Table 2.2.** Field sites in Narragansett Bay, RI where research was conducted during summer 2009. Each site had a restoration oyster bed and adjacent non-oyster control site. Data indicate date of restoration bed establishment, site area (m2), mean density of oysters (# per $m^2$) and mean shell length of oysters (mm).

| Site | Date established | Oyster/Control | Site Area ($m^2$) | Oyster density (per $m^2$) | Oyster size (mm) |
|---|---|---|---|---|---|
| Bissel Cove | 2006 | Oyster | 2,972 | 18.67 ± 6.4 | 54.6 ± 15.4 |
| Bissel Cove | | Control | 1,204 | | |
| Town Pond | 2008 | Oyster | 400 | 80.0 ± 41.0 | 11.4 ± 4.9 |
| Town Pond | | Control | 410 | | |
| Smelt Brook | 2003 | Oyster | 1,860 | 33.6 ± 7.2 | 65.6 ± 11.4 |
| Smelt Brook | | Control | 853 | | |

**Table 2.3.** Summary of statistical results for mean percent total nitrogen and carbon and mean abundance of infaunal (3-way ANOVA) and epifaunl invertebrates and finfish (2-way ANOVA). Statistical *p* values and F values (with degrees freedom DF) are reported.

| Source | Nitrogen | Carbon | Infaunal Invertebrates | Epifaunal Invertebrates | Finfish |
|---|---|---|---|---|---|
| Site | | | | | |
| F(df) | 2.87 (1) | 2.88 (1) | 3.21 (1) | 0.61 (1) | 0.51 (1) |
| *p* | 0.11 | 0.39 | <0.02 | 0.88 | 0.89 |
| Time | | | | | |
| F(df) | 2.87 (3) | 2.88 (3) | 3.21 (3) | 0.61 (3) | 0.51 (3) |
| *p* | 0.31 | 0.62 | <0.02 | 0.29 | 0.39 |
| Location | | | | | |
| F(df) | 2.87 (2) | 2.88 (2) | 3.21 (2) | N/A | N/A |
| *p* | <0.0001 | <0.0002 | <0.001 | | |
| Site x Time | | | | | |
| F(df) | 2.87 (3) | 2.88 (3) | 3.21 (3) | 0.61 (3) | 0.51 (3) |
| *p* | 0.18 | 0.09 | 0.50 | 0.99 | 0.96 |
| Time x Location | | | | | |
| F(df) | 2.87 (6) | 2.88 (6) | 3.21 (5) | N/A | N/A |
| *p* | 0.30 | 0.22 | 0.34 | | |
| Site x Location | | | | | |
| F(df) | 2.87 (2) | 2.88 (2) | 3.21 (2) | N/A | N/A |
| *p* | 0.45 | 0.20 | <0.01 | | |

**Table 2.4.** Summary of statistical results for mean abundance of infaunal polychaetes, crustaceans and gastropods (3-way ANOVA). Statistical *p* values and F values (with degrees freedom DF) are reported.

| Source | Polychaetes | Crustaceans | Gastropods |
|---|---|---|---|
| Site | | | |
| F(df) | 2.58 (1) | 4.99 (1) | 2.48 (1) |
| *p* | <0.05 | <0.05 | 0.24 |
| Time | | | |
| F(df) | 2.58 (3) | 4.99 (3) | 2.48 (3) |
| *p* | <0.05 | <0.02 | 0.07 |
| Location | | | |
| F(df) | 2.58 (2) | 4.99 (2) | 2.48 (2) |
| *p* | <0.002 | <0.0001 | <0.001 |
| Site x Time | | | |
| F(df) | 2.58 (3) | 4.99 (3) | 2.48 (3) |
| *p* | 0.44 | 0.06 | 0.17 |
| Time x Location | | | |
| F(df) | 2.58 (5) | 4.99 (5) | 2.48 (5) |
| *p* | 0.56 | <0.001 | 0.31 |
| Site x Location | | | |
| F(df) | 2.58 (2) | 4.99 (2) | 2.48 (2) |
| *p* | <0.02 | 0.12 | 0.59 |

**Table 2.5:** Summary of statistical results for mean species richness of infaunal (3-way ANOVA) and epifaunl invertebrates and finfish (2-way ANOVA). Statistical *p* values and F values (with degrees freedom DF) are reported.

| Source | Infaunal Invertebrates | Epifaunal Invertebrates | Finfish |
|---|---|---|---|
| Site | | | |
| F(df) | 4.42 (1) | 0.10 (1) | 3.30 (1) |
| *p* | <0.0001 | 0.82 | <0.01 |
| Time | | | |
| F(df) | 4.42 (3) | 0.10 (3) | 3.30 (3) |
| *p* | <0.001 | 0.94 | 0.21 |
| Location | | | |
| F(df) | 4.42 (2) | N/A | N/A |
| *p* | <0.02 | | |
| Site x Time | | | |
| F(df) | 4.42 (3) | 0.10 (3) | 3.30 (3) |
| *p* | 0.59 | 0.97 | 0.99 |
| Time x Location | | | |
| F(df) | 4.42 (5) | N/A | N/A |
| *p* | 0.11 | | |
| Site x Location | | | |
| F(df) | 4.42 (2) | N/A | N/A |
| *p* | 0.52 | | |

**Table 2.6.** Species diversity of infaunal and epifaunal invertebrates and finfish on oyster bed and control sites, calculated with the Simpson's and Shannon-Weiner diversity indices.

| | Simpson's Index | | Shannon-Weiner Index | |
|---|---|---|---|---|
| | Oyster | Control | Oyster | Control |
| Infaunal Invertebrates | 5.18 | 5.19 | 0.85 | 0.83 |
| Epifaunal Invertebrates | 2.49 | 2.48 | 0.47 | 0.46 |
| Finfish | 2.11 | 1.45 | 0.48 | 0.31 |

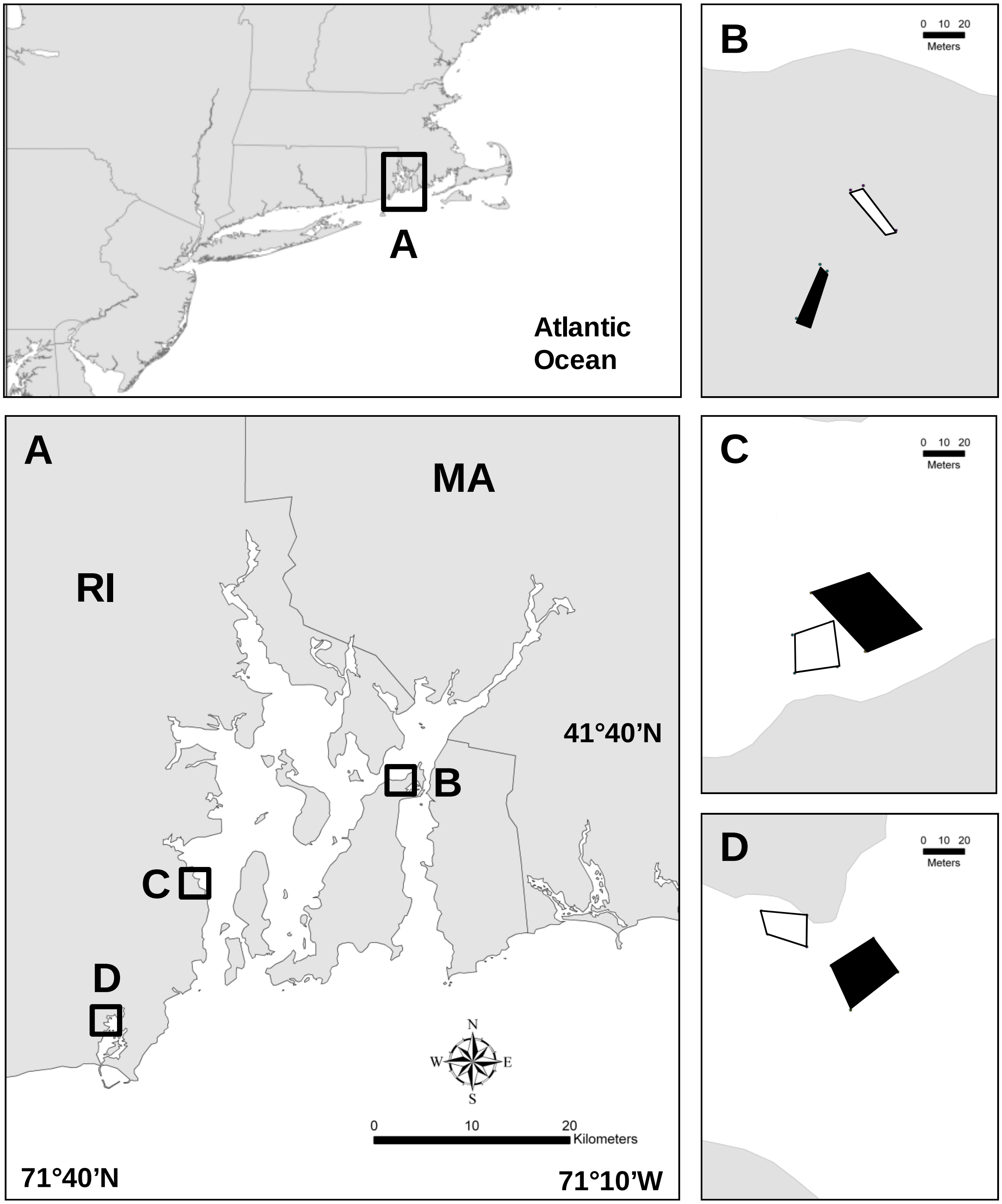
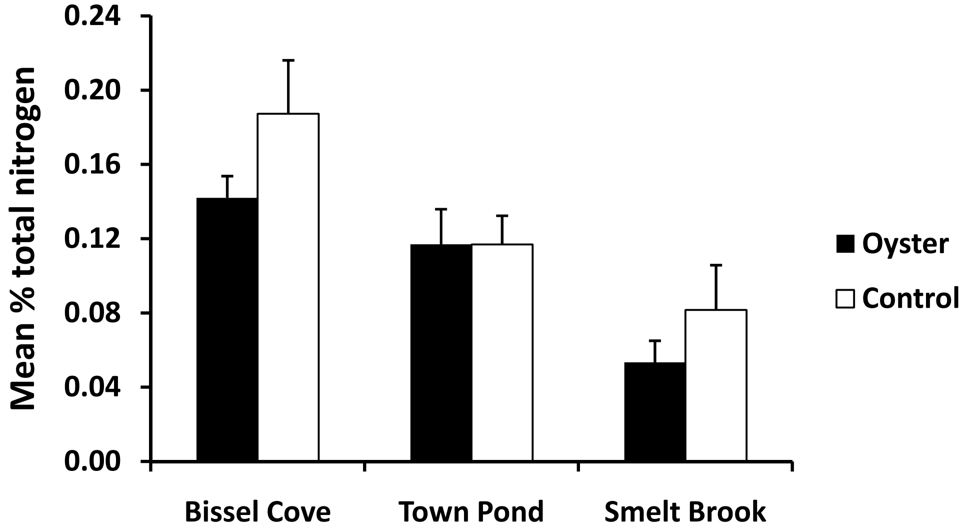



**Figure 2.1.** Map of Narragansett Bay, Rhode Island **(A)**, showing geographic location of field study sites at Town Pond **(B)**, Bissel Cove **(C)** and Smelt Brook Cove **(D)**. OB (black) and NOB (white) sites are outlined at each of the field locations.

**A.**




**B.**

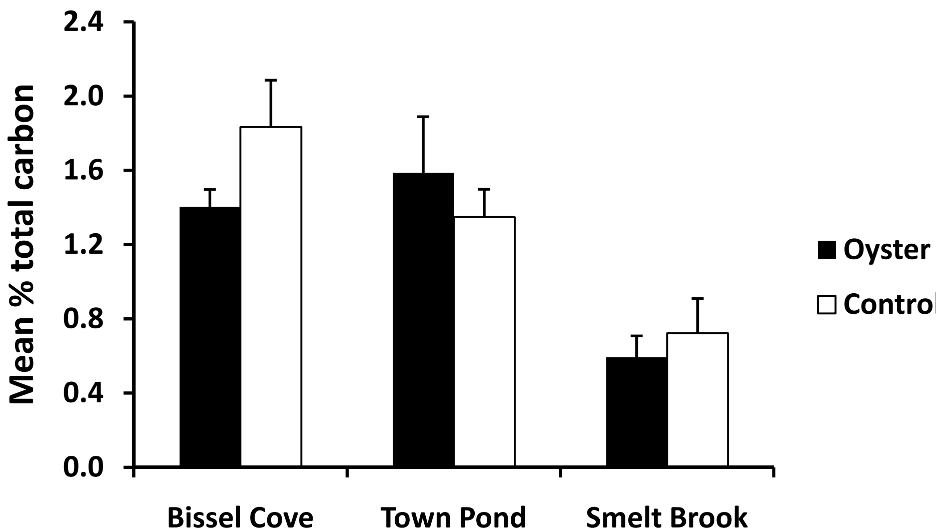
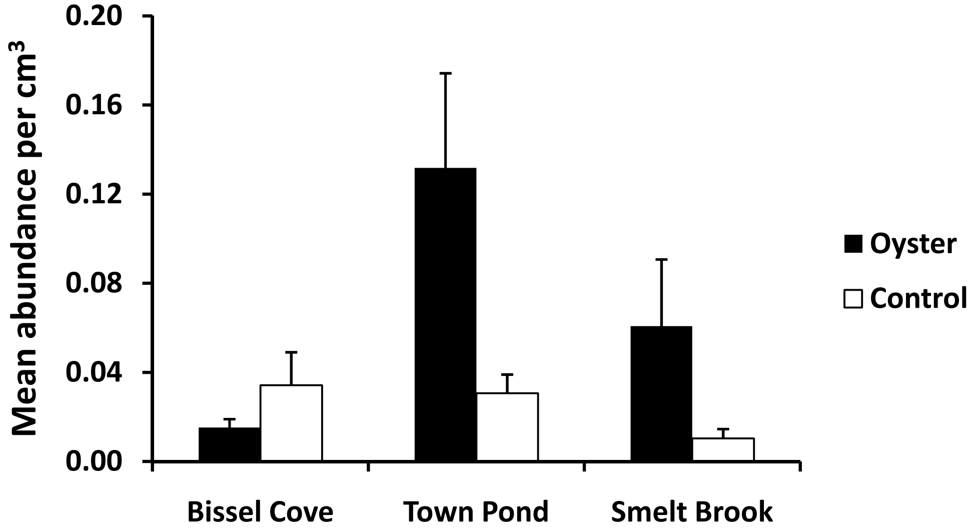



**Figure 2.2.** Mean percent total dry mass (+ 1 standard error) of sediment nitrogen (**A**) and carbon (**B**) sampled at OB and NOB sites with benthic core samples during summer 2009.

**A.**




**B.**

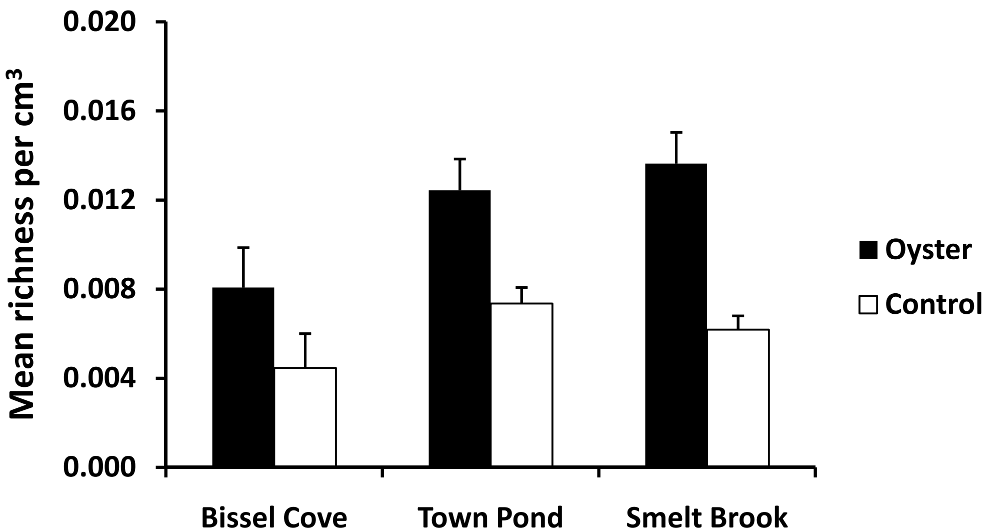
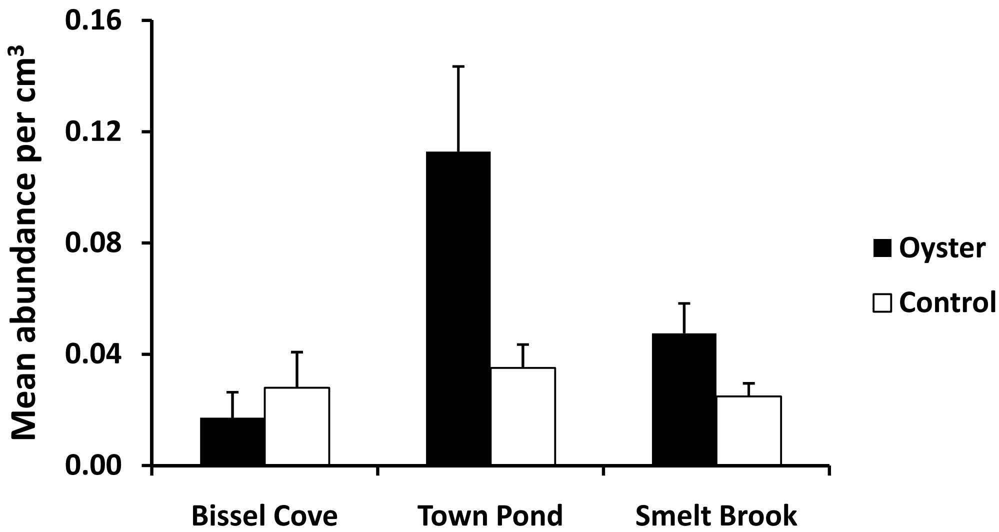


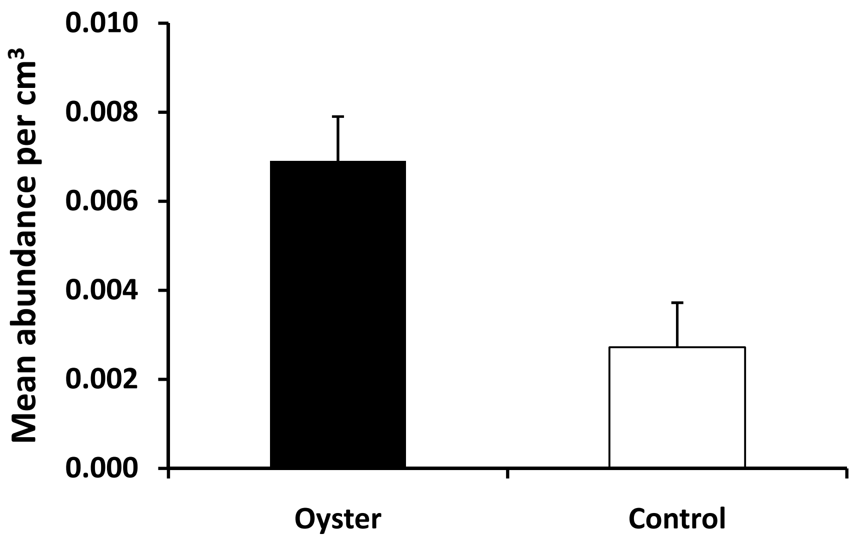

**Figure 2.3.** Mean abundance (# per $cm^3$ + 1 standard error) (**A**) and mean species richness (# species per $cm^3$ + 1 standard error) (**B**) of infaunal invertebrates sampled at OB and NOB sites with benthic core samples during summer 2009.

**A.**



0.16
0.12
0.08
0.04
0.00
Mean abundance per cm3
Bissel Cove
Town Pond
Smelt Brook
Oyster
Control


**B.**



0.010
0.008
0.006
0.004
0.002
0.000
Mean abundance per cm3
Oyster
Control

**C.**

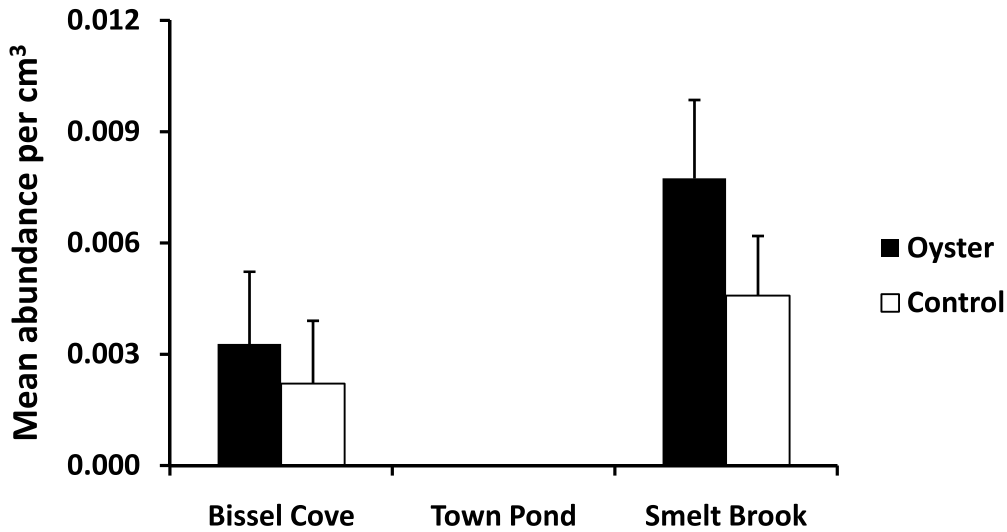
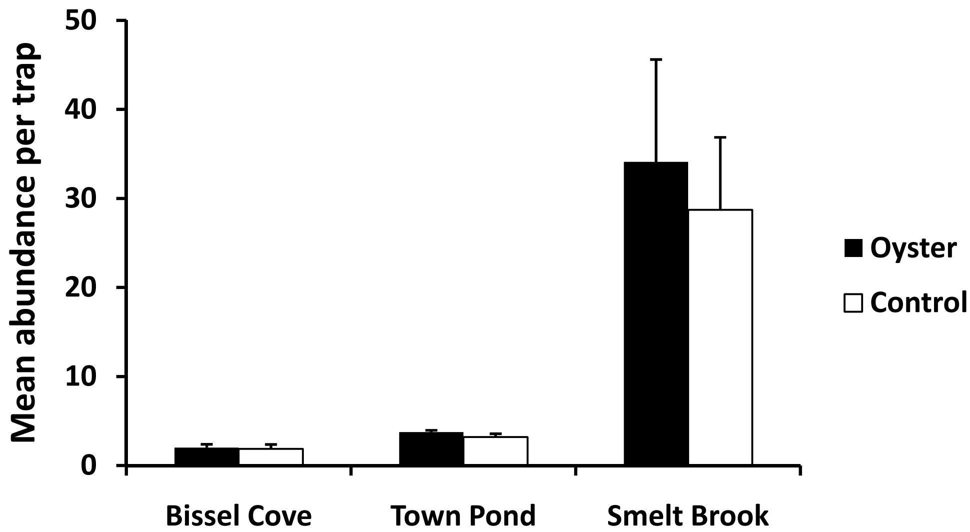



**Figure 2.4.** Mean abundance (# per $cm^3$ + 1 standard error) of polychaetes (**A**), crustaceans (**B**) and gastropods (**C**) sampled at OB and NOB sites with benthic core samples during summer 2009.

A.




B.

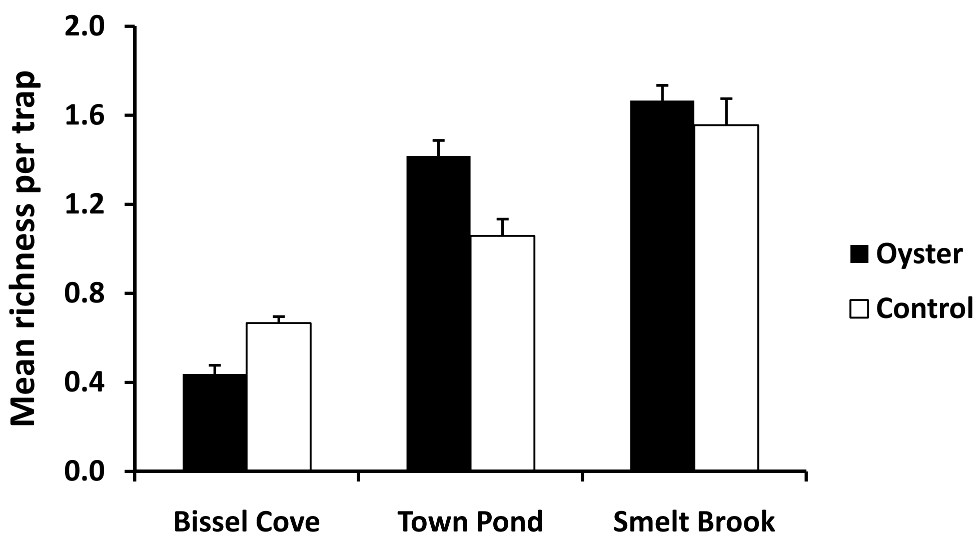
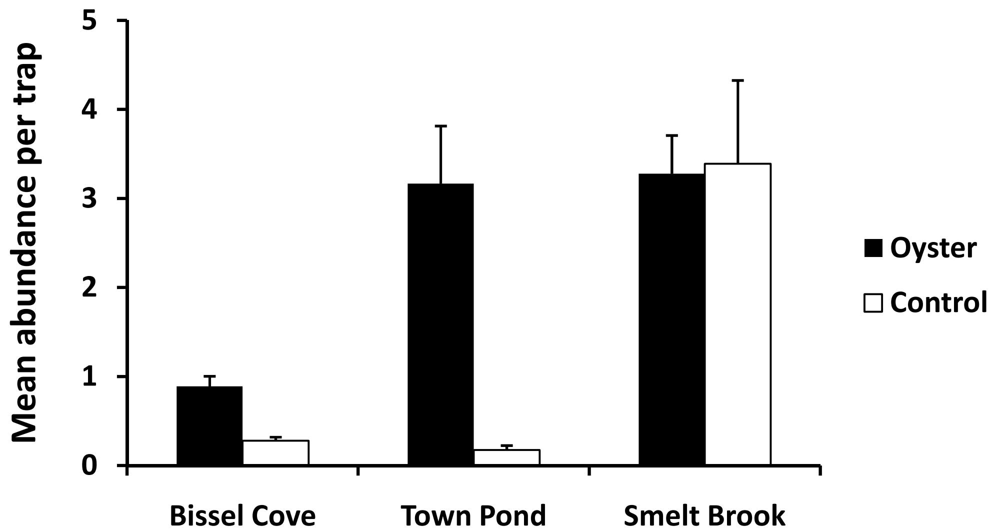



**Figure 2.5.** Mean abundance (# invertebrates per trap + 1 standard error) (**A**) and mean species richness (# species per trap + 1 standard error) (**B**) of epifaunal invertebrates sampled at OB and NOB sites with baited traps during summer 2009.

**A.**




**B.**

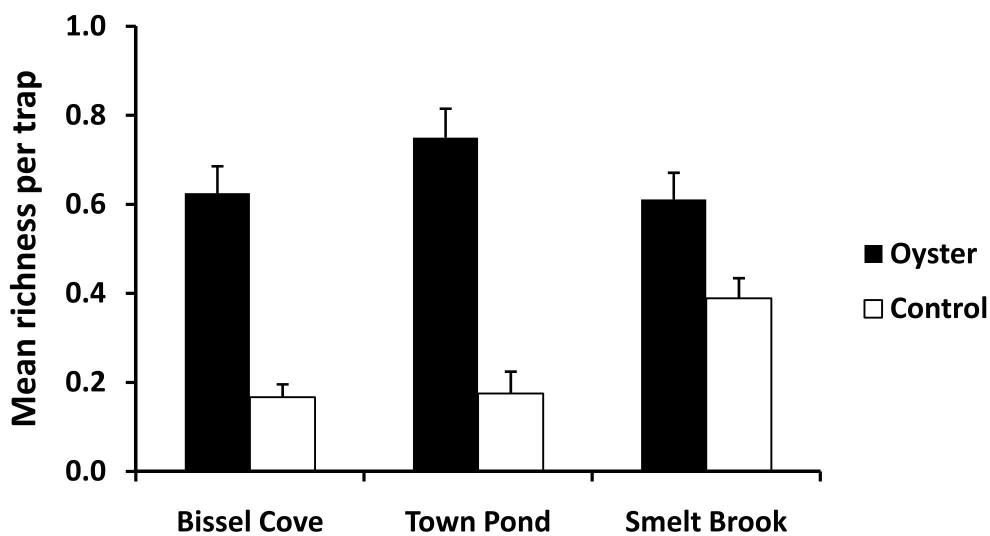



**Figure 2.6.** Mean abundance (# fish per trap + 1 standard error) (**A**) and mean species richness (# species per trap + 1 standard error) (**B**) of finfish sampled at OB and NOB sites with baited traps during summer 2009.

**Appendix I.** Marine fauna documented from field sampling during summer 2009 on oyster beds and control sites at Bissel Cove, Town Pond and Smelt Brook Cove in Narragansett Bay, RI (total quanity documented for each).

| Common Name | Classification | Latin Name | Oyster | Control |
|---|---|---|---|---|
| Eastern Oyster | Bivalvia | *Crassotrea virginica* | 7 | 0 |
| Soft-Shell Clam | Bivalvia | *Mya arenaria* | 19 | 10 |
| Northern Quahog | Bivalvia | *Mercenaria mercenaria* | 0 | 10 |
| Crab Parts | Crustacea | | 2 | 0 |
| Gammarid Amphipod | Crustacea | Gammaridae | 116 | 69 |
| Aoridae Amphipod | Crustacea | Aoridae | 34 | 14 |
| Grass Shrimp | Crustacea | *Paleomonetes vulgaris* | 345 | 244 |
| Sand Shrimp | Crustacea | *Crangon septemspinosa* | 1 | 16 |
| Zostera Shrimp | Crustacea | *Hippolyte* sp. | 1 | 0 |
| Mud Crab | Crustacea | Xanthidae | 23 | 6 |
| Green Crab | Crustacea | *Carcinus maenas* | 73 | 54 |
| Blue Crab | Crustacea | *Callinectes sapidus* | 1 | 0 |
| Hermit Crab | Crustacea | *Pagurus* spp. | 5 | 3 |
| Spider Crab | Crustacea | *Libinia* sp. | 1 | 0 |
| Mummichog | Finfish | *Fundulus heteroclitus* | 93 | 57 |
| Striped Killifish | Finfish | *Fundulus majalis* | 37 | 5 |
| 3-Spine Stickleback | Finfish | *Gasterosteus aculeatus* | 1 | 2 |

| | | | | |
|---|---|---|---|---|
| 4-Spine Stickleback | Finfish | *Apeletes quadracus* | 9 | 1 |
| Winter Flounder | Finfish | *Pseudopleuronectes americanus* | 3 | 1 |
| Longhorn Sculpin | Finfish | *Myoxocephalus octodecemspinosus* | 4 | 3 |
| Goby | Finfish | *Gobiosoma* spp. | 2 | 0 |
| Atlantic Silverside | Finfish | *Menidia menidia* | 3 | 1 |
| Northern Pipefish | Finfish | *Sygnathus fuscus* | 1 | 0 |
| Eastern Mudsnail | Gastropoda | *Ilyanassa obsoleta* | 426 | 348 |
| Waved Whelk | Gastropoda | *Buccinum undatum* | 5 | 12 |
| Slipper Shell | Gastropoda | *Crepidula fornicata* | 13 | 0 |
| Burrowing Scale Worm | Polychaeta | *Sthenelais boa* | 52 | 34 |
| Clam Worm | Polychaeta | *Nereis* spp. | 417 | 240 |
| Blood Worm | Polychaeta | *Glycera* spp. | 85 | 185 |
| Capittellid Worm | Polychaeta | Capittellidae | 421 | 416 |
| T-Headed Worm | Polychaeta | *Scalibregma inflatum* | 6 | 3 |
| Bamboo Worm | Polychaeta | *Clymenella* spp. | 40 | 47 |
| Paddle Worm | Polychaeta | Phyllodocidae | 49 | 33 |
| Cement Tube Worm | Polychaeta | *Sabellaria vulgaris* | 1 | 0 |
| Feather Duster Worm | Polychaeta | *Sabella microphthalma* | 0 | 1 |

| | | | | |
|---|---|---|---|---|
| Cone Worm | Polychaeta | *Pectinaria gouldii* | 0 | 2 |
| Ophelia Worm | Polychaeta | *Ophelia* sp. | 0 | 1 |