Delaware Bay New Jersey
Oyster Seedbed Monitoring Program
2019 Status Report

February 6, 2020

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Executive Summary

The 2019 Program monitored dermo disease, oyster growth, and oyster mortality monthly at six fixed sites, four transplant sites, and ten shellplant sites. The Program also continued its long-term disease analyses for the annual Fall Oyster Stock Assessment Survey by collecting condition indices and dermo disease data from 22 seedbeds as well as MSX disease data from seven fixed monitoring sites.

Temperature was near or slightly above seasonal averages throughout the year. High fresh water inflow in the later part of 2018 and during the spring of 2019 depressed salinity well below seasonal averages for much of the year. This increased freshwater inflow depressed MSX and dermo diseases across the seed beds but elevated mortality on the uppermost beds of the (normally) Very Low Mortality region. Mean oyster size decreased throughout the year, apparently as a result of high survival of young oysters. Dermo disease followed typical seasonal and spatial patterns, but prevalence was below average throughout the year and substantially fewer oysters have entered the winter with detectable infections than in most years (43% vs 73%). The low prevalence of dermo likely contributed to the relatively low levels of mortality observed during 2019 despite warm temperatures and high salinity in the latter portion of the season. Transplants and shell plants performed similar to nearby beds, but with slightly elevated disease and mortality as time progressed – a pattern that has been previously reported.

Long-term spatial patterns of dermo show a general increase from upper to lower bay beds, but levels in the center of the fishery (Cohansey to Shell Rock) have been more variable in recent years, sometimes sustaining higher levels of dermo disease than oysters further down bay. Long-term mortality also continues to show a general increase from upper to lower beds, but mortality from freshets has considerably increased current and long-term mortality on the apparently misnamed "Very Low Mortality" region which sustained the highest level of mortality in 2019. Despite this, long-term annual patterns from the Fall survey continue to indicate an attenuation in both duration and amplitude of interannual dermo and mortality cycling. In fact, bay-wide mortality no longer appears to be cycling with dermo and has decreased from 20-30% in the 1990s to less than 20% over the past five years. MSX was detected at low prevalence and intensity on several beds in Fall 2019, and in other areas of the Bay throughout the year.

The overall picture continues to be one of improvement, but remains highly dependent upon environmental conditions, particularly temperature, salinity and Delaware River discharge in any given year. Increased freshwater inflow, even with freshet driven mortality events, has been beneficial in curtailing dermo related mortality. Continued monitoring of disease and mortality across the natural seedbeds, on transplants and on shell plants is warranted to evaluate performance and inform management of the resource, particularly in the face of climate change and upstream management of reservoirs that impacts freshwater inflow. As production in the lower bay increases via aquaculture and revitalization of leased grounds, monitoring efforts should expand to those areas since pathogens have no allegiance to wild or farmed populations.

Introduction

The Delaware Bay Oyster Seedbed Monitoring Program tracks disease, growth and mortality of oysters on the Delaware Bay, New Jersey public oyster beds located in the upper portion of the Bay (Figure 1). The purpose is to provide information that supports the sustainable management of the oyster resource in this region of the bay. Oyster production that occurred on privately owned leases, oyster farms or in waters outside the New Jersey portion of the Delaware Bay oyster fishery is not the focus of this report though some information may be included where relevant.

Oyster mortality on the Delaware Bay oyster beds is caused by a variety of factors including predation, siltation, freshets, disease and fishing. Prior to 1957 the focus of mortality was on predation by drills with the abundance and location predominantly controlled by salinity driven by the amount of freshwater inflow (Carriker 1955). Since the appearance of *Haplosporidium nelsoni* (the agent of MSX disease) in 1957, disease mortality has been the primary concern (Powell et al. 2008). Following a severe and widespread MSX epizootic in 1986, the Delaware Bay population has developed significant resistance to MSX disease that extends into low salinity regions where MSX is not typically prevalent in oysters (Ford and Bushek 2012). Nevertheless, routine monitoring continues to detect the MSX parasite in Delaware Bay and naïve oysters quickly succumb to the disease indicating that virulence remains high. In 1990, an epizootic of dermo disease occurred. Dermo disease is a form of the molluscan disease perkinsosis that is specific to the eastern oyster *Crassostrea virginica* and caused by the alveolate protist *Perkinsus marinus*. Its appearance in 1990 was not the first occurrence of *P. marinus* in Delaware Bay, but previous occurrences were associated with importations of oysters from the lower Chesapeake Bay (Ford 1996) and were often short-lived. 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). It is likely that *P. marinus* was present in the bay for many years prior to 1990 at levels below detection or at least not causing levels of mortality to warrant concern. Since 1990, dermo disease has been a major source of oyster mortality in Delaware Bay and a primary concern for managing the oyster fishery and the oyster stock (Bushek et al. 2012).

Following 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 three major groups: Low Mortality (LM) beds (formerly called the upper seedbeds), Medium Mortality (MM) beds (formerly called the upper-central seedbeds), and High Mortality (HM) beds (formerly called central and lower seedbeds). These designations are positively correlated to increases in salinity from about 5 to 20 ppt. The higher salinities generally promote better growth and meat quality but also tend to favor predators and disease. A group of beds above the low mortality region was added to the survey in 2007 after some reconnaissance indicated that their abundance represented a significant proportion of the natural population and should therefore be included in the overall management of the fishery. These beds were collectively designated Hope Creek in 2007, but were subsequently subdivided into Hope Creek, Fishing Creek and Liston Range and categorized as the Very Low Mortality (VLM) beds, although they periodically experience very high mortality in response to freshets such as that following tropical storms Irene and Lee in 2011

(Munroe et al. 2013). Current area management strategies separate Shell Rock (SR) from the original medium mortality region and further subdivide the remaining medium mortality region beds into Medium Mortality Transplant (MMT) and Medium Mortality Market (MMM) beds (Figure 1) based on how they are managed within the fishery. Additional details on management strategies and actions are available in annual stock assessment workshop reports at http://hsrl.rutgers.edu/SAWreports/index.htm.

The majority of fresh water entering the system comes from the Delaware River and tributaries located above the oyster beds. Nevertheless, 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 complex ways. These factors undoubtedly interact to influence larval dispersal, recruitment and growth, disease transmission dynamics and, ultimately, disease mortality (Wang et al. 2012).

The temporal and spatial sampling efforts of the Oyster Seedbed Monitoring Program are designed to continually develop a better understanding of factors influencing oyster growth, disease and mortality to inform management and sustain a viable fishery as well as a healthy oyster population and a functional ecosystem. A major objective is to identify seasonal and interannual patterns of disease, mortality, recruitment and growth through time. The core effort monitors six sites along the salinity gradient on monthly basis and a spatially comprehensive survey in the Fall. The monitoring supports additional directed research and sampling efforts that are necessary to develop a fuller understanding of the oyster population within the Delaware Bay ecosystem. As funding permits, these efforts include monitoring transplants (i.e., oysters moved from upper to lower seedbeds), shellplants (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 recruitment zone near the Cape Shore then moved and replanted on the seedbeds). The 2019 objectives for the Oyster Seedbed Monitoring Program were to:

1. Continue the standard monthly time series monitoring New Beds, Bennies, Shell Rock, Cohansey, Arnolds, and Hope Creek for size, mortality and dermo disease
2. Conduct dermo and MSX assays and determine condition indices for each bed sampled during the 2019 Fall Stock Assessment Survey
3. Monitor growth, disease and mortality on 2017 through 2019 shell plantings
4. Monitor growth mortality and disease on the 2018 and 2019 intermediate transplants

Objectives 1 and 2 comprise the basis of the long-term 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). In 2010 Hope Creek was added as part of the monthly monitoring program. Objective 3 was initiated as part of the Delaware Bay Oyster Restoration program designed to enhance recruitment on the seedbeds. Shell planting is an annual effort of the management plan for sustaining and rebuilding the oyster beds, scaled by available funds. Objective 4 examines the performance of the intermediate transplant program that moves oysters downbay from upbay beds. This activity provides access to a portion of the resource that is otherwise unavailable to direct market harvest, but was available to the former "Bay Season" seed fishery (Fegley et al., 2003). In addition to sustaining the industry it helps to rebuild and sustain harvested beds.

Methods

Monthly monitoring occurred at six sites along a transect spanning the salinity gradient from Hope Creek to New Beds. Transplant and shellplant sites were included to evaluate performance and inform management activities. Monthly reporting to the Delaware Bay Section of the New Jersey Shell Fisheries Council provided timely information on seasonal changes for management and harvest needs. A spatially comprehensive sampling occurred during the annual Delaware Bay New Jersey oyster stock assessment in Fall 2019. These data were evaluated and compared to long-term data to provide insight into inter-annual patterns, long-term trends, and factors affecting the oyster stock.

Figure 1 depicts the sampling locations for the 2019 Annual Fall Oyster Stock Assessment with beds outlined in black and area management regions indicated by brown dotted lines. Management activities and this report reference both regions and beds as appropriate. Beds that fall within the jurisdiction of the state of Delaware comprise about 10-15% of the oyster population in the main stem of the Bay but are not considered in the report nor shown in Figure 1. For sampling, the beds shown in Figure 1 were divided into grids measuring 0.2 x 0.2 minutes of latitude and longitude (roughly 26 acres or 10.5 hectares each). Dots in Figure 1 represent locations of grids selected via a stratified random sampling design for the Fall oyster stock assessment; a subsample of which, generally one high quality and one medium quality, were selected for Fall disease sampling. Additional details on regions, beds and sampling design are provided in Powell et al. (2008 and 2012) as well as Alcox et al. (2017).

Monthly samples were collected from April through November for Objectives 1, 3 and 4 as indicated in Tables 1 and 2. Table 3 identifies beds that have been monitored since 1990 as part of the long-term Fall dermo monitoring program that is affiliated with the Annual Fall Oyster Stock Assessment. Table 4 specifies the grids sampled during the 2019 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 R/V James W Joseph. Bottom water temperature and salinity were recorded with a handheld YSI® Pro2030 instrument at each site. A composite bushel (37 L total volume with one third coming from each dredge tow[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 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 from the composite bushel were returned to the laboratory where shell heights (hinge to bill) were measured to determine size frequency from each site. Care was taken to avoid any bias in sampling oysters by systematically working through the sample until

[1] At Arnolds and Hope Creek, sample volumes were halved.

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 and countered to some extent by clumping when oysters attach to one another (Morson et al. 2018). 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 (i.e., weighted) for intensity using the "Mackin scale" from zero (= pathogen not detected) to five (= heavily infected) after Ray (1954). These values, including zeros, were averaged to produce a weighted prevalence (WP), which provides an estimate of the average disease level in the sample of oysters (Mackin 1962, Dungan and Bushek 2015). The average intensity of infections, which excludes samples scored as zero, was similarly determined. Though related and similar, each measure provides a different understanding of how disease may or may not be impacting the population.

Samples for Objective 2 were collected during the Annual Fall Stock Assessment Survey using the commercial oyster boat F/V HW Sockwell. The stock assessment survey consists of a stratified random sampling of the medium and high quality grids on the 23 beds that are outlined in Figure 1 and listed in Table 4 (see Ashton-Alcox et al. 2017 for survey method details). The two lowermost beds, Ledge and Egg Island, contain very few oysters and are sampled in alternate years; Egg Island was sampled during 2019. 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. 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 Objectives 3 and 4, samples were collected monthly from April through November (Table 1) for sites manipulated as indicated in Table 2. All of these sites were monitored as described for objective 1 with the following modifications for objective 3. Shellplant samples for objective 3 continued monitoring the 2017 and 2018 shell plantings, and initiated the 2019 shell plantings listed in Table 2 – the latter of which was only sampled during the final 3 months. On each shellplant site, at least three and up to five 1-minute dredge tows were 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 were 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 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 (n = 50-100 per site). No disease sampling was performed on the 2019 shellplants. Disease sampling began in April on the 2017 shellplants and in July on the 2018 shellplants.

Results and Discussion

Freshwater Inflow. The Delaware River Basin Commission is tasked with maintaining sufficient flow to prevent upward movement of the salt line (defined here as 250 mg/L) below the city of Philadelphia to maintain drinking water standards, protect industries from corrosive effects of salt water and to protect aquatic life, including oysters located further downstream (DRBC 2020). This is done by maintaining a minimum flow at Trenton but releasing water as needed from reservoirs located in the watershed during periods of low flow. Reservoirs are also used to store water for other purposes and as catch basins for flood control. When full, water must be released to be prepared for flood control. Such was the situation at the start of 2019 following high levels of precipitation during the latter half of 2018 as reported last year. This necessitated controlled releases to alleviate the accumulated volumes of water in various reservoirs throughout the basin. Data obtained from the USGS stream gauge at Trenton (Figure 2) shows high levels of fresh water discharge well above the 106-yr daily median flow for much of the year. The seasonal pattern of declining discharge from April to September remained above median levels despite declining in magnitude over time. Discharge levels briefly fell below the long-term median around October, but increased above median levels thereafter. High discharge decreases water residence time over the oyster beds as it reduces salinity, both of which are associated with reductions in disease and can lead to increased mortality on the uppermost oyster beds (Munroe et al. 2013).

Temperature. Water temperatures measured during 2019 collections followed a typical seasonal increase and decrease with little spatial variability across the seedbeds (Figure 3A). Temperatures were near or slightly above average levels measured since 1999 with warmer than average temperatures occurring in the latter half of the year (Figure 4A). Spawning temperatures were reached by mid-June and remained at this level into September.

Salinity. Salinity followed the typical estuarine gradient, increasing from upbay to downbay beds (Figure 3B). The high fresh water inflow shown in Figure 2 depressed salinity during the first half of the year but the general seasonal pattern remained and salinity ended the year higher than average (Figures 3B and 4B). We did not monitor salinity daily, but observed elevated mortality (see below and Figure 3G, H and I) on Hope Creek that was likely related to low salinity stress similar to that described by Munroe et al. (2013). From the monthly salinity data, it appears that Hope Creek salinity remained below 6 from the start of sampling to July. Munroe et al. (2013) associated high mortality in 2011 with a depression of salinity below 7 for a period of just 20 days.

Temperature and salinity are arguably the most important environmental factors controlling oyster growth, reproduction, disease and mortality. The conditions observed over the seedbeds during 2019 below the Very Low Mortality region that includes Hope Creek were favorable for growth and reproduction, but not particularly favorable to the development of disease and consequent mortality as described below. Low salinity is also often associated with lower levels of predation, particularly by oyster drills (Carriker 1955, Manzi 1970).

Oyster size. Shell height (measured hinge to bill) roughly corresponds to age and therefore provides insight into both the size and age structure of the population. Seasonal changes in a population's mean shell height may be affected by growth, recruitment and mortality (both natural mortality and fishing mortality). Over the past few years, oystermen have consistently commented on the large size of oysters present across the seedbeds and this is evident in the increase in average size since 2014 (Figure 5). Overall, mean shell height decreased during 2019, but this was highly variable across the beds with large declines on New Beds and Bennies and little change elsewhere (Figure 3C), bringing the end of season mean size to levels below the long-term average (figure 4C). Because mortality has not been particularly high as described below, the decreases observed during 2019 likely represent survival of smaller oysters and a return to both size and age distributions that had previously been out of balance (see recent HSRL Stock Assessment Reports https://hsrl.rutgers.edu/SAWreports/index.htm). Continued high survival of recruits could depress the overall mean size of oysters further.

Dermo Disease. Dermo prevalence (the percent of the population with detectable infections), weighted prevalence (WP; the average intensity of dermo in the population, including uninfected oysters) and intensity (the average level of infections in infected animals only) followed typical spatial and seasonal patterns (Figures 3D-F). That is, each increased from spring to summer and began to decrease in fall with levels increasing with salinity from upper to lower bay beds. Overall, however, dermo prevalence and weighted prevalence were depressed for much of the year relative to long-term averages (Figures 4D and E) while those that were infected tended to have average intensities that more closely followed the average seasonal pattern (Figure 4F). Two things appear to have caused this. First, high freshwater inflow depressed dermo on the upper beds, namely Hope Creek and Arnolds (Figure 3D). Second, an influx of small oysters on Bennies reduced the percent of oysters with detectable infections there. This reduction in prevalence will reduce the weighted prevalence even without reductions in the average infection intensity. As a result, the population as a whole entered the winter with a relatively low level of dermo but some of the important lower bay beds such as Shell Rock and Nantuxent were still relatively heavily infected.

Mortality. The low levels and delayed onset of dermo disease just described was associated with relatively low levels of mortality (Figures 3G-I and 4G-I). An epizootic is defined as a sudden increase in the appearance or intensification of a disease that may or may not be associated with mortality. Under this definition, despite the widespread prevalence and seasonal intensification of dermo disease, Delaware Bay did not experience a dermo epizootic during 2019, but the potential for an epizootic to develop and cause significant mortality remains high. In contrast to the rest of the Bay, Hope Creek and Arnolds displayed unusually high levels of mortality clearly associated with low salinity stress caused by the high discharge of fresh water from the Delaware River (Figure 2).

Transplants, shellplants and replants. Figure 6 shows the conditions and performance of 2017, 2018 transplants during 2019. For comparison, the mean of each metric measured at the long-term Shell Rock and New Beds sites are shown. The monthly monitoring samples were generally offset by about a week from routine monthly samples due to sampling and scheduling logistics. Temperature and salinity (Figure 6A and B) were effectively identical; apparent differences in salinity are attributed to sampling different tidal stages on different dates. No particular or surprising trends in size were apparent. Dermo levels on transplant sites were similar to the long-term site value, but reached slightly higher levels by July and remained higher than the long-term site until November. The levels of dermo (>1.5 weighted prevalence) were sufficient to cause mortality (Bushek et al. 2012), but relatively little mortality was observed after an initial bout of overwinter mortality (Figure 6G, H and I). Previous monitoring efforts have indicated transplants develop higher levels of disease and higher rates of mortality by the end of the first year that continues into the second year, but this was not the case in 2019.

Ten shell plants have been placed on six different beds during the past three years (Table 2). Growth varied among shellplants (Figure 7A) with largest increases on 2018 shellplants ranging from 20 to 30 mm while 2017 plants grew 8 to 20 mm. The 2019 shell plants had reached 20-30 mm by November indicating a rapid growth rate before we began monitoring them. Mortality varied from 1.5 to 14% and generally decreased with age of the shell plant (Figure 7B). Dermo increased on 2017 and 2018 shellplants across the season with higher levels occurring in the older year class, but none reached levels expected to begin causing detectable levels of mortality (Figure 7C). The mortality observed was likely due to predation or siltation. Shell planting remains one of the most positive management efforts to sustain and increase oyster abundance, and should be pursued annually to the level that resources permit. No replanting occurred in 2018 or 2019, but replanting remains a potentially valuable management strategy. Similarly, spat-on-shell technologies (i.e., remote setting of hatchery-reared oyster larvae) provide an alternative that has worked in other locations and warrants consideration.

Long-Term Fall Patterns. Examination of dermo prevalence, weighted prevalence and mortality by bed indicated a significant departure from long-term patterns during 2019 (Figure 8). The long-term patterns typically increase from upper to lower bay beds. Since 2013, dermo prevalence and weighted prevalence have been highest in the central portion of the resource with the highest levels often on or around Shell Rock. The processes that make this a productive oyster region may similarly make it conducive for dermo disease. Fall 2019, dermo levels were below mean long-term values on all beds, and generally below the 95% confidence intervals; only Bennies Sand exceeded its long-term mean prevalence. More striking were the Fall box count fractions on medium to high mortality beds (those below Upper Middle). Those beds saw mortality levels that were uncharacteristically low, often near 50% of the respective long-term means. In stark contrast, mortality increased above long term means by as much as a factor of three on beds in the VLM and LM regions which suffered from salinity stress described above.

Figure 9 depicts annual dermo prevalence, weighted prevalence and box-count estimated mortality from 1989 to 2019 for each mortality region. Each parameter generally decreases from high to low mortality regions. Dermo prevalence and weighted prevalence track each other well within and across regions, but mortality patterns on the low and very low mortality regions are distinct from the medium and high mortality regions. Within the high and medium mortality regions, mortality lags disease by about one year. In the LM and VLM regions, mortality is nearly out of phase with dermo disease indicating that dermo is not a primary cause of mortality in these regions. Since 1990, there have been two periods of low dermo disease, 1996 and 2004, and we appear to be entering a third. Dermo intensity was much more volatile in the early portion of the time series, but this volatility has dampened in the latter half of the time series (Figure 9B). This dampening also corresponds to a reduction in Fall box count mortality (Figure 9C).

Many factors such as temperature, salinity and recruitment are known to influence dermo disease (Villalba et al. 2004) but the confluence and interaction of these factors is difficult to predict. Moreover, while there is some understanding of how these factors influence spatial and seasonal variation in dermo disease, it is less clear how they interact to influence interannual variation. The bay wide data continue to indicate an attenuation of dermo-induced mortality in the three successive epizootics across the medium and high mortality regions (Figure 10). This observation could be entirely environmentally driven or it 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. Alternatively, dermo virulence have declined over time. Lagged correlations between river flow and WP produce a significant negative correlation (Bushek et al. 2012). Additional analyses as well as directed studies and experiments are necessary to develop a better understanding of what factors are at play and, more importantly to this assessment, whether or not management strategies can improve the situation.

Figure 11 depicts the regional mortality rates from each fall assessment since 1990 as a function of dermo disease level (weighted prevalence). Bushek et al. (2012) demonstrated that once weighted prevalence begins to exceed 1.5 mortality begins to increase exponentially. In Figure 12, VLM and LM regions show no increase in mortality with dermo infection level because all infections are below the 1.5 threshold. A relationship begins to develop across the medium mortality regions as infections increase. This relationship is strongest across the high mortality region where it explains approximately 47% of the annual variability in mortality. The 2019 data points show relatively low mortality where oysters were beyond the reach of the ongoing freshet and dermo levels near or well below 1.5 weighted prevalence. The continued fresh water inflow, stimulated largely by controlled releases of water from reservoirs up the Delaware River Basin appears to have reduced dermo levels sufficiently to eliminate it as a leading source of mortality during 2019. This relationship warrants additional study and coordination with the entities managing water flow through the Delaware River Basin.

Because MSX has not been problematic on the seedbeds for nearly two decades, samples from only seven beds along the upbay-downbay gradient have been examined during the fall survey (Table 4). MSX was detected in eight of the 140 oysters assayed; a prevalence of just 5.7% (Figure 12A), from four of the seven beds (Figure 12 C). Curiously, as in 2018, one infection was from Hope Creek where infections are normally rare as this is a low salinity refuge from MSX (Ford et al. 2012). Two infections each were detected at Shell Rock and New Beds, and three were detected at Egg Island. The infections at the very low and high mortality beds were rare (less than 10 plasmodia) to very light (11-100 plasmodia) and the infections at Shell Rock bed were rare to light (more than 100 plasmodia); no systemic or advanced infections were observed (Figure 12C). A single rare MSX infection was observed out of a sample of 20 oysters in July 2019 on a leased ground in section C of the lower bay below the natural beds, with no other infections observed from April through November. Hatchery spawned Cape Shore natives were also tested April through November 2019; MSX was detected at 10% prevalence in April, 5% in May, and 5% in September with no systemic infections observed. Previous years have found MSX distributed across the seed beds and these data confirm its continued presence in the bay albeit at low levels. MSX remains a threat to the Delaware Bay oyster population as it continues to cause mortalities elsewhere along the East Coast. Therefore, it remains an important component of the monitoring program to understand sources of mortality from year to year. Because MSX can cause mortality in spring and appears to be more prevalent in the lower bay, it is recommended that some level of routine monitoring of MSX occur throughout the year to improve surveillance.

Additionally, there have been requests to monitor dermo disease and mortality on aquaculture leases as that activity increases. There are several logistical problems owing to the different culture environments and methods (intertidal vs subtidal, source and age of seed, husbandry differences among farms, etc.). Nevertheless, to provide a baseline we began monitoring a hatchery line produced from wild broodstock collected from the Cape Shore to provide an index of disease. The stock was spawned in 2017 and was 25 mm with no detectable infections when monitoring began in April 2017. By November 2019 they were 81 mm in shell length with 85% prevalence, a weighted prevalence of 2.4 and an average intensity of 2.8. We plan to continue this monitoring in subsequent years using two-year old animals that are near or have reached market size. Because these will be single cohorts and not a population, they will be more comparable to tracking shell plants than the population present on other areas of the seed beds. Expansion of monitoring onto subtidal areas can be considered, but how to do that and eliminate or minimize effects due to gear, husbandry or other factors will need to be carefully considered when designing a sampling strategy. The Delaware Bay NJ Oyster Stock Assessment Review Committee should consider the value of such information to the management of the Delaware Bay oyster population and fishery.

Science Advice

- Continue to examine the spatial and temporal relationships between environmental drivers of temperature, salinity and fresh water inflow on disease and mortality. Explore the potential of controlling disease and mortality through coordination of reservoir releases up the estuary with appropriate agencies. Plots of temperature, salinity and discharge over time and space may provide some exploratory insight.

- Because of the complex relationships between prevalence, intensity and weighted prevalence of dermo disease and how they change with temperature and salinity, consider plotting long-term seasonal patterns by bed to look for further insights.

- Investigate the potential evidence for the development of dermo disease resistance and/or attenuation of dermo virulence. Plot the relationship of disease by size class and explore it spatially and temporally for changes.

- Take advantage of freshet-induced mortality and the degradation of a large input of boxes as a mechanism to get a natural estimate of disarticulation rates. It may be possible to do this on lower bay beds during periods of low mortality.

- Consider where and when mortality is occurring during the year to help interpret fall mortality patterns.

- Revisit prior analyses of inshore versus offshore disease and mortality.

- Compile condition index data, although highly variable, to show current year versus long-term means by bed along the bay axis.

Acknowledgements

This report is dedicated to the memory of Susan Ford, Professor Emerita, who began a formal program to monitor dermo disease and its impacts on the fishery in 1990. Program guidance for 2019 was provided by the Oyster Industry Science Steering Committee, the Delaware Bay Shellfisheries Council and the Stock Assessment Review Committee with funding from Rutgers University and the State of New Jersey. This work was supported by the USDA National Institute of Food and Agriculture Hatch project accession number 1009201 through the New Jersey Agricultural Experiment Station, Hatch project NJ32114. In kind support was provided by Bivalve Packing, Inc. through the contribution of vessel time and staff. HSRL staff and students along with NJDEP Bureau of Shellfisheries staff, especially Craig Tomlin and Andrew Hassall, provided field, logistical and technical support during 2019.

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Table 1. 2019 sampling schedule for the NJ Delaware Bay Oyster Seed Bed Long-term Monitoring Program. The six long-term sites are Hope Creek grid 64, Arnolds grid 18, Cohansey grid 44, Shell Rock corner of grids 10, 11, 19 & 20, Bennies grid 110 and New Beds grid 26. Nantuxent grid 10, Cape Shore natives and a Maurice River Cove lease were the additional sites of interest that were sampled in 2019. Shellplant and transplant sites are described in Table 2. Parameters measured include temperature, salinity, dissolved oxygen, counts of live oysters and boxes, size frequency (shell height), and dermo levels.

Date	Samples	Vessel	Captain
April 23, 2019	6 long-term sites+1extra site	NJDEP RV James W. Joseph	Andrew Hassall
April 30, 2019	2 intermediate transplant sites 6 2017-18 shellplant sites + 1 additional site	NJDEP RV James W. Joseph	Andrew Hassall
May 14, 2019	6 long-term sites+1 extra sites	NJDEP RV James W. Joseph	Andrew Hassall
May 23, 2019	4 intermediate transplants 6 2017-18 shellplant sites	NJDEP RV James W. Joseph	Andrew Hassall
Jun 17, 2019	6 long-term sites+2 extra sites	NJDEP RV James W. Joseph	Andrew Hassall
June 24, 2019	4 intermediate transplants 6 2016-17 shellplant sites	NJDEP RV James W. Joseph	Andrew Hassall
July 15, 2019	6 long-term sites+1 extra sites	NJDEP RV James W. Joseph	Andrew Hassall
July 22, 2019	4 intermediate transplants 6 2017-18 shellplant sites	NJDEP RV James W. Joseph	Andrew Hassall
August 19, 2019	6 long-term sites+2 extra sites	NJDEP RV James W. Joseph	Craig Tomlin
August 28, 2019	4 intermediate transplants 6 2016-17 shellplant sites	NJDEP RV James W. Joseph	Craig Tomlin
September 16, 2019	6 long-term sites+1 extra sites	NJDEP RV James W. Joseph	Craig Tomlin
September 30, 2019	4 intermediate transplants 10 2017-19shellplant sites	NJDEP RV James W. Joseph	Andrew Hassall
October 15, 2019	6 long-term sites+2 extra sites	NJDEP RV James W. Joseph	Andrew Hassall
October 22, 2019	4 intermediate transplants 10 2017-19 shellplant sites	NJDEP RV James W. Joseph	Craig Tomlin
November 19, 2019	6 long-term sites+1extra site 2 intermediate transplants	NJDEP RV James W. Joseph	Andrew Hassall
November 25, 2019	2 intermediate transplants 10 2017-19 shellplant sites	NJDEP RV James W. Joseph	Andrew Hassall

Table 2. Additional enhancement sites sampled during 2019.

Bed	Grid	Plant material	Plant yr
Nantuxent	22	ocean quahog	2019
Bennies Sand	24	ocean quahog	2019
Shell Rock	3	ocean quahog	2019
Cohansey	70	ocean quahog	2019
Hog Shoal	4	ocean quahog	2018
Shell Rock	68	ocean quahog	2018
Ship John	14	ocean quahog	2018
Bennies Sand	41	ocean quahog	2017
Shell Rock	37	ocean quahog	2017
Cohansey	50	ocean quahog	2017
Shell Rock	42	low mortality transplant	2019
Bennies Sand	34,35	medium mortality transplant	2019
Bennies	72	medium mortality transplant	2018
Bennies	58	medium mortality transplant	2018

Table 3. Record of collections for annual fall dermo monitoring since 1990. X indicates bed was sampled in respective year for that column. Prior to 2008, not all beds were sampled. Beginning in 2008, all beds were sampled every year except Ledge and Egg Island which were alternated annually due to a general lack of oysters. Beds are listed approximately 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	--	--	17	18	19
Hope Creek																		X	X	X	--	--	X	X	X
Liston Range																			X	X	--	--	X	X	X
Fishing Creek																			X	X	--	--	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	X	X
Upper Arnolds														X		X	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	X	X
Upper Middle																	X	X	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	X	X
Cohansey	X	X	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	X	X
Ship John	X	X	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	X	X
Bennies Sand	X	X	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	X	X
Nantuxent		X		X		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	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	X	X
Strawberry	X		X		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	X	X
Beadons	X	X	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	X	X
Egg Island	X	X	X	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. 2019 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	51	10	10	14
Hope Creek	86	10	10	14
Hope Creek	63			12
Hope Creek	75			10
Fishing Creek	4	10		13
Fishing Creek	26	10		13
Fishing Creek	25			14
Fishing Creek	37			10
Liston Range	24	10		15
Liston Range	11	10		16
Liston Range	17			12
Liston Range	5			7
Round Island	4	10		13
Round Island	17	10		13
Round Island	1			12
Round Island	12			12
Upper Arnolds	3	10		13
Upper Arnolds	15	10		13
Upper Arnolds	4			12
Upper Arnolds	22			12
Arnolds	7	10	10	10
Arnolds	19	10	10	10
Arnolds	45			15
Arnolds	67			15
Upper Middle	48	10		13
Upper Middle	64	10		13
Upper Middle	1			12
Upper Middle	36			12
Middle	37	10		12
Middle	10	10		14
Middle	1			13
Middle	38			11
Cohansey	9	10	10	10
Cohansey	48	10	10	10
Cohansey	16			15
Cohansey	60			15
Sea Breeze	18	10		12
Sea Breeze	30	10		15
Sea Breeze	38			12
Sea Breeze	14			11
Ship John	26	10		15
Ship John	58	10		15
Ship John	51			10
Ship John	21			10

Bed	Grid	Dermo	MSX	CI
Shell Rock	75	10	10	12
Shell Rock	25	10	10	14
Shell Rock	85			11
Shell Rock	7			13
Bennies Sand	5	10		15
Bennies Sand	26	10		15
Bennies Sand	4			10
Bennies Sand	30			10
Bennies	85	10	10	13
Bennies	27	10	10	13
Bennies	56			12
Bennies	146			12
Nantuxent	10	10		14
Nantuxent	12	10		12
Nantuxent	15			12
Nantuxent	26			12
Hog Shoal	6	10		14
Hog Shoal	10	10		14
Hog Shoal	1			11
Hog Shoal	19			11
New Beds	23	10	10	10
New Beds	42	10	10	18
New Beds	12			10
New Beds	37			12
Strawberry	21	10		23
Strawberry	10	10		17
Strawberry	2,29			10
Hawks Nest	17	10		13
Hawks Nest	27	10		15
Hawks Nest	26			11
Hawks Nest	3			11
Beadons	15	10		12
Beadons	3	10		12
Beadons	4			14
Beadons	8			12
Vexton	9	10		13
Vexton	19	10		14
Vexton	11			13
Vexton	18			10
Egg Island	All	20	20	6
Total beds	**22**	**22**	**7**	**22**
Total grids	**86**	**44**	**14**	**86**
Total oysters		**440**	**140**	**1056**

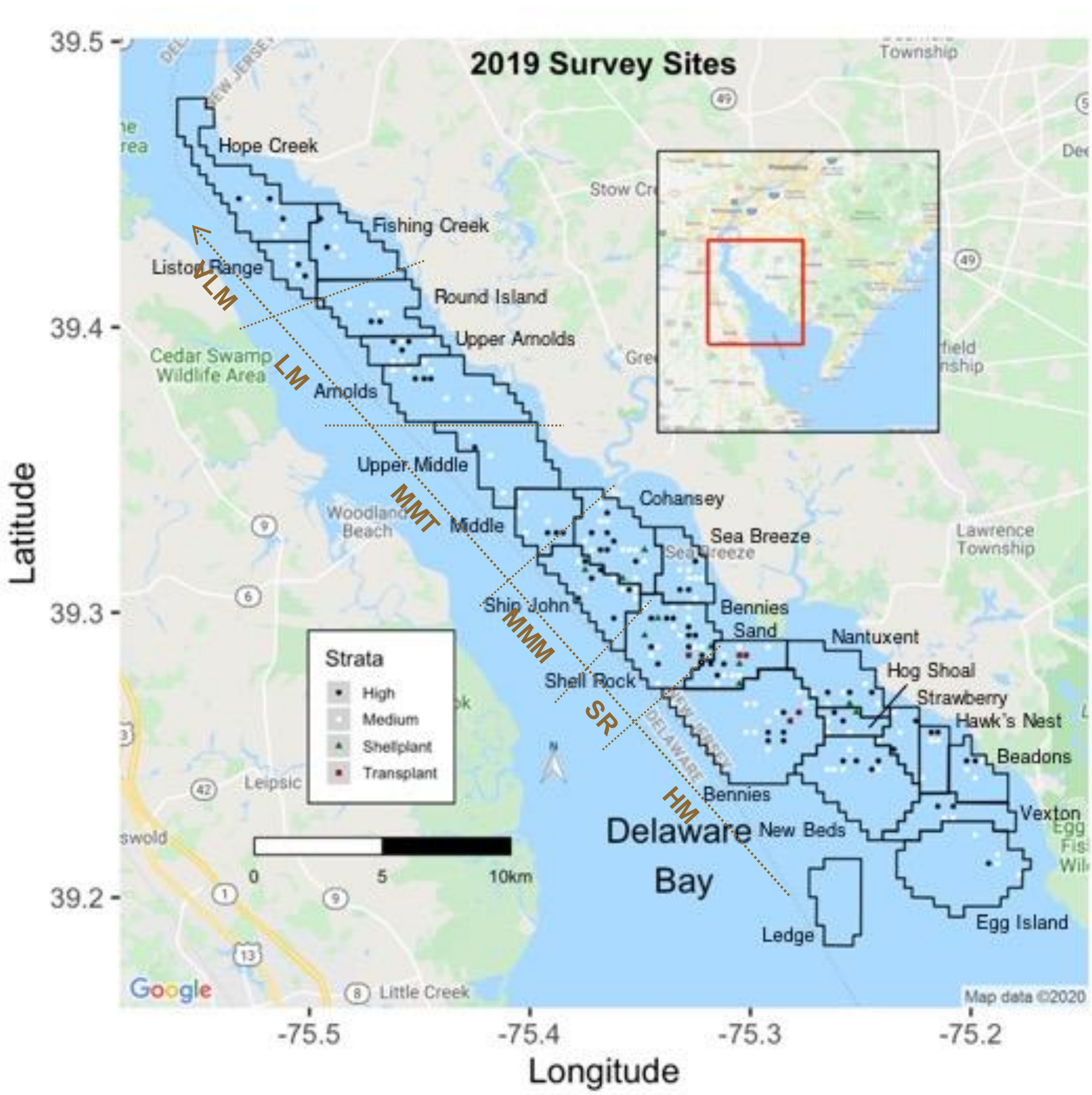

Figure 1. Footprint of the Delaware Bay, NJ public oyster beds (aka 'seedbeds'). Black lines demarcate named beds with management regions indicated by brown dotted lines (abbreviations as in text). The sites for the 2019 stock assessment survey are indicated by dots. A stratified random sampling program identified black and white dots for high and medium density strata, respectively, whereas red dots were transplant sites and green dots were shellplant sites. See Alcox et al. (2017) for full description.

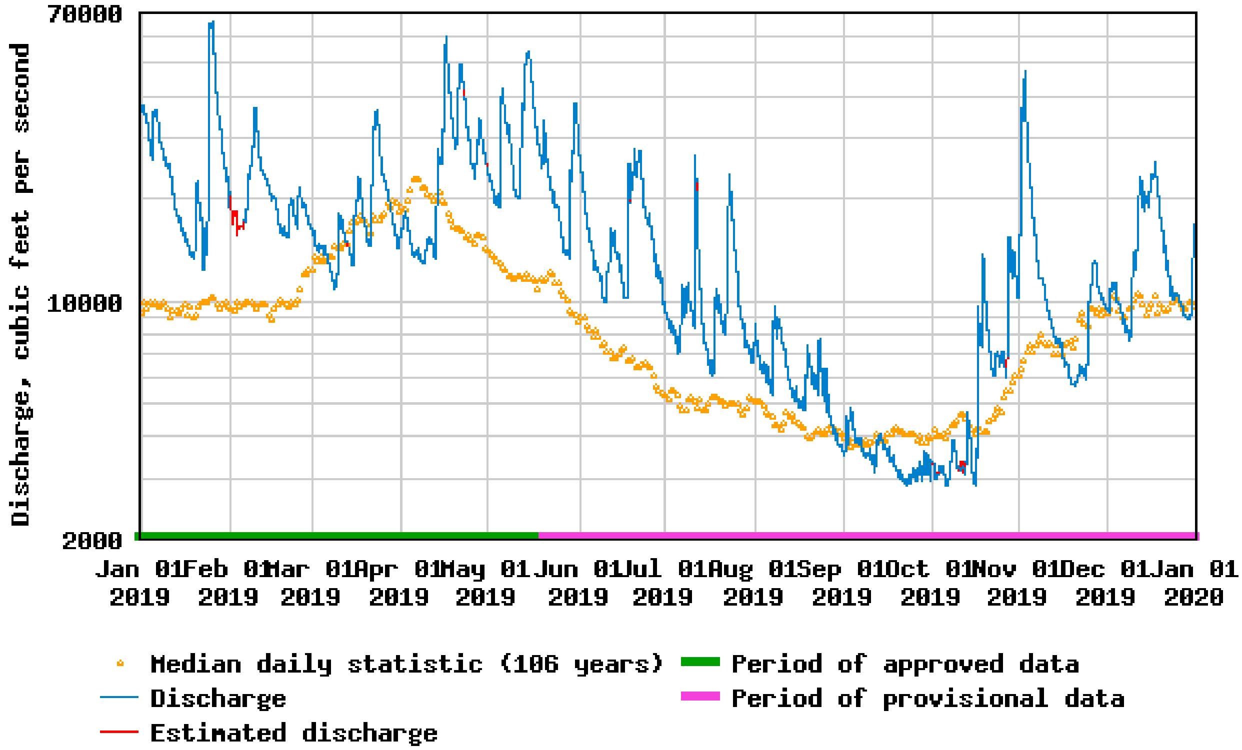

Figure 2. USGS discharge from Delaware River at Trenton (USGS station 01463500) during 2019. Freshwater inflow was well above the long-term median for much of the year. These conditions reduced salinity over the oyster beds as shown in figures 3 and 4 below.

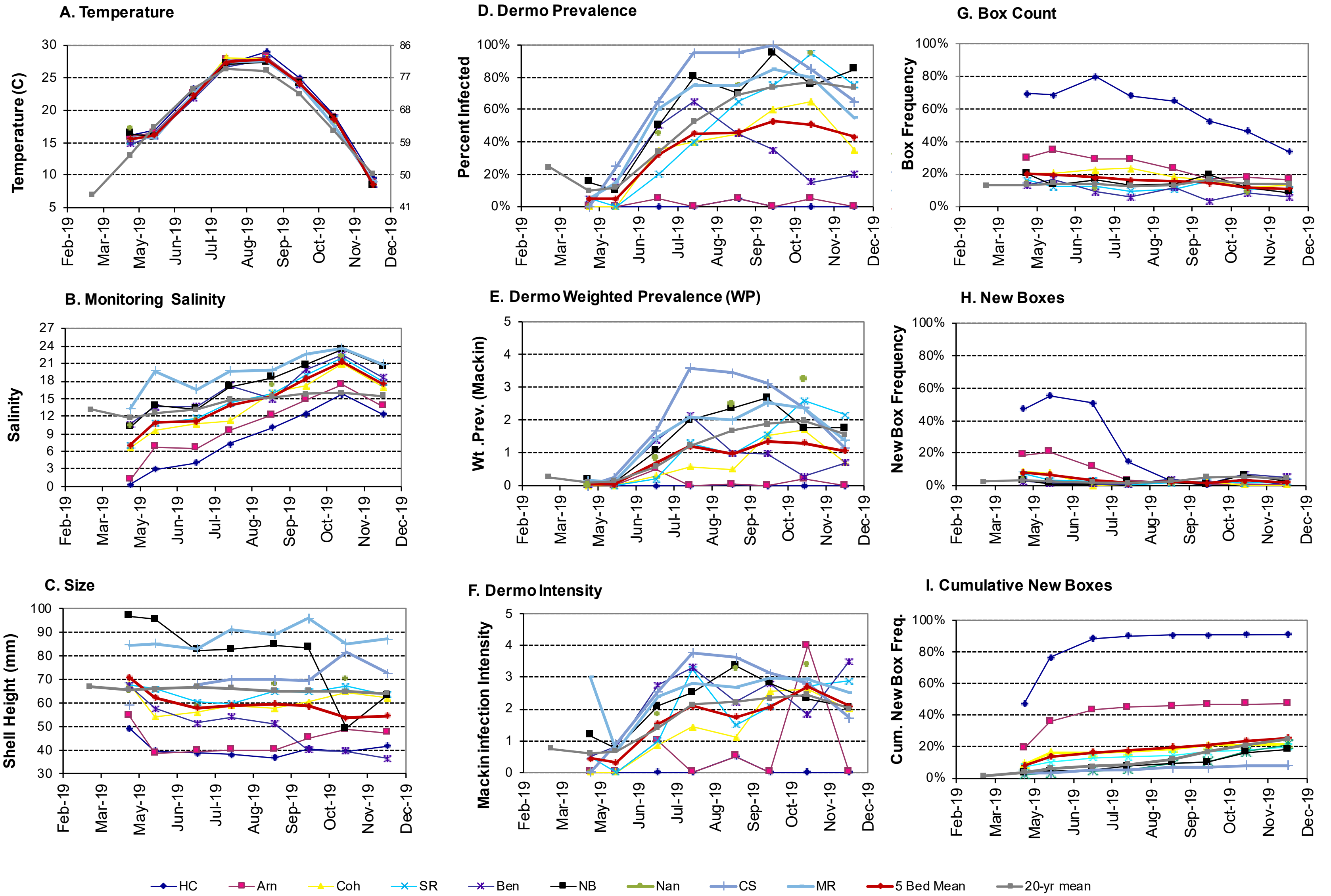

Figure 3. Results of 2019 Seed Bed Monitoring Program. Panels present data as labeled. HC = Hope Creek, Arn = Arnolds, Coh = Cohansey, SR = Shell Rock, Ben = Bennies, NB = New Beds, Nan = Nantuxent, CS = Cape Shore, MR = Maurice River Cove.

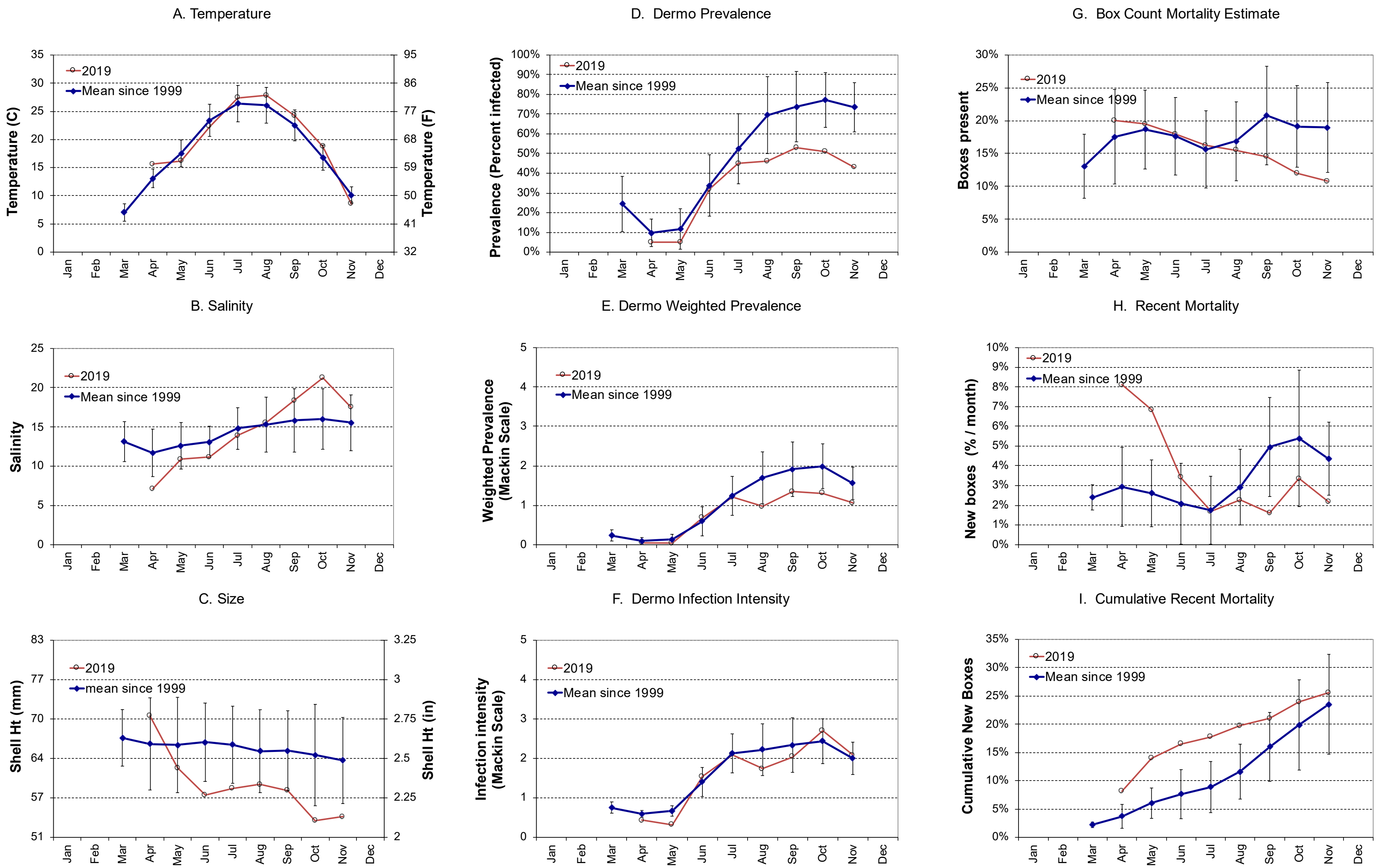

Figure 4. Seasonal patterns of the 2019 average Arnolds, Cohansey, Shell Rock, Bennies and New Beds) compared to the long-term values. Panels arranged as in Figure 3. Error bars represent one standard deviation.

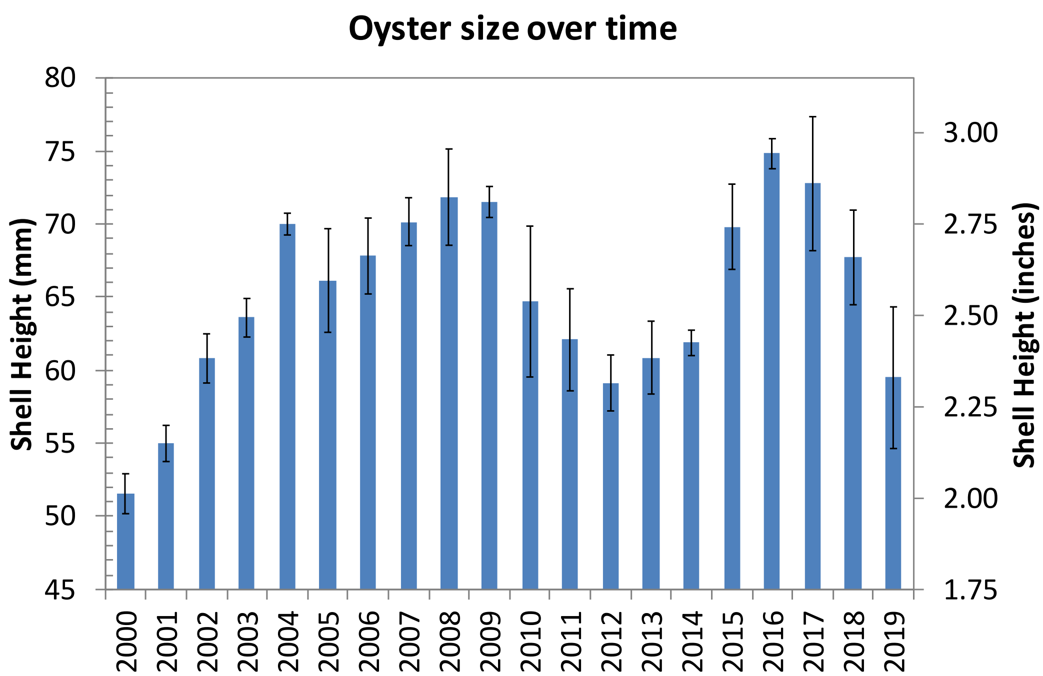

Figure 5. Interannual variation in mean shell height of oysters collected monthly between from Delaware Bay NJ oyster seedbeds. Error bars represent one standard deviation of the mean of all oysters measured throughout each year. N = 50-100 oysters per month from each of the five primary long-term beds (Arnolds, Cohansey, Shell Rock, Bennies and New Beds) sampled from March to November.

Figure 6. Performance of 2017 through 2019 transplants relative to nearby sites (means from New Beds and Shell Rock as insufficient oysters from the long-term Bennies site precluded using it in these comparisons). Panels arranged as in Figure 3.

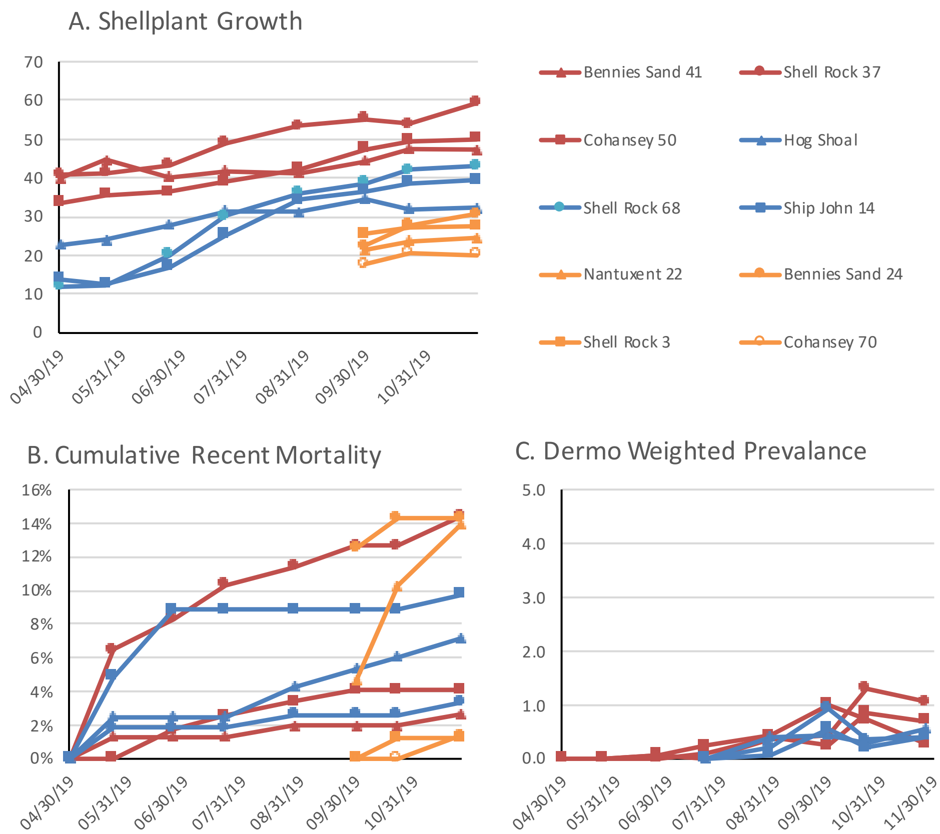

Figure 7. Performance of shellplants monitored during 2019. Monitoring for growth (A) and mortality (B) began in September during the year of each plant with a hiatus from November to April each year thereafter. Dermo monitoring (C) began in July following the year of planting. High initial levels of mortality are usually caused by predation or siltation.

A.

B.

C.

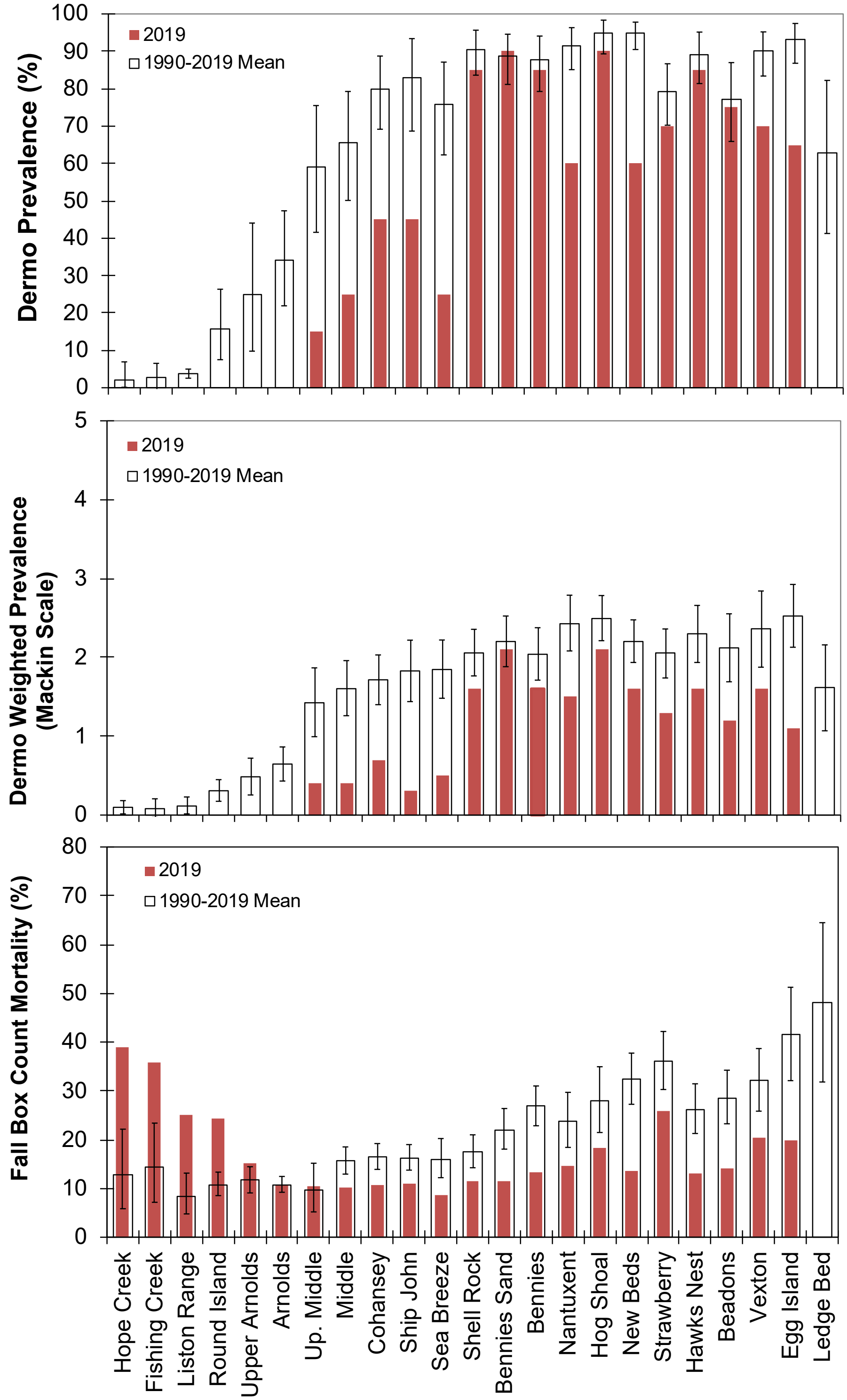

Figure 8. Long-term spatial patterns of dermo prevalence (A), dermo weighted prevalence (B) and natural mortality (C) across the oyster beds. From left to right, beds are listed upbay to downbay. Not all beds have been sampled every year (see Table 3). Ledge was not sampled in 2019. Error bars represent 95% confidence intervals.

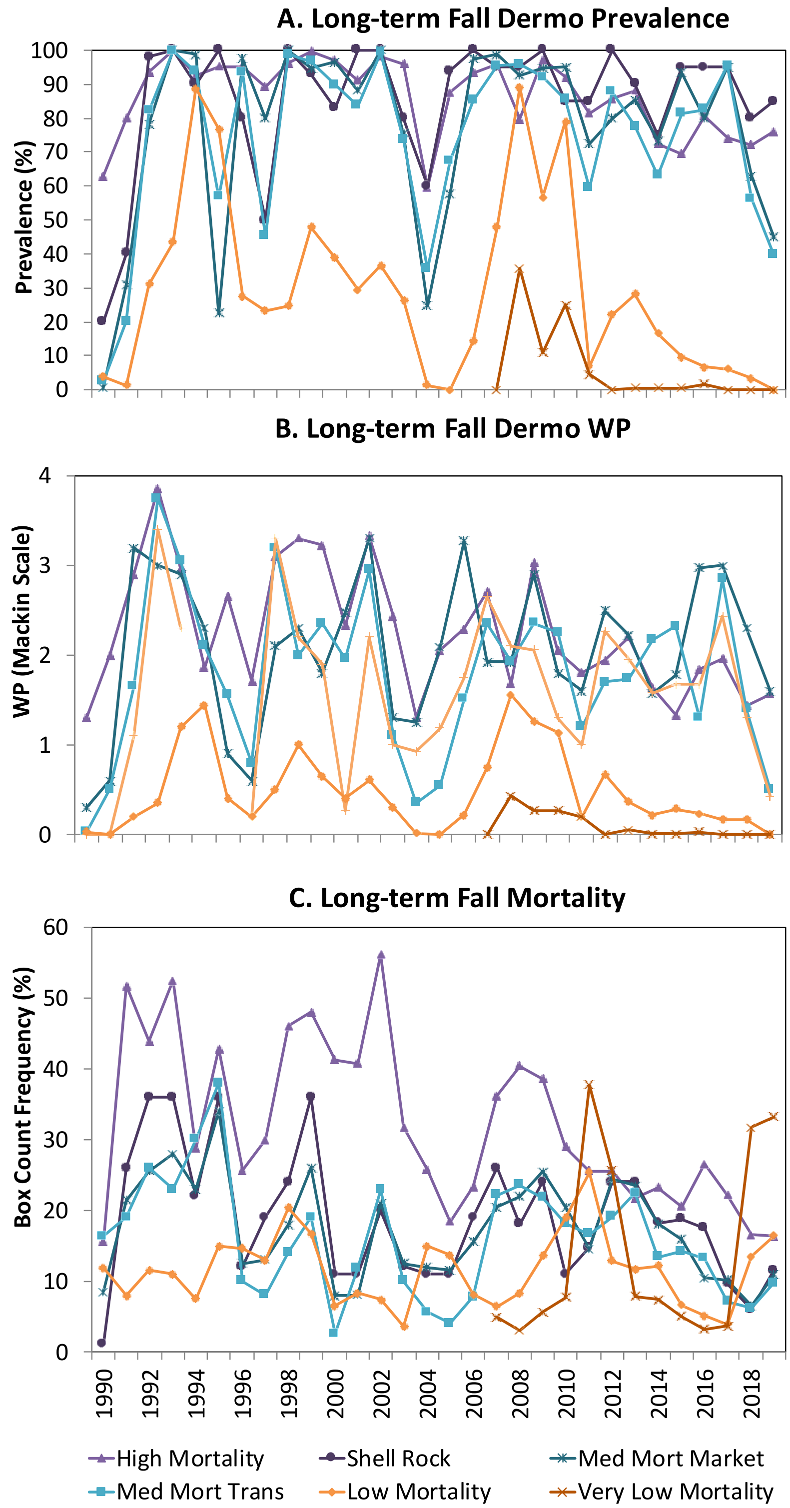

Figure 9. Annual Fall dermo prevalence (A), weighted prevalence (B) and box count mortality (C) on New Jersey Delaware Bay seedbeds. Regions correspond to management regions in Figure 1.

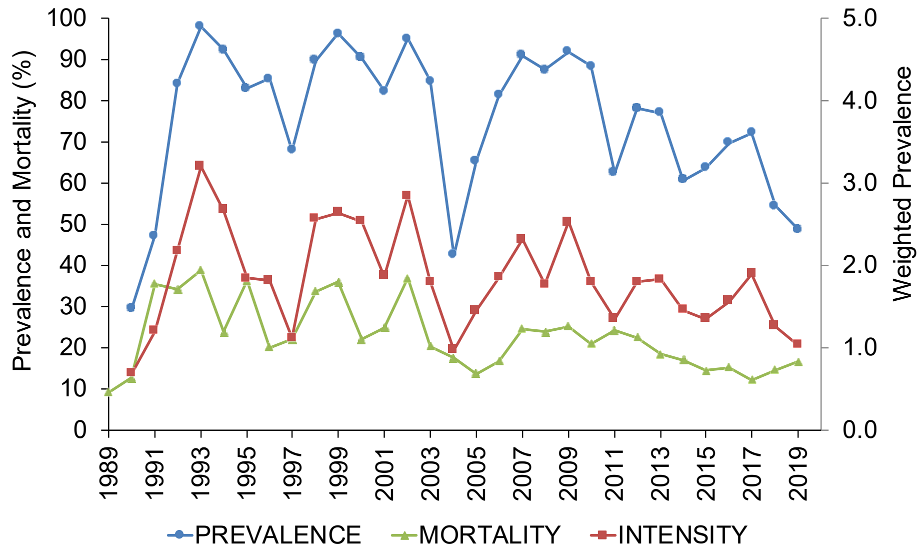

Figure 10. Long-term patterns of Fall dermo prevalence, intensity (weighted prevalence) and mortality averaged across the five beds monitored since 1990 (Arnolds, Cohansey, Shell Rock, Bennies and New Beds). These data appear to show cycles with an approximate periodicity of seven years, and a dampening of the cycling resulting in lower levels of each metric over time.

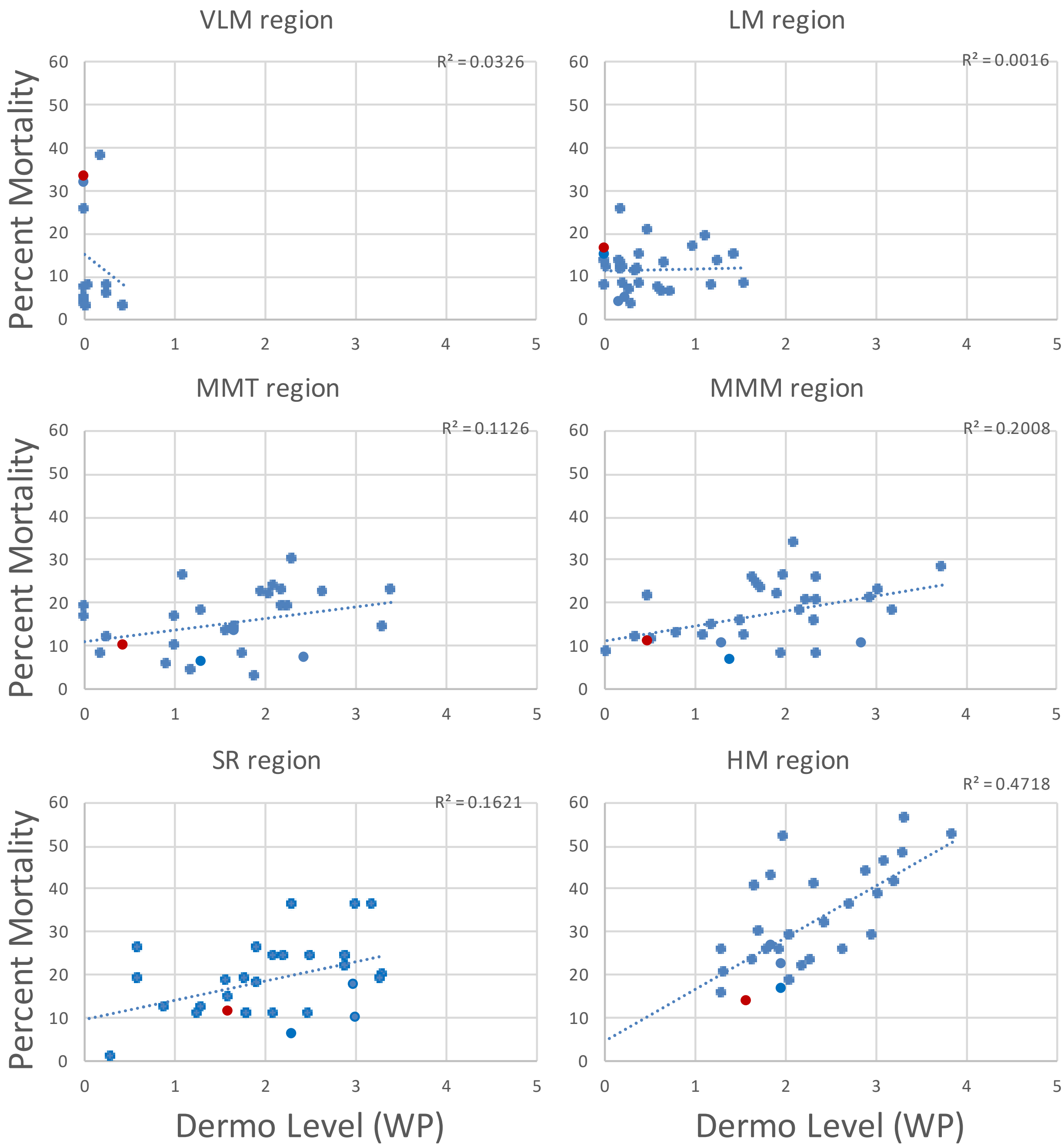

Figure 11. Region mortality as a function of dermo disease levels since 1990 (2007 for the VLM region). Red points represent 2018 data. VLM = Very Low Mortality region, LM = Low Mortality region, MMT = Medium Mortality Transplant region, MMM = Medium Mortality Market region, SR = Shell Rock, and HM = High Mortality Region.

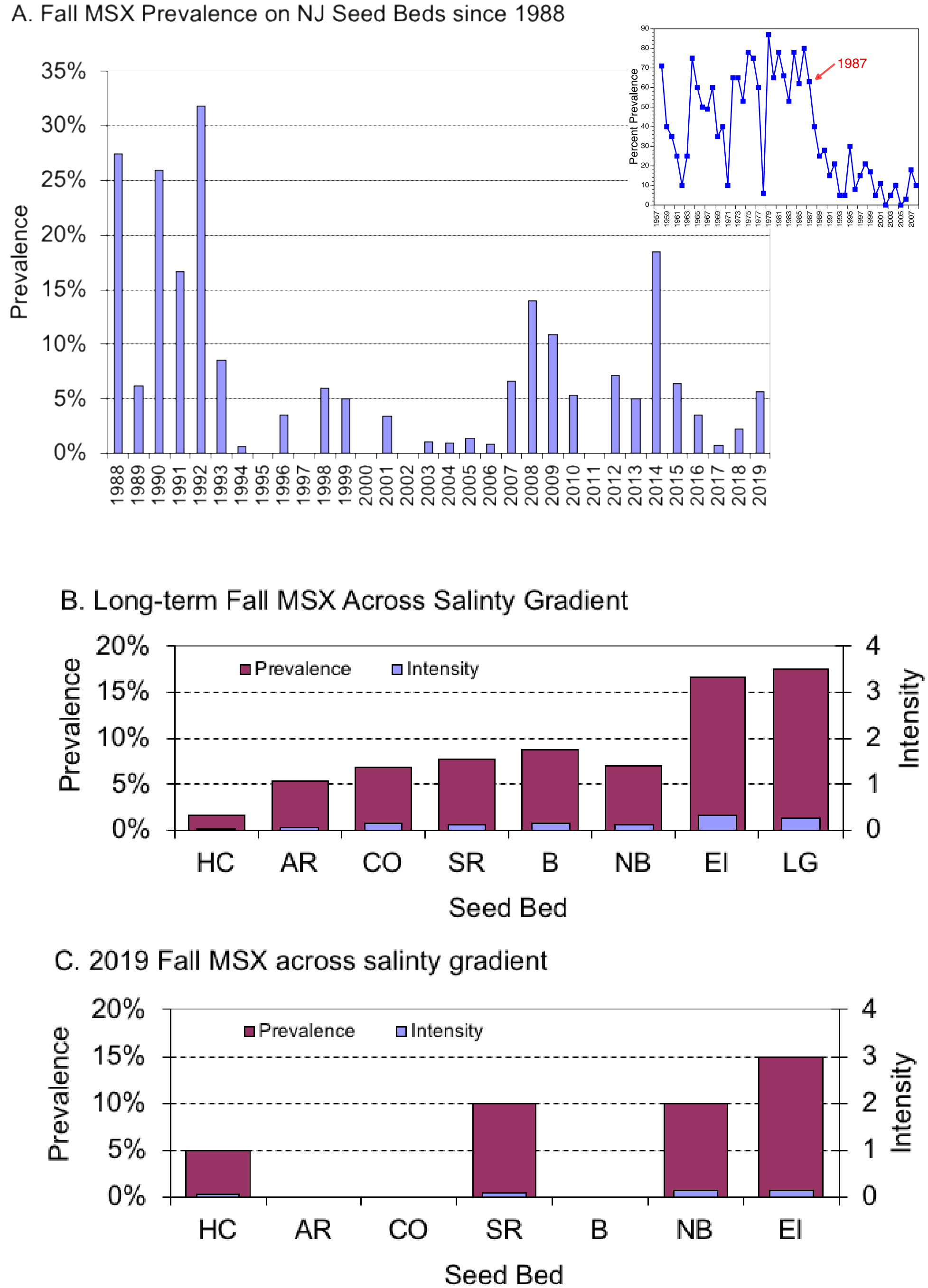

Figure 12. MSX disease on the New Jersey Delaware Bay oyster seedbeds. A. Annual Fall MSX prevalence across all beds since 1988 (2007 for HC). Inset shows lower Delaware Bay levels for comparison from Ford and Bushek (2012). B. Total fall MSX prevalence and intensity (weighted prevalence on a scale of 0 to 4) across seedbed salinity gradient since 1988. C. 2019 Fall MSX prevalence and intensity across seedbeds. HC = Hope Creek, AR = Arnolds, CO = Cohansey, SR = Shell Rock, B = Bennies, NB = New Beds, EI = Egg Island.