Delaware Bay New Jersey
Oyster Seedbed Monitoring Program
2021 Status Report

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Executive Summary

The 2021 Seedbed Monitoring (SBM) Program tracked oyster size, dermo disease and oyster mortality monthly at six fixed sites, two additional sites of interest, seven shellplant sites and three intermediate transplant sites. The Program also continued its long-term disease analyses for the annual Fall Oyster Stock Assessment Survey by assessing meat condition and dermo disease from 23 beds as well as MSX disease data from eight fixed monitoring sites.

Monthly monitoring indicated that temperature was above a 22-yr average from June to November during 2021. Moderate freshwater inflow throughout the spring and early summer maintained salinity near seasonal averages but larger rainfall events from mid-Summer through Fall depressed salinity across the sampling area. Mean oyster size increased on most beds during the year and relative to the prior two years. Dermo disease followed typical seasonal and spatial patterns, but levels were generally below average and this likely contributed to relatively low levels of mortality observed during 2021. By comparison, the 2-yr old cohort monitored on the Cape Shore flats incurred higher levels associated with mortality reported by farmers in the region.

Fall spatial patterns of dermo showed the typical increase from upper to lower bay beds with highest levels observed from Shell Rock south. Overall, however, levels remain relatively low with respect to the time series and oysters on nearly all beds entered winter with dermo levels below long-term means. Mortality was notably low across all high mortality beds and did not show as great an increase from upper to lower bay beds reflected in the long-term timeseries. The long-term patterns from the Fall survey continues 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 several years. MSX continues was present at low prevalence and intensity on mid- and lower bay beds in Fall 2021, and in other areas of the bay throughout the year. Although still quite low, prevalence and intensity has increased.

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 to inform management of the resource, particularly in the face of climate change, upstream management of reservoirs that impact freshwater inflow, and increasing aquaculture activities.

Introduction

The Delaware Bay Oyster Seedbed Monitoring (SBM) 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 is included where relevant and available.

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, predation by oyster drills was a primary concern with their abundance and distribution determined by salinity which was controlled 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 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 (Ford et al. 2012). In 1990, an epizootic of dermo disease occurred and changed the population dynamics of the system further. Dermo disease is a form of the molluscan disease perkinsosis that is specific to the eastern oyster *Crassostrea virginica*. It is caused by the alveolate protist *Perkinsus marinus*. Prior to 1990, occurrences of dermo disease were associated with importations of oysters from the lower Chesapeake Bay (Ford 1996) and often subsided once importations ceased presumably due to the colder climate. 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. With the continuing progression of global warming and climate change, dermo disease has remained a major source of oyster mortality in Delaware Bay since 1990 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 salinity which increases from an average of about 6 to 18 across these beds. Higher salinity generally promotes better growth and meat quality but also favors predation and disease. A group of beds above the low mortality region was added to the survey in 2007 after reconnaissance indicated a high abundance of oysters in a region that the fishery had exploited in the past and wished to do so again. 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 in reference to the level of disease-induced mortality they experience –

the VLM beds experience little disease, but episodic high mortality occurs in response to freshets (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 from the Haskin Shellfish Research Laboratory website: 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. Additional 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 deeper insights of the dynamics controlling 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) as well as other natural events (e.g., freshets) and additional experiments that may be sanctioned. The 2021 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 2021 Fall Stock Assessment Survey
3. Monitor growth, disease and mortality on 2019 through 2021 shell plantings
4. Monitor growth, mortality and disease on the 2021 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

COVID-19 Impacts: Despite the continuing COVID-19 pandemic sampling proceeded for the 2021 season albeit with reduced staff resulting in a slower pace. Data from 2020, however are incomplete due to a curtailment in work activities that prevented sampling, reduced shellplanting and restricted the amount of samples that could be collected as staff restrictions were lifted. No essential data is missing from 2021.

Monthly monitoring occurred at the six long-term sites along a transect spanning the salinity gradient from Hope Creek to New Beds as well as two additional sites of interest (Nantuxent and Cape Shore). Reports were presented to regularly held video conferences the Delaware Bay Section of the New Jersey Shell Fisheries Council to provide 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 2021. All data were evaluated and compared to prior years to provide insight into inter-annual patterns, long-term trends, and factors affecting the oyster stock.

Figure 1 depicts the sampling locations for the 2021 Annual Fall Oyster Stock Assessment with beds outlined in black and area management regions are roughly indicated by blue 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. Details on regions, beds and sampling design are provided in Powell et al. (2008 and 2012) as well as Alcox et al. (2017). Briefly, 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). Monthly samples were collected at fixed stations using a composite bushel of three 1-minute tows with a 0.81 m wide oyster dredge from the R/V James R Joseph. 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 (see below). Grid quality is determined by relative oyster density within each bed as described in Alcox et al. (2017). When ranked by oyster abundance, high quality grids contain 50% of the total oyster abundance, medium quality grids contain the next 48% of total oyster abundance, and low quality grids contain less than 2% of the total oyster abundance on a bed.

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 2021 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 (i.e., dead oysters with meat remaining in the valves), boxes (i.e., hinged oyster valves without any meat remaining) and live oysters. Because boxes persist for varying amounts of time, they were further categorized as new (i.e., no indication of fouling with little sedimentation inside valves) or old (i.e., 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 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 impacts 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 3 (see Ashton-Alcox et al. 2017 for survey method details). Although normally sampled in alternate years due to a low abundance of oysters, both Ledge and Egg Island were sampled during 2021 following indications of recent recruitment and increased abundance. 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 2019 and 2020 shell plantings, and initiated the 2021 shell plantings listed in Table 2 – the latter of which was only sampled during

[1] At Arnolds and Hope Creek, sample volumes were halved due to small size of the oysters.

the final 3 months. On each shellplant site, three 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. If five tows were insufficient to collect 100 oysters the effort was stopped and all oysters collected to that point were used. Care was taken to avoid sampling bias while sorting the catch 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 2021 shellplants as it was in its first year and not expected to have contracted any disease by this point.

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 = 0.25 ppt) below the city of Philadelphia to maintain drinking water standards, protect industries from corrosive effects of salt water and to protect aquatic life located further downstream (DRBC 2021). This is done by maintaining a minimum flow at Trenton via the metered release of water from reservoirs located in the watershed. 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. River flow during 2021 began following median levels but increased considerably from late summer though fall (Figure 2). 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) while reducing mortality from disease and predation on the beds located further down the bay.

Temperature and Salinity. Temperature and salinity are arguably the most important environmental factors controlling oyster growth, reproduction, disease and mortality. The conditions observed over the seedbeds during 2021 were more or less typical with respect to the past 22 years. Water temperatures measured during 2021 collections followed a typical seasonal cycle with little spatial variability across the seedbeds but were warmer than average from June to November (Figures 3A and 4A). Spawning temperatures were reached between June and July sampling dates. Salinity followed the typical estuarine gradient, increasing from upbay to downbay beds (Figure 3B) and followed the 22-yr mean (Figure 4B) but the increase late summer and into the Fall was inhibited by large increases in freshwater inflow that persisted during the latter half of the year inflow (Figure 2).

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). Mean shell height remained relatively stable on most beds during 2021 (Figure 3C). Intuitively, oysters should grow over the summer and increase in size, but average size may not increase or even decrease over the season as small spat become large enough to be measured while larger older animals are harvested or die. In 2021, the overall average size measured increased, but did not exceed the long-term average (Figure 4C). Figure 5 shows how oyster size has changed annually and shows a cyclical pattern that is likely reflective of the interplay between recruitment and mortality such that mean size increases when mortality and recruitment are low while decreasing as recruitment increases along with mortality of larger sized oysters. Current size frequencies are dominated by smaller oysters with a mean of 68 mm (2.7 inches).

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) but were generally lower than long-term means in the latter portion of the season (Figures 4D-F). That is, each measure of dermo disease increased to a peak in fall with levels increasing with the salinity gradient. These observations support a continued suppression of dermo disease that is likely related to elevated levels of freshwater inflow during several previous years as well as the periodic spikes in freshwater flow during 2021 (Figure 2). Additionally, an influx of small oysters in 2020 on Bennies and New Beds has continued to reduce the level of dermo on those beds although prevalence increased this year. The population as a whole entered the winter with a relatively low level of dermo, but several important beds such as Shell Rock, Nantuxent and Cohansey were still relatively heavily infected.

The situation at the Cape Shore was entirely different with very high levels of dermo detected in July that was associated with mortality reported by growers (Figure 3D-F). Here, a 2 yr-old year class of a hatchery line produced from NEH broodstock collected from the Cape Shore was monitored to provide an index of disease pressure. Using a single cohort from a single line stabilizes variation arising from different culture environments and methods such as intertidal vs subtidal, source and age of seed, husbandry differences among farms, and other factors. In 2021, these oysters became heavily infected with dermo in June and sustained heavy infections through the fall. This is partly due to the fact that the oysters monitored at the Cape Shore were from a single cohort of near market- or market-size oysters. Corresponding mortality data is not available. Monitoring aquacultured populations will be important to determine how they interact with the fishery as these populations will undoubtedly interact via disease transmission and reproduction.

Mortality. The low levels of dermo disease just described was associated with relatively low levels of mortality (Figures 3G-H and 4G-H). These plots all show mortality rates below longterm means. Figures 3I and 4I show rates of mortality that are roughly parallel to the long-term mean indicating similar rates of mortality over time. Shell Rock was an exception with a large mortality event in September. 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 2021, but the potential for an epizootic to develop and cause significant mortality remains high.

Transplants, shellplants and replants. Figure 6 shows the conditions and performance of 2021 transplants compared to the five bed mean of the long term sites. 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 long-term site values. Values were higher than the five bed mean because that mean includes values from beds in regions upbay and less impacted by disease. 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 2021.

Seven shell plants have been placed on four different beds during the past three years (Table 2). Growth varied among shellplants (Figure 7A) with largest increase on the 2020 shellplant at ~ 24 mm while 2019 plants grew 8 to 14 mm. The 2021 shell plants had reached 19 mm by November indicating a rapid growth rate before we began monitoring them. Mortality varied from 5 to 36% and generally increased with age of the shell plant (Figure 7B). Dermo increased on 2019 and 2020 shellplants across the season with levels occurring in both year classes equivalent to the recipient beds (Figure 7C and D). 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 2021, 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 continued significant departure from long-term patterns during 2021 (Figure 8). The long-term patterns typically increase from upper to lower bay beds, but since 2013, dermo prevalence and weighted prevalence have been highest in the central portion of the fishery 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 2021, dermo levels were below mean long-term values on many beds, and often below the 95% confidence intervals, but near or above levels on several beds. Most striking were the low Fall box count fractions on high mortality beds. Those beds saw mortality levels that were uncharacteristically low, often near or below 50% of their respective long-term mean. Mortality was also below long-term means across the Low and Very Low Mortality beds. Only Shell Rock and Middle, sustained mortality levels above longterm means.

Figure 9 depicts annual dermo prevalence, weighted prevalence and box-count estimated mortality from 1989 to 2021 for each mortality region. Each parameter generally decreases from high to low mortality regions. Exceptions are predominantly related to freshets causing mortality in the 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. 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) or resistance (the ability of an oyster to limit the development of an infection) to dermo disease. Alternatively, dermo virulence may 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 11, VLM and LM regions show no increase in mortality with dermo infection level because all infections are below the 1.5 threshold – the high mortality events in the VLM were a result of freshets. 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 46% of the annual variability in mortality. The 2021 data points all show relatively low mortality, even on the HM region where dermo levels were approaching 2. Highest mortality was on SR (19%) where dermo WP was 1.8 and had been above 2.0 since August. The pulses of fresh water entering the system appear to be associated with curbing dermo levels sufficiently to eliminate it as a leading source of mortality during 2021. This relationship warrants additional study and coordination with the entities managing water flow through the Delaware River Basin Commission.

Because MSX has not been problematic on the seedbeds for nearly two decades, samples from only eight beds along the upbay-downbay gradient have been examined during the fall survey (Table 4). MSX was detected in eight of the 160 oysters assayed; a prevalence of just 2.1% (Figure 12A). Over the past 33 years, MSX infections occur at a higher prevalence and intensity with increasing salinity (Figure 12B). In 2021, one infection was detected at each of Cohansey and Shell Rock, and three each at Egg Island and Ledge (Figure 12C). Most infections were rare (less than 10 plasmodia) to very light (11-100 plasmodia) with the only systemic, advanced infection observed at Egg Island (Figure 11C), a higher salinity site where MSX disease is more likely to occur (Ford et al. 2012). Hatchery spawned disease resistant stocks held on aquaculture racks at Cape Shore were also tested April through November 2021. MSX was detected at 20% prevalence in April, 16% in May, 5% in July, and 10% in November with systemic infections observed in April and May, and an advanced infection observed in April. 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.

Science Advice

- Continue to examine the spatial and temporal relationships between environmental drivers of temperature, salinity and fresh water inflow on disease and mortality. Long-term patterns now provide a clear indication that dermo levels drop following freshets resulting in a net positive effect on the population (through reduced mortality). The potential of controlling disease and mortality through coordination of reservoir releases up the estuary should be explored with appropriate agencies.

- 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.

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

- Consider revisiting 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.

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Table 1. 2021 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 and the Rutgers Cape Shore Lab were the additional sites of interest that were sampled in 2021. Cape Shore was sampled by foot and dates were not always coincident with other sites but generally within 2 or 3 days. 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 19, 2021	6 long-term sites + 2 extra sites and 1-2020 shellplant site	NJDEP RV James W. Joseph	Andrew Hassall
April 27, 2021	4 shellplant sites	NJDEP RV James W. Joseph	Andrew Hassall
May 17, 2021	6 long-term sites + 1 extra site	NJDEP RV James W. Joseph	Andrew Hassall
May 27, 2021	5 shellplant sites and 3 intermediate transplant sites	NJDEP RV James W. Joseph	Andrew Hassall
June 23, 2021	6 longterm sites + 1extra	NJDEP RV James W. Joseph	Andrew Hassall
June 28, 2021	5 shellplant sites and 3 intermediate transplant sites	NJDEP RV James W. Joseph	Andrew Hassall
July 19, 2021	6 long-term sites + 1 extra site	NJDEP RV James W. Joseph	Andrew Hassall
July 26, 2021	5 shellplant sites and 3 intermediate transplant sites	NJDEP RV James W. Joseph	Andrew Hassall
August 16, 2021	6 long-term sites + 1 extra site	NJDEP RV James W. Joseph	Andrew Hassall
August 30, 2021	5 shellplant sites and 3 intermediate transplant sites	NJDEP RV James W. Joseph	Craig Tomlin
September 20, 2021	6 long-term sites + 1 extra site	NJDEP RV James W. Joseph	Andrew Hassall
September 27, 2021	7 shellplant sites and 3 intermediate transplant sites	NJDEP RV James W. Joseph	Andrew Hassall
October 21, 2021	6 long-term sites + 1 extra site	NJDEP RV James W. Joseph	Andrew Hassall
October 28, 2021	7 shellplant sites and 3 intermediate transplant sites	NJDEP RV James W. Joseph	Andrew Hassall
November 17, 2021	6 long-term sites + 1 extra site	NJDEP RV James W. Joseph	Andrew Hassall
November 23, 2021	7 shellplant sites and 3 intermediate transplant sites	NJDEP RV James W. Joseph	Craig Tomlin

Table 2. Additional enhancement sites sampled during 2021. Due to extenuating circumstances related to COVID-19, only the current year shell plant was sampled during 2020. Normal sampling resumed in 2021 adding an additional day to the sampling schedule.

Bed	Grid	Plant material	Plant yr
Nantuxent	22	clam shell	2019
Bennies Sand	24	clam shell	2019
Shell Rock	3	clam shell	2019
Cohansey	70	clam shell	2019
Bennies Sand	34/35	clam shell	2020
Nantuxent	9	clam shell	2021
Shell Rock	6	clam shell	2021
Bennies	60	medium mortality transplant	2021
Nantuxent	21	medium mortality transplant	2021
Shell Rock	60	low mortality tansplant	2021

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. This year, however, both Ledge and Egg Island were sampled. 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	--	--	19	20	21
Hope Creek (HC)																		X	X	X	--	--	X	X	X
Liston Range (LR)																			X	X	--	--	X	X	X
Fishing Creek (FC)																			X	X	--	--	X	X	X
Round Island (RI)	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	--	--	X	X	X
Upper Arnolds (UA)														X		X	X	X	X	X	--	--	X	X	X
Arnolds (AR)	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 (UM)																	X	X	X	X	--	--	X	X	X
Middle (MI)	X	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	--	--	X	X	X
Cohansey (CO)	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 (SB)														X	X	X	X	X	X	X	--	--	X	X	X
Ship John (SJ)	X	X	X	X	X		X			X	X	X	X	X	X	X	X	X	X	X	--	--	X	X	X
Shell Rock (SR)	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 (BS)	X	X	X	X	X			X	X	X	X	X	X		X	X	X	X	X	X	--	--	X	X	X
Bennies (Ben)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	--	--	X	X	X
Nantuxent (Nan)		X		X		X		X		X	X	X		X		X	X	X	X	X	--	--	X	X	X
Hog Shoal (HS)		X		X						X		X	X	X	X	X	X	X	X	X	--	--	X	X	X
New Beds (NB)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	--	--	X	X	X
Strawberry (ST))	X		X		X								X	X	X	X	X	X	X	X	--	--	X	X	X
Hawks Nest (HN)	X		X		X		X		X		X		X	X	X	X	X	X	X	X	--	--	X	X	X
Beadons (Bea)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	--	--	X	X	X
Vexton (Vex)										X		X	X	X	X	X	X	X	X	X	--	--	X	X	X
Egg Island (EI)	X	X	X	X	X	X	X	X		X	X	X		X		X		X		X	--	--	X		X
Ledge Bed (LB)			X		X				X		X		X		X		X		X		--	--		X	X

Table 4. 2021 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	35	10		15
Hope Creek	85	10		15
Hope Creek	52			10
Hope Creek	74			10
Hope Creek	63		20	0
Fishing Creek	4	10		15
Fishing Creek	43	10		15
Fishing Creek	25			10
Fishing Creek	8			10
Liston Range	12	10		16
Liston Range	14	10		14
Liston Range	18			10
Liston Range	24			10
Round Island	16	10		15
Round Island	73	10		15
Round Island	11			10
Round Island	24			10
Upper Arnolds	5	10		15
Upper Arnolds	9	10		15
Upper Arnolds	13			10
Upper Arnolds	18			10
Arnolds	9	10		15
Arnolds	46	10		15
Arnolds	15			12
Arnolds	26			8
Arnolds	18		20	0
Upper Middle	63	10		15
Upper Middle	18	10		15
Upper Middle	71			12
Upper Middle	47/49			8
Middle	33	10		13
Middle	39	10		14
Middle	27			12
Middle	40			11
Cohansey	15	10		13
Cohansey	57	10		15
Cohansey	5			11
Cohansey	66			11
Cohansey	44		20	0
Sea Breeze	14	10		15
Sea Breeze	23	10		15
Sea Breeze	30			10
Sea Breeze	38			10
Ship John	25	10		15
Ship John	47	10		15
Ship John	28			10
Ship John	35			10
Shell Rock	17	10		15
Shell Rock	41	10		15
Shell Rock	15			10
Shell Rock	27			10
Shell Rock	10,11		20	0
Bennies Sand	20	10		13
Bennies Sand	35	10		15
Bennies Sand	3			11
Bennies Sand	13			11
Bennies	135	10		13
Bennies	56	10		15
Bennies	7			11
Bennies	100			11
Bennies	110		20	0
Nantuxent	12	10		15
Nantuxent	17	10		15
Nantuxent	14			10
Nantuxent	66			10
Hog Shoal	2	10		14
Hog Shoal	13	10		15
Hog Shoal	6			11
Hog Shoal	9			11
New Beds	10	10		15
New Beds	53	10		15
New Beds	23			10
New Beds	55			10
New Beds	26		20	0
Strawberry	28	10		13
Strawberry	5	10		15
Strawberry	10			10
Strawberry	24			12
Hawks Nest	2	10		10
Hawks Nest	27	10		15
Hawks Nest	25			18
Hawks Nest	5,17			7
Beadons	9	20		28
Beadons	3,18			12
Vexton	3	10		15
Vexton	18	10		15
Vexton	10			10
Vexton	19			10
Egg Island	44	10	10	13
Egg Island	83	10	10	17
Egg Island	62			20
Ledge	7	10	10	14
Ledge	13	10	10	8
Ledge	6			14
Ledge	15			14
Total beds		**23**	**8**	**23**
Total grids		**45**	**10**	**89**
Total oysters		**460**	**160**	**1140**

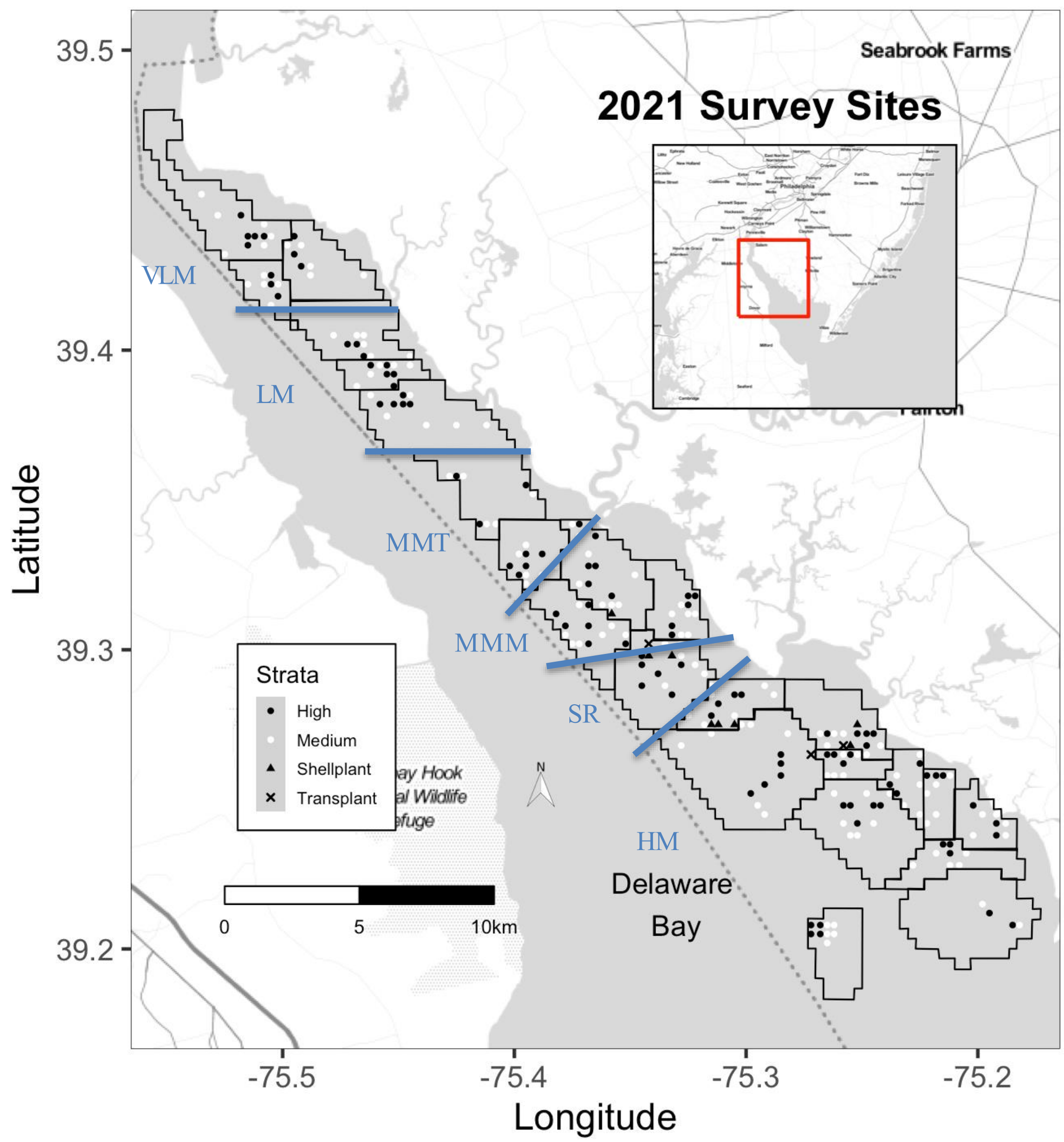

Figure 1. Footprint of the Delaware Bay, NJ public oyster beds (aka 'seedbeds'). Black lines demarcate named beds (see Alcox et al. 2017) with management regions approximated by blue lines (abbreviations as in text). The sites for the 2021 stock assessment survey are indicated by dots. A stratified random sampling program identified black and white dots for high and medium density strata, respectively, whereas x denotes transplant sites and triangles were shellplant sites. See Alcox et al. (2017) for full description.

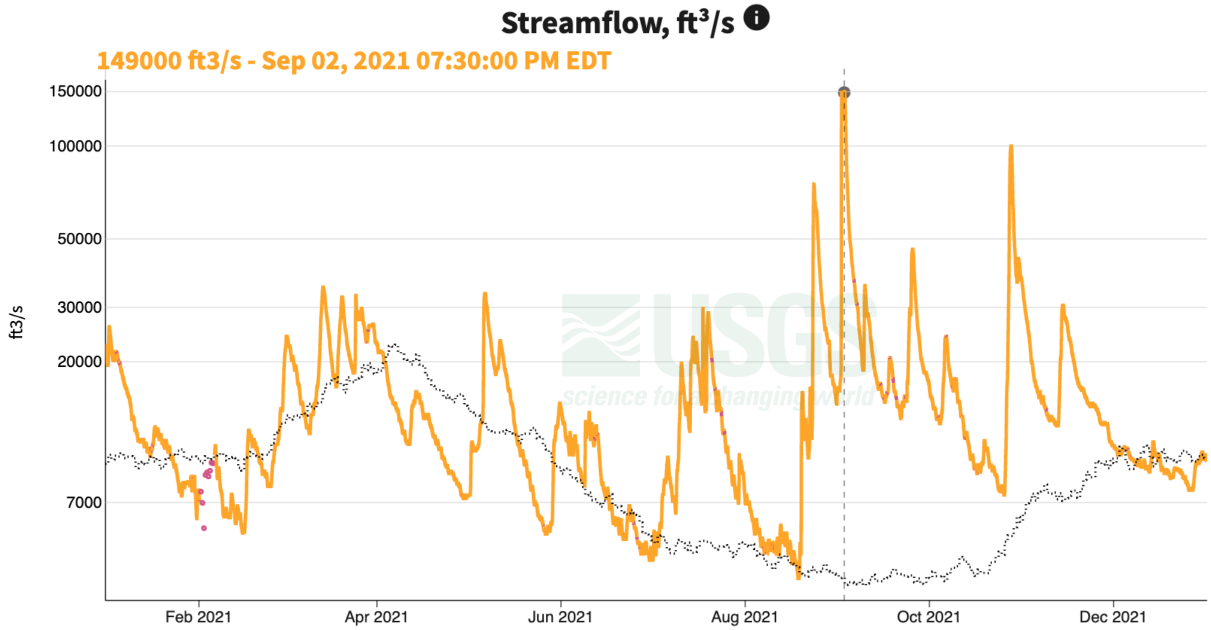

Figure 2. Delaware River discharge measured at Trenton, NJ USGS monitoring station 01463500. Yellow line represents daily discharge for 2021 relative to the 1913-2020 median values shown as a dotted black line. Flows were well above median values for much of the latter half of 2021 resulting in depressed salinity across all beds. The peak indicated by the dotted black vertical line of 149,000 cubit ft per second was associated with severe flooding from Hurricane Ida. Data source: https://waterdata.usgs.gov/monitoring-location/01463500/#parameterCode=00060&startDT=2021-01-01&endDT=2021-12-31

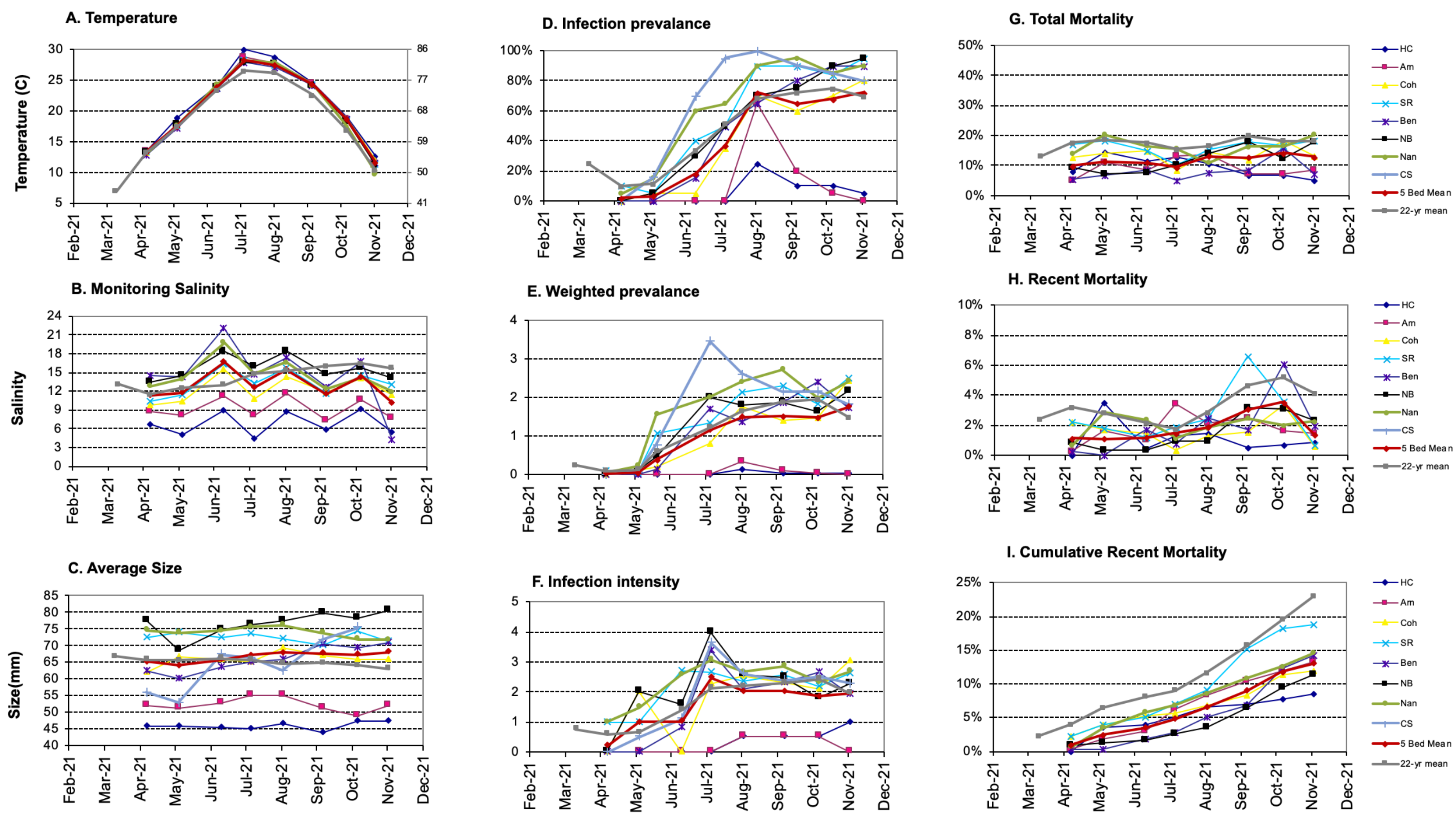

Figure 3. Results of 2021 Seed Bed Monitoring Program. Panels present data as labeled. HC = Hope Creek, Arn = Arnolds, Coh = Cohansey, SR = Shell Rock, Ben = Bennies, NB = New Beds, Nan = Nantuxent, CS = Cape Shore.

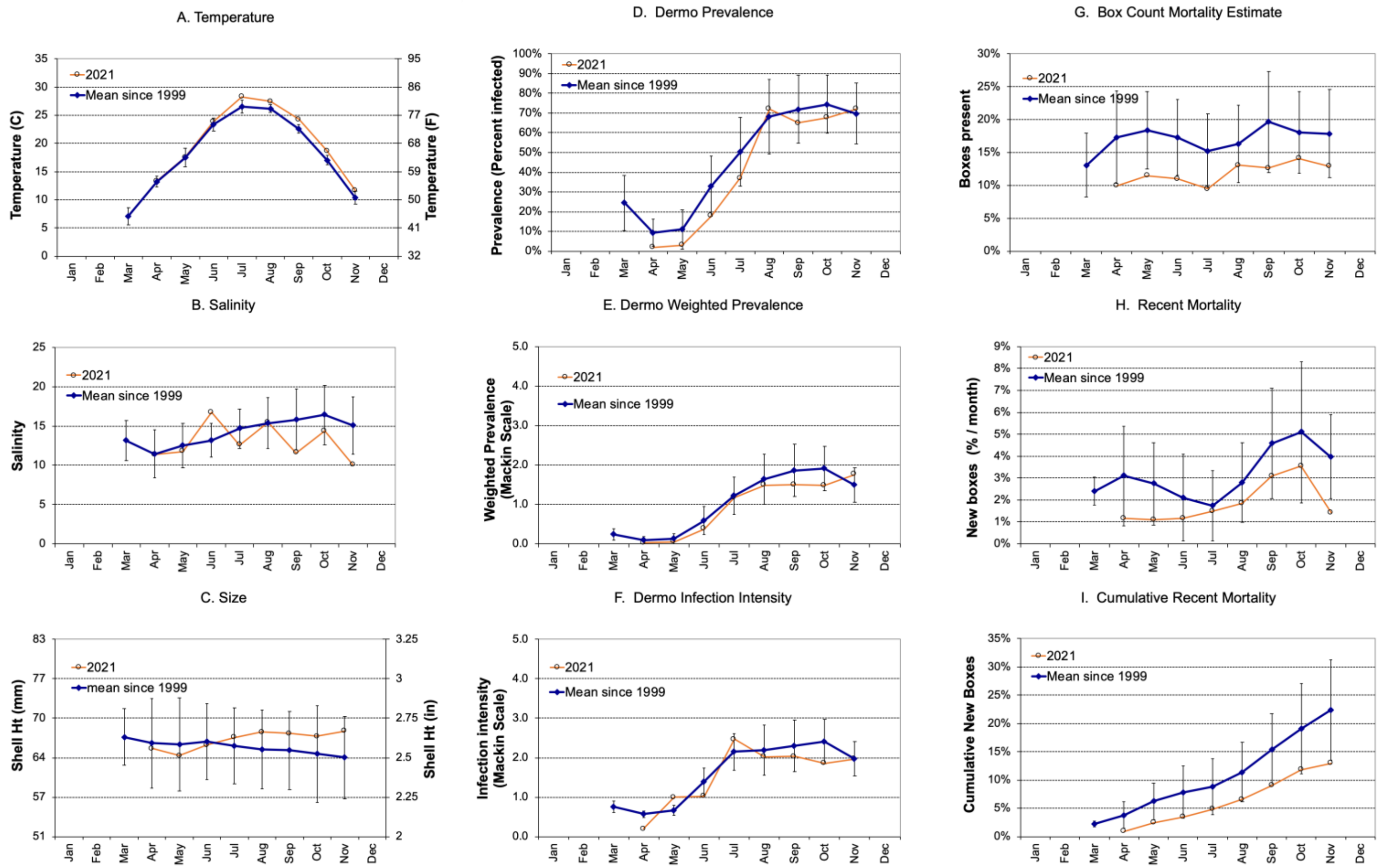

Figure 4. Seasonal patterns of the 2021 average Arnolds, Cohansey, Shell Rock, Bennies and New Beds) compared to the long-term values. Panels arranged as in Figure 3. Error bars represent one standard deviation.

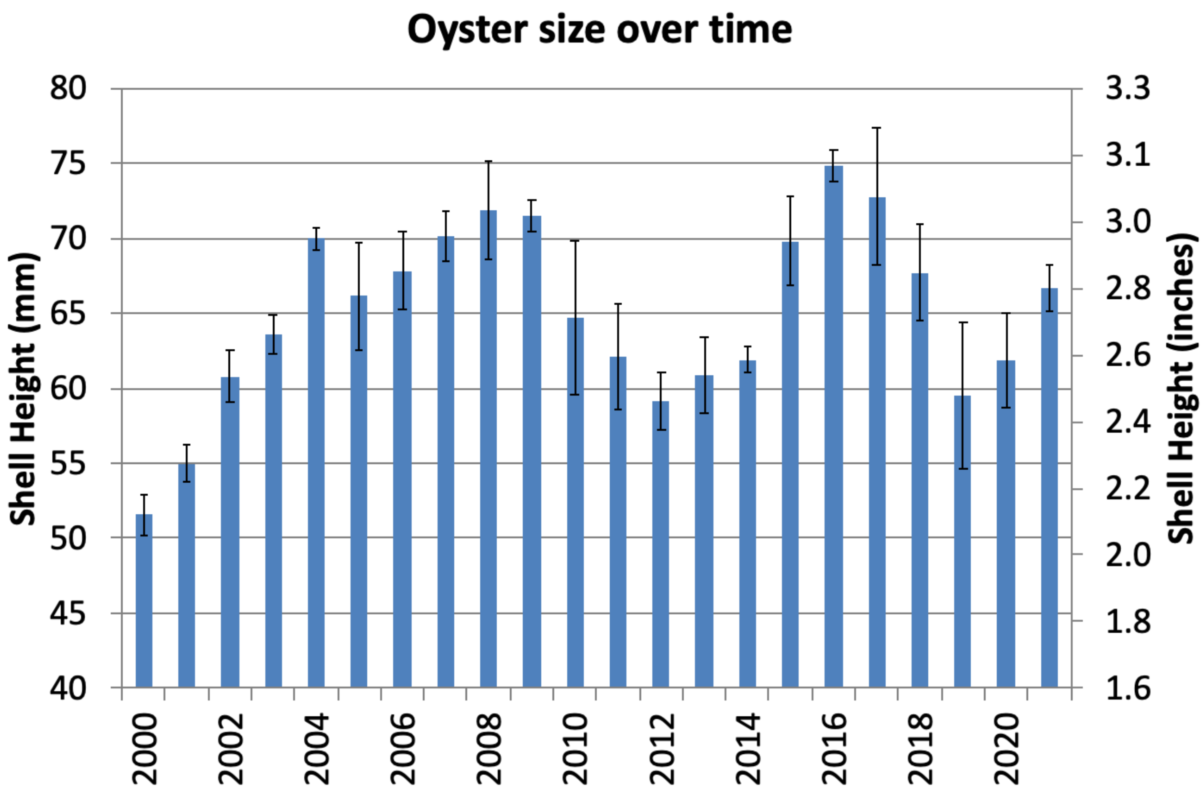

Figure 5. Interannual variation in mean shell height of oysters collected monthly between from Delaware Bay NJ oyster seedbeds. Error bars represent one standard deviation of the mean of all oysters measured throughout each year. N = 50-100 oysters per month from each of the five primary long-term beds (Arnolds, Cohansey, Shell Rock, Bennies and New Beds) sampled from March to November. Samples from 2021 were collected from April to November.

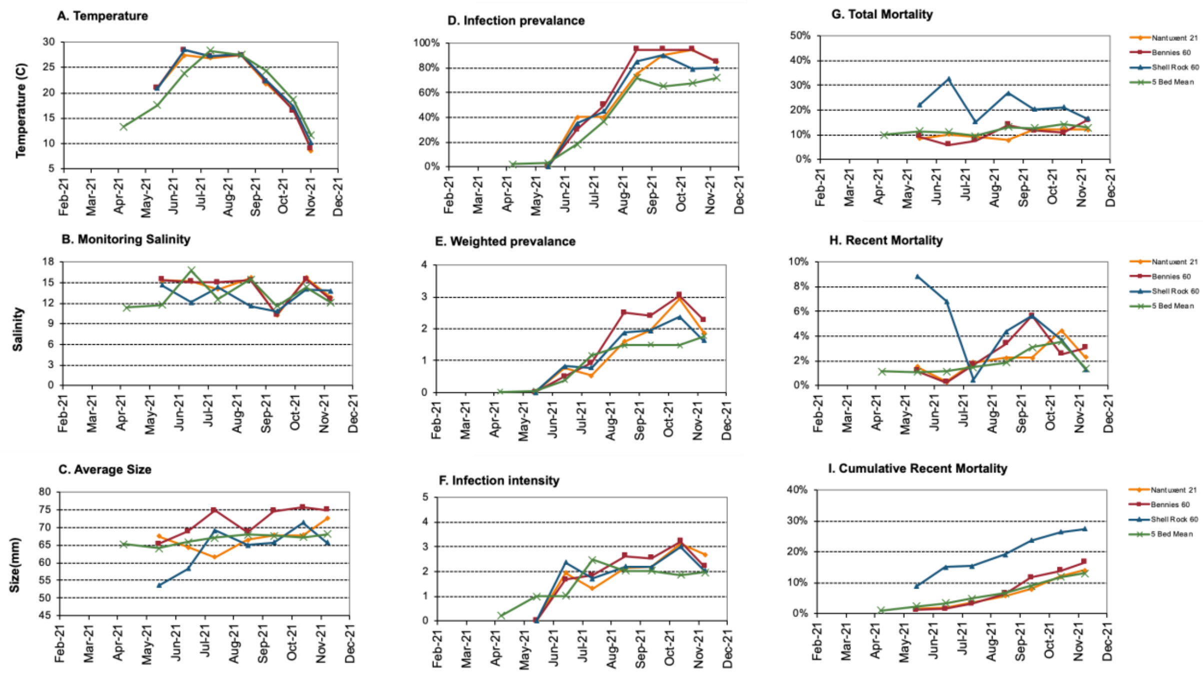

Figure 6. Performance of 2021 transplants relative to the five bed mean from monthly monitoring sites. Panels arranged as in Figure 3.

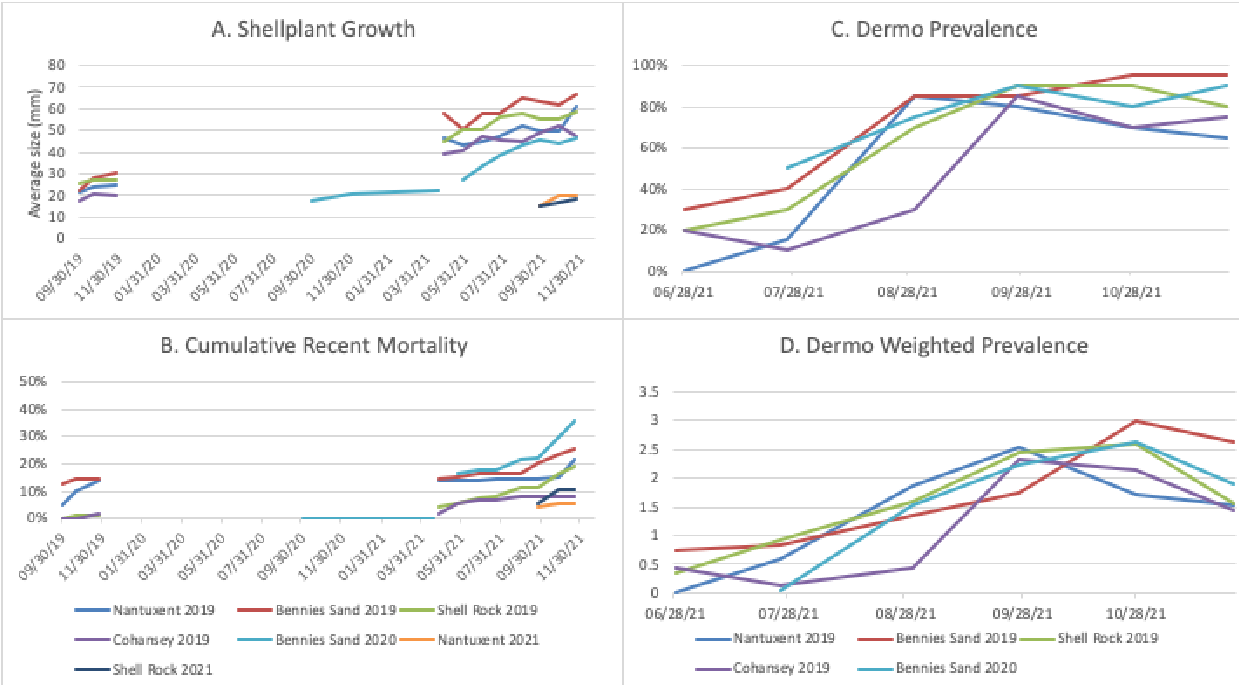

Figure 7. Performance of shellpalnts monitored during 2021. Monitoring for growth and mortality began monthly in September during the year of the plant. Dermo monitoring began in July following the year of planting. The 2019 shellplants were not sampled during 2020 due to Covid 19 restrictions but sampling resumed in April of 2021.

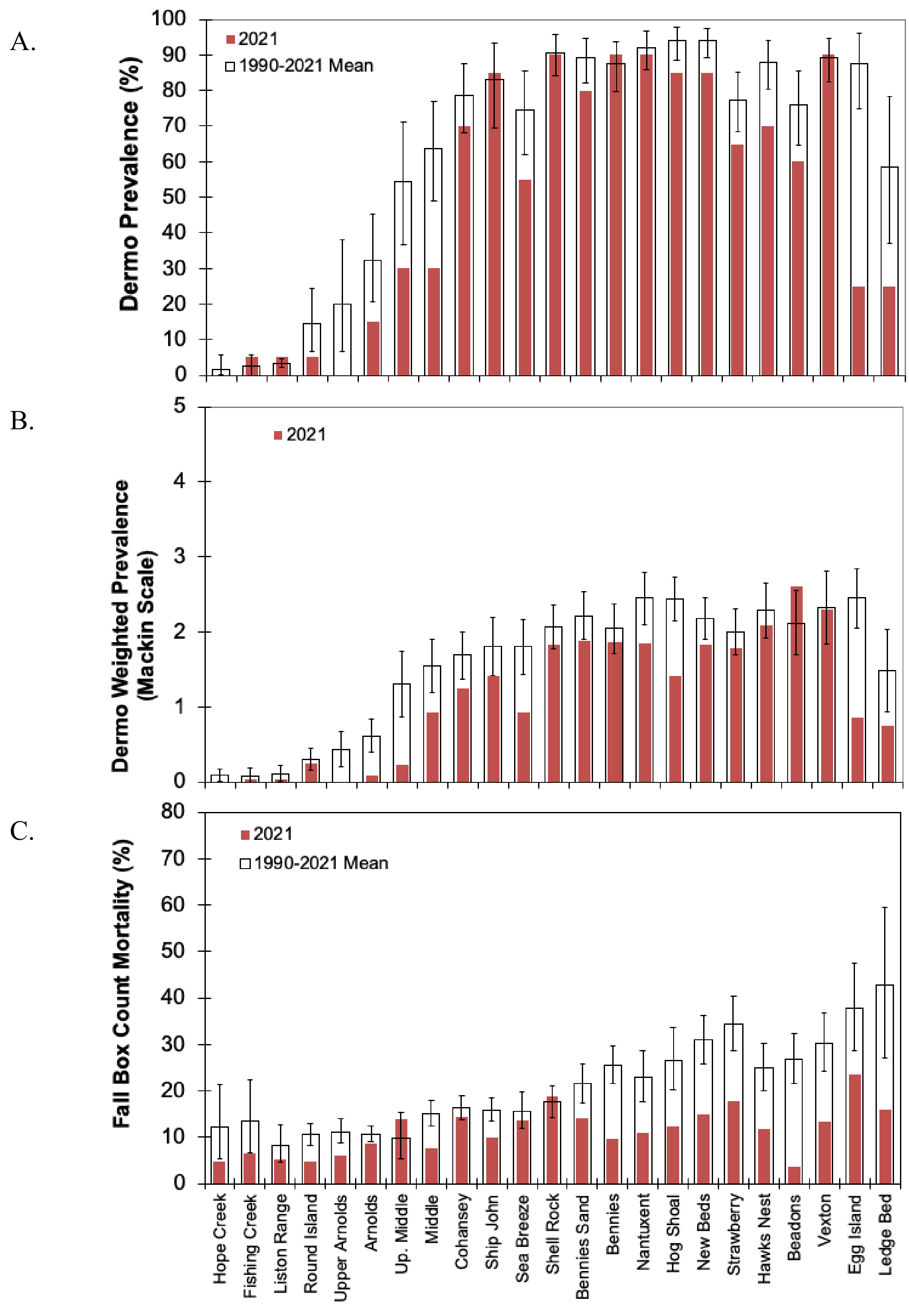

Figure 8. Long-term spatial patterns of dermo prevalence (A), dermo weighted prevalence (B) and natural mortality (C) across the oyster beds. From left to right, beds are listed upbay to downbay. Not all beds have been sampled every year (see Table 3). Egg Island was not sampled in 2020. Error bars represent 95% confidence intervals.

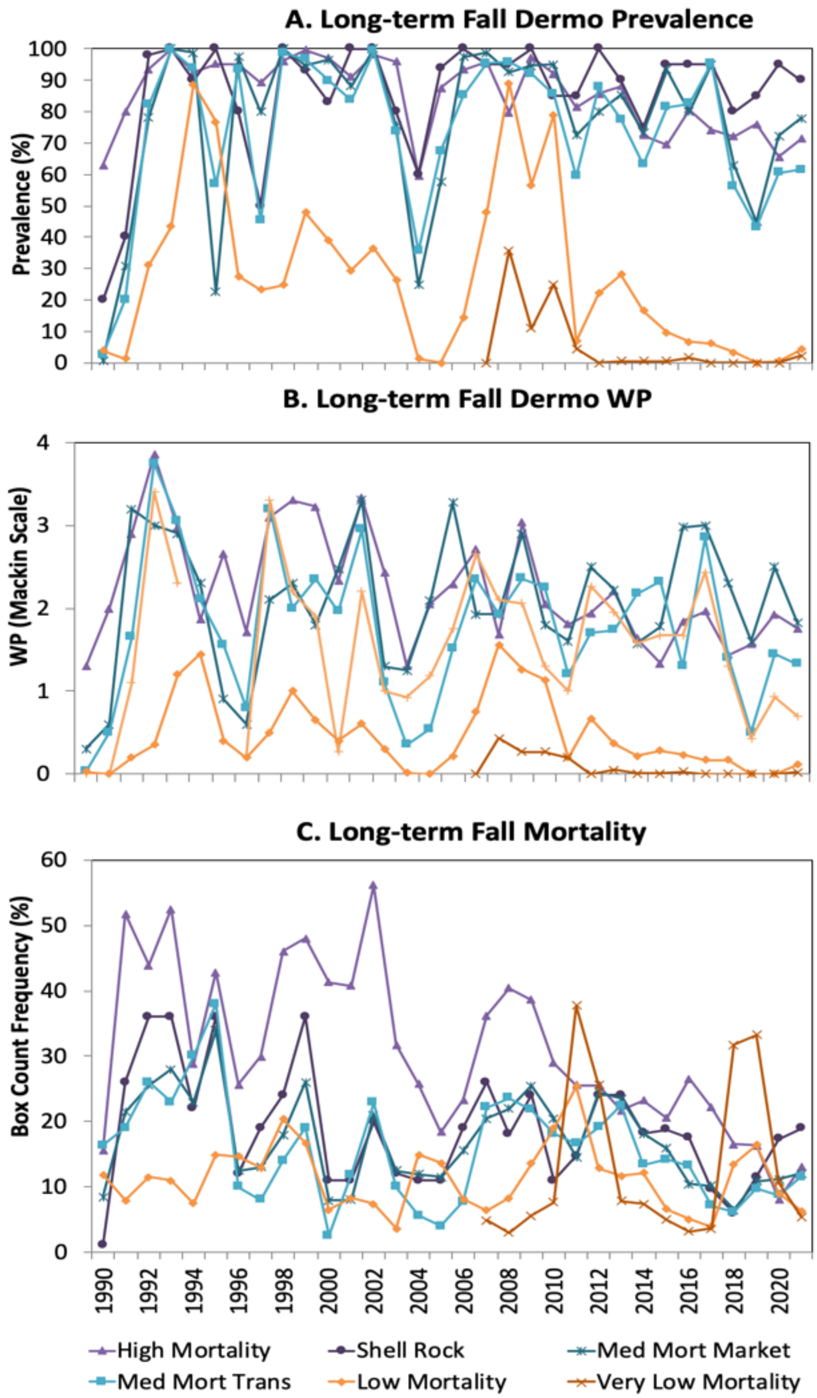

Figure 9. Annual Fall dermo prevalence (A), weighted prevalence (B) and box count mortality (C) on New Jersey Delaware Bay seedbeds. Regions correspond to management regions in Figure 1.

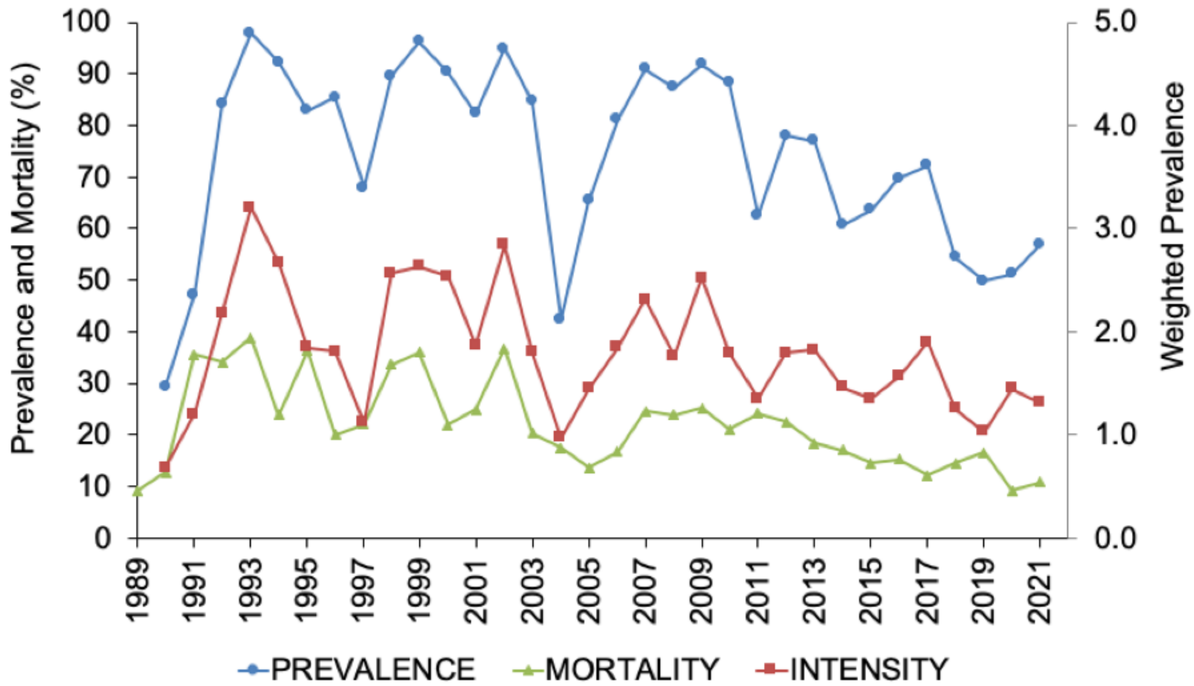

Figure 10. Long-term patterns of Fall dermo prevalence, intensity (weighted prevalence) and mortality averaged across the five beds monitored since 1990 (Arnolds, Cohansey, Shell Rock, Bennies and New Beds). These data appear to show cycles with an approximate periodicity of seven years, and a dampening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

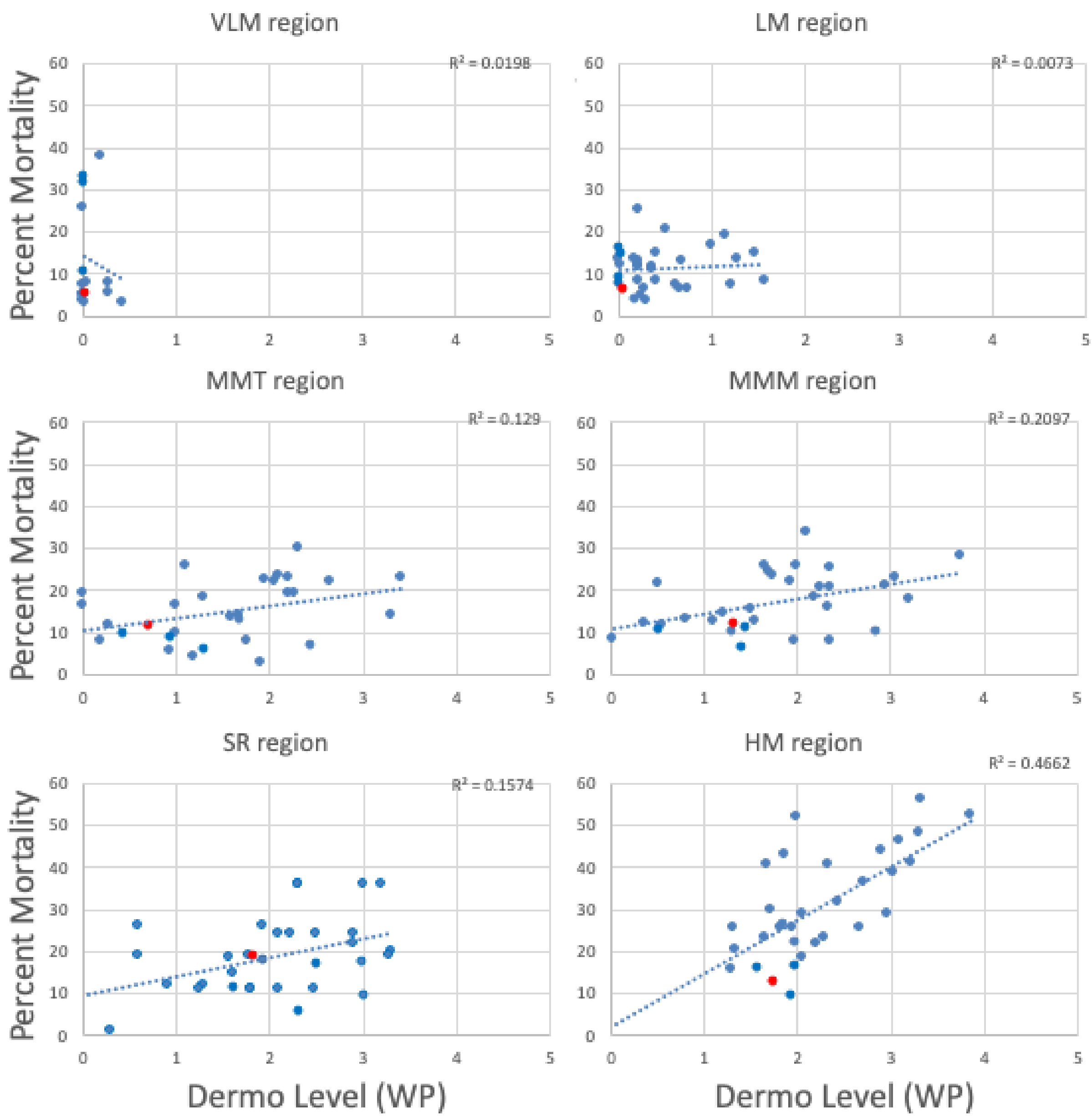

Figure 11. Region mortality as a function of dermo disease levels since 1990 (2007 for the VLM region). Red points represent 2021 data. VLM = Very Low Mortality region, LM = Low Mortality region, MMT = Medium Mortality Transplant region, MMM = Medium Mortality Market region, SR = Shell Rock, and HM = High Mortality Region.

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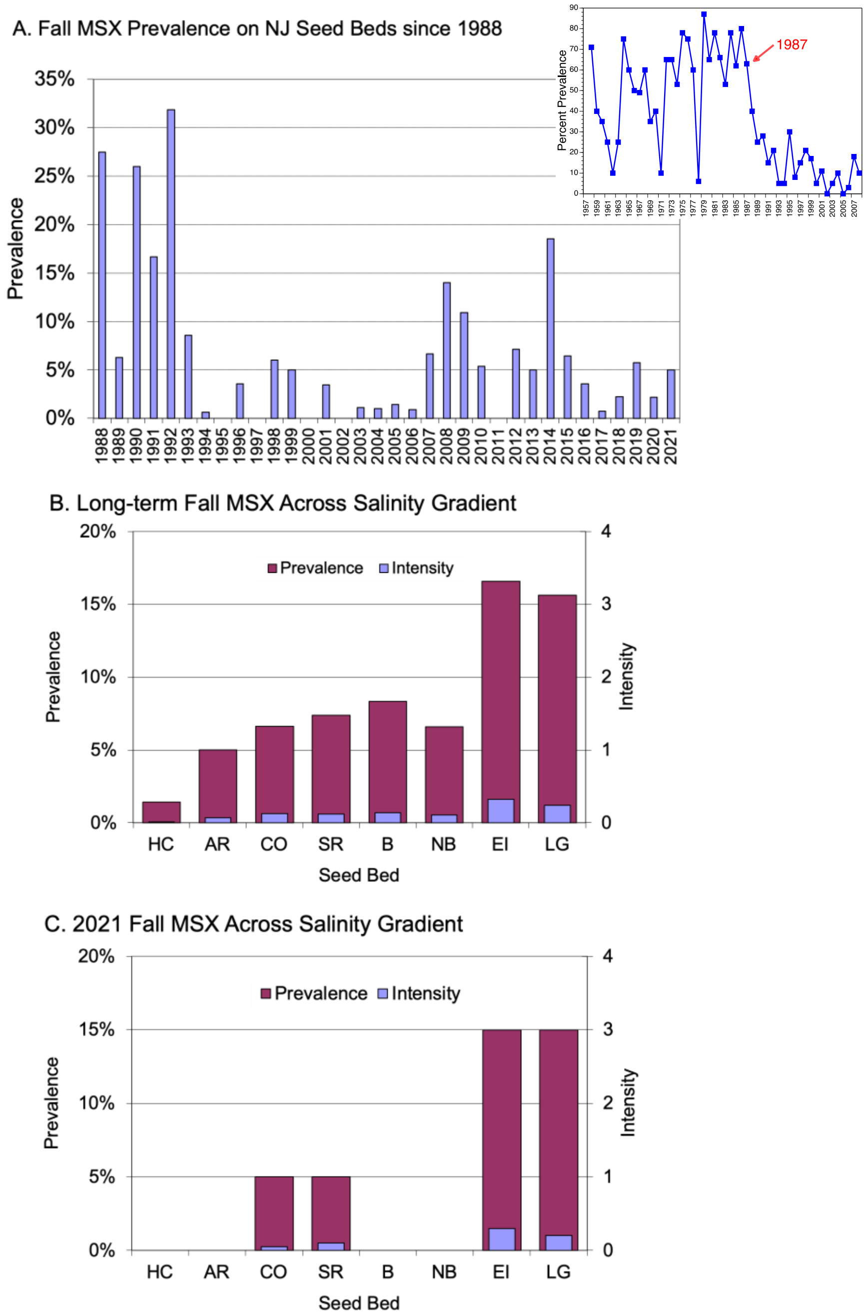

Figure 12. MSX disease on the New Jersey Delaware Bay oyster seedbeds. A. Annual Fall MSX prevalence across all beds since 1988 (2007 for HC). Inset shows lower Delaware Bay levels for comparison from Ford and Bushek (2012). B. Total fall MSX prevalence and intensity (weighted prevalence on a scale of 0 to 4) across seedbed salinity gradient since 1988. C. 2021 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, LG = Ledge.