Delaware Bay New Jersey
Oyster Seedbed Monitoring Program
2009 Status Report

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New Jersey Delaware Bay Oyster Seedbeds

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Executive Summary:

The 2009 Delaware Bay New Jersey Oyster Seedbed Monitoring Program followed Dermo disease, oyster growth, and oyster mortality at five long-term monitoring sites, four 2007 shell plant sites, three 2008 shell plant sites and four 2009 shell plant sites. Reductions in monitoring efforts over previous years reflect budgetary limitations (elimination of monitoring transplant sites and some shell plant sites) and an inability to find planted shell on some 2007 and 2008 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; specifically, the NSF EID project monitored MSX and Dermo at several additional sites and conducted disease challenge experiments using oysters from different regions of the bay.

Data from 2009 monthly monitoring indicate that size distributions of oysters continue to remain skewed towards larger animals, largely resulting from continued reductions in recruitment reported by the Stock Assessment Workshop during the past several years. Seasonal water temperature tracked the previous decadal mean and did not vary across the five long-term monitoring sites. Salinity followed the typical up bay-down bay gradient across monitoring sites. It remained relatively stable during the year until increasing from August through October. These conditions of large oysters, typical seasonal temperature cycling and increasing late summer salinity combined to favor the persistence of a Dermo epizootic. High disease levels may have contributed to low condition indices observed during the fall survey (see the Stock Assessment Workshop report). The continuation of the epizootic was reflected in the monthly box count frequency (an estimate of mortality), which was persistently higher than average during monthly sampling. The estimated fraction of new boxes, those from oysters which had apparently died during the previous month, followed mean levels from the past decade, decreasing slightly during the latter half of the year. MSX disease has increased slightly in recent years, but remains at low levels.

Prognosis: Dermo continues to pose a considerable threat to oysters on the NJ Delaware Bay seedbeds. During 2009 Dermo disease levels peaked in September, but many animals still entered the winter with relatively heavy infections as measured during the annual fall survey (88% prevalence and 2.5 weighted prevalence on the Mackin Scale) and in the Seedbed Monitoring program. Since 1990, only six of 20 years have shown higher Dermo levels during the fall random sampling. There remains a weak indication of a seven year cycle, but responsible factors remain unclear. 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 2010. 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 is not monitored by this program. Monthly monitoring provides timely information on seasonal changes for the Shellfish Council. Long-term spatial monitoring provides insight into inter-annual patterns, including long-term trends and potential factors affecting observed patterns. 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 small experiment 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 (= perkinsosis, caused by the protozoan *Perkinsus marinus*) occurred. This was not the first appearance of this disease, but previous appearances were associated with importations of oysters from the lower Chesapeake Bay. Termination of those importations resulted in the 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. In 2007 oysters above Round Island were added to the survey after survey data indicated that their abundance represented a significant proportion of the population and should be included in management of the oyster resource. These oysters 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 (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 2009 objectives for the Seedbed Monitoring Program were:

1. Continue the standard monthly seedbed monitoring time series
2. Conduct Dermo and MSX assays and determine condition indices for the 2009 Fall Stock Assessment Random Sampling Survey
3. Monitor growth, mortality and disease on selected 2007, 2008 and 2009 shell plants
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. This also provides essential baseline/background information against which the success of other objectives and independent research can be evaluated. 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, details will be reported elsewhere. 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 took over the program in 2003, but Dr. Ford continues to provide valuable advice and assistance.

Methods

Figure 1 depicts the grid system used during 2009 for the seedbed monitoring program. Beds that fall in the jurisdiction of the state of Delaware are not shown. The grid system is nearly contiguous, but the 23 areas differentiated by color represent concentrations of oysters 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. Samples were collected from April through November for

Objective 1 and 3 as indicated in Tables 1 and 2, respectively. Table 3 lists the beds and grids that were monitored for shell plants and replants. Note that no transplant beds were monitored during 2009 due to insufficient funding. Table 4 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 5 specifies the grids sampled during the Annual Fall Stock Assessment to complete Objective 2. As indicated above, the dotted lines in Figure 1 demarcate the low, medium and high mortality zones that correspond with salinity regimes of 0-15 ppt, 5-20 ppt and 10-24 ppt. Management activities and this report reference both regions and beds as appropriate.

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. 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 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 this 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 as dredge efficiency studies have shown (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 weighted using the "Mackin scale" from zero (= pathogen not detected) to five (= heavily infected) (Ray 1954). These values were averaged to produce a weighted prevalence (Mackin 1962), which provides an estimate of the average disease level in the sample of oysters. During June and July, sex was determined for each oyster sacrificed for Dermo analysis to identify any crude trends in sex ratio.

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 random sampling of the medium and high quality grids on the 23 named beds (colored grids in Figure 1). 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 5. 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 April through November (Table 2) for sites manipulated as indicated in Table 3. Limited funding precluded collection of samples in March. At least three and up to five 1-minute dredge tows were systematically

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

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 where collected until 100 live oysters were acquired. 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 each month and for Dermo analyses (n = 20 per site) during July, 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. In June 2008, a portion of the 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 2009.

Results and Discussion

Water temperatures measured during 2009 collections across the seedbeds followed typical patterns with a peak in July and little spatial variability (Figure 2A). Moreover, monthly temperature measurements match average levels measured since 1990 (Figure 2B). Salinity followed a typical spatial pattern, increasing from upbay to downbay beds (Figure 2C). Levels were relatively constant from April to July, then increased rapidly before declining again after considerable rainfall during October (Figure 2D). This combination of temperature and salinity 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 while the Ship John station was operational. Unfortunately, this station was not operational from mid-May to November. 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. During 2009, mean shell height of oysters from the five long-term monitoring sites indicated three groupings that correspond to other upbay-downbay groupings (Figure 3). Oysters on Arnolds, a low mortality bed, hovered around the legal minimum harvest size of 2.5 inches (64 mm), during 2009. Mean size at Arnolds decreased slightly during the year and may be attributable to transplant operations which have moved larger animals from Arnolds downbay as part of the intermediate transplant program to support the direct market harvest. Oysters on medium mortality beds of Cohansey and Shell Rock grouped together and began the year smaller than oysters at Arnolds; an atypical pattern that may reflect several consecutive years of unusually low recruitment on Arnolds. As the season progressed, however, mean size increased on Cohansey and Shell Rock and exceeded that observed on Arnolds after June. On the high mortality beds (Bennies and New Beds), mean size was initially quite high, but decreased throughout the year. These beds routinely receive higher recruitment relative to beds further up bay even in years labeled recruitment failures. The pattern observed probably reflects a combination of recruitment adding smaller animals while natural mortality and fishing removed larger animals. Averaging the mean size across these beds for each year since 2000 provides a striking increase in the mean size of oysters across the seedbeds (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.

A secondary concern signaled by the changes in shell height may be how age structure might affect fertilization success, particularly if the population relies on younger individuals to contribute a significant fraction of gametes during spawning. 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. Table 6 shows that there were fewer males present in upbay populations during the June 23 and July 20 collections. Oysters were well into the gametogenic cycle by the June 23 monthly sample collection and gametes remained readily apparent into August, although most oysters appeared to have spawned by the August 17th collection. Temperature data (Figure 2) indicate conditions warm enough to stimulate spawning (25^{o}C = 77^{o}F) were reached by mid-July. While it takes only a few males to produce enough sperm to fertilize all the eggs that can be produced by the females in the population, data from several studies suggest that the abundance of sperm produced by benthic broadcast spawners, like oysters, may be a limiting factor in reproductive success due to dilution, currents, non-synchronous spawning, and other variables that affect the probability of sperm finding an egg (Levitan and Petersen 1995). Enhancing recruitment is probably the single most important strategy that can be employed to protect the sustainability of the oyster population on the seedbeds.

The shell planting program began in 2005 to enhance recruitment on the seedbeds after several consecutive years of recruitment failures put the stock at risk. The program has successfully increased recruitment as detailed in previous annual stock assessment reports. The program provides the opportunity to obtain specific data on growth and mortality of young animals (age class 0-2) as the planted shell (ocean quahog or surf clam shell) is traceable through time. Figure 4 shows the growth of the initial cohorts that set on this planted material since 2005. The data indicate that oysters grow 20-30 mm on average (about 1 inch) during the year they set, nearly 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. Impressively, there is 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.

Dermo prevalence, weighted prevalence (WP) and intensity followed typical seasonal and spatial 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. Similar patterns and disease levels occurred in the previous two years. The patterns were very similar to the previous two years, indicating the continuation of an epizootic that spread across the medium mortality beds and into the low mortality beds. By July, weighted prevalence at New Beds, Bennies and Shell Rock exceeded 1.5, a level expected to begin causing noticeable mortality. By August, levels on Cohansey and Arnolds exceeded a WP of 1.5. By the end of the sampling season in November, only disease levels on Arnolds had fallen below a WP of 1.5. The severity of the epizootic is more clearly illustrated in Figures 5B, 5D and 5F, which compare the annual seedbed monitoring mean levels to mean seedbed levels since 1999. For each measure, 2009 values exceed long-term mean values, often by one standard deviation or more.

Total box counts from monthly samples are shown in Figure 6A and B. Bennies shows dramatic fluctuations that are likely attributable to difficulties in finding high concentrations of oysters in general. The quality of the grid sampled appears to have declined significantly in recent years. New Beds shows a sharp decline in September and October which may be a result of recruitment or growth of younger animals into size classes that are sampled. Lowest box counts were consistently observed on Arnolds which is typical in most years and corresponds to this being classified as a low mortality bed. Box counts on Arnolds as well as Cohansey and Shell Rock, increased during late summer to fall following corresponding increases in Dermo disease. As mentioned in previous reports, the fluctuations in box count data is noteworthy because it is not consistent from year to year and sample collection for the annual stock assessment survey may be influenced by such fluctuations. Boxes are labile with half lives generally less than a year so the timing of mortality can significantly contribute to error for estimates made but once annually (Ford et al. 2006). Counts of new or recent boxes indicated that the majority of the 2009 mortality occurred from August to November (Figure 6C and D). A mortality event in April is also evident and likely represents over winter mortality enhanced by high Dermo levels observed during fall 2008. A similar spring mortality event is expected in 2010 as many animals entered the winter with relatively high Dermo infections (Figure 5). Cumulative recent mortality estimates indicate somewhat greater mortality occurred than estimated by total box counts (Figure 6C and E) and may account for a portion of the persistent underestimate of mortality by the annual stock assessment models (Powell et al. 2007). Using cumulative recent box count estimates and 20% mortality as a definition of an epizootic mortality (the level used in previous stock assessments), all beds monitored monthly experienced epizootic mortalities in 2009.

Samples for the 2009 Random Sampling Stock Assessment were collected between October 29 and November 3. Condition indices and size frequencies were reported elsewhere as part of the stock assessment. Details of Dermo and mortality are presented below. 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 5). Of 137 oysters examined, only 15 infections were detected overall and only 3 infections were systemic. MSX prevalence and intensity increased from upbay to downbay but prevalence did not exceed 30% and weighted prevalence did not exceed 0.5 on any bed sampled (Figure 7a). Despite the absence of MSX epizootics, the pathogen is clearly still present and examination of fall MSX prevalence on seedbeds since 1988 shows a recent increase (Figure 7b). In other areas of the mid-Atlantic and beyond, MSX continues to be a serious problem and oysters from areas where MSX has never or rarely been detected are highly susceptible. These data and observations indicate the importance of continuing to monitor the status of MSX.

Figure 8 compares survival of Hope Creek oysters against Shell Rock oysters deployed on aquaculture racks at the Cape Shore and in Cape May. Mortality curves of adult oysters transplanted to the Cape Shore where they were held in bags are similar with both stocks sustaining high mortality (93%) by the end of the trial (Figure 8A). Disease sampling presented last year indicated that Shell Rock oysters were collected with slightly heavier Dermo and MSX infections and this may explain the earlier onset of mortality in Shell Rock adults versus Hope Creek adults held in bags at the Cape Shore. By the end of the study both stocks had similar infection levels suggesting they may possess similar levels of resistance and tolerance to Dermo disease. In contrast, offspring from these stocks showed lower mortality in the Shell Rock stock (Figure 8B) when both were deployed in Cape May Harbor. Furthermore, in October 2009, MSX and Dermo disease was lower in Shell Rock compared to Hope Creek (MSX prevalence of 5 vs 30% and Dermo weighted prevalence of 0.5 vs 1.3, respectively). These data suggest that Hope Creek oysters may not be as resistant or tolerant to Dermo or MSX disease as oysters from Shell Rock. Additional disease analyses and monitoring will continue on the offspring in 2010, but further studies will be necessary to make any definitive conclusions.

Figures 9, 10 and 11 depict annual fall Dermo prevalence, Dermo infection intensity (= weighted prevalence) and fall box-count estimated mortality from 1989 to 2009 for the entire seedbed region (upper panel), the low mortality beds (second panel), the medium mortality beds (third panel) and the high mortality beds (bottom panel). Dermo prevalence and intensity remained high in 2009 continuing an epizootic that began after a low in 2004. Since 1990 there have been two low periods; 1997 and 2004 (Figures 9 and 10). The lows occurred every seven years since 1990, suggesting there may be a seven year cycle. 2009 is the fifth year following 2004, indicating that 2010 may be another relatively high disease level if the seven year cycle is more than coincidental. Many factors such as temperature, salinity and recruitment 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 or seasonal variations in Dermo disease, it is less clear how they interact to influence interannual variation.

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 11). Note that mortality appears to lag disease by about one year. 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 apparent seven year periodicity is based on brief periods of disease remission centered around 1997 and 2004. Unfortunately, periods of remission appear to be much shorter than the duration of the epizootics. There is also an apparent attenuation of mortality in the three successive epizootics. This observation remains difficult to interpret, but could indicate a positive response leading to an increase in tolerance to Dermo disease: tolerance being the relative ability of an oyster to survive an infection of a given intensity versus resistance which is the ability of an oyster to limit the development of an infection. In any case, it appears that Dermo-induced mortalities can be expected to continue in 2010.

Examination of Dermo prevalence and Dermo intensity on a bed-by-bed basis in Figures 12 and 13 indicated that levels were higher than long-term means on all but two of the most upper bay beds (Liston Range and Fishing Creek). Mortality follows suit with few exceptions (Figure 14). Figure 15 plots long-term Dermo infections against long-term mortality for each bed. The upper panel uses weighted prevalence which averages the ranked infection intensity assigned by a trained technician. The 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%. These beds define the medium mortality zone. Once Dermo levels exceed 2.0, average mortality increases to between 25 and 40%. Interestingly, beds in this third group segregate further into those with weighted prevalence between 2.0 and 2.5 and those with weighted prevalence between 2.5 and 3.0. The former group contains Bennies Sand, Bennies, New Beds, Strawberry and Ledge, which (excluding Strawberry) tend to be slightly up bay and/or offshore compared to the other beds that tend to lie inside the cove formed by Bennies and Egg Island Points (Nantuxent, Hog Shoal, Hawk's Nest, Beadons, Vexton and Egg Island). Reasons for this discrepancy are not clear and may relate to differences in transmission dynamics, physical conditions favoring Dermo proliferation (e.g., temperature and salinity), differences in host resistance, differences in parasite virulence, or some combination of these factors. Given our current limited understanding, the latter two factors seem less likely than either of the first two. A better understanding of these processes could enhance management strategies to increase oyster production and sustainability of the fishery. The lower panel of Figure 15 converts weighted prevalence values to the number of parasites per gram of tissue using a formula derived by Choi et al. (1990). In each case, the beds segregate into three or four disease and mortality zones which are generally designated high, medium and low mortality zones. Choi et al. (1990) determined that the Mackin Scale used to assign infection intensity rankings is essentially a $\log_{10}$ scale. While the upper panel shows that two thresholds of Dermo intensity appear to exist at weighted prevalence of 1.5 and 2.0, above which distinct increases in mortality occur, the lower panel not only confirms this but adds some insight about how Dermo can persist in the population. That is, Dermo infections intensify exponentially according to a logarithmic function approximating base 10. This means that infections can linger at low levels for long periods with little effect, but once they reach certain levels, they can develop quickly unless there is a counteracting force to slow them down. Thus, the medium mortality beds can quickly reach Dermo levels observed on the high mortality beds thereby increasing the Dermo mortality risk.

Figure 16 shows the individual data points for each bed and each year sampled since 1990. The overall relationship between Dermo weighted prevalence and mortality estimated by fall-survey box counts is highly significant and explains nearly 40% of the variation in mortality (Figure 16A). This relationship suggests that for each integer increment in weighted prevalence, mortality will increase by about 9% on average 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 and increases progressively as Dermo levels increase (Figure 16B, C and D). Dermo levels are too low to impact mortality on the low mortality beds. As a result, Dermo is not a predominant cause of mortality on the low mortality beds (Figure 16B), but increases in importance on the medium and high mortality beds. It is tempting to compare mortality rates for different Dermo levels in Figures 16 C 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 16 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. 2009 sampling schedule for the NJ Delaware Bay Oyster Seedbed Long-term Monitoring Program. The five 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. Parameters measured include temperature, salinity, counts of live oysters and boxes, size frequency (shell height), and Dermo levels.

Date	Samples	Vessel	Captain
Apr 17, 2009	5 long-term sites	NJDEP RV Zephryus	Craig Tomlin
May 18, 2009	5 long-term sites	NJDEP RV Zephryus	Jason Hearon
Jun 22, 2009	5 long-term sites	NJDEP RV Zephryus	Jason Hearon
Jul 20, 2009	5 long-term sites	NJDEP RV Zephryus	Jason Hearon
Aug 17, 2009	5 long-term sites	NJDEP RV Zephryus	Craig Tomlin
Sep 21, 2009	5 long-term sites	NJDEP RV Zephryus	Jason Hearon
Oct 20, 2009	5 long-term sites	NJDEP RV Zephryus	Craig Tomlin
Nov 24, 2009	5 long-term sites	NJDEP RV Zephryus	Craig Tomlin

Table 2. 2009 sampling schedule for monitoring shell plants.

Date	Samples	Vessel	Captain
Apr 17, 2009	NJ 07&08 plants	NJDEP RV Zephyrus	Craig Tomlin
May 18, 2009	NJ 07&08 plants	NJDEP RV Zephyrus	Jason Hearon
Jun 22, 2009	NJ 07&08 plants	NJDEP RV Zephyrus	Jason Hearon
Jul 20, 2009	NJ 07&08 plants	NJDEP RV Zephyrus	Jason Hearon
Aug 17, 2009	NJ 07&08 plants	NJDEP RV Zephyrus	Craig Tomlin
Sep 16, 2009	NJ 09 plants	NJDEP RV Zephyrus	Craig Tomlin
Sep 21, 2009	NJ 07&08 plants	NJDEP RV Zephyrus	Jason Hearon
Oct 20, 2009	NJ 07&08 plants	NJDEP RV Zephyrus	Craig Tomlin
Nov 18, 2009	NJ 09 plants	NJDEP RV Zephyrus	Craig Tomlin
Nov 24, 2008	NJ 07&08 plants	NJDEP RV Zephyrus	Craig Tomlin

Table 3. Shell plant and transplant sites sampled during 2009. Replant = shell planted in lower Delaware Bay then moved to bed indicated after spat have recruited.

Bed	Grid	Plant material	Plant yr
Ship John	22	ocean quahog shell	2007
Ship John	48	ocean quahog shell	2007
Middle	34	ocean quahog shell & surf clam replant	2007
Cohansey	59	surf clam replant	2007
Cohansey	64	surf clam replant	2008
Bennies Sand	8	ocean quahog shell	2008
Nantuxent	17	ocean quahog shell	2008
Shell Rock	21	ocean quahog shell & surf clam replant	2009
Bennies Sand	21	ocean quahog shell & surf clam replant	2009
Nantuxent	24	ocean quahog shell	2009
Tonger’s Bed	Maurice River Cove	surf clam replant	2009

Table 4. 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**
Hope Creek																		X	X	X
Liston Range																			X	X
Fishing Creek																			X	X
Round Island	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
Arnolds	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
Middle	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
Sea Breeze															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
Shell Rock	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
Bennies	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
Hog Shoal		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
Strawberry	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
Beadons	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
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	

Table 5. 2009 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.

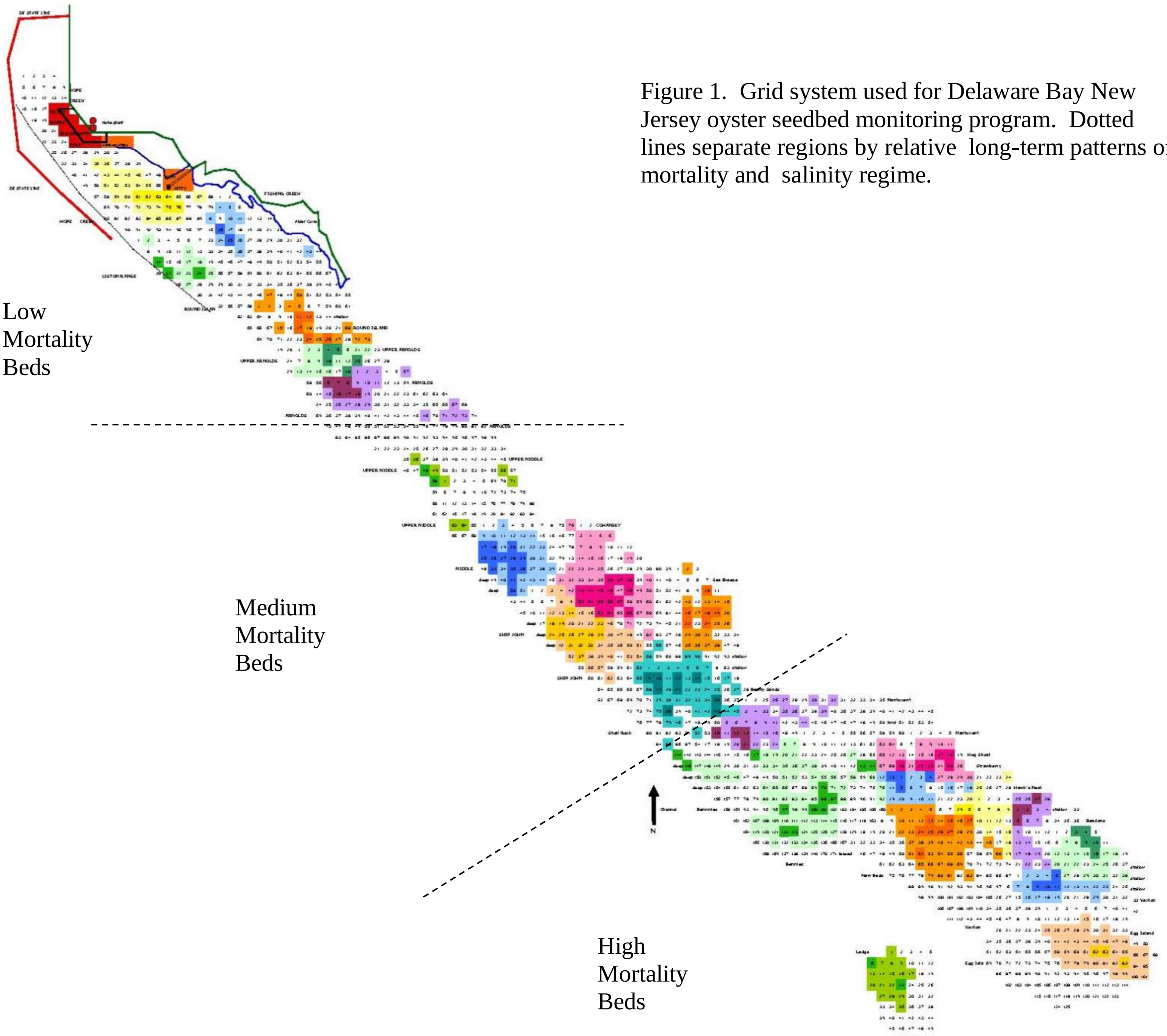
Bed	Grid	Dermo	MSX	CI
Hope Creek	46	10	10	7
Hope Creek	75	10	10	11
Hope Creek	63			17
Hope Creek	76			15
Fishing Creek	5	10		15
Fishing Creek	25	10		14
Fishing Creek	10			8
Fishing Creek	16			8
Fishing Creek	17			3
Liston Range	2	10		15
Liston Range	24	10		15
Liston Range	17			10
Liston Range	23			10
Round Island	1	10		13
Round Island	11	10		15
Round Island	5			11
Round Island	18			11
Upper Arnolds	4	10		14
Upper Arnolds	22	10		15
Upper Arnolds	8			11
Upper Arnolds	9			10
Arnolds	28	10	10	14
Arnolds	8	10	10	15
Arnolds	19			10
Arnolds	9			11
Upper Middle	1			16
Upper Middle	58	10		17
Upper Middle	64	10		17
Middle	20	10		15
Middle	12			9
Middle	13			11
Middle	43	10		15
Cohansey	50	10	10	15
Cohansey	1	10	10	13
Cohansey	45			11
Cohansey	20			11
Sea Breeze	19			10
Sea Breeze	18	10		15
Sea Breeze	36	10		15
Sea Breeze	24			10
Ship John	14	10		15
Ship John	35	10		15
Ship John	52			10
Ship John	28			10
Shell Rock	52	10	10	5
Shell Rock	14	10	10	6
Shell Rock	85			17
Shell Rock	29			15
Shell Rock	43			7

Bed	Grid	Dermo	MSX	CI
Bennies Sand	24	10		15
Bennies Sand	4	10		15
Bennies Sand	19			10
Bennies Sand	32			10
Bennies	86	10	10	6
Bennies	27	10	10	6
Bennies	122			12
Bennies	85			14
Bennies	98			12
Nantuxent	18	10		15
Nantuxent	20	10		15
Nantuxent	13			10
Nantuxent	68			10
Hog Shoal	10	10		15
Hog Shoal	5	10		15
Hog Shoal	12			10
Hog Shoal	6			10
New Beds	53	10	10	15
New Beds	13	10	10	13
New Beds	42			11
New Beds	23			12
New Beds	29			3
Strawberry	5	10		29
Strawberry	6	10		10
Strawberry	8			5
Strawberry	18			7
Hawks Nest	24	10		13
Hawks Nest	2	10		12
Hawks Nest	13			13
Hawks Nest	26			12
Beadons	4	10		15
Beadons	22	10		12
Beadons	18			11
Beadons	16			9
Beadons	7			3
Vexton	10	7		10
Vexton	22	2		3
Vexton	9	11		27
Vexton	19			2
Egg Island	66	11	11	0
Egg Island	44	5	5	2
Egg Island	99	3	3	0
Egg Island	31	1		1
Egg Island	63			1
Egg Island	98			1
Total beds	**22**	**22**	**7**	**22**
Total grids	**94**	**47**	**15**	**94**
Total oysters		**440**	**140**	**1052**

Table 6. 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. Individuals whose sex was not discernable are not shown. No hermaphrodites were detected in these samples.

	June 22, 2009		**July 20, 2009**		**Combined**	
Bed	Males	Females	Males	Females	Males	Females
Arnolds	35	60	30	70	33	65
Cohansey	40	55	30	70	35	63
Shell Rock	35	65	35	65	35	65
Bennies	55	45	40	60	48	53
New Beds	60	40	45	45	53	43
Overall	45	53	36	52	41	58

Figure 1. Grid system used for Delaware Bay New Jersey oyster seedbed monitoring program. Dotted lines separate regions by relative long-term patterns of mortality and salinity regime.



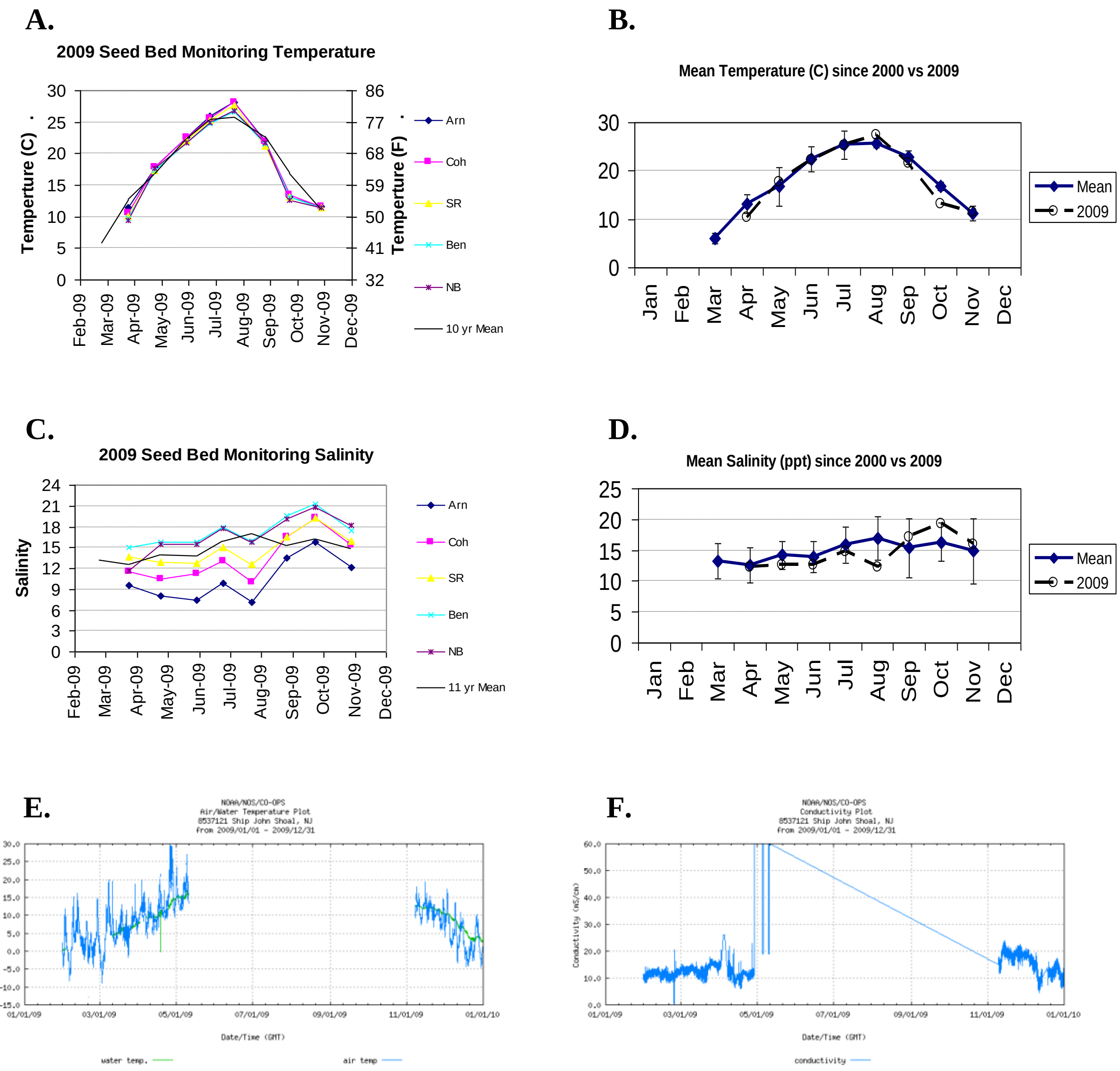
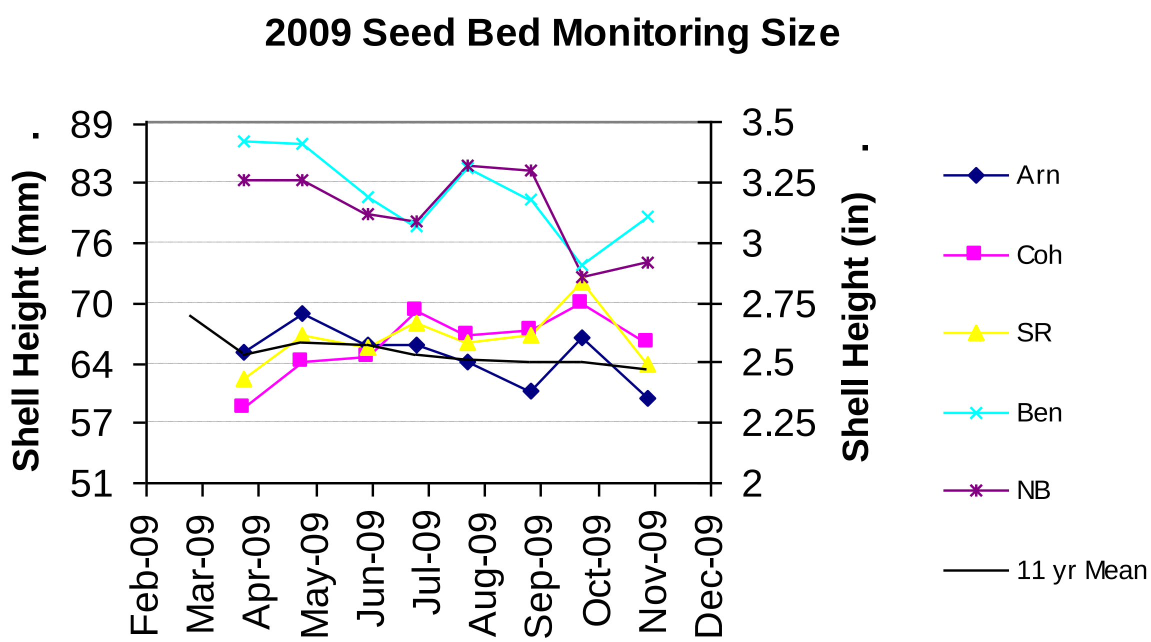


Figure 2. Monthly bottom water temperature and salinity measurements taken during seedbed monitoring at long-term stations and at a continuous monitoring station at the Ship John Shoal Light. A) 2009 temperatures for each bed. B) 2009 mean temperature across beds and mean temperature across beds since 2002. C) 2009 salinity for each bed. D) 2009 mean salinity across beds and mean temperature across beds since 2002. E) Continuously monitored temperature at Ship John Shoal Light during 2009. F) Continuously monitored conductivity (a surrogate for salinity) at Ship John Shoal Light during 2009. Ship John Shoal Light monitoring data are publicly available in near real-time and archival data http://tidesandcurrents.noaa.gov/. Note that the Ship John station maintained by NOAA was inactive for most of the 2009 season.

A.



B.

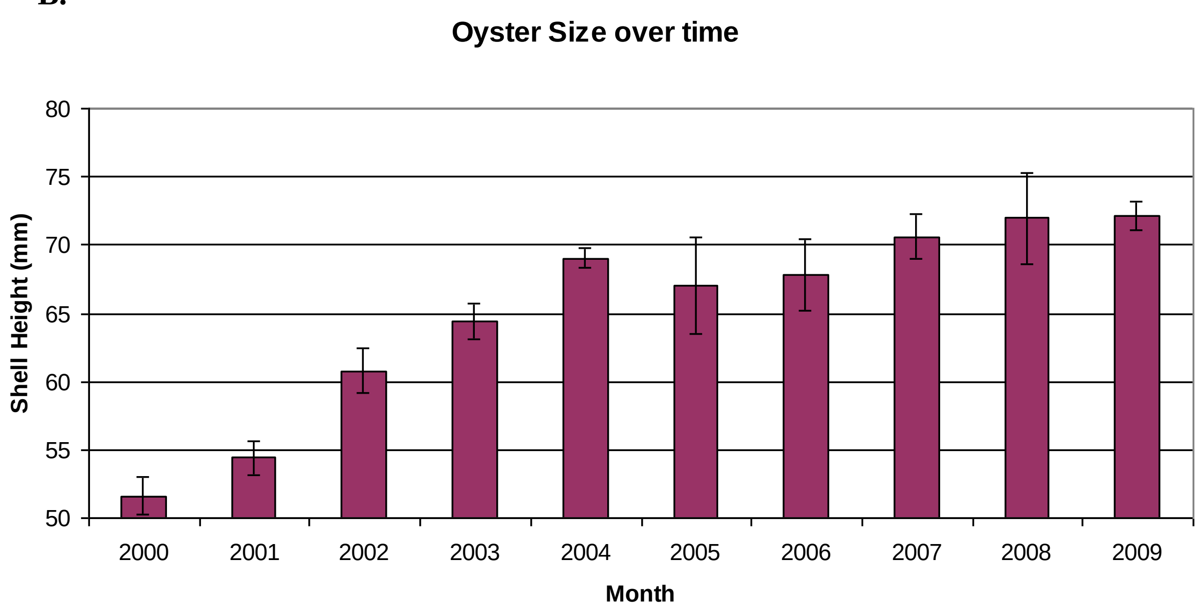


Figure 3. Mean size of oysters collected from Delaware Bay NJ oyster seedbeds. A) Mean size collected in monthly dredge samples by bed. B) Mean monthly size averaged across beds.

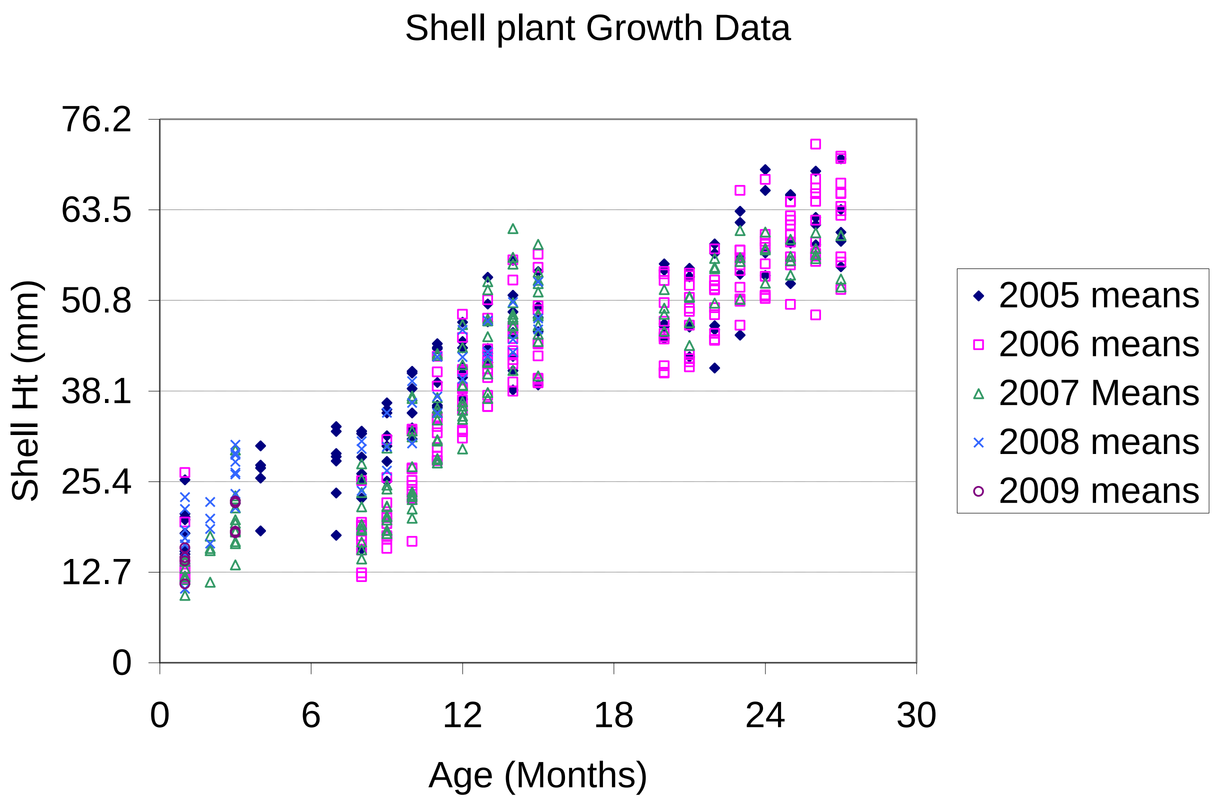


Figure 4. Comparison of growth on shell plantings since 2005. Data are means of up to 100 individuals collected monthly from individual shell plantings. Initial collections are made in September of the year of the shell is planted. Age during the first collection is presumed to be about one month since setting, but oysters could be a few days to three months old at that point depending on the actual shell plant date and the timing of actual setting on the planted shell.

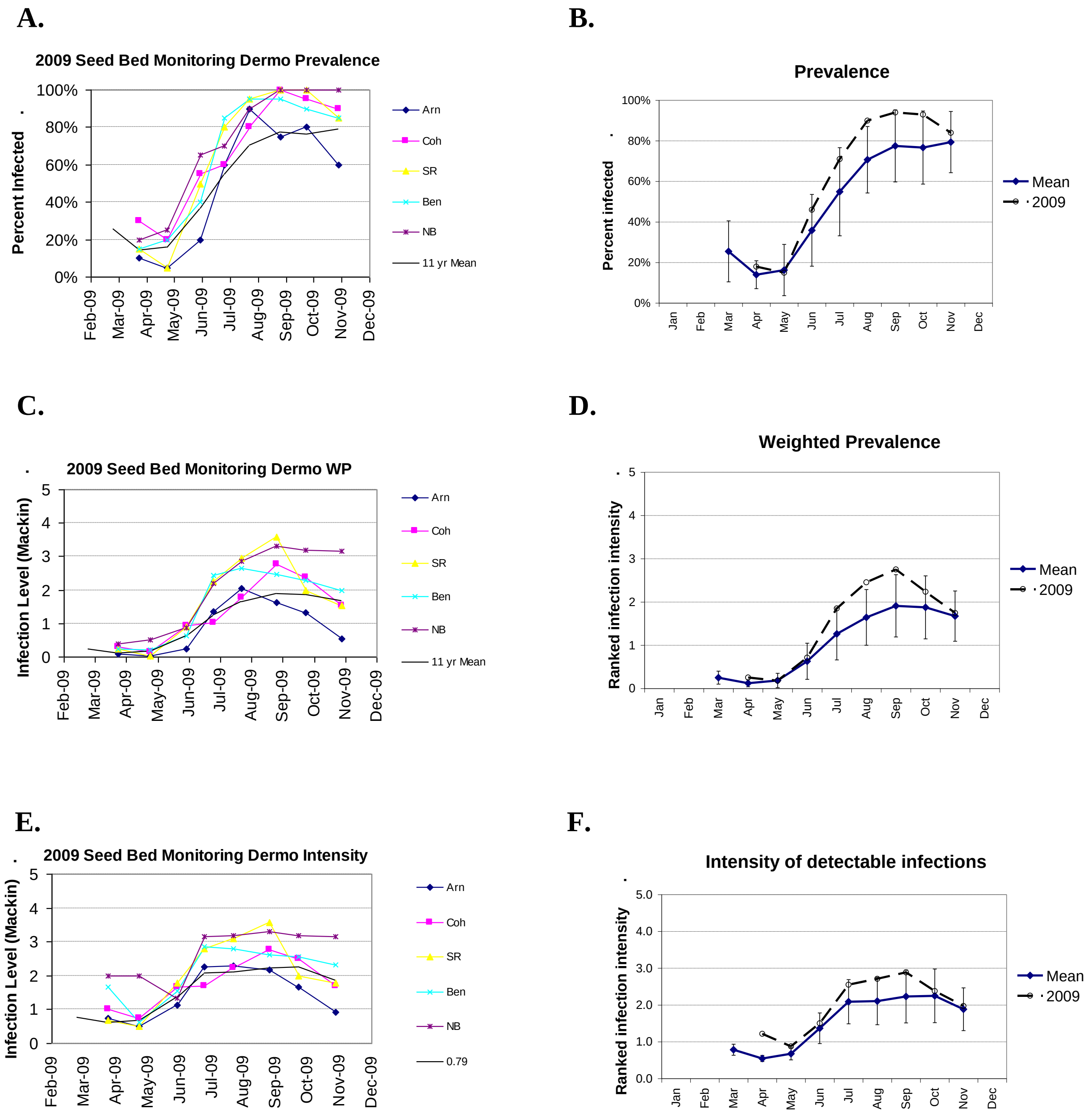


Figure 5. Monthly measures of Dermo disease in oysters from New Jersey Delaware Bay seedbeds during 2009. Prevalence = percent of infected oysters. Weight prevalence (WP) = the average Mackin scale Dermo infection intensity rank of all oysters sampled including those with no detectable infection (i.e., rank = zero). Intensity = average Mackin rank of detectable infections only. Right panels compare mortality for 2009 from five long-term beds with mean and standard deviation since 1999.

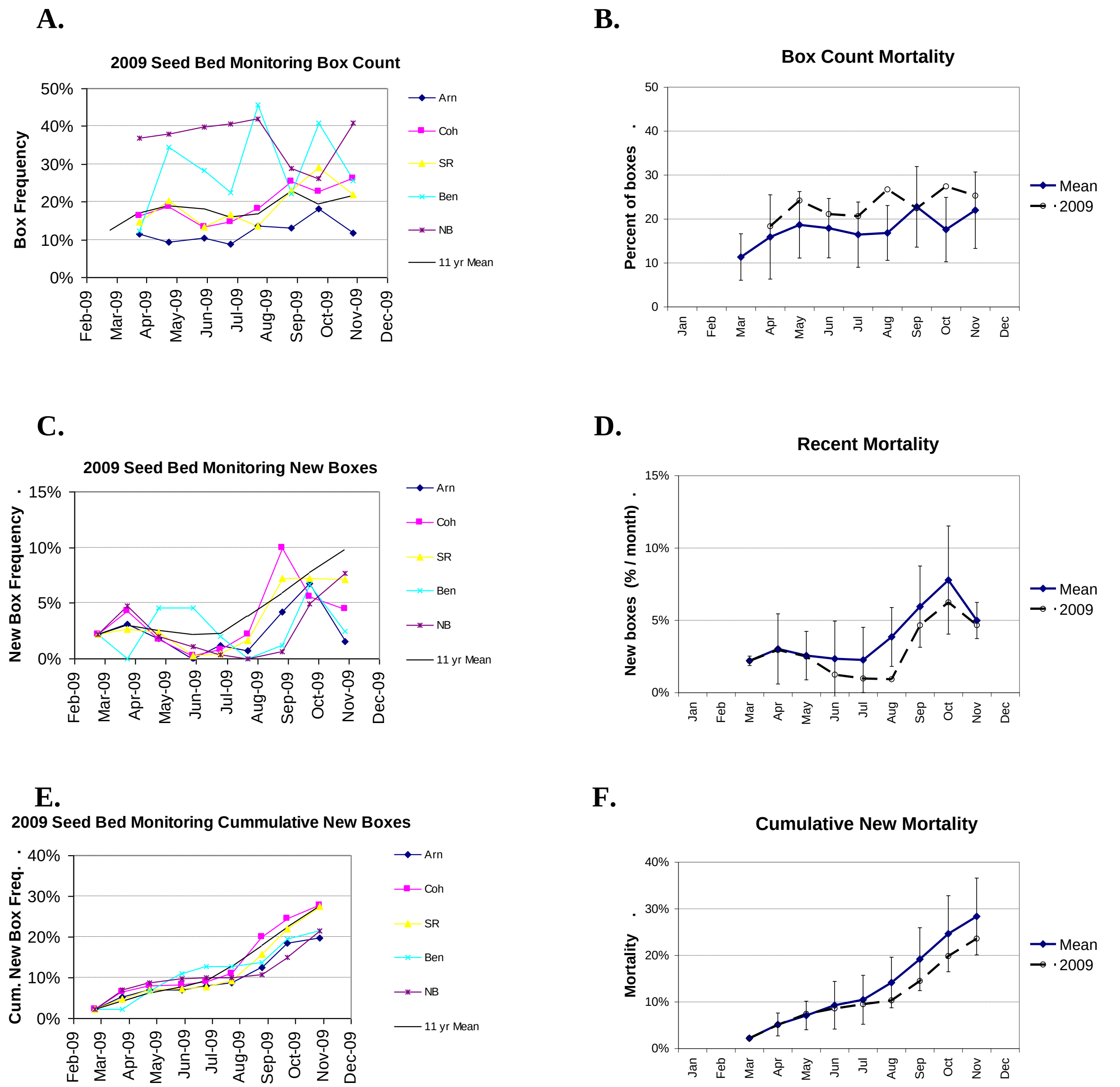
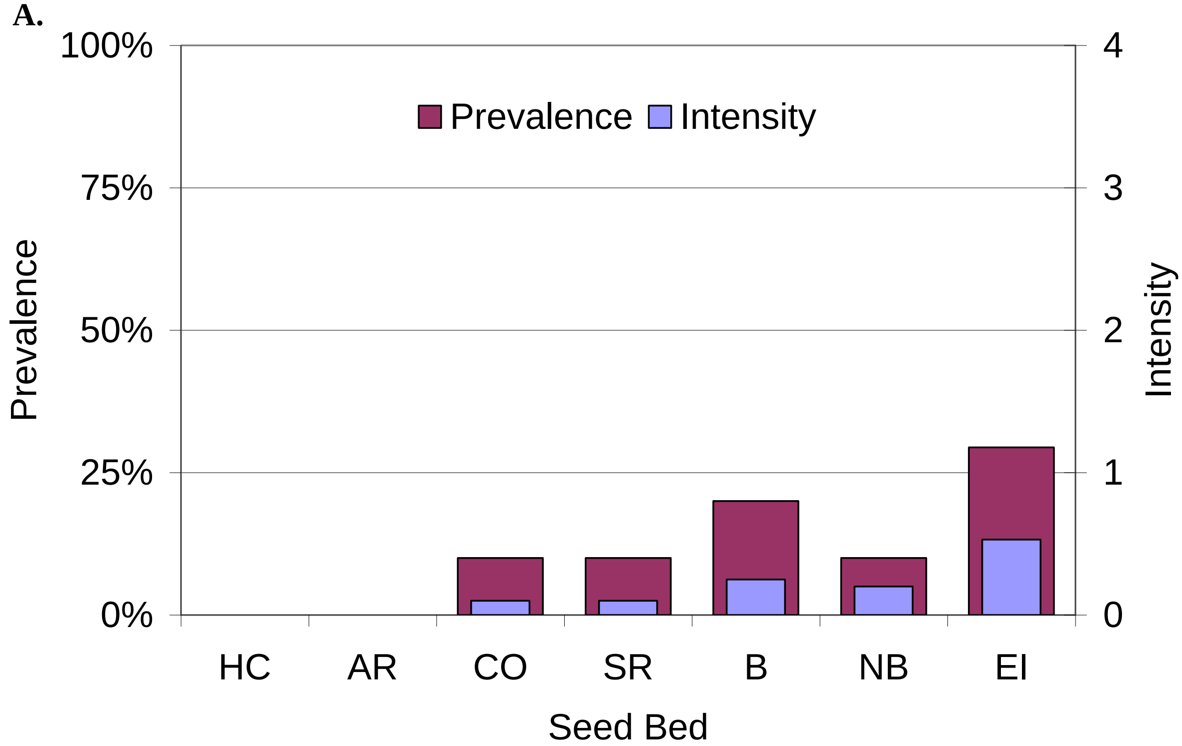


Figure 6. Monthly estimates of oyster mortality on the New Jersey Delaware Bay seedbeds. Left panels show mortality by bed. Right panels compare mortality for 2009 from five long-term beds with mean and standard deviation since 1999.

A.



B.

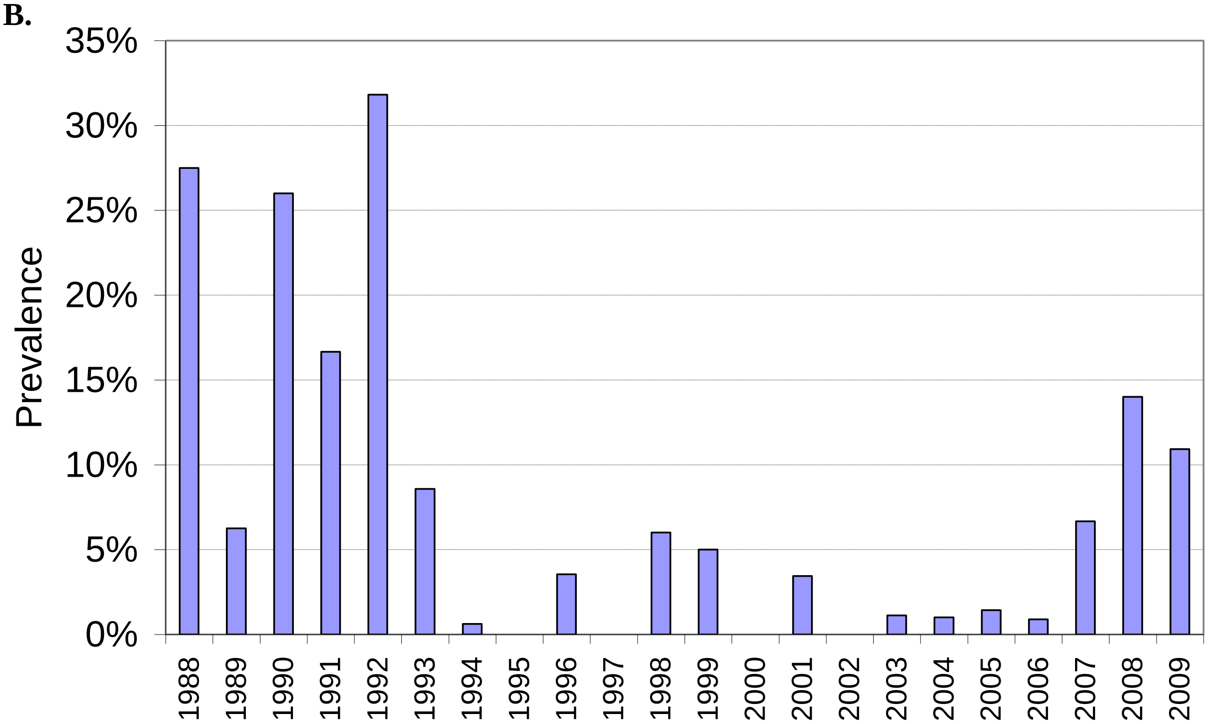
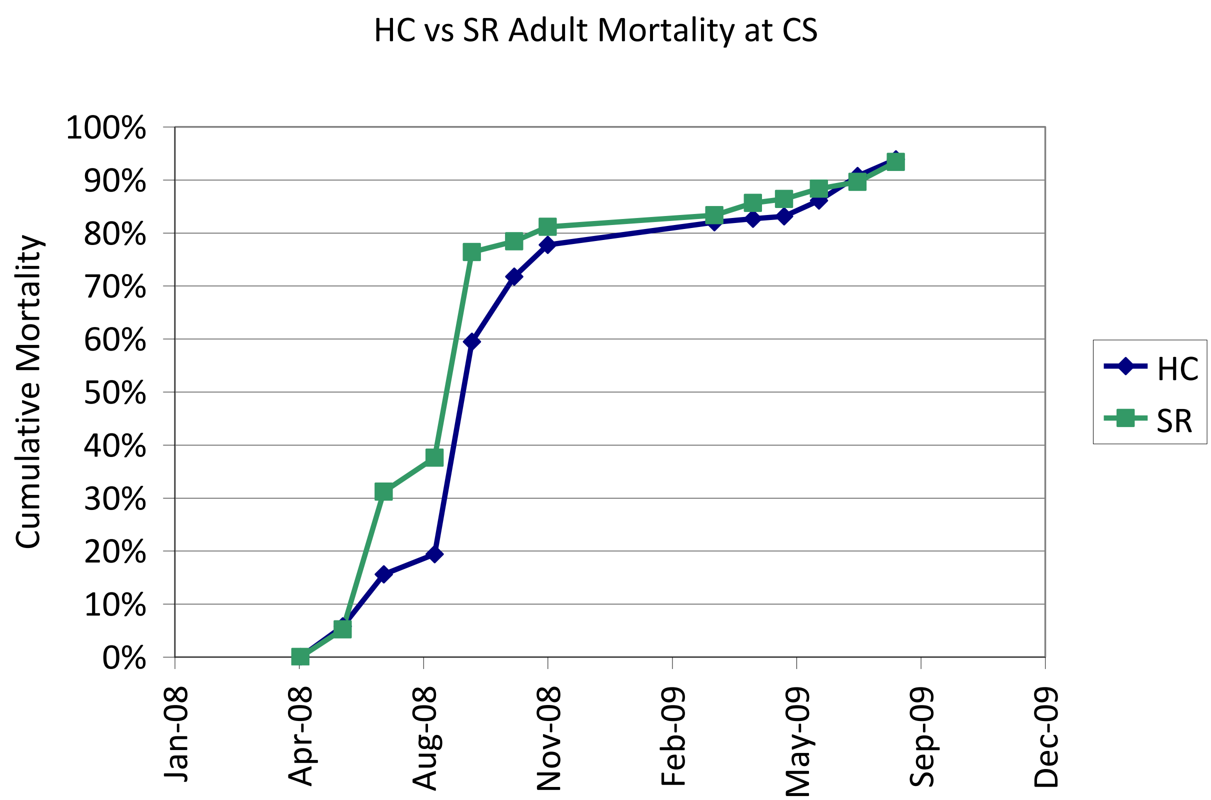


Figure 7. MSX disease on the New Jersey Delaware Bay oyster seedbeds. (A). 2009 Fall MSX prevalence and intensity (weighted prevalence on a scale of 0 to 4). Beds are listed upbay to downbay from left to right: HC = Hope Creek, AR = Arnolds, CO = Cohansey, SR = Shell Rock, B = Bennies, NB = New Beds, EI = Egg Island. (B). Annual Fall MSX Prevalence.



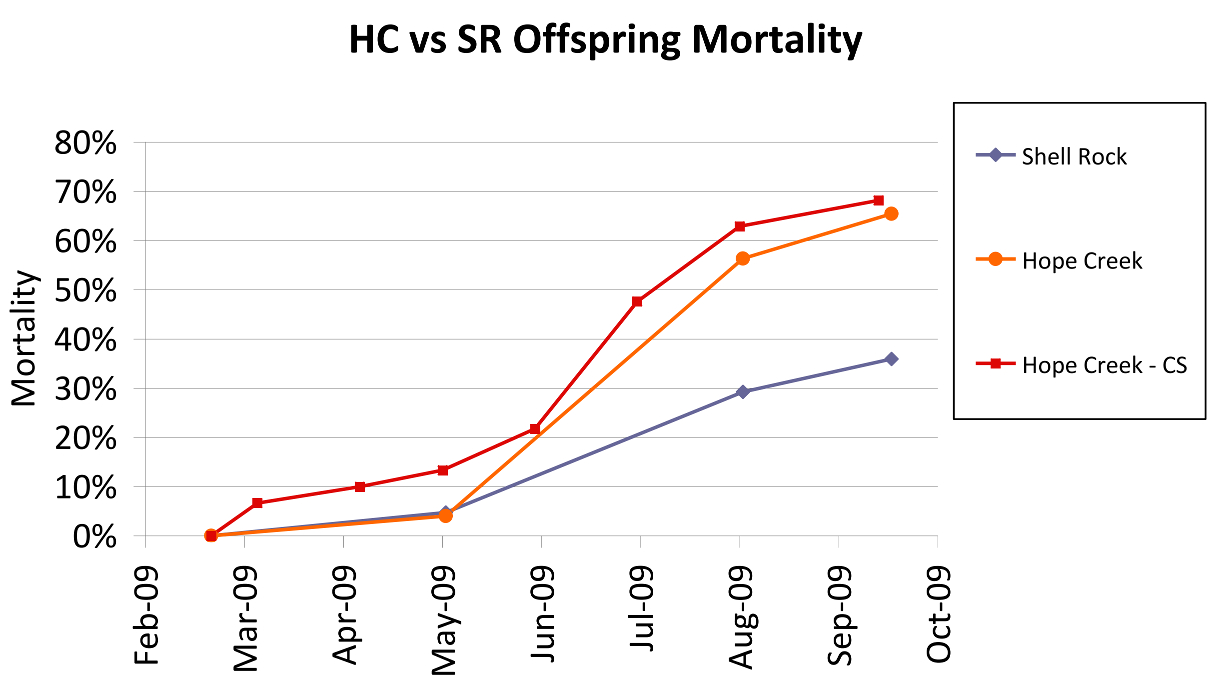


Figure 8. (A)Survival of adult oysters collected from Hope Creek (HC) and Shell Rock (SR) that were held in bags on racks at the Cape Shore flats. (B) Survival of offspring from those oysters held in bags in Cape May Harbor or Cape Shore (CS). No Shell Rock offspring were held at CS.

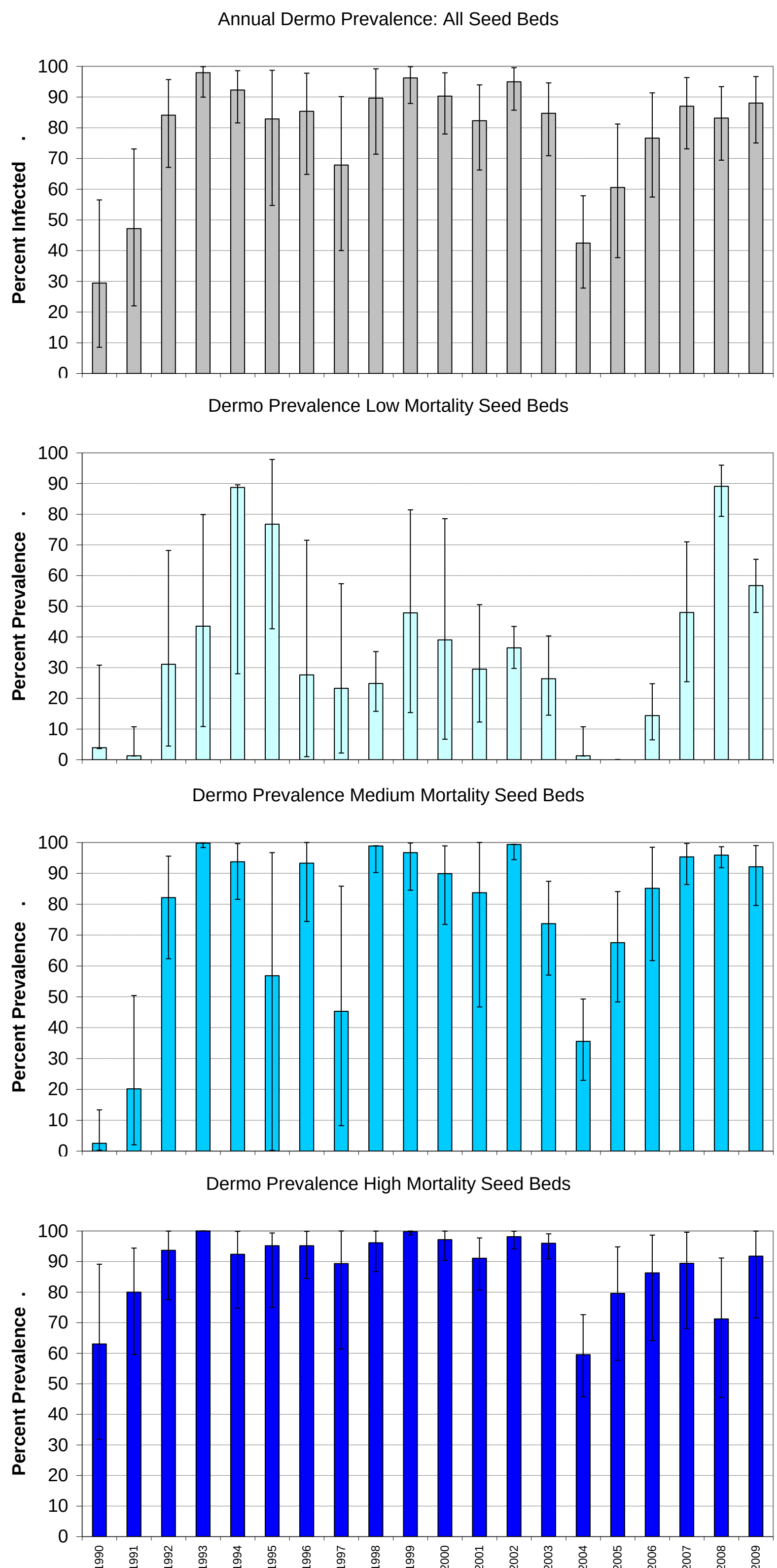


Figure 9. Annual mean fall Dermo prevalence on New Jersey Delaware Bay seedbeds.

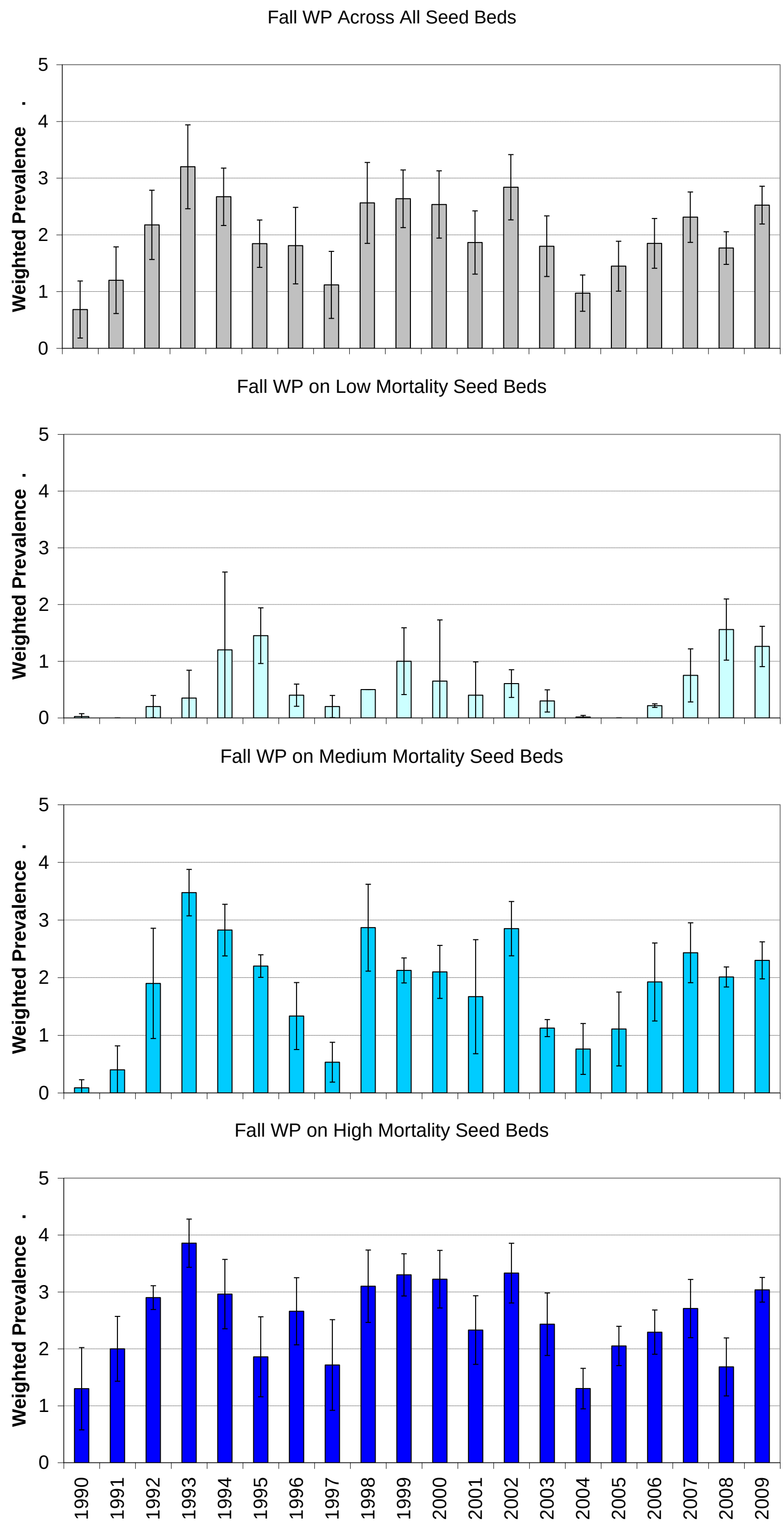


Figure 10. Annual mean fall Dermo weighted prevalence on New Jersey Delaware Bay seedbeds.

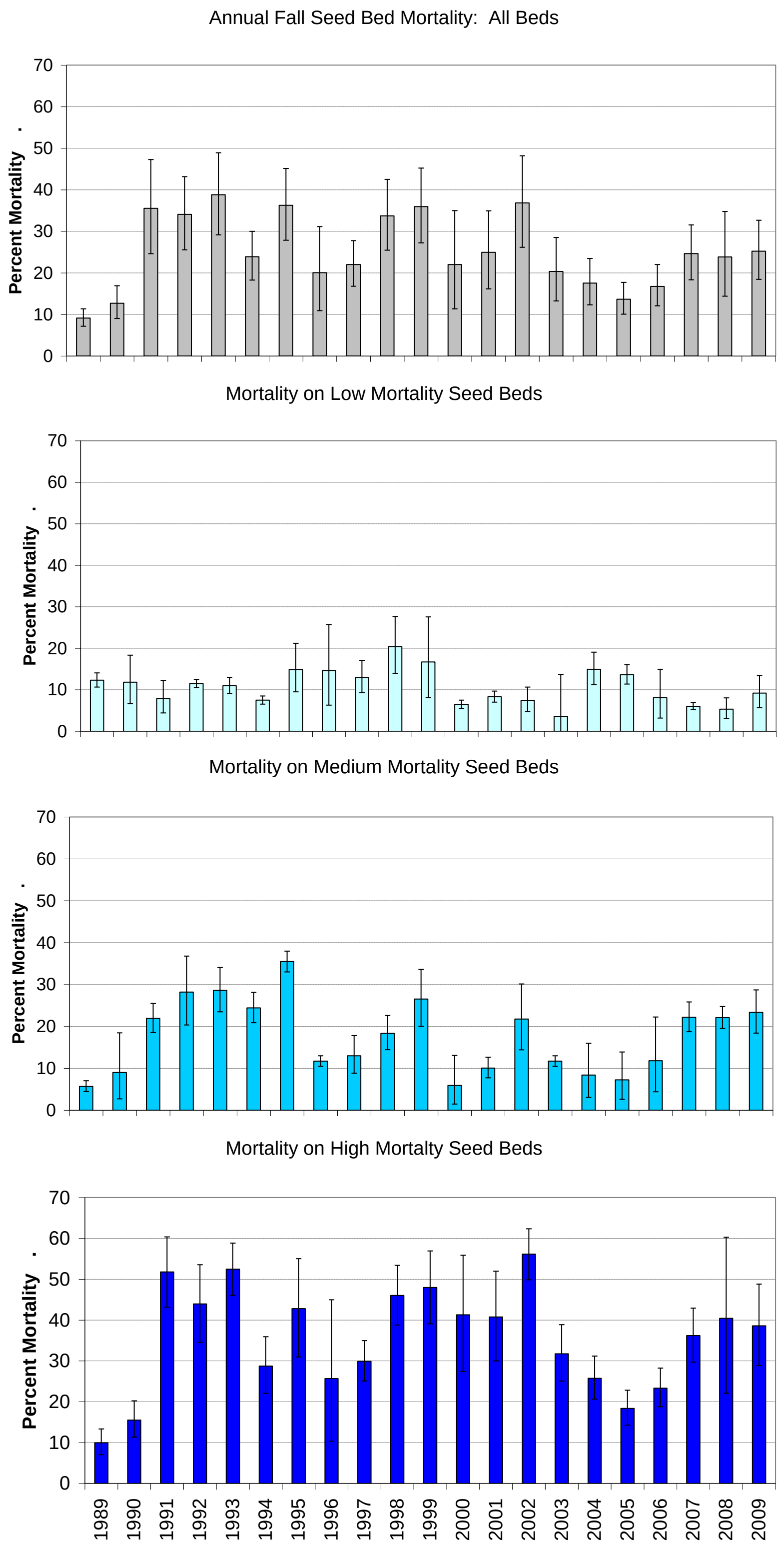


Figure 11. Annual mean fall box-count estimated mortality on New Jersey’s Delaware Bay oyster seedbeds.

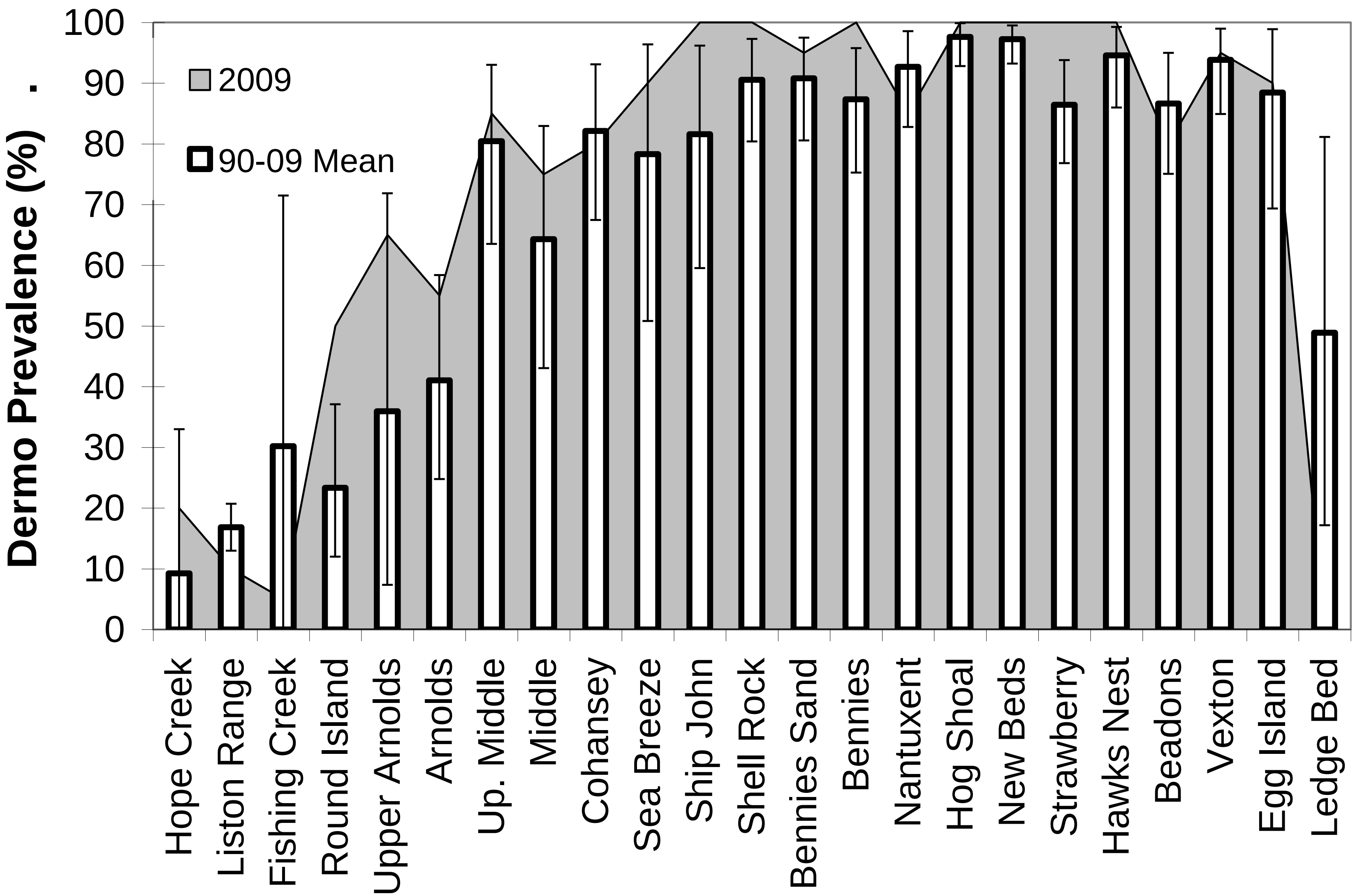


Figure 12. Comparison of average fall *Perkinsus marinus* (Dermo) prevalence in oysters on New Jersey Delaware Bay seedbeds since 1990 (open bars with 95% confidence intervals) with 2009 levels (shaded area). Not all beds have been sampled every year (see Table 5). Ledge was not sampled in 2009.

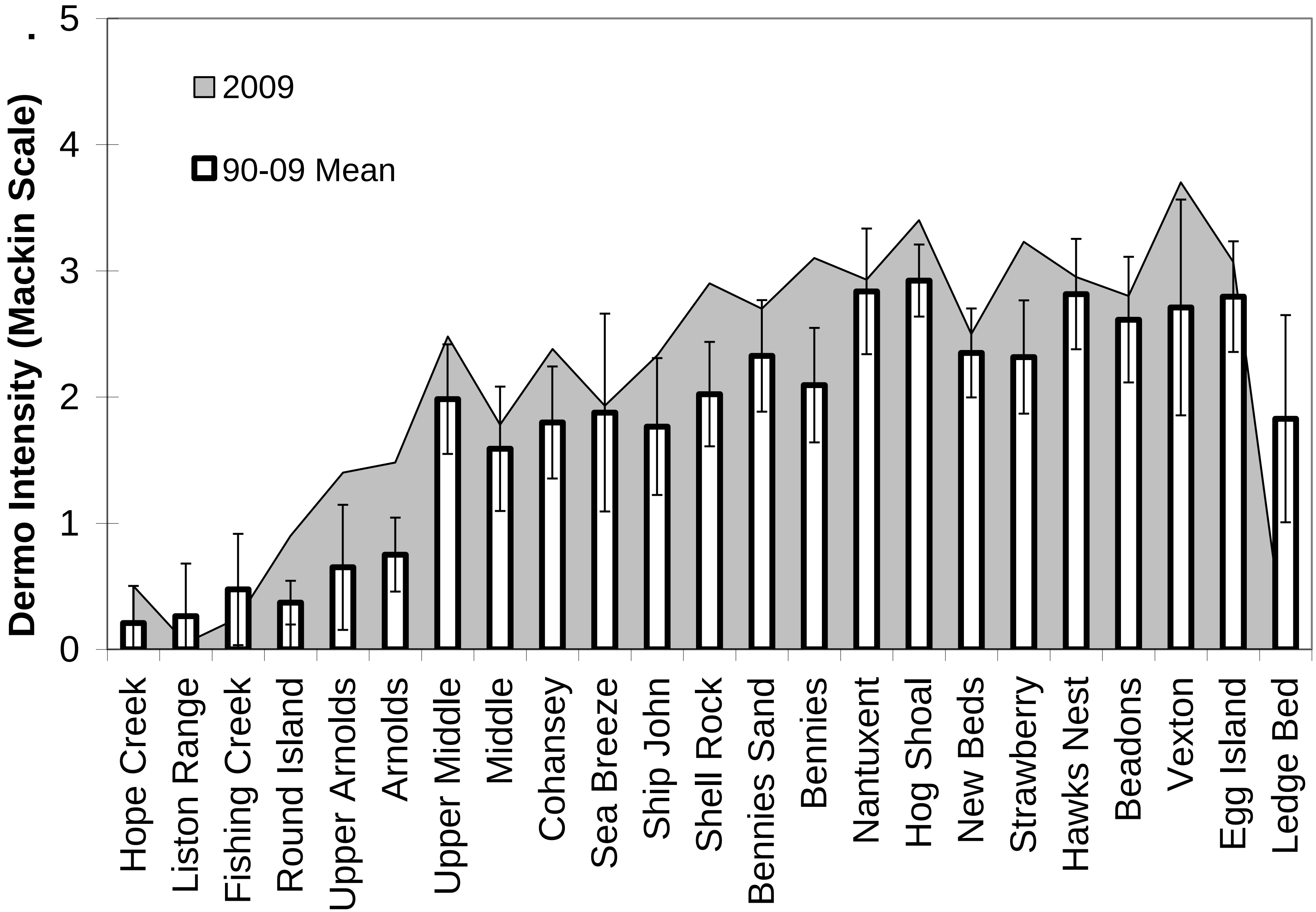


Figure 13. Comparison of average fall Dermo infection intensities (weighted prevalence) in oysters on New Jersey Delaware Bay seedbeds since 1990 (open bars with 95% confidence intervals) with 2009 levels (shaded area). Not all beds have been sampled every year (see Table 5). Ledge was not sampled in 2009.

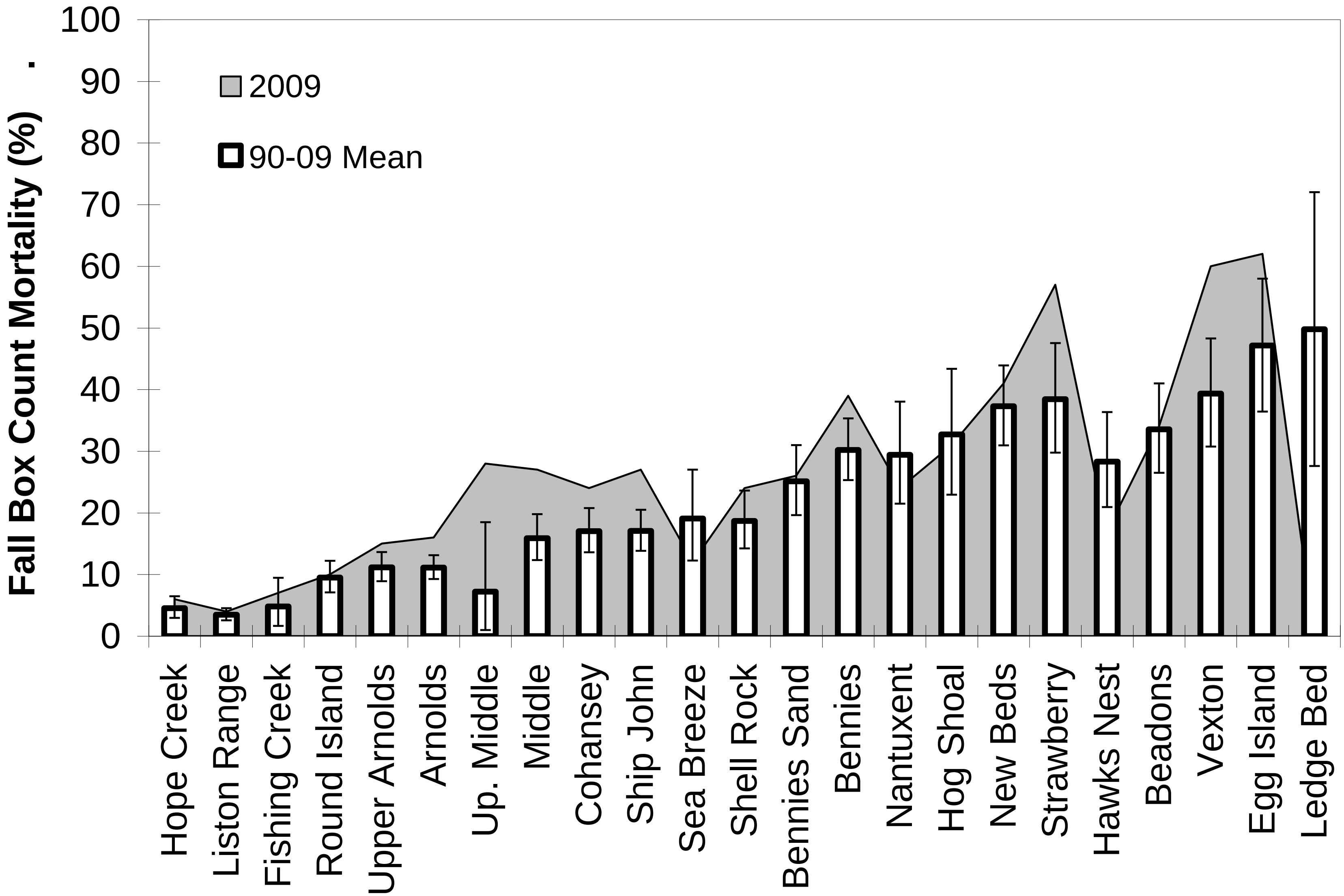

Fall Box Count Mortality (%)
100
90
80
70
60
50
40
30
20
10
0
2009
90-09 Mean
Hope Creek
Liston Range
Fishing Creek
Round Island
Upper Arnolds
Arnolds
Up. Middle
Middle
Cohansey
Ship John
Sea Breeze
Shell Rock
Bennies Sand
Bennies
Nantuxent
Hog Shoal
New Beds
Strawberry
Hawks Nest
Beadons
Vexton
Egg Island
Ledge Bed

Figure 14. 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 2009 levels (shaded area). Not all beds have been sampled every year (see Table 5). Ledge was not sampled in 2009.

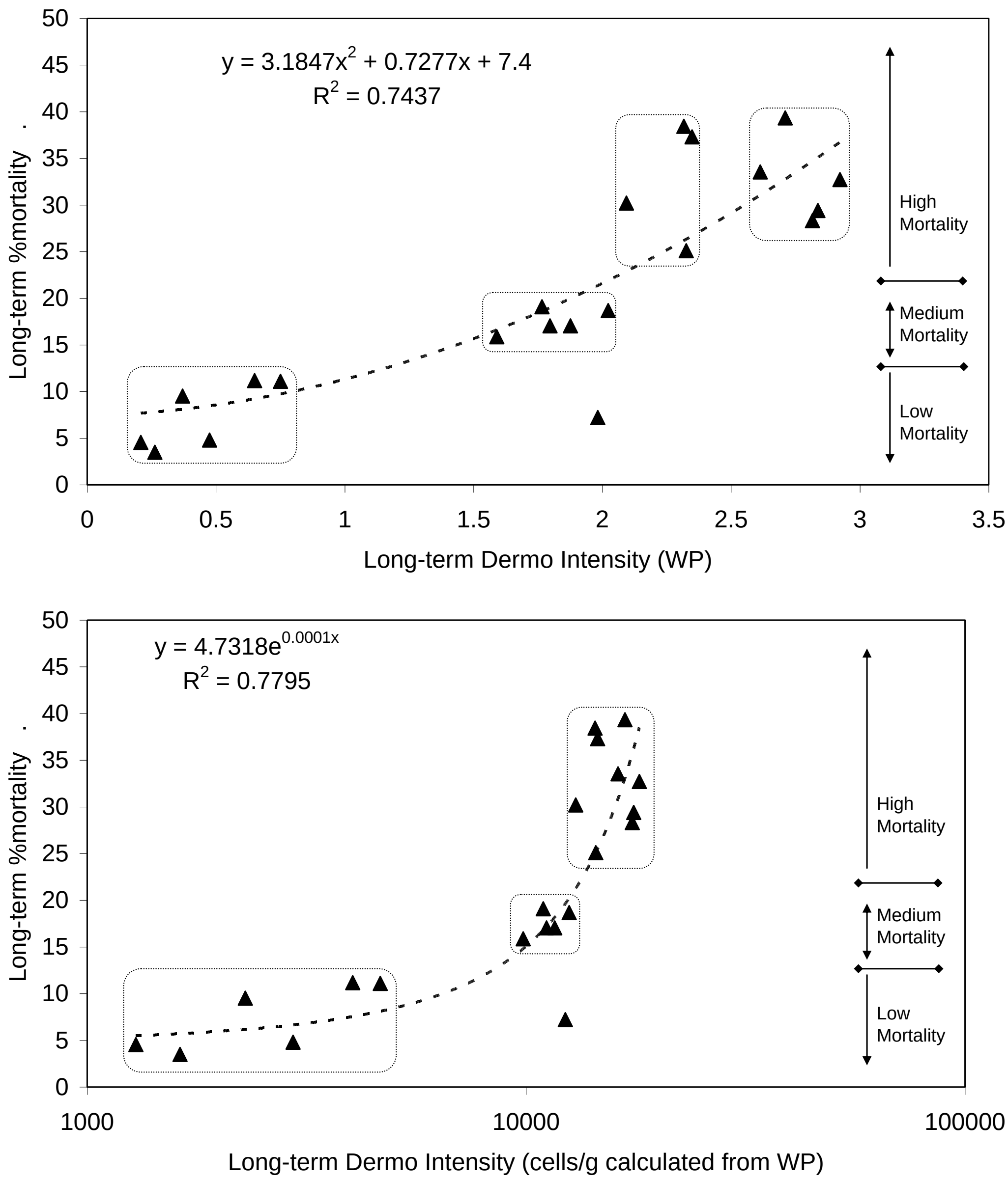


Figure 15. Relationship between long-term mean percent fall box count mortality estimate and the long-term mean intensity of Dermo infections since 1990. Data are individual bed estimates. Error bars are not shown for clarity. The relationship is approximately linear and indicates thresholds for Dermo-caused mortality at weighted prevalence of about 1.5 and 2 relative to the mortality incurred. Boxes represent clusters of beds in distinct regions and fall along the x-axis as follows: Hope Creek, Round Island, Liston Range, Upper Arnolds, Fishing Creek, Arnolds; Middle, Ship John, Cohansey, Sea Breeze, Shell Rock, Bennies, Strawberry, Bennies Sand, New Beds, Vexton, Beadons, Hawks Nest, Nantuxent and Hog Shoal. Upper middle (5% mortality), Ledge (50% mortality) and Egg Island (48%) mortality represent outliers largely resulting from inconsistent sampling over the time series. The trend line is a third order polynomial forced through a 5% mortality representing the average mortality on the upper seedbeds encompassed by the left most box. 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).

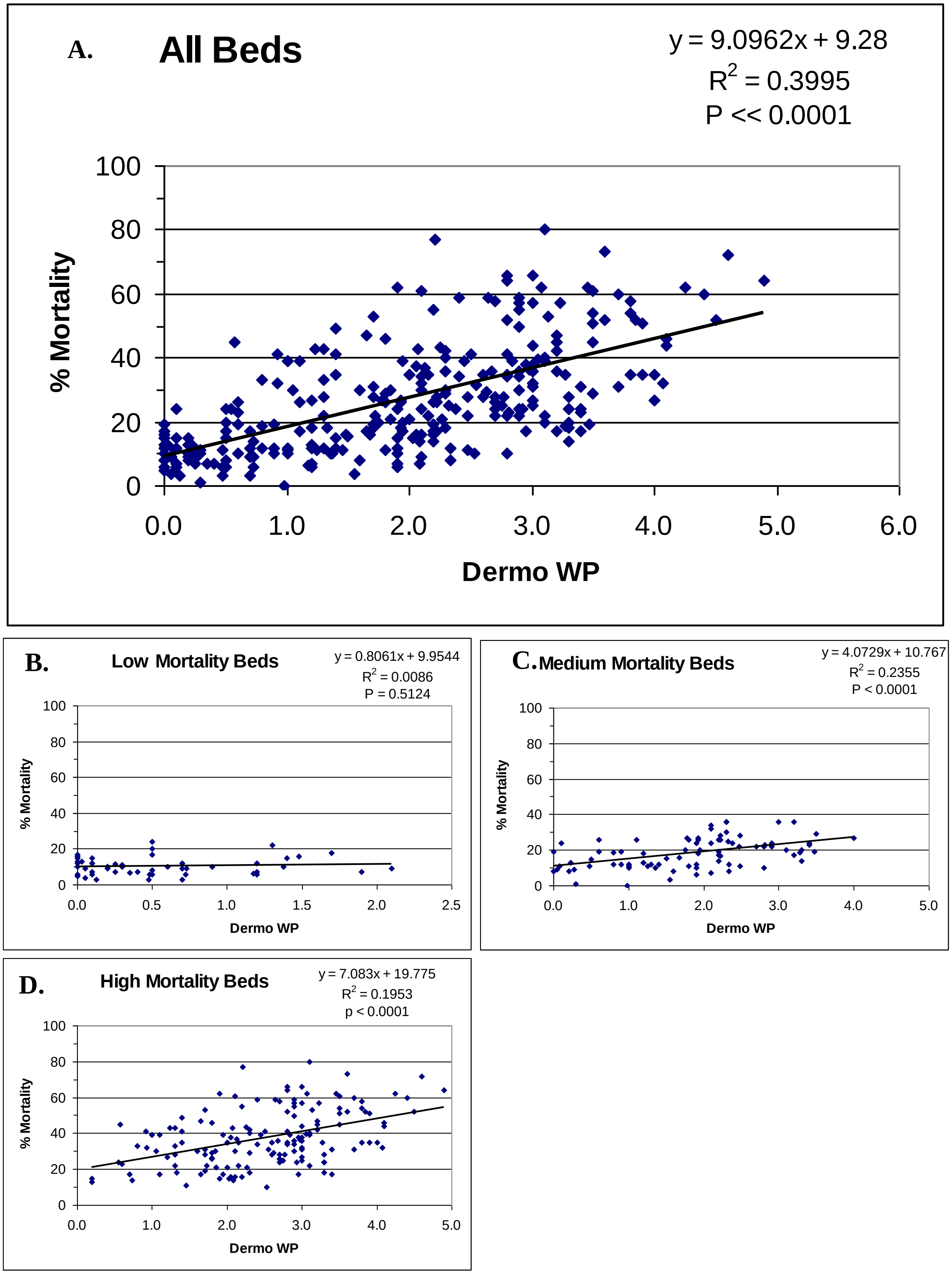


Figure 16. Relationships between fall box count mortality and Dermo infection levels (WP). Data are values for individual beds collected during the Random Sampling Program from 1990 through 2009.