Delaware Bay New Jersey
Oyster Seedbed Monitoring Program
2010 Status Report

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New Jersey Delaware Bay Oyster Seedbeds

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Executive Summary:

The 2010 Delaware Bay New Jersey Oyster Seedbed Monitoring Program followed Dermo disease, oyster growth, and oyster mortality at six long-term monitoring sites (a Hope Creek site was added this year), two 2008 shell plant sites, two 2009 shell plant sites and two 2010 shell plant sites. Reductions in financial support necessitated reducing monitoring efforts at shell plant sites and eliminating monitoring of transplant sites. The program also continued its participation in the Fall Random Sampling Oyster Stock Assessment Survey by collecting condition indices from 22 seedbeds, Dermo disease data from 22 seedbeds and MSX disease data from seven seedbeds. A project funded independently by the National Science Foundation Ecology of Infectious Diseases program (NSF EID) provided additional disease and mortality data that is valuable to this long-term monitoring effort by specifically evaluating the susceptibility of oysters from the uppermost beds against oysters in potential recipient areas for the intermediate transplant program. The intermediate transplant program moves oysters from dense areas closed to harvesting in the upper portion of the bay, down bay to open areas as a mechanism to provide access to a portion of these oysters by the fishery. The experiment compared oysters from Hope Creek, the uppermost seedbed, with Shell Rock, the primary bed supporting the fishery.

Monthly monitoring data from 2010 indicated favorable temperatures and salinities for Dermo disease development during critical periods of the year. Mean oyster size appears to be declining following improvements in oyster recruitment. High disease levels resulted, but, along with mortality, varied widely across the seedbeds. These variations may reflect variation in recruitment. Nevertheless, the data indicate a continuation of the third major Dermo epizootic with a possible seven year periodicity. MSX disease, which had been increasing in recent years albeit at relatively low levels historically, declined noticeably.

Prognosis: Dermo continues to pose a considerable threat to oysters on the NJ Delaware Bay seedbeds while MSX lingers in the background. Dermo disease levels peaked in September, but were declining rapidly as winter approached. If the seven year cycle that is apparent in the data holds, then Dermo impacts would be expected to decline in 2011. Factors responsible for such a cycle remain unclear. The signal is weak and the time series remains short relative to the length of the cycle. Temperature, salinity and recruitment are the best understood factors governing Dermo levels. A strong depression in temperature and salinity during spring and into the fall appears to be the best hope for a reduction in Dermo disease during 2011. Although it remains present, MSX does not appear to be a serious threat in the coming year.

Introduction

The Delaware Bay Seedbed Monitoring Program tracks disease, growth and mortality of oysters on the Delaware Bay New Jersey seedbeds. The purpose is to provide information that supports the management of the New Jersey Delaware Bay oyster resource for sustainable harvest. Oyster production that occurs on privately owned leases below the state managed natural seedbeds or in closed waters is not monitored by this program. Monthly monitoring provides timely information on seasonal changes for the New Jersey Department of Environmental Protection Bureau of Shellfisheries and the New Jersey Delaware Bay Shellfisheries Council. Long-term spatial monitoring provides insight into inter-annual patterns, including long-term trends and potential factors affecting the oyster stock. Support and guidance is provided by the Oyster Industry Science Committee of the Delaware Bay Shellfisheries Council and the Stock Assessment Review Committee.

Oyster mortality on the Delaware Bay seedbeds is caused by a variety of factors including predation, siltation, freshets and disease. Since the appearance of *Haplosporidium nelsoni* (the agent of MSX disease) in 1957, disease mortality has been the primary concern. Following two distinct periods of severe MSX epizootics, the Delaware Bay population as a whole appears to have developed significant resistance to MSX disease. A study conducted in 2005 as part of the Delaware Bay Seedbed Monitoring program supported this contention (Ford and Bushek 2006) and is being investigated further with support from the National Science Foundation. Nevertheless, naïve oysters routinely deployed at the Rutgers Cape Shore field site become heavily infected, indicating that the parasite is still present in the Bay. In 1990, an epizootic of Dermo disease occurred (a form of perkinsosis, caused by the protozoan *Perkinsus marinus*). This was not the first appearance of *P. marinus* in Delaware Bay, but previous appearances were associated with importations of oysters from the lower Chesapeake Bay (Ford 1996). Termination of those importations resulted in the virtual disappearance of the disease. The 1990 appearance of Dermo disease was not associated with any known importations but was related to a regional warming trend after which the documented northern range of *P. marinus* was extended to Maine (Ford 1996). Dermo disease is now a major source of oyster mortality in Delaware Bay and a primary focus of the Seedbed Monitoring Program.

Since the appearance of Dermo disease in 1990, average mortality on the seedbeds, as assessed by total box counts during the fall survey, has fallen into 3 major groups (Figure 1): low mortality seedbeds (formerly called the upper seedbeds), medium mortality seedbeds (formerly called the upper-central seedbeds), and high mortality beds (formerly called central and lower seedbeds). These designations correspond to increases in salinity regime from the low to high mortality beds. Beds above Round Island were added to the survey in 2007 after sampling data indicated that their abundance represented a significant proportion of the population and should be included in management of the seedbeds. These beds were collectively designated Hope Creek in 2007, but were subsequently subdivided into three new beds: Hope Creek, Fishing Creek and Liston Range.

The majority of fresh water entering the system comes from the Delaware River and tributaries located above the oyster beds, however, inputs from several tributaries that enter the bay adjacent to the seedbeds (Hope Creek, Stow Creek, Cohansey River, Back Creek, Cedar

Creek and Nantuxent Creek) combine with the geomorphologic configuration of the shoreline to influence salinity, nutrients, food supply, circulation and flushing in ways that are not completely understood. These factors undoubtedly interact to influence the spatial and temporal prevalence and intensity of disease and mortality on the seedbeds. Continued long-term spatial monitoring as well as directed research sampling efforts are needed to better understand these dynamics.

Area management strategies typically follow the mortality designations in Figure 1, but have recently managed Shell Rock independently after the Stock Assessment Review Committee identified Shell Rock as a bed of key importance to the natural stock and to the industry. The temporal and spatial sampling efforts of the Seedbed Monitoring Program are designed to continually develop a better understanding of factors influencing oyster growth, disease and mortality patterns to support adaptive management efforts. As funding permits, these efforts include monitoring transplants (i.e., oysters moved from upper to lower seedbeds), shell plants (i.e., shell placed directly on the seedbeds to increase the supply of clean cultch for recruitment), and replants (i.e., cultch planted in the lower bay high set zone near the Cape Shore then moved and replanted on the seedbeds). The 2010 objectives for the Seedbed Monitoring Program were to:

1. Continue the standard monthly seedbed monitoring time series, adding Hope Creek
2. Conduct Dermo and MSX assays and determine condition indices for the 2010 Fall Stock Assessment Random Sampling Survey
3. Monitor growth, mortality and disease on selected 2008, 2009 and 2010 shell plantings
4. Compare susceptibility of Hope Creek and Shell Rock oysters to MSX and Dermo disease

Objectives 1 and 2 comprise the basis of the long-term seedbed monitoring program that provides fundamental information necessary for both immediate and long-term adaptive management of the resource. These objectives also provide essential baseline/background information against which the success of other objectives and independent research can be evaluated. Objective 1 began in 1998 with five beds (Arnolds, Cohansey, Shell Rock, Bennies and New Beds) and 2010 was the first year Hope Creek was part of the monthly monitoring program. Objective 3 is related to the Delaware Bay Oyster Restoration program designed to enhance recruitment on the seedbeds. Results on growth and mortality are summarized here to help develop a better understanding of these management activities. The initial intent during 2010 was to monitor transplants from the uppermost seedbeds, but co-mixing of plantings as well as difficulty in identifying transplants resulted in shifting limited financial resources to continue monitoring shell plants. Objective 4 was initiated after the 2008 SAW and expanded with additional funding from an NSF project investigating oyster disease in Delaware Bay.

HSRL staff and students, especially Iris Burt, along with NJDEP Bureau of Shellfisheries staff, especially Jason Hearon and Craig Tomlin, provided field, logistical and technical support during 2009. Emily Scarpa performed histology for MSX. Dr. Susan Ford initiated the Dermo monitoring program (now called the seedbed monitoring program) in 1990 with primary assistance from her technician, Robert Barber. Dr. Bushek has lead the program since 2003 and Dr. Ford continues to provide valuable advice and assistance.

Methods

Figure 1 depicts the grid system used during 2010 for the seedbed monitoring program. The blue lines in Figure 1 demarcate the low, medium and high mortality zones that correspond with salinity regimes of approximately 0-15 ppt, 5-20 ppt and 10-24 ppt. Management activities and this report reference both regions and beds as appropriate. Beds that fall in the jurisdiction of the state of Delaware are not monitored nor shown. The grid system is nearly contiguous, but contains several gaps. The 23 areas differentiated by color represent concentrations of oysters (= beds) that are referenced by historical names traditionally used by the industry and resource managers. On any given bed, 98% of the oysters exist on the colored grids while only 2% exist at low density on the surrounding grids; 50% of the oysters exist on the darker colored grids (‘high quality’ strata) and the remaining 48% exist on the lighter colored grids (‘medium quality’ strata). Monthly samples were collected from April through November for Objective 1 and 3 as indicated in Tables 1 and 2, respectively. Table 3 shows which beds have been monitored since 1990 as part of the long-term Dermo monitoring program that is affiliated with the Annual Fall Oyster Stock Assessment. Table 4 specifies the grids sampled during the Annual Fall Oyster Stock Assessment to complete Objective 2.

To complete Objective 1, three one-minute tows with a 0.81 m (2.7 ft) oyster dredge were collected at each site using about 14 m (46 ft) of cable from the NJDEP R/V Zephyrus. Bottom water temperature and salinity were recorded with a handheld YSI® 85 meter for each sample. A composite bushel consisting of randomly collected oysters and boxes from the three replicate dredge hauls (approximately one third of a bushel from each haul[1]) was created and then sorted to enumerate gapers (= dead oysters with meat remaining in the valves), boxes (= hinged oyster valves without any meat remaining) and live oysters. Boxes were further categorized as new (= no indication of fouling with little sedimentation inside valves) or old (= heavily fouled and/or containing extensive sediments) to provide an indication of recent mortality. These data were used to estimate mortality as described by Ford et al. (2006). Up to one hundred randomly selected oysters (> 20 mm) from the composite bushel were returned to the laboratory where shell heights (hinge to bill) were measured to determine size frequency in the population. Care was taken to avoid any bias in sampling oysters by systematically working through the sample until 100 oysters were identified. It is understood that the sampling gear will bias the collection toward larger animals (Powell et al. 2007), but such bias is presumed constant across sampling dates. Twenty individuals representing the size frequency distribution were then sacrificed for Ray’s fluid thioglycollate medium assay (RFTM, Ray 1952, 1966) to determine prevalence and intensity of Dermo infections. The percent of oysters in the sample with detectable infections is termed the prevalence. Each infection was then scored using the “Mackin scale” from zero (= pathogen not detected) to five (= heavily infected) (Ray 1954). These values, including zeros, were averaged to produce a ‘weighted prevalence’ (Mackin 1962), which provides an estimate of the average disease level in the sample of oysters. Sex and gross reproductive status was determined for each oyster sacrificed for Dermo analysis during June and July.

Samples for Objective 2 were collected during the Fall Stock Assessment using the commercial oyster boat H. W. Sockwell. The stock assessment survey consists of a stratified

[1] At Arnolds and Round Island, total sample volume was only one half a bushel; subsamples were adjusted accordingly.

random sampling of the medium and high quality grids on the 23 named beds (colored grids in Figure 1). Ledge and Egg Island beds contain very few oysters and are only sampled in alternate years; Ledge was sampled during 2010. After samples were collected for the stock assessment, the remaining catch was searched to collect oysters for disease analysis, size frequency and condition as indicated in Table 4. Oysters for disease analysis were collected to represent the general size distribution of oysters in the sample, excluding spat and yearlings. Oysters for size frequency and condition index were collected without regard to size. Dermo was diagnosed as described above. MSX was diagnosed using standard histology (Howard et al. 2004).

To complete Objective 3, samples were collected monthly from May through November (Table 1) for sites manipulated as indicated in Table 2. Attempts to collect representative samples from transplant grids failed in May, so efforts were shifted to shellplant sites as described previously. At least three and up to five 1-minute dredge tows were systematically searched on deck for planted shell containing live or dead oysters until 100 live oysters attached to planted shell were collected. All boxes and gapers encountered during this process where collected. In some instances, five tows were insufficient to collect 100 oysters, but time limitations precluded devoting additional effort to any one site. Care was taken to search systematically and avoid sampling bias by working systematically through the sample until 100 live spat or oysters were collected. Boxes were enumerated and categorized as new or old as described above. Live oysters attached to planted shell were returned to the laboratory for size measurements and for Dermo analyses each month (n = 20 per site). No disease sampling was performed on the 2010 shell plants that were sampled only during September and November.

To complete Objective 4, live oysters from Shell Rock and Hope Creek were transplanted to the Cape Shore and held in bags on racks in early spring 2008. Mortality was monitored monthly and samples collected periodically for disease analyses. Adults were collected again in May 2010 and compared with a naïve stock from Maine. In June 2008, a portion of the Hope Creek and Shell Rock oysters were strip spawned in the hatchery to produce offspring. Offspring were held in the Cape Shore nursery until November 2008, and then moved to a dock in Cape May harbor for the winter. In March 2009, offspring were split into replicate bags and deployed on racks in Cape May harbor and at Cape Shore. Shell Rock offspring were not numerous enough to deploy in both locations so all were deployed in Cape May as the primary question concerned resistance to MSX. Mortality and disease was monitored periodically through October 2010.

Results and Discussion

Water temperatures measured during 2010 collections across the seedbeds followed a typical seasonal increase and decrease with a peak in July and little spatial variability, however, temperatures were much warmer than the recent decadal mean during June and July (Figure 2A, B). Salinity levels followed a typical spatial pattern, increasing from upbay to downbay beds (Figure 2C). Salinity levels were relatively low at the beginning of the year but increased steadily from April to September with levels higher than average in August and September, before declining to more average levels (Figure 2D). Warm temperatures early in the season combined with high salinities later in the season tend to favor the development and transmission of Dermo infections. Continuous monitoring of temperature (Figure 2E) and salinity (Figure 2F) at the NOAA PORTS Ship John Shoal Light station (http://tidesandcurrents.noaa.gov/) corresponded with data collected during seedbed monitoring. As indicated by Figures 2E and 2F, temperature and salinity can vary widely within a day. The Seedbed Monitoring Program only measures salinity when collecting oysters and only over those sites being sampled. An array of continuous monitoring stations across the seedbeds may facilitate a better interpretation of conditions that influence recruitment, growth, disease and mortality of oysters.

Seasonal changes in mean shell height may be affected by recruitment and growth, natural mortality, and fishing mortality. Mean size data (shell height) collected during 2010 show relatively erratic patterns that reflect the difficulty in obtaining a uniform sample from month to month across some of the beds, particularly New Beds and Bennies. Overall, however, mean shell height fluctuated near or around the long-term mean (Figure 3A), which is near the legal minimum harvest size of 2.5 inches (64 mm). Averaging the mean size across these beds for each year since 2000 provides a striking increase in the mean size of oysters over time (Figure 3B). This pattern is most readily explained by a lack of recruitment of smaller animals over several years and should remain a cause for concern, but it does appear that recent increases in recruitment may be shifting mean size down.

A concern following several consecutive recruitment failures in the past decade has been the potential effect that a changing age/size structure may have on sex ratios and fertilization success. Oysters are protandric, that is some will begin their lives as males then change to females later in life. Hence, an older population is likely to have more females present and the distribution of males may be insufficient to maintain adequate fertilization success. For this reason, oysters sacrificed for Dermo during June and July were examined to determine gender. Results from 2010 indicate a slight bias (60:40) towards females (Table 5). Oysters were clearly mature by June and most had spawned by August and were no longer reproductive.

The shell planting program began in 2005 to enhance recruitment on the seedbeds after several consecutive years of recruitment failures. The program has successfully increased recruitment (see previous annual stock assessment reports) and because the planted shell (ocean quahog or surf clam shell) is traceable through time, it provides an opportunity to obtain specific data on growth and mortality of young animals (age class 0-2). Figure 4 shows the growth and mortality of the initial cohorts that set on this planted material each year since 2005. The data indicate that oysters reach a size of nearly 25 mm (about 1 inch) on average during the year they set, essentially double in size the following year, and, on average, reach a legal harvestable size (63.5 mm or 2.5 inches) by the end of the next year, with little difference in variability from year to year. These data fit well with the conventional dogma that it takes 2-3 years for oysters to reach market size in Delaware Bay. They also indicate that spat, on average, may be 20 mm or more by October when the Fall Stock Assessment sampling takes place. The maximum mean size of spat on a shell plant in October was 30 mm. Therefore, the maximum size of spat set at 20 mm in the stock assessment survey is low and will bias annual recruitment estimates low while overestimating the abundance of juvenile oysters. In contrast, the minimum average size from a shell plant sampled during October one year after the planting is 38 mm. Given this difference, it would seem that spat size limits of about 35 mm would reconcile this error. Mortality data suggest large differences in mortality among years, but much of this is likely due to poor estimation of very early mortality during the year of the planting. Beginning in spring of the year following the plant year indicates most populations follow a similar pattern and similar trend. Therefore, not counting mortality that occurs between setting and spring of the following year, mortality on shell plantings (combines direct plants and replants) is on the order of 25 to 30 percent.

Dermo prevalence, weighted prevalence (WP) and intensity followed typical seasonal patterns across the seedbeds (Figure 5). All three measures increased from a low in spring to a peak in late summer and were generally higher on beds in higher salinity regions although levels continue to be higher than normal on the upper beds, particularly Cohansey and Arnolds. Similar patterns and disease levels occurred in the previous three years, indicating an upbay movement of the disease that continues an epizootic which has spread across the medium mortality beds and into the low mortality beds. By July, weighted prevalence at all beds except Arnolds and Hope Creek exceeded 1.5, a level expected to begin causing noticeable mortality. By August, Arnolds was near a WP of 1.5. Dermo levels peaked in August and were dropping quickly by November although most still remained above 1.5. The severity of the epizootic is most clearly illustrated in Figures 5B, 5D and 5F, which compare the annual seedbed monitoring mean levels to mean seedbed levels since 1999. As in the previous year, 2010 values exceed long-term mean values for much of the year, often by one standard deviation.

Box count frequencies from monthly samples are shown in Figure 6. Total box counts (Figures 6a and 6b) are influenced by the addition of new boxes and the disarticulation of old boxes, both of which can vary across the year. New boxes tend to appear in two peaks during the year; a smaller peak in spring sometimes called over wintering mortality and a large peak in fall following intensification of Dermo disease (Figure 6d). In 2010, the spring mortality was heavily driven by upper bay mortality which may have been influenced by freshets as well as high disease levels that persisted through winter. High variability in total box count frequency occurred on New Beds and Bennies (Figure 6a) and may partially be explained by smaller sample sizes from those sites. Figure 6b shows a higher than average abundance of boxes present across the seedbeds during 2010. Cumulative recent box counts provide an estimate of mortality during the year (Figure 6e). Cumulative recent mortality was relatively high on Cohansey, and especially so on Arnolds where mortality is typically more similar to that observed on Hope Creek. The high cumulative mortality on Bennies was partially related to smaller sample size. Number of oysters collected from New Beds and Bennies for mortality estimates were typically only half to one quarter or fewer the number collected from other beds. Overall, cumulative mortality was above the long-term mean with a total mortality of just over 35% by the end of the year across all sites (Figure 6f). Box counts are known to be an underestimate of mortality, but it is worth noting that cumulative recent box count mortality exceeds the total box count mortality, indicating that boxes are labile and that any annual box count estimate is likely to be an even greater underestimate of mortality. Regardless of which measure is used, using 20% mortality as a definition of an epizootic (the level used in the Delaware Bay Oyster Stock Assessments), all beds monitored monthly except Hope Creek experienced epizootic mortalities in 2010.

Figure 7 depicts results of the field exposures to evaluate susceptibility of oysters on the very low mortality beds. The upper panel compares survival of Hope Creek and Shell Rock adults against each other and a naïve stock of oysters from Maine in common garden experiments at Cape May and Cape Shore. Because we know the number of oysters deployed and can account for every oyster during each sampling period, these are actual mortality curves, not estimates like box count data collected from wild populations. Each line represents a separate bag of oysters and duplicate bags of each stock were deployed. Mortality was greatest in the Maine stock regardless of site, indicating native adults are more tolerant of disease and other conditions at these two sites. In 2008, no difference in mortality was observed between Hope Creek and Shell Rock adults deployed at these sites, but Hope Creek adults sustained higher mortality than Shell Rock oysters at both sites in 2010. Overall, mortality was greatest at Cape Shore where Dermo was more intense. These data agree with survival of offspring presented in the lower panel. Hope Creek offspring sustained virtually 100% mortality by the end of the second year of exposure at Cape Shore and more than 80% had died by that time at Cape May. By comparison, Shell Rock offspring sustained less than 60% mortality in Cape May, suggesting they are more tolerant or resistant of MSX disease. Shell Rock offspring were not exposed at Cape Shore due to limited survival through the hatchery and nursery phase. These observations suggest that while oysters from the very low mortality seedbeds are less susceptible than naïve oyster populations, they are more susceptible than oysters from other areas of the seedbeds. This information may influence the formulas used for the intermediate transplant program to move oysters from the low and very low mortality beds. Specifically, because these oysters sustain higher mortality rates when moved down bay they will have a higher natural mortality rate than the local oysters. As such, their contribution to the market size oysters on the recipient bed should be discounted by an amount relative to this differential mortality. Otherwise, this mortality is not accounted for in any of the population modeling.

Samples for the 2010 Random Sampling Stock Assessment were collected on October 19, October 29, November 12 and November 13. Condition index and size frequency data were provided for inclusion in the "Report of the 2011 Stock Assessment Workshop" (Powell et al. 2011). Because MSX has not been problematic on the seedbeds for nearly two decades, samples from only seven beds along the up to down bay gradient were examined (Table 4). Of 130 oysters examined, only 7 infections were detected overall and only 3 infections were systemic. Because so few infections were detected, no upbay-downbay pattern was evident with respect to either prevalence or intensity (Figure 8a). Despite the absence of recent MSX epizootics, the pathogen is clearly still present and can cause considerable mortality in susceptible stocks (Figure 8). Examination of fall MSX prevalence on the seedbeds since 1988 shows a recent small increase that may now be subsiding (Figure 8b). Because MSX continues to be a serious problem in other areas and remains deadly to naïve oyster stocks, monitoring for MSX remains a high priority.

Figure 9 depicts annual fall Dermo prevalence (upper panel), Dermo infection intensity (= weighted prevalence) (middle panel) and fall box-count estimated mortality (bottom panel) from 1989 to 2010 for each mortality region. Dermo prevalence and intensity remained relatively high in 2010 continuing an epizootic that began after a low in 2004 but is showing some signs of reprieve. Mortality roughly tracks the same spatial and temporal patterns as Dermo disease, with greatest correspondence on the high mortality beds and least on the low mortality beds (Figure 9 bottom panel). Note that mortality appears to lag disease by about one year. Since 1990, there have been two relatively low periods (1997 and 2004) that suggest a seven year cycle. If such a cycle holds, then 2011 may be a year of reprieve. Unfortunately, periods of remission appear to be much shorter than the duration of the epizootics. Many factors such as temperature, salinity and recruitment, however, are known to influence Dermo disease and the confluence of these factors is difficult to predict. Moreover, while there is some understanding of how these factors influence spatial and seasonal variations in Dermo disease, it is less clear how they interact to influence inter-annual variation. As mentioned in previous years, the apparent cycling may be driven by larger regional climate patterns, but this remains a hypothesis in need of additional research and continued monitoring. The data also indicate an apparent attenuation of mortality in the three successive epizootics across the medium and high mortality regions. This observation remains difficult to interpret, but could indicate an increase in tolerance (the relative ability of an oyster to survive an infection of a given intensity) versus resistance (the ability of an oyster to limit the development of an infection) to Dermo disease. Regardless of the explanation, it appears that Dermo-induced mortalities can be expected to continue in 2011.

Examination of Dermo prevalence and Dermo intensity on a bed-by-bed basis in Figures 10 and 11 indicated a change in the typical increase from upbay to downbay beds. Specifically, Dermo levels appeared to shift upbay with higher than average levels on the low mortality beds, average levels across the medium mortality beds, and average to lower than average levels on the high mortality beds. Mortality followed a very similar pattern (Figure 12). Figure 13 shows the relationship between the average Dermo level and average mortality by bed. Mortality levels from Figure 12 are used along the y-axis in both panels. The upper panel uses weighted prevalence from Figure 11 while the lower panel converts these weighted prevalence values to parasite burdens after Choi et al. (1990). In both panels, the various mortality regions fall out into zones clearly defined by disease level. The low and very low mortality beds comprise a low disease zone with weighted prevalence of Dermo generally well below 1.0 on the Mackin Scale. This low mortality zone generally experiences an estimated 5 to 12% annual mortality. Beds on which Dermo intensities increase above a weighted prevalence of 1.5 experience annual mortalities of 15 to 20% and are designated the medium mortality zone. Once Dermo levels exceed 2.0, average mortality increases to 25-40%. The lower panel drives home the point that the Mackin Scale is basically a base 10 log scale. In each case, the beds segregate into mortality zones by about a doubling from 5,000 to 10,000 to 20,000 cells per gram. This means that infections can linger at low levels for long periods with little effect and then suddenly they develop quickly into lethal infections across two doublings of the parasite. Note the precarious position of Shell Rock at the edge of the medium mortality zone.

Figure 14 shows the individual data points for each bed and each year sampled since 1990 as one plot and then broken down by mortality region (very low and low mortality regions combined). The overall relationship between Dermo weighted prevalence and mortality estimated by fall survey box counts is highly significant ($p < 0.001$) and explains nearly 40% of the variation in mortality (Figure 14a). This relationship suggests that for each integer increment in weighted prevalence, mortality will increase by about 9% across the seedbeds (95% CI ±1.3). When examined by bed region the relationship disappears on the low mortality beds where Dermo is relatively low, but then increases progressively as Dermo levels increase over medium and high mortality regions (Figure 14b, c and d). Dermo levels are too low to impact mortality on the low mortality beds. As a result, Dermo does not appear to be a major cause of mortality on the low mortality beds (Figure 14b), but increases in importance on the medium and high mortality beds. It is tempting to compare mortality rates for different Dermo levels in Figures 14c and d. For example, a Dermo weighted prevalence of 3 on the high mortality beds corresponds to double the mortality rate indicated on the medium mortality beds. This is, however, misleading as monthly monitoring (Figure 5) indicates that infections on higher mortality beds exist at higher levels for longer periods of time, leading to a higher annual mortality rate. That is, lower bay beds typically experience higher Dermo levels sooner and for longer periods of time resulting in higher rates of mortality over time. The intercepts of regression lines in Figure 14 imply that the background mortality rate across the seedbeds is about 10%, but may be as high as 20% on the high mortality beds. Note, however, that there are relatively few measures of Dermo weighted prevalence below 1.0 on the high mortality beds and none of zero. Collectively, these data indicate that a significantly greater recruitment rate is required to sustain downbay populations compared to upbay populations.

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Table 1. The 2010 sampling schedule for the NJ Delaware Bay Oyster Seedbed Monitoring Program. The long-term sites are Arnolds grid 18, Cohansey grid 44, Shell Rock corner of grids 10,11,19,20, Bennies grid 110 and New Beds grid 26. In 2010, Hope Creek grid 17 was added as a sixth bed to monthly monitoring program in recognition of the integration of the uppermost seedbeds into the stock assessment program. Intermediate transplant and shell plant sites monitored are listed in Table 2. Parameters measured include temperature, salinity, counts of live oysters and boxes, size frequency (shell height), and Dermo levels.

Date	Samples	Vessel	Captain
Apr 19, 2010	6 long-term sites	NJDEP RV Zephryus	Jason Hearon
May 17, 2010	6 long-term sites 3 intermediate transplants	NJDEP RV Zephryus	Jason Hearon
Jun 21, 2010	6 long-term sites 2008, 2009 shell plant sites	NJDEP RV Zephryus	Jason Hearon
Jul 19, 2010	6 long-term sites 2008, 2009 shell plant sites	NJDEP RV Zephryus	Jason Hearon
Aug 23, 2010	6 long-term sites 2008, 2009 shell plant sites	NJDEP RV Zephryus	Craig Tomlin
Sep 20, 2010	6 long-term sites 2008, 2009, 2010 shell plant sites	NJDEP RV Zephryus	Craig Tomlin
Oct 18, 2010	6 long-term sites 2008, 2009 shell plant sites	NJDEP RV Zephryus	Jason Hearon
Nov 18, 2010	6 long-term sites 2008, 2009, 2010 shell plant sites	NJDEP RV Zephryrus	Craig Tomlin

Note: Funds were insufficient to monitor both shell plants and transplants. The initial decision to collect transplant data was abandoned after the first examination of the transplant sites. Each transplant site (SR22, Ben86 and Ben87) contained a mix of material from several different locations, making following changes in movement from any single location intractable. Beginning in June, funding was shifted to support collection of additional growth data on shell plant sites.

Table 2. Shell plant sites sampled during 2010. Replant = shell planted in lower Delaware Bay then moved to bed indicated after spat have recruited.

Bed	Grid	Plant material	Plant yr
Cohansey	64	surf clam replant	2008
Bennies Sand	8	ocean quahog shell	2008
Shell Rock	21	ocean quahog & surf clam shell mix	2009
Bennies Sand	15	ocean quahog & surf clam shell mix	2009
Bennies Sand	4	surf clam shell	2010
Shell Rock	23	ocean quahog & surf clam shell mix	2010

Table 3. Record of collections for annual fall Dermo monitoring since 1990. X indicates bed was sampled in respective year for that column. Beds are listed more or less by latitude, although some lie at the same latitude with different longitudes.

SEEDBED	**90**	**91**	**92**	**93**	**94**	**95**	**96**	**97**	**98**	**99**	**2000**	**01**	**02**	**03**	**04**	**05**	**06**	**07**	**08**	**09**	**10**
Hope Creek																		X	X	X	X
Liston Range																			X	X	X
Fishing Creek																			X	X	X
Round Island	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X
Upper Arnolds														X		X	X	X	X	X	X
Arnolds	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Upper Middle																	X	X	X	X	X
Middle	X	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X
Cohansey	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Sea Breeze															X	X	X	X	X	X	X
Ship John	X	X	X	X	X		X			X	X	X	X	X	X	X	X	X	X	X	X
Shell Rock	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Bennies Sand	X	X	X	X	X			X	X	X	X	X	X		X	X	X	X	X	X	X
Bennies	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Nantuxent		X		X		X		X		X	X	X		X		X	X	X	X	X	X
Hog Shoal		X		X						X		X	X	X	X	X	X	X	X	X	X
New Beds	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Strawberry	X		X		X								X	X	X	X	X	X	X	X	X
Hawks Nest	X		X		X		X		X		X		X	X	X	X	X	X	X	X	X
Beadons	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Vexton										X		X	X	X	X	X	X	X	X	X	X
Egg Island	X	X	X	X	X	X	X	X		X	X	X		X		X		X		X	
Ledge Bed			X		X				X		X		X		X		X		X		X

Table 4. 2010 Delaware Bay Oyster Seedbed Stock Assessment Survey grids sampled for Dermo, MSX, condition index (CI) and size frequencies. Numbers represent grid ID or the number of oysters processed.

Bed	Grid	Dermo	MSX	CI
Hope Creek	53	10	10	15
Hope Creek	76	10	10	15
Hope Creek	46			10
Hope Creek	64			10
Fishing Creek	26	10		15
Fishing Creek	16	10		15
Fishing Creek	25			10
Fishing Creek	4			10
Liston Range	25	10		15
Liston Range	14	10		15
Liston Range	21			10
Liston Range	2			10
Round Island	26	10		15
Round Island	5	10		15
Round Island	11			8
Round Island	50			4
Round Island	18			8
Upper Arnolds	10	10		14
Upper Arnolds	14	10		15
Upper Arnolds	16			10
Upper Arnolds	25			11
Arnolds	16	10	10	15
Arnolds	73	10	10	13
Arnolds	19			11
Arnolds	8			11
Upper Middle	48	10		15
Upper Middle	56	10		15
Upper Middle	36			10
Upper Middle	64			10
Middle	44	10		15
Middle	28	10		15
Middle	18			5
Middle	33			4
Middle	30			11
Cohansey	57	10	10	10
Cohansey	23	10	10	10
Cohansey	60			15
Cohansey	36			15
Sea Breeze	24	10		14
Sea Breeze	36	10		15
Sea Breeze	2			5
Sea Breeze	16			16
Ship John	31	10		14
Ship John	47	10		12
Ship John	20			11
Ship John	5			13
Shell Rock	35	10	10	15
Shell Rock	3	10	10	11
Shell Rock	27			10
Shell Rock	7			14

Bed	Grid	Dermo	MSX	CI
Bennies Sand	11	10		15
Bennies Sand	35	10		15
Bennies Sand	3			10
Bennies Sand	24			10
Bennies	123	10	10	14
Bennies	34	10	10	9
Bennies	6			14
Bennies	85			13
Bennies	98			12
Nantuxent	18	10		15
Nantuxent	64	10		15
Nantuxent	13			10
Nantuxent	21			10
Hog Shoal	5	10		15
Hog Shoal	16	10		15
Hog Shoal	3			10
Hog Shoal	6			10
New Beds	17	10	10	11
New Beds	54	10	10	14
New Beds	66			13
New Beds	14			12
Strawberry	9	10		20
Strawberry	29	10		19
Strawberry	12			8
Strawberry	18			3
Hawks Nest	5	10		15
Hawks Nest	28	10		15
Hawks Nest	3			10
Hawks Nest	9			10
Beadons	4	10		15
Beadons	16	10		14
Beadons	3			8
Beadons	21			4
Beadons	24			9
Vexton	10	10		19
Vexton	22	9		9
Vexton	7	1		3
Vexton	5			19
Ledge	16	7	7	0
Ledge	9	1	1	0
Ledge	23	2	2	0
Ledge	28	1	1	0
Total beds	**22**	**22**	**7**	**22**
Total grids	**92**	**45**	**16**	**89**
Total oysters		**430**	**131**	**1050**
Transplant grids:				
Bennies	86T	20	0	0
Bennies	87T	20	0	0
Shell Rock	22T	20	0	0

Table 5. Sex ratios detected during monthly seedbed monitoring expressed as the percentage of males or females detected in each Dermo sample (n = 20, data are shown as percent). Beds are listed from upbay to down bay. Hermaphrodites (one on Bennies in July) and individuals whose sex was not discernable are not shown (one on New Beds each month and one on Arnolds in June).

	June 21, 2010		**July 20, 2010**		**Combined**	
Bed	Males	Females	Males	Females	Males	Females
Hope Creek	30	40	45	55	38	48
Arnolds	35	60	40	60	38	60
Cohansey	50	50	45	55	48	53
Shell Rock	55	45	35	65	45	55
Bennies	15	85	30	55	23	75
New Beds	45	50	40	65	43	53
Overall	38	55	39	59	39	57

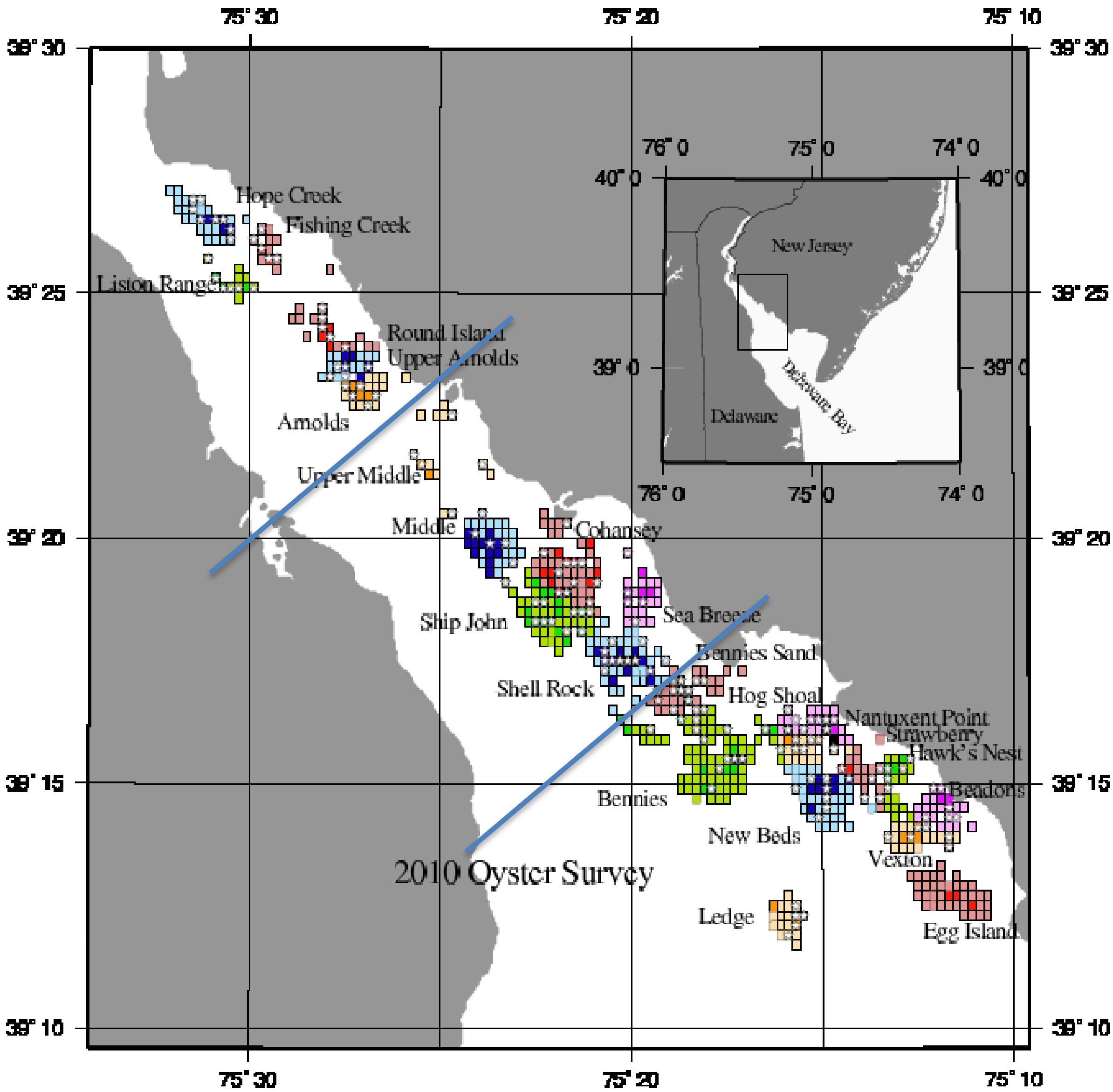


Figure 1. Footprint of the Delaware Bay, NJ state managed oyster beds (aka 'seedbeds') from Powell et al. (2011). Colors differentiate boundaries of named beds with darker colors indicating higher densities of oysters. Stars indicate sampling locations for the 2010 Fall Random Sampling program from which a subset were sampled for MSX, Dermo and condition. Blue diagonal lines differentiate the low mortality beds as the upper portion of the seedbed region, the medium mortality beds as the central portion of the seedbeds, and the high mortality beds as the lower portion of the seedbed region.

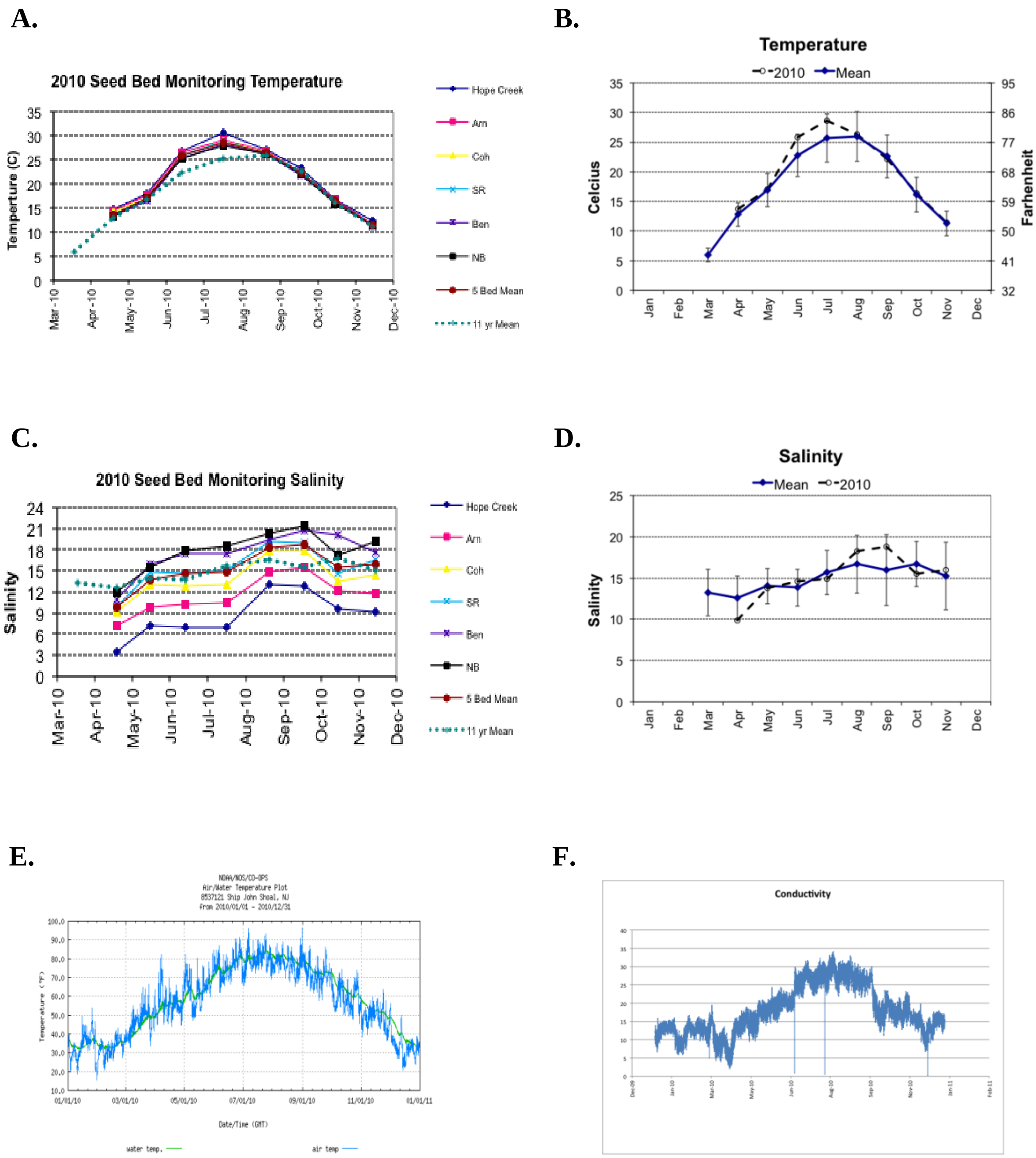
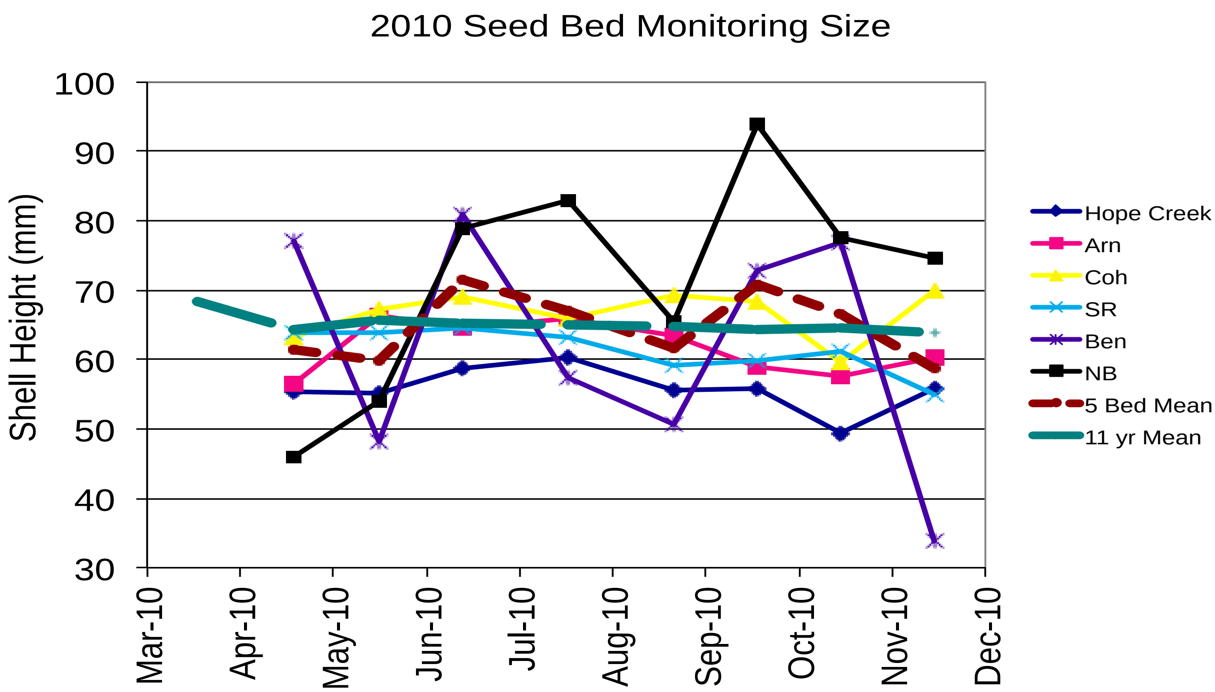


Figure 2. Monthly bottom water temperature and salinity measurements taken during seedbed monitoring at long-term stations and at a continuous monitoring station at the Ship John Shoal Light. A) 2010 temperatures for each bed. B) 2010 mean temperature across beds and mean temperature across beds since 2002. C) 2010 salinity for each bed. D) 2010 mean salinity across beds and mean temperature across beds since 2002. E) Continuously monitored temperature at Ship John Shoal Light during 2010. F) Continuously monitored conductivity at Ship John Shoal Light during 2010. Ship John Shoal Light monitoring data are publicly available in near real-time and archival data http://tidesandcurrents.noaa.gov/.

A.



B.

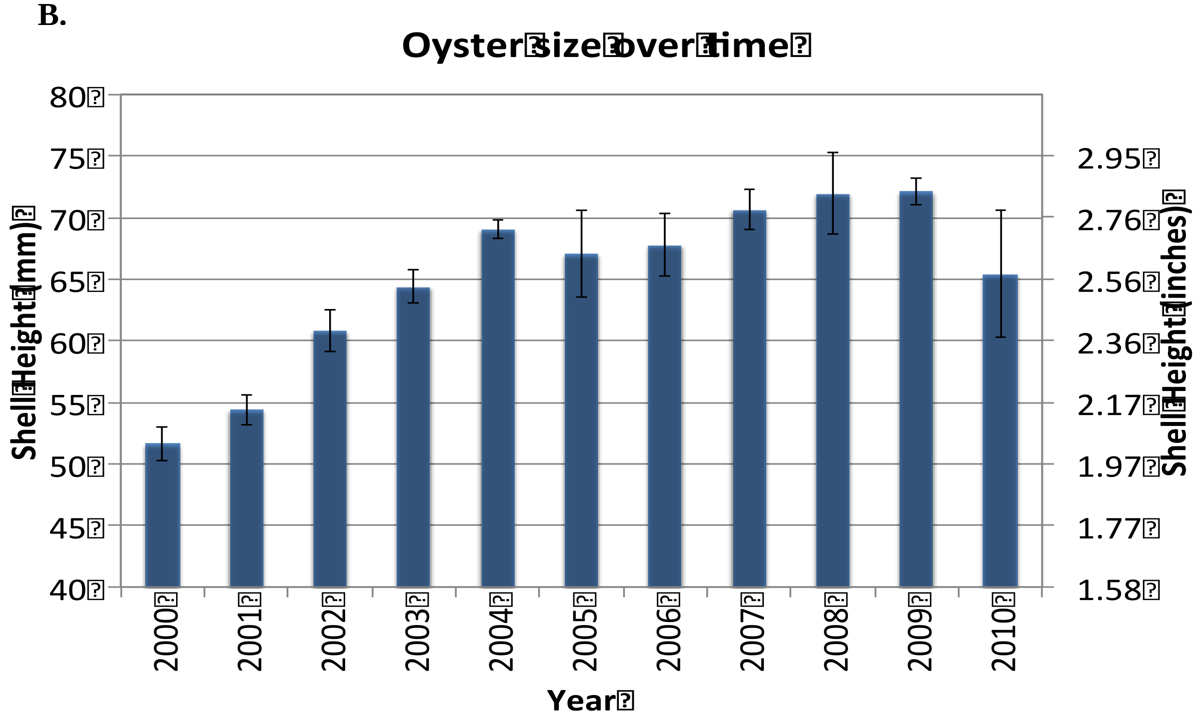
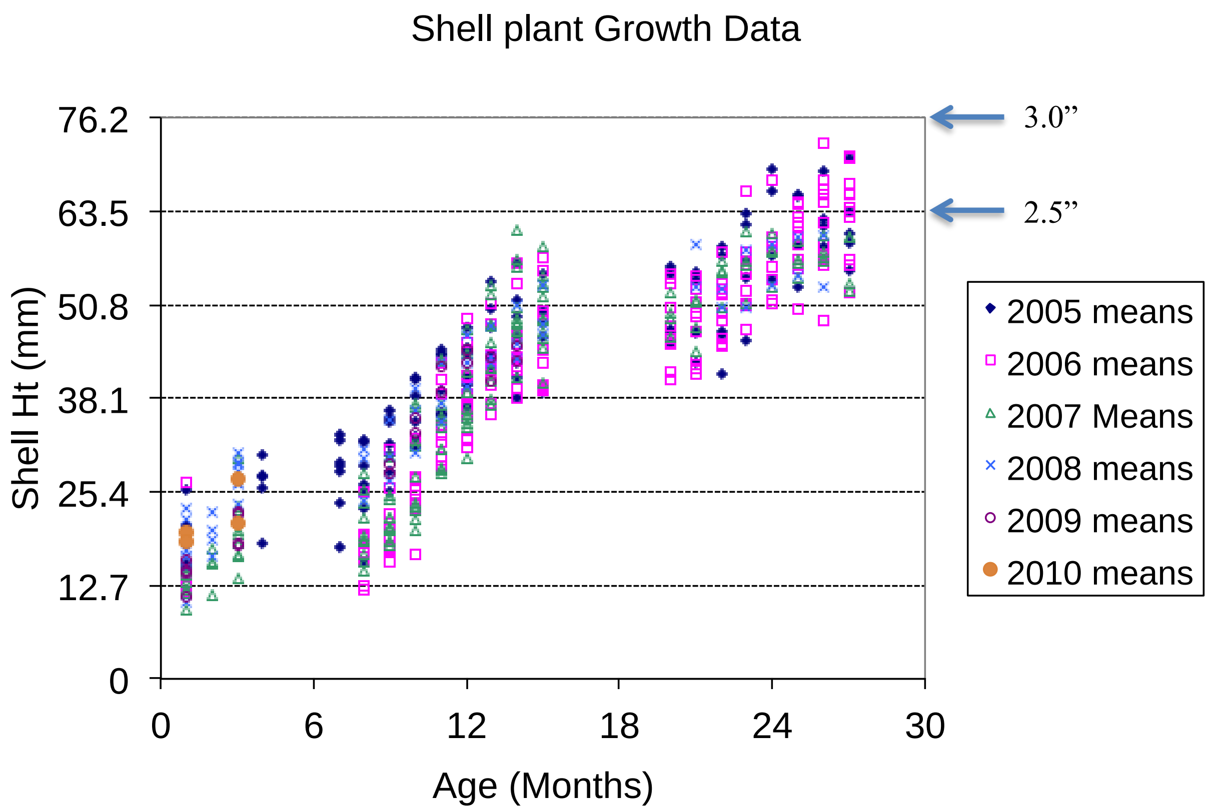


Figure 3. Mean size of oysters collected from Delaware Bay NJ oyster seedbeds. A) Mean size collected in monthly dredge samples by bed. B) Mean monthly (April – September) size averaged across beds annually.



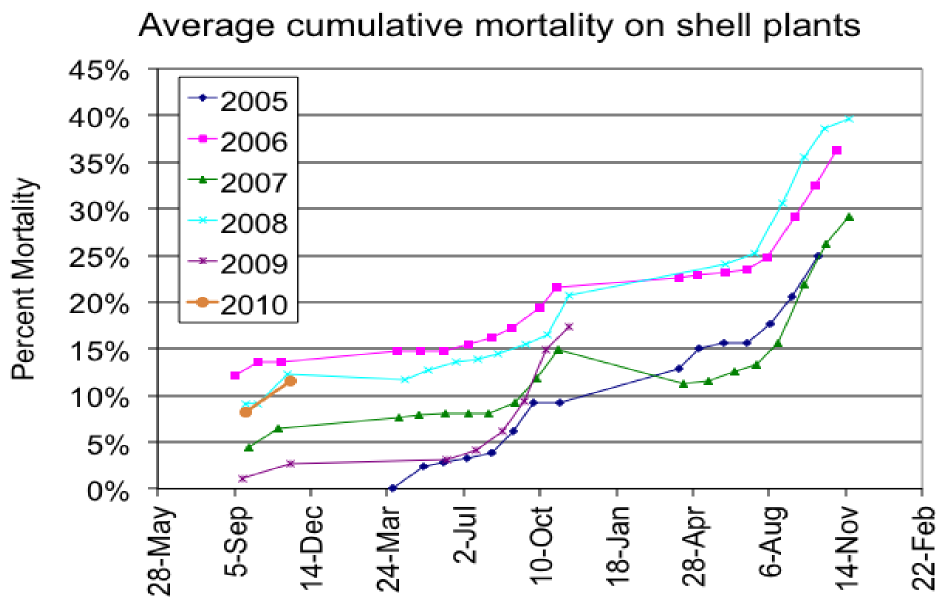


Figure 4. Growth and mortality on shell plantings since 2005. Growth data are monthly means of up to 100 individuals from each shell planting. Mortality data are averaged across plantings. Initial collections are made the year the shell is planted. Age during the first collection is presumed to be about one month, but could be a few days to three months depending on the timing of setting during that year. Efforts were made to only measure oysters from the year class corresponding to the year of the shell plant.

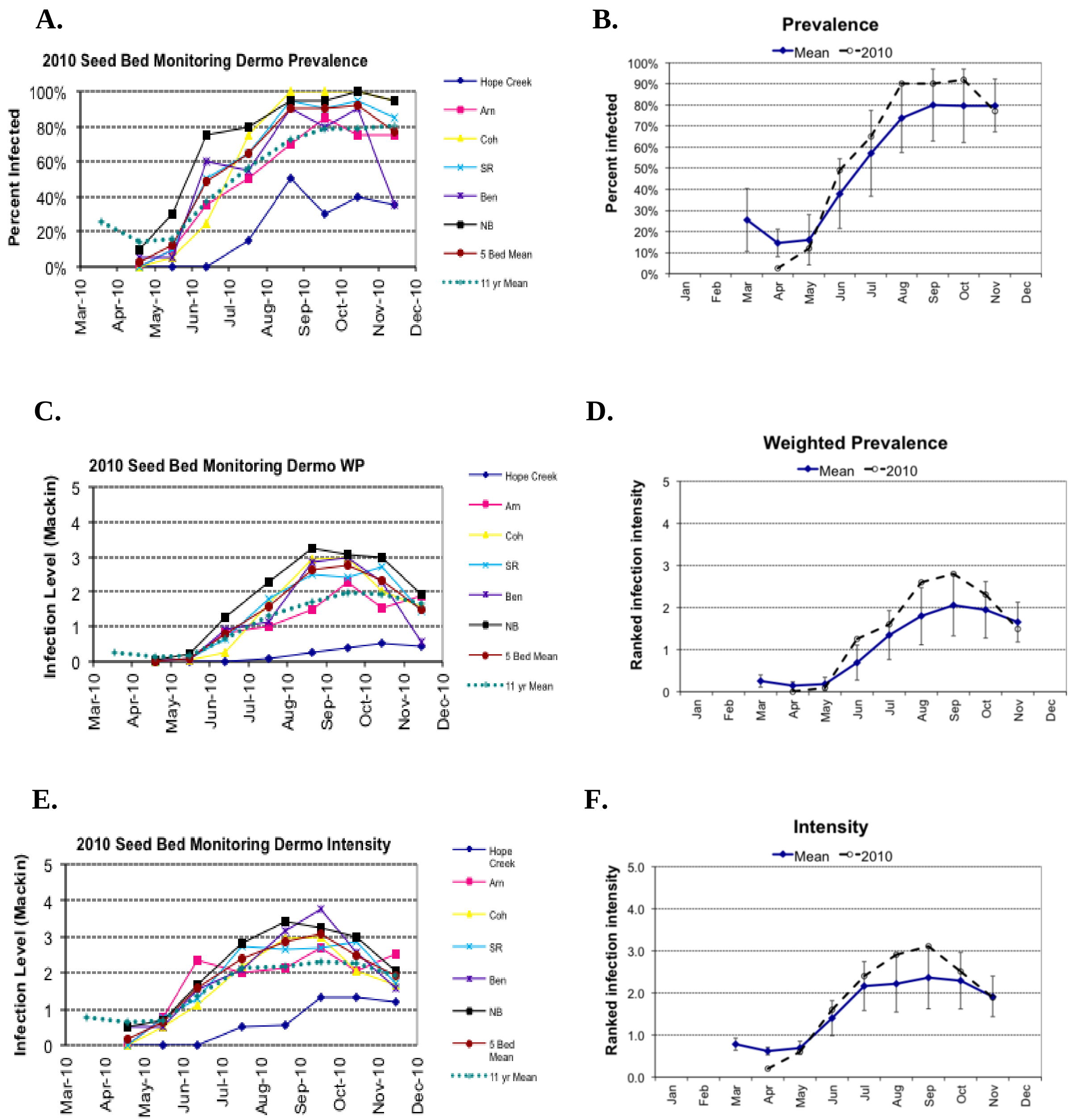
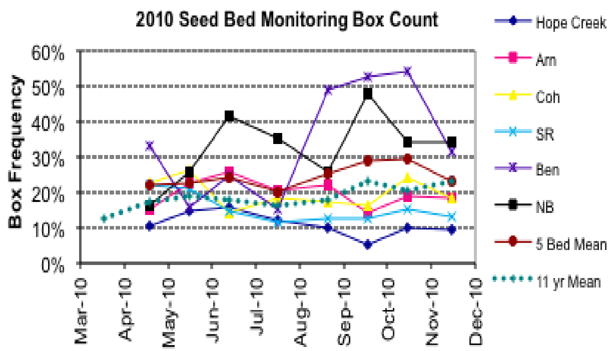


Figure 5. Monthly measures of Dermo disease in oysters from New Jersey Delaware Bay. Prevalence = percent of infected oysters. Weight prevalence (WP) = the average Mackin scale Dermo infection intensity rank of all oysters sampled including those with no detectable infection (i.e., rank = zero). Intensity = average Mackin rank of detectable infections only. Right panels compare mortality for 2010 with mean and standard deviation since 1999 on five long-term monitoring beds (Arnolds, Cohansey, Shell Rock, Bennies and New Beds).

A.



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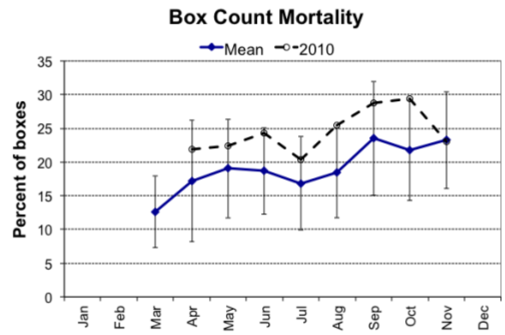
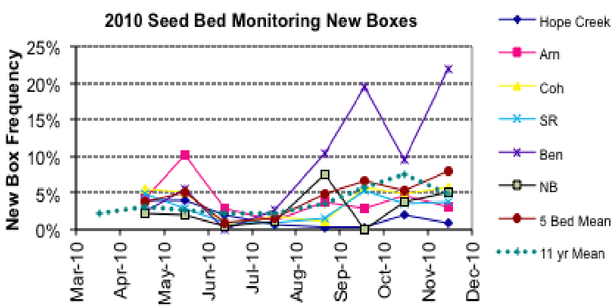
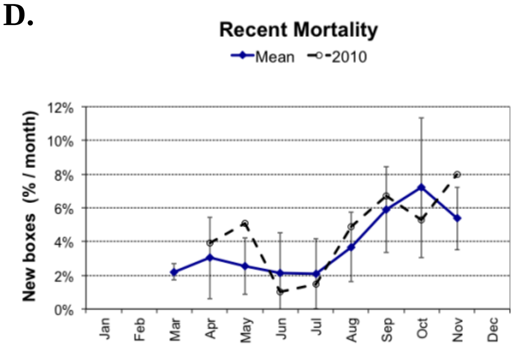


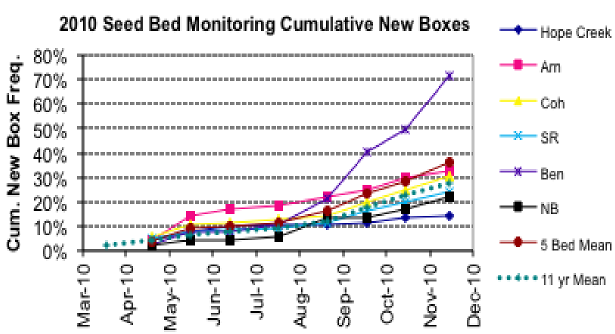
C.



D.



E.



F.

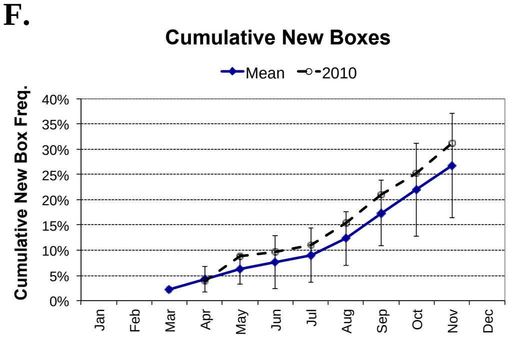


Figure 6. Monthly estimates of oyster mortality on the New Jersey Delaware Bay seedbeds. Left panels show mortality by bed. Right panels compare mortality for 2010 with mean and standard deviation since 1999 on five long-term monitoring beds (Arnolds, Cohansey, Shell Rock, Bennies and New Beds).

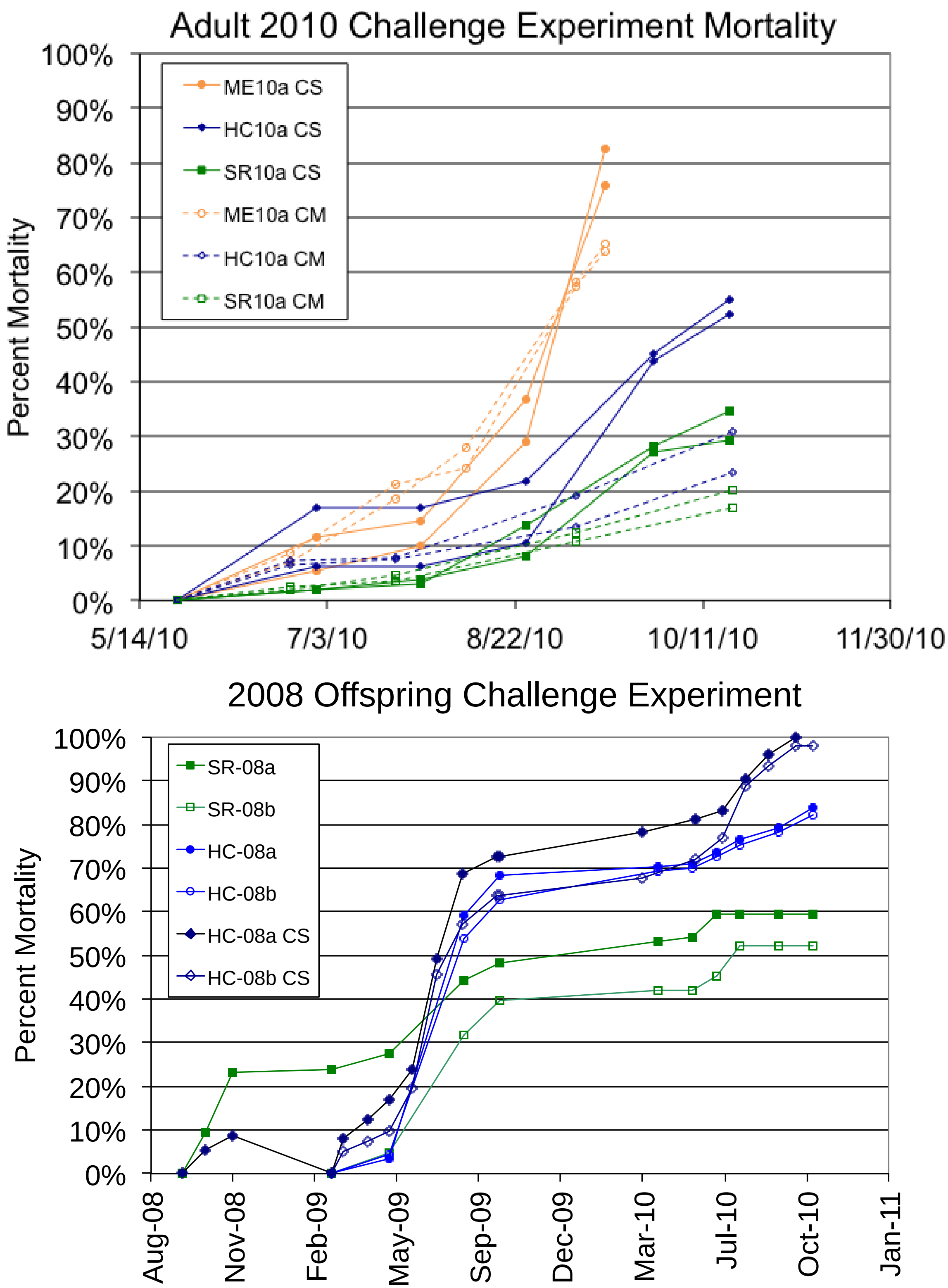


Figure 7. (A) Survival of adult oysters collected from Hope Creek (HC), Shell Rock (SR) and Maine (ME) that were held in bags on racks at Cape Shore and Cape May. (B) Survival of offspring from SR and HC broodstock at Cape May and Cape Shore

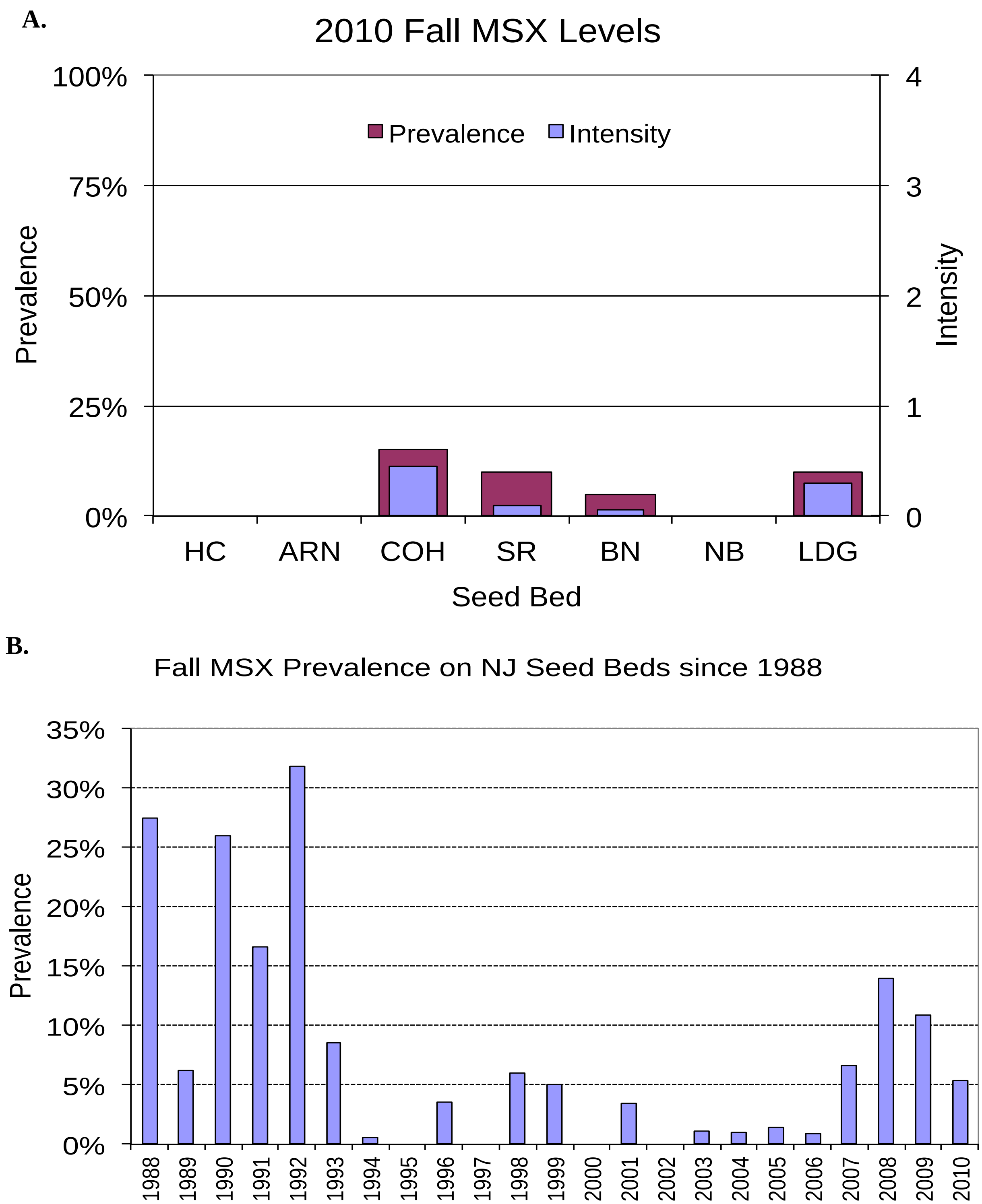


Figure 8. MSX disease on the New Jersey Delaware Bay oyster seedbeds. (A). 2010 Fall MSX prevalence and intensity (weighted prevalence on a scale of 0 to 4). Beds are listed upbay to downbay from left to right: HC = Hope Creek, AR = Arnolds, CO = Cohansey, SR = Shell Rock, B = Bennies, NB = New Beds, LDG = Ledge. (B). Annual Fall MSX Prevalence.

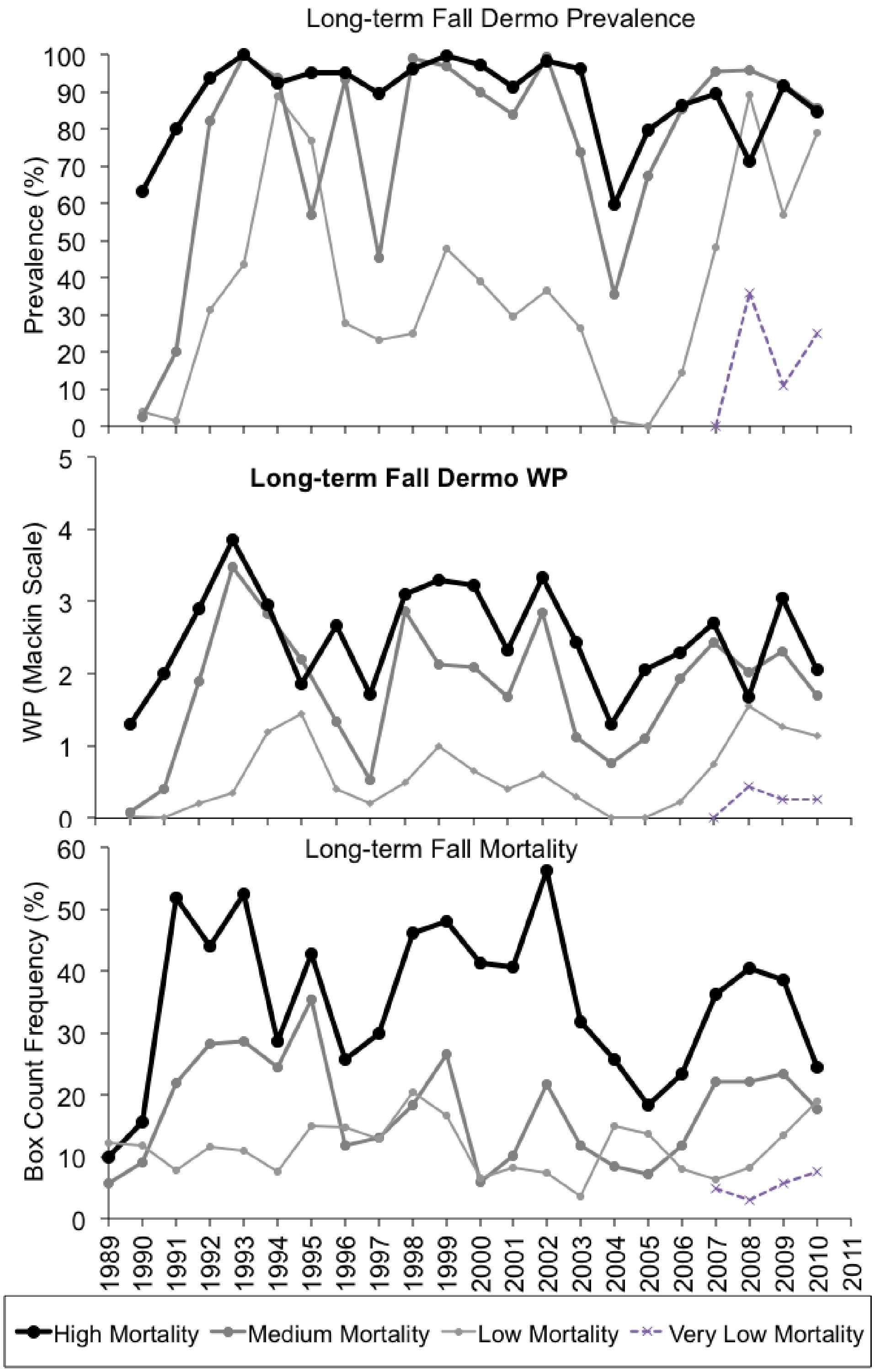


Figure 9. Annual Fall Dermo prevalence, weighted prevalence and box count mortality on New Jersey Delaware Bay seedbeds.

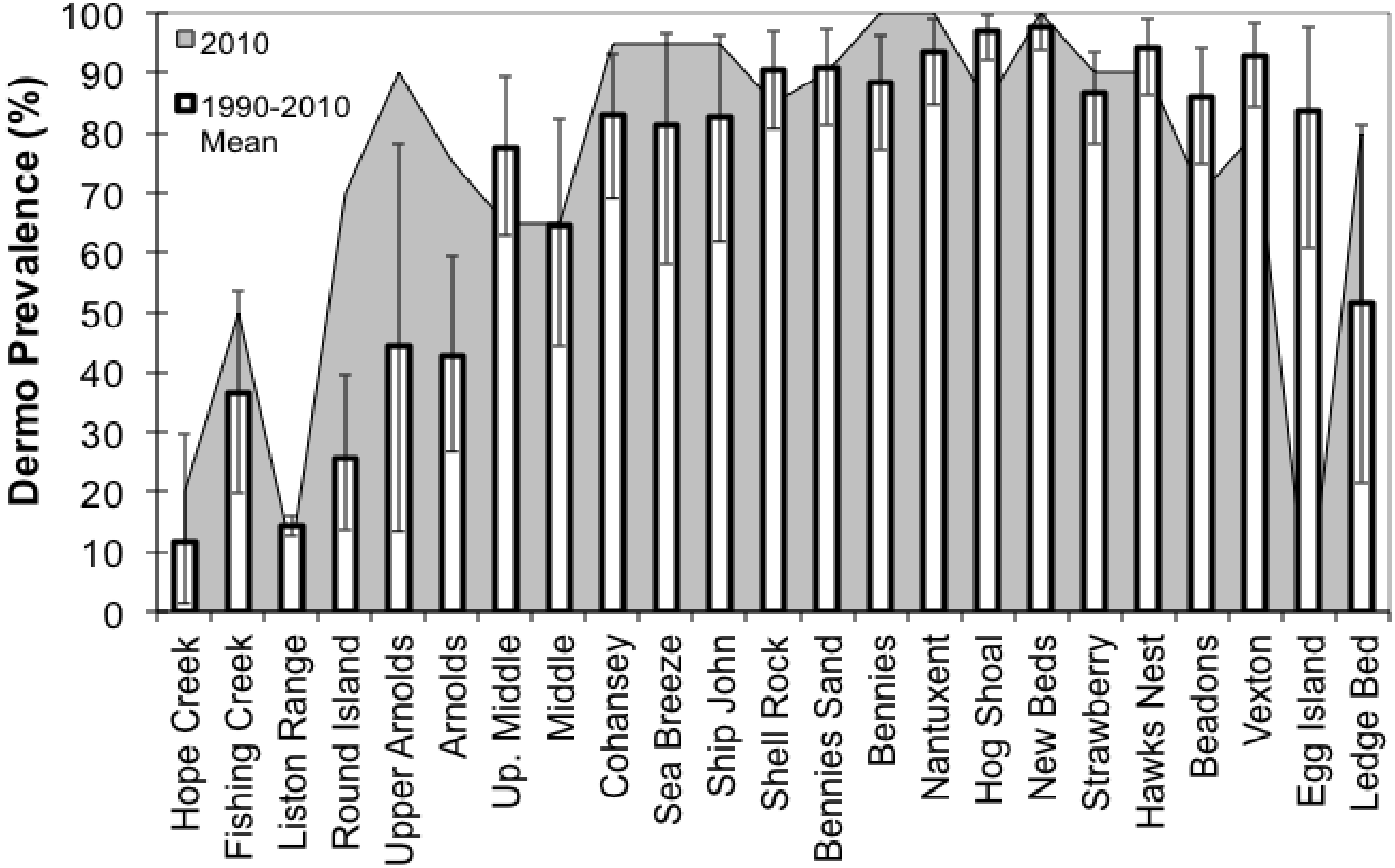


Figure 10. Comparison of average fall *Perkinsus marinus* (Dermo) prevalence in oysters on New Jersey Delaware Bay seedbeds since 1990 (open bars with 95% confidence intervals) with 2010 levels (shaded area). Not all beds have been sampled every year (see Table 5). Egg Island was not sampled in 2010.

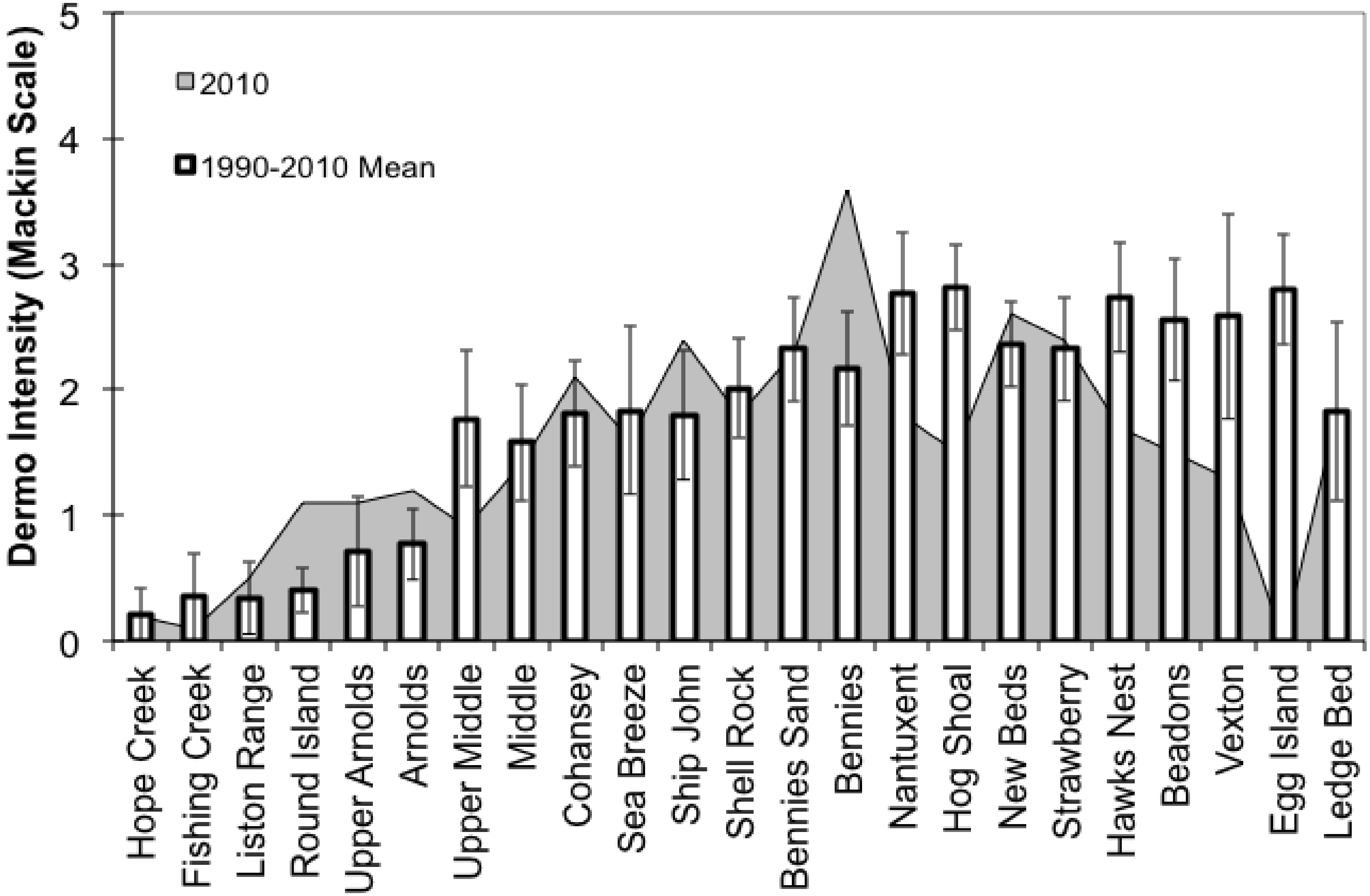


Figure 11. Comparison of average fall Dermo infection intensities (weighted prevalence) in oysters on New Jersey Delaware Bay seedbeds since 1990 (open bars with 95% confidence intervals) with 2010 levels (shaded area). Not all beds have been sampled every year (see Table 5). Egg Island was not sampled in 2010.

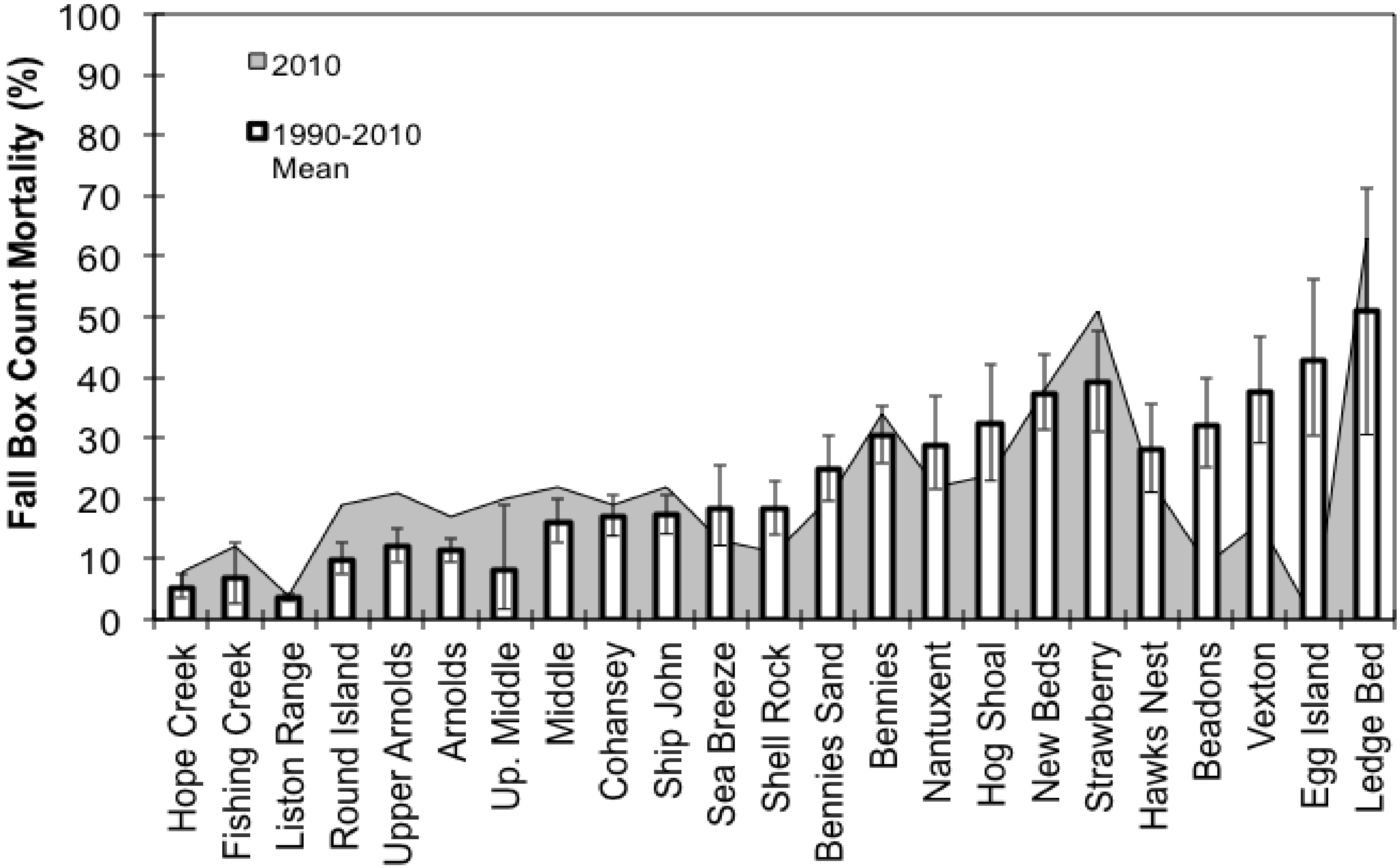


Figure 12. Comparison of average annual fall estimated box-count mortality of oysters on New Jersey Delaware Bay seedbeds since 1989 (open bars with 95% confidence intervals) with 2010 levels (shaded area). Not all beds have been sampled every year (see Table 5). Egg Island was not sampled in 2010.

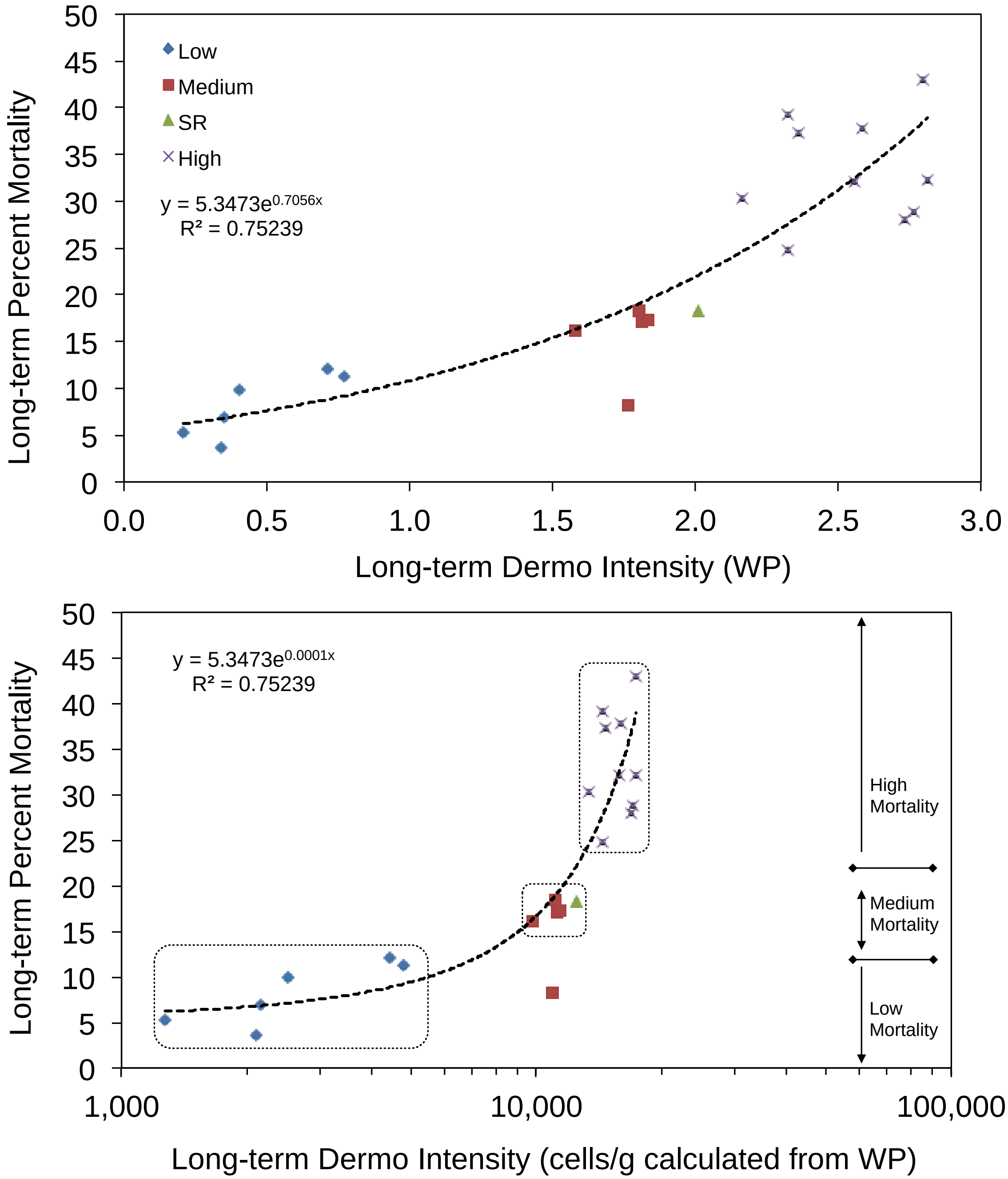


Figure 13. Relationship between long-term mean percent Fall box count mortality estimate and the long-term mean intensity of Dermo infections since 1990. Data are individual bed estimates. Error bars are not shown for clarity. The upper panel uses weighted prevalence while the lower panel converts weighted prevalence values in the upper panel to densities of the parasite per gram of wet tissue after Choi et al. (1990). Boxes represent clusters of beds in regions designated as low, medium and high mortality. SR = Shell Rock bed. The relationships indicate thresholds for Dermo-caused mortality at weighted prevalence of about 1.5 and 2 relative to the mortality incurred.

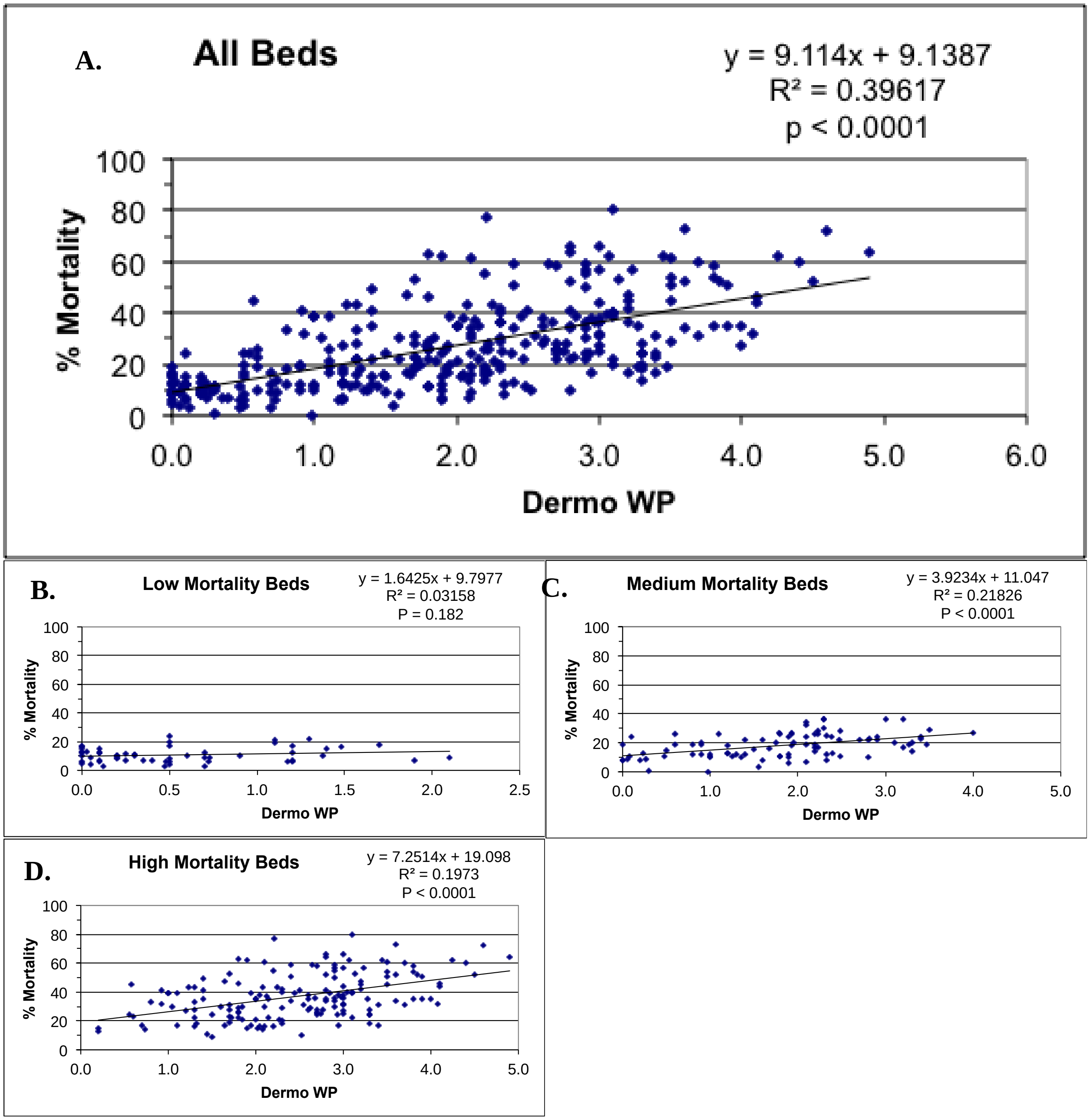


Figure 14. Relationships between fall box count mortality and Dermo infection levels (WP). Data are values for individual beds collected during the Random Sampling Program from 1990 through 2010.