Delaware Bay New Jersey
Oyster Seedbed Monitoring Program
2023 Status Report

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Executive Summary

The 2023 Seedbed Monitoring (SBM) Program tracked oyster size, dermo disease and oyster mortality monthly at six fixed sites, three additional sites of interest, seven shellplant sites and seven intermediate transplant sites. The Program also continued its long-term disease analyses for the annual Fall Oyster Stock Assessment Survey by assessing dermo disease from 23 beds as well as MSX disease data from eight fixed monitoring sites.

Monthly monitoring indicated that temperature was consistent with a 23-yr average from May to November during 2023. Moderate freshwater inflow throughout the spring and early summer maintained salinity near seasonal averages though elevated salinity was observed in April and June. Mean oyster size decreased on many beds during the year due to a large recruitment event on the upper beds in 2022. Dermo disease followed typical seasonal and spatial patterns, but levels were generally close to long-term averages during 2023.

Fall spatial patterns of dermo showed the typical increase from upper to lower bay beds with highest levels observed from Shell Rock south where many beds sustained dermo levels higher than average relative to the time series. These lower bay beds will enter winter with higher levels of dermo infection than has occurred in recent years. In contrast, dermo levels were below the time series averages from Ship John north and nearly absent on Arnolds and above. Box counts indicated high levels of mortality on the lower Bay beds, but box counts elsewhere were similar or lower than those observed last year (2022). The overall long-term patterns from the Fall survey continues to indicate an attenuation of dermo and mortality over time. Bay-wide mortality stopped cycling with dermo around 2015 and has decreased from 20-30% in the 1990s to less than 15% since 2020. MSX was only detected on New Beds and Egg Island during the Fall survey, apparently ending another brief increase in prevalence and intensity.

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 and likely explains the difference between upper and lower bay rates of dermo infection as well as the apparent suppression of MSX. 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 and the impacts of freshwater inflow that can be determined in part by upstream reservoir management. This is particularly important in the face of climate change 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 beyond the scope of this annual report though some information may be included when 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, predation by oyster drills was a primary concern with their abundance and distribution determined by salinity which is 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 continued MSX disease pressure (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 and not causing levels of mortality to warrant concern. With the continuing progression of global warming and climate change, dermo disease has persisted continuously in Delaware Bay since 1990 and is 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 correlated to salinity which increases from around 6 in the uppermost beds to about 18 or so on those beds located further downbay. 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 a survey indicated the presence of a high abundance of oysters was present in an area that the fishery had exploited in the past but consider of negligible importance. Except for episodic freshets (Munroe et al. 2013), the low salinity across this region minimizes predation and disease resulting in very low mortality in most years, hence their designation as the Very Low Mortality (VLM). It is worth noting that the low salinity also reduces growth and condition such that oysters are generally small even though they may be relatively old. 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) corresponding to their management 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: https://hsrl.rutgers.edu/documents/delaware-bay-oyster-stock-assessment-reports/.

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, growth, disease transmission dynamics, and 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 healthy oyster population and a functional ecosystem that can sustain a viable commercial fishery. 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 conducts a spatially comprehensive survey in the Fall. The monitoring supports additional directed research and sampling efforts to develop insights into the dynamics controlling the oyster population within the Delaware Bay ecosystem. As funding permits, these efforts include monitoring transplants (oysters moved from upper to lower seedbeds), shellplants (shell placed directly on the seedbeds to increase the supply of clean cultch for recruitment), and replants (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 2023 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 for each bed sampled during the 2023 Fall Stock Assessment Survey
3. Monitor growth, disease and mortality on 2021 through 2023 shell plantings
4. Monitor growth, mortality and disease on the 2022 and 2023 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. During 2023, samples of oysters collected for objective 1 were fixed for potential histological examination to help assess any seasonal mortality from sources other than dermo disease. 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: Data from 2020 are incomplete due to a curtailment in work activities but no essential data is missing from 2021 to present.

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 three additional sites of interest (Nantuxent, Egg Island and Cape Shore). Reports were presented during scheduled meetings of 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 2023. 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 2023 Annual Fall Oyster Stock Assessment with beds outlined in black. Different management regions are indicated by different colors. 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) and other annual reports available on the Haskin Shellfish Research Laboratory website. 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 NJ Division of Fisheries and Wildlife’s R/V James W Joseph. Dots in Figure 1 represent locations from a stratified random sampling design for the Fall oyster stock assessment. Two locations within each bed, typically one each of high and medium density strata, were sampled for disease assessment (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, the high-density strata contains 50% of the total oyster abundance, the medium density strata contains the next 48% of total oyster abundance, and the low density strata contains the remaining 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 Table 1. Table two lists the beds sampled for objectives 3 and 4 and the respective enhancement activity for each location. 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

2023 Annual Fall Oyster Stock Assessment to complete Objective 2 along with respective sample sizes for dermo, MSX and condition index analyses.

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 measured for shell height (hinge to bill of the flat or right valve) to determine the size frequency of oysters 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). 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 sites were monitored as described for Objective 1 with the following modifications for Objective 3. Objective 3 continued monitoring the 2021 and 2022 shell plantings, and initiated sampling of the 2023 shell

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

plantings listed in Table 2 – the latter of which was only sampled during 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 2023 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 so that reservoirs can be used for flood control. Discharge typically decreases from the end of winter through late summer which causes salinity to increase across the oyster beds (see below). During 2023, discharge fell below long-term levels for much of the spring and early summer permitting ocean water to penetrate further upbay and increase salinity even higher during this portion of the year (Figure 2). Lower discharge increases water residence time over the oyster beds, which can increase the retention of larvae as well as free living forms of oyster pathogens such as dermo. During the remainder of the year, discharge was well above average. Higher discharge decreases residence time of water and reduces salinity pushing disease and predators in a downbay direction.

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 2023 were average with respect to the past 23 years. Water temperatures measured during 2023 collections followed a typical seasonal cycle with little spatial variability across the seedbeds (Figure 3A and B). Spawning temperatures (approximately 25 C = 77 F) were reached between June and July sampling dates. Salinity followed the typical estuarine gradient, increasing from upbay to downbay beds (Figure 3C), and generally increased through the year but with seasonally high levels observed in April and June (Figure 3D). This salinity pattern reflects the river discharge data from Trenton shown in Figure 2.

Oyster size. Within a given salinity regime, shell height roughly corresponds to age and therefore provides insight into both the size and age structure of the population. Seasonal changes in the mean shell height of a population may be affected by growth, recruitment and mortality (including harvest). Mean shell height remained relatively stable during 2023 but increased with salinity (Figure 3E and F). Intuitively, oysters should grow over the summer and increase in size, but as younger, smaller oysters recruit into the population, average size may actually decrease over the season. This can be exaggerated if older animals are harvested or die. Figure 4 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. Mean oyster size decreased in 2023 as the result of a relatively large recruitment event on the upper beds in 2022. The overall 2023 size frequency had a mean of 62 mm (2.4 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 increasing across the summer with the upper bay beds showing much lower levels of infection (Figure 5A, C and E). Average levels followed the typical season patterns (Figure 5 B, D and F). Recruitment during the year as well as the summer freshwater inflow is likely responsible for part of the September declines in dermo disease, but mortality of heavily infected animals (see below) may also be a contributing factor. The population as a whole entered the winter with higher than average levels of dermo, a situation that could lead to spring mortality or may initiate the intensification of dermo at higher starting point next year.

Mortality. Mortality across the upper beds was negligible, but variable in other regions increasing with salinity (Figure 6A, C and E). Spikes in mortality were observed on Bennies, New Beds and Shell Rock in June and on Nantuxent in September, with higher spikes observed again on Bennies and New Beds in October and November, respectively (Figure 6C). As a result, cumulative mortality reached 45% on Bennies and 30% on New Beds.

Transplants and shellplants. Figures 7 and 8 show dermo and mortality on the 2022 and 2023 transplants. Dermo followed expected seasonal patterns (panels A and C in Figures 7 and 8) and were similar in magnitude to long-term monitoring sites (Figure 5). Dermo levels followed the salinity gradient, increasing in prevalence and intensity from Low to High Mortality regions. The levels of dermo exceeded 1.5 WP on all sites, except those placed on the Low Mortality region, and that was sufficient to cause mortality as reported by Bushek et al. (2012). Mortality for both year plants was higher on Shell Rock than the High Mortality region. It is worth noting that transplanted oysters cannot be distinguished from oysters originating on the site, so it is not necessarily that transplanted oysters match the local oysters with respect to disease and mortality, rather that transplantation of oysters does not appear to alter local patterns of dermo and mortality.

Seven shell plants have been placed on four different beds during the past three years (Table 2). Growth varied among shellplants (Figure 9A) with the largest increase on the 2022 shellplants averaging 22.6 mm while the 2021 plant grew and average of 8.6 mm. The 2023 shell plants had reached 19 mm by November indicating modest growth before sampling stopped. Mortality varied from 2 to 31% and was mostly noted on the Nantuxent 2022 plant site. (Figure 9C). Dermo increased on 2021 plants during 2022 but remained below levels of the recipient beds (Figure 6D). 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 2023, 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. Fall levels of dermo and mortality generally increased from low salinity areas in the upper bay to higher salinity areas of the lower bay (Figure 10). Above Sea Breeze, dermo and mortality were lower than long-term means, but at or above long-term means on Sea Breeze and most beds below Sea Breeze. Curiously there no oysters sampled on Beadons were infected, but virtually all oysters on Beadons were small yearlings or large spat. The inshore beds of Strawberry, Hawks Nest, Beadons and Vexton in the High Mortality region continue to show low levels of mortality despite relatively high levels of dermo and warrants further investigation to determine if this reflects the high proportion of juvenile oysters observed on Beadons or if something else is happening in this region as oyster density is relatively low on all of these beds.

Figure 11 depicts annual dermo prevalence, weighted prevalence and box-count estimated mortality from 1989 to 2023 for each mortality region. Each parameter generally decreases from high to low mortality regions. Exceptions are related to freshets that cause mortality in the Very Low and Low Mortality regions while suppressing mortality in the other regions. This puts the VLM and LM regions out of phase with the other regions that generally track each other well. 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 11B). This dampening also corresponds to a reduction in Fall box count mortality (Figure 11C).

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 over time (Figure 12). Moreover, the bay-wide pattern of attenuation shown in Figure 12 indicates a decoupling of dermo and mortality as dermo has attenuated. It is tempting to think this is an indication of the development of resistance (the ability to prevent infections) and/or tolerance (the ability to endure infections), but figure 11 suggests there remains a strong environmental component associated with the salinity gradient determined by freshwater inflow. 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 important and whether management strategies can effectively improve the situation.

Figure 13 depicts the regional mortality rates from each fall assessment since 1990 as a function of dermo weighted prevalence. Bushek et al. (2012) demonstrated that once weighted prevalence begins to exceed 1.5 mortality begins to increase exponentially. In Figure 13, 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 about 48% of the annual variability in mortality. It is worth noting that the highest mortality on an individual bed was on Bennies where dermo WP was 2.2 and had been above 2.0 since August when it peaked at 3.0.

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 only 6 of the 140 oysters assayed: a prevalence of just 4.3% (Figure 14A). Over the past 33 years, MSX infections nearly always occur at a higher prevalence and intensity as salinity increases (Figure 14B). In 2023, infections were only detected at two high salinity sites (Figure 14C). These infections were in the early stages of progression, generally restricted to epithelial cells, with only one that was systemic and none were advanced. Previous years have found MSX distributed across the seed beds and these data confirm its continued presence in the Bay although with a much more limited impact than levels observed prior to 1990. Because MSX can cause mortality in spring and appears to be more prevalent in the lower bay, it was recommended that some level of routine monitoring of MSX occur throughout the year to improve surveillance. Figure 15 shows highest prevalence in spring, albeit low and of low intensity, and much lower prevalence during the remainder of the year. This pattern corresponds with prior studies on the seasonality of MSX. Collectively, these data indicate that MSX remains a threat to the Delaware Bay oyster population. It continues to cause mortalities elsewhere along the East Coast. Its persistence in Delaware Bay serves to help maintain resistance that has developed in the native population (Ford and Bushek 2012). Therefore, it remains an important component of the monitoring program to understand sources of mortality from year to year.

Science Advice

- Continue to examine the spatial and temporal relationships between environmental drivers of temperature, salinity and freshwater 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 to examine current year versus long-term means by bed along the bay axis.

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References

Ashton-Alcox, K., D. Bushek, J Gius, J. Morson and D. Munroe. 2017. Stock Assessment Workshop: New Jersey Delaware Bay Oyster Beds (19th SAW) February 14-15, 2016. Final Report. 127 pp. https://hsrl.rutgers.edu/SAWreports/SAW2017.pdf

Bushek, D., S.E. Ford and I. Burt. 2012. Long-term patterns of an estuarine pathogen along a salinity gradient. *J Marine Research.* 70:225-251.

Carriker, M.R. 1955. Critical review of biology and control of oyster drills *Urosalpinx* and *Eupleura*. US DOI FWS. Special Scientific Report: Fisheries No, 148, Washington, D.C. 150 pp. https://spo.nmfs.noaa.gov/sites/default/files/legacy-pdfs/SSRF148.pdf

DRBC 2021. Delaware River Basin Commission website. Salt Line. Accessed February 1, 2021. https://www.state.nj.us/drbc/hydrological/river/salt-front.html

Dungan, C.F. and D. Bushek. 2015. Development and applications of Ray's fluid thioglycollate media for detection and manipulation of *Perkinsus spp*. pathogens of marine molluscs. J. Invert. Pathol., 131: 68–82. http://dx.doi.org/10.1016/j.jip.2015.05.004.

Fegley, S. R., S. E. Ford, J. N. Kraeuter, and H. H. Haskin. 2003. The persistence of New Jersey's oyster seedbeds in the presence of MSX disease and harvest: management's role J. Shellfish Res. 22:451-464.

Ford, S.E. 1996. Range extension by the oyster parasite *Perkinsus marinus* into the northeastern United States: Response to climate change? *J. Shellfish Res*. 15:45-56.

Ford, S.E. and D. Bushek. 2012. Development of resistance to an introduced marine pathogen by a native host. *J. Marine Research*, 70(2-3):205-223.

Ford, S.E., M.J. Cummings and E.N. Powell. 2006. Estimating mortality in natural assemblages of oysters. *Estuaries and Coasts*, 29 (3): 361-374.

Ford, S.E., E. Scarpa, D. Bushek. 2012. Spatial and temporal variability of disease refuges in an estuary: Implications for the development of resistance. J. Mar. Res. 70:253-277. DOI: 10.1357/002224012802851850

Howard D.W., E.J. Lewis, B.J. Keller and C.S Smith (eds). 2004. Histological Techniques for Marine Bivalve Mollusks and Crustaceans. NOAA Tech. Memo NOS NCCOS 5, 218 pp.

Mackin, J.G. 1962. Oyster disease caused by *dermocystidium marinum* and other microorganisms in Louisiana. *Publ. Inst. Mar. Sci. Univ. Tex.*, 7:132-229.

Morson, J. M., D. Munroe, K. Ashton-Alcox, E. N. Powell, D. Bushek, and J. E. Gius. 2018. Density-dependent capture efficiency of a survey dredge and its influence on the stock assessment of eastern oysters (*Crassostrea virginica*) in Delaware Bay. *Fisheries Research, 205*, 115-121. DOI: 10.1016/j.fishres.2018.04.012

Munroe, D., A. Tabatabai, I. Burt, D. Bushek, E.N. Powell, and J. Wilkin. 2013. Oyster Mortality and Disease in Delaware Bay: Impact and Recovery Following Hurricane Irene and Tropical Storm Lee. Estuarine, Coastal and Shelf Science, 135:209-219.

Powell, E. N., J. M. Morson, K. A. Alcox, and Y. Kim. 2012. Accommodation of the sex ratio in eastern oysters to variation in growth and mortality across the estuarine salinity gradient in Delaware Bay. *J. Mar. Biol. Assoc.* U.K., doi: 10.1017/S0022377807006861, Published online by Cambridge University Press 24 April 2012.

Powell, E.N., K.A. Ashton-Alcox and J.N. Kraeuter. 2007. Reevaluation of eastern oyster dredge efficiency in survey mode: Application in stock assessment. *North Amer. J. Fisheries Management*., 27(2): 492-511

Powell, E.N ., K.A. Ashton-Alcox, J.N. Kraeuter, S.E. Ford and D. Bushek. 2008. Long-term trends in oyster population dynamics in Delaware Bay: Regime shifts and response to disease. *J. Shellfish Res.* 27:729-755.

Ray, S.M. 1952. A culture technique for the diagnosis of infection with *dermocystidium marinum* Mackin, Owen, and Collier in oysters. *Science* 116:360-361.

Ray, S.M. 1954. Biological Studies of *dermocystidium marinum*. The Rice Inst. Pamphlet, Special Issue.

Ray, S.M. 1966. A review of the culture method for detecting *dermocystidium marinum*, with suggested modifications and precautions. *Proc. Natl. Shellfish. Assoc.* 54:55-69.

Villalba, A., K.S. Reece, M.C. Ordás, S.M. Casas and A. Figueras. 2004. Perkinsosis in molluscs: A review. Aquat. Liv. Res., 17: 411-432. doi:10.1051/alr:2004050.

Wang, Z., D. Haidvogel, D. Bushek, S. Ford, E. Hoffman, E. Powell and J. Wilkins. 2012. Circulation and water properties and their relationship to the oyster disease, MSX, in Delaware Bay. *J. Mar. Res*. 70:279-308.

Table 1. 2023 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, Egg Island and the Rutgers Cape Shore Lab were the additional sites of interest that were sampled in 2023. 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 20, 2023	6 long-term sites, 1 extra site, 2 shellplant sites 1 intermediate transplant site	NJDEP RV James W. Joseph	Andrew Hassall
May 5, 2023	2 intermediate transplant sites, 2 shellplant sites, 1 extra site	NJDEP RV James W. Joseph	Andrew Hassall
May 16, 2023	6 long-term sites, 1 extra site, 1 intermediate transplant site	NJDEP RV James W. Joseph	Andrew Hassall
May 23, 2023	4 shellplant sites and 6 intermediate transplant sites	NJDEP RV James W. Joseph	Andrew Hassall
June 19, 2023	6 long-term sites, 2extra sites, 1 intermediate transplant site	NJDEP RV James W. Joseph	Craig Tomlin
June 26, 2023	4 shellplant sites and 6 intermediate transplant sites	NJDEP RV James W. Joseph	Craig Tomlin
July 17, 2023	6 long-term sites, 1 extra site 1 intermediate transplant site	NJDEP RV James W. Joseph	Craig Tomlin
July 24, 2023	4 shellplant sites and 6 intermediate transplant sites	NJDEP RV James W. Joseph	Craig Tomlin
August 17, 2023	6 long-term sites, 1 extra sites, 1 intermediate transplant site	NJDEP RV James W. Joseph	Craig Tomlin
August 23, 2023	4 shellplant sites, 1 extra site, 6 intermediate transplant sites	NJDEP RV James W. Joseph	Craig Tomlin
September 20, 2023	6 long-term sites, 1 extra sites 1intermediate transplant site	NJDEP RV James W. Joseph	Craig Tomlin
September 25, 2023	7 shellplant sites and 6 intermediate transplant sites	NJDEP RV James W. Joseph	Craig Tomlin
October 17, 2023	6 long-term sites, 1 extra site, 2 intermediate transplant sites	NJDEP RV James W. Joseph	Andrew Hassall
October 18, 2023	7 shellplant sites and 5 intermediate transplant sites	NJDEP RV James W. Joseph	Andrew Hassall
November 20, 2023	6 long-term sites, 1 extra site 2 intermediate transplant sites	NJDEP RV James W. Joseph	Craig Tomlin
December 8, 2023	7 shellplant sites and 5 intermediate transplant sites	NJDEP RV James W. Joseph	Craig Tomlin

Table 2. Enhancement sites sampled during 2023.

Bed	Grid	Plant material	Plant yr
Nantuxent	9	clam shell	2021
Shell Rock	6	clam shell	2021
Nantuxent	20	clam shell	2022
Shell Rock	14	clam shell	2022
Bennies Sand	3	medium mortality transplant	2022
Shell Rock	10	low mortality transplant	2022
Upper Arnolds	10	very low mortality transplant	2022
Nantuxent	8	medium mortality transplant	2023
Shell Rock	9	low mortality transplant	2023
Ship John	35	low mortality transplant	2023
Bennies	124	clam shell	2023
Shell Rock	13	clam shell	2023
Ship John	15	clam shell	2023

Table 3. Record of collections for annual fall dermo monitoring since 1990. X indicates bed was sampled in respective year for that column. 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. In 2021, however, both Ledge and Egg Island were sampled. Beds are listed approximately by latitude from north to south, 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	- -	- -	21	22	23
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	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. 2023Delaware 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	73	10		15
Hope Creek	51	10		15
Hope Creek	44			10
Hope Creek	73			10
Hope Creek	63		20	0
Fishing Creek	36	10		15
Fishing Creek	25	10		15
Fishing Creek	4			10
Fishing Creek	10			10
Liston Range	30	10		15
Liston Range	24	10		15
Liston Range	12			10
Liston Range	2			10
Round Island	14	10		15
Round Island	25	10		15
Round Island	2			10
Round Island	12			10
Upper Arnolds	9	10		15
Upper Arnolds	12	10		15
Upper Arnolds	3			10
Upper Arnolds	17			10
Arnolds	15	10		15
Arnolds	46	10		15
Arnolds	9			10
Arnolds	57			10
Arnolds	18		20	0
Upper Middle	36	10		15
Upper Middle	71	10		15
Upper Middle	63			10
Upper Middle	56			10
Middle	39	10		15
Middle	34	10		15
Middle	40			10
Middle	51			10
Cohansey	33	10		15
Cohansey	59	10		15
Cohansey	10			10
Cohansey	5			10
Cohansey	44		20	0
Sea Breeze	31	10		15
Sea Breeze	14	10		15
Sea Breeze	19			10
Sea Breeze	24			10
Ship John	58	10		25
Ship John	25	10		15
Ship John	30			10

Bed	Grid	Dermo	MSX	CI
Shell Rock	24	10		15
Shell Rock	46	10		15
Shell Rock	35			10
Shell Rock	4			10
Shell Rock	10,11		20	0
Bennies Sand	6	10		15
Bennies Sand	44	10		15
Bennies Sand	26			10
Bennies Sand	30			10
Bennies	76	10		15
Bennies	33,34	10		10
Bennies	123			13
Bennies	100			12
Bennies	110		20	0
Nantuxent	32	10		15
Nantuxent	24	10		15
Nantuxent	7			10
Nantuxent	15			10
Hog Shoal	1	10		15
Hog Shoal	4	10		15
Hog Shoal	6			10
Hog Shoal	12			10
New Beds	79,54	10		12
New Beds	28	10		21
New Beds	22			17
New Beds	26		20	0
Strawberry	5,10,21	10		10
Strawberry	9	10		23
Strawberry	28			2
Hawks Nest	25	10		17
Hawks Nest	17	10		10
Hawks Nest	2			13
Hawks Nest	27			10
Beadons	25	10		13
Beadons	3,18	10		13
Vexton	4	10		17
Vexton	10	10		18
Vexton	12,17,19			15
Egg Island	28	20	20	0
Egg Island	mix			44
Total beds		**22**	**7**	**22**
Total grids		**47**	**7**	**90**
Total oysters		**440**	**140**	**1055**

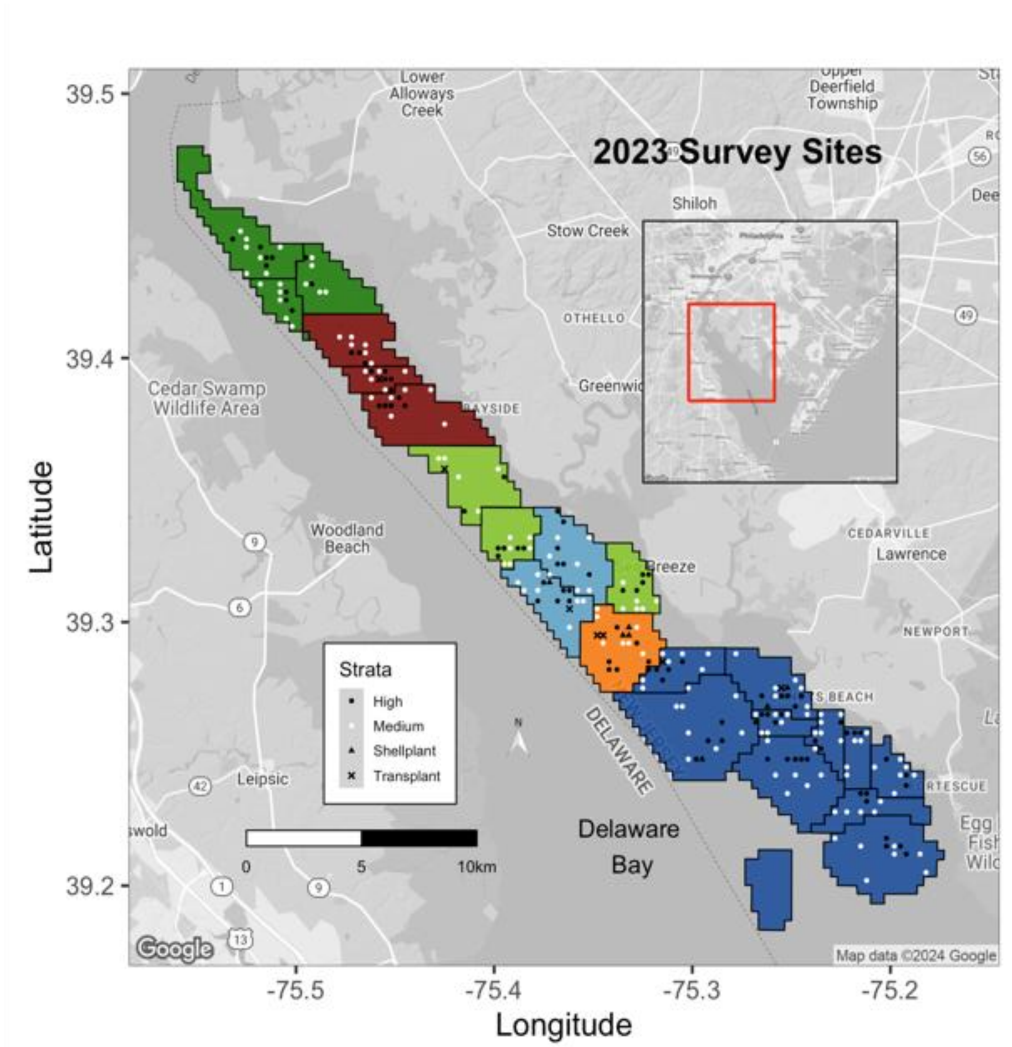

Figure 1. Footprint of the Delaware Bay, NJ public oyster beds (aka 'seedbeds'). Black lines demarcate named beds (see Alcox et al. 2017). Beds of the same color represent different management regions (dark green = very low mortality region, maroon = low mortality region, light green = medium mortality transplant region, light blue = medium mortality management region, orange = Shell Rock region, dark blue = high mortality region). The sites for the 2023 stock assessment survey are indicated by dots. Black dots are in high density strata and white dots are in medium density strata that were identified from a stratified random sampling design to determine overall bed oyster abundance. Transplant sites and shellplant sites are denoted by x's and triangles, respectively. See Alcox et al. (2017) for full description of the stratified random sampling design and management regions.

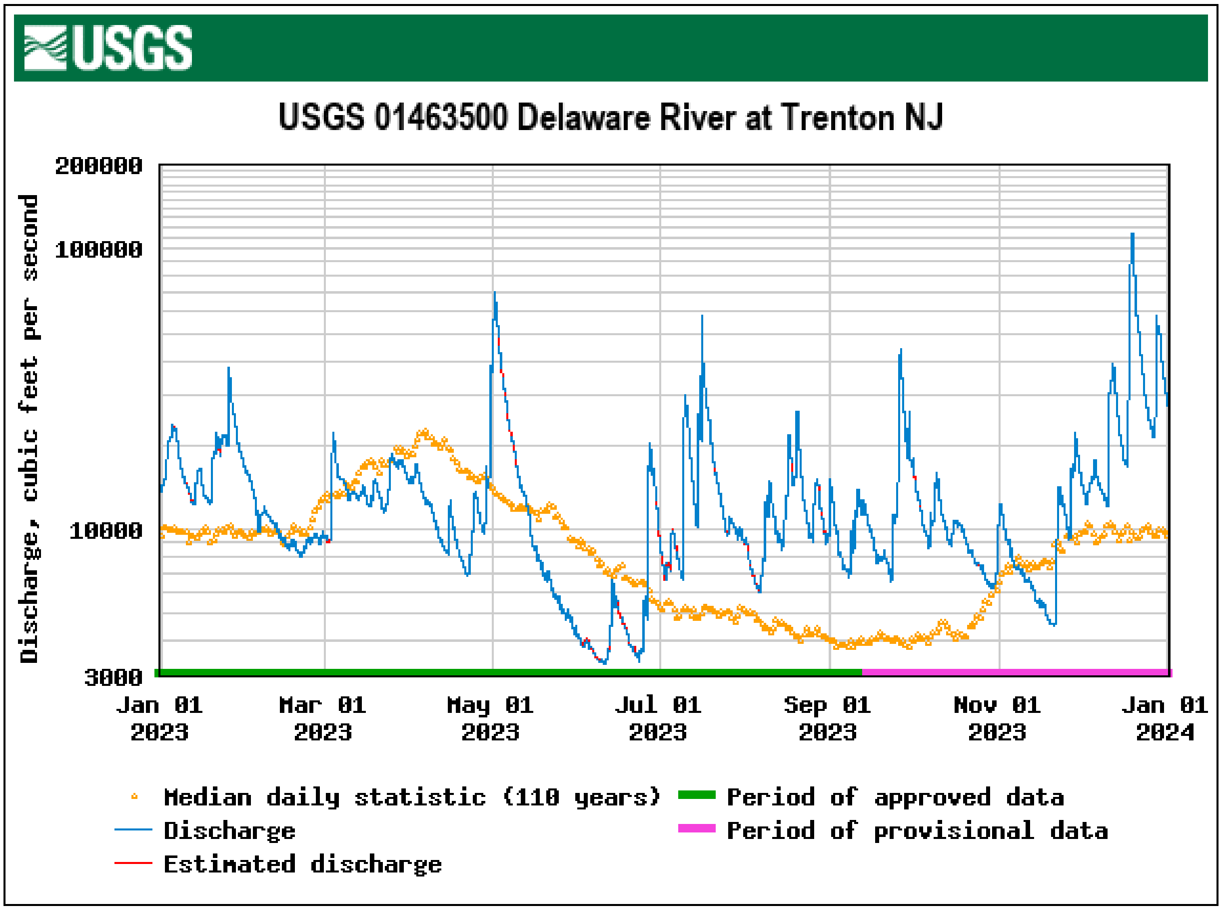

Figure 2. Delaware River discharge measured at Trenton, NJ USGS monitoring station 01463500. Yellow line represents daily discharge relative to the 1913-2022 median values. Flows were well above median values for much of the latter half of 2023. Data source: https://nwis.waterdata.usgs.gov/nwis/uv/?ts_id=195092&format=img_stats&site_no=01463500&begin_date=20230101&end_date=20240101

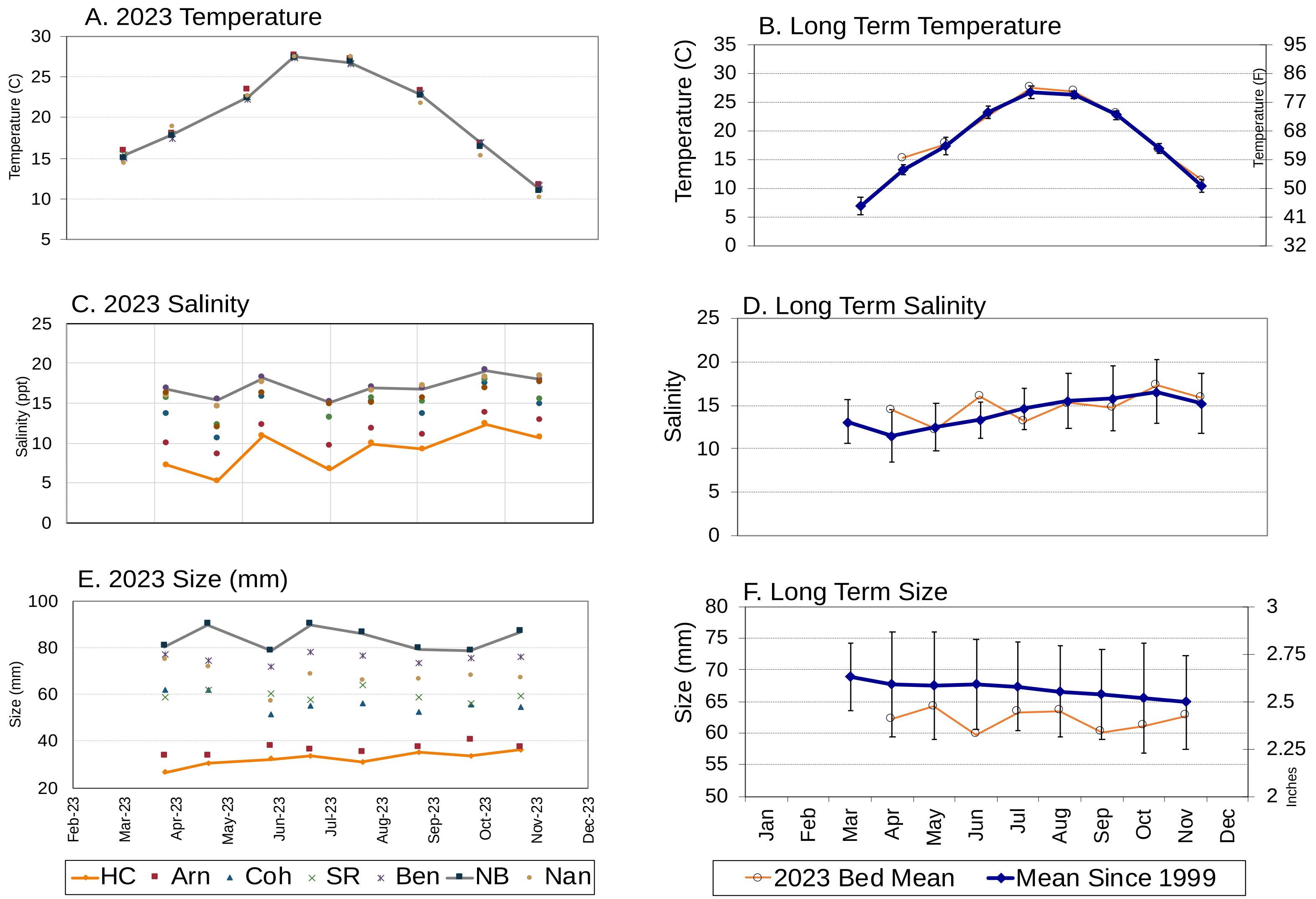

Figure 3. Results of 2023 Seed Bed Monitoring Program monthly temperature (A), salinity (C) and size frequencies (E) compared to the long-term mean data (B, D, and F, respectively). Panels present data as labeled. HC = Hope Creek, Arn = Arnolds, Coh = Cohansey, SR = Shell Rock, Ben = Bennies, NB = New Beds, Nan = Nantuxent.

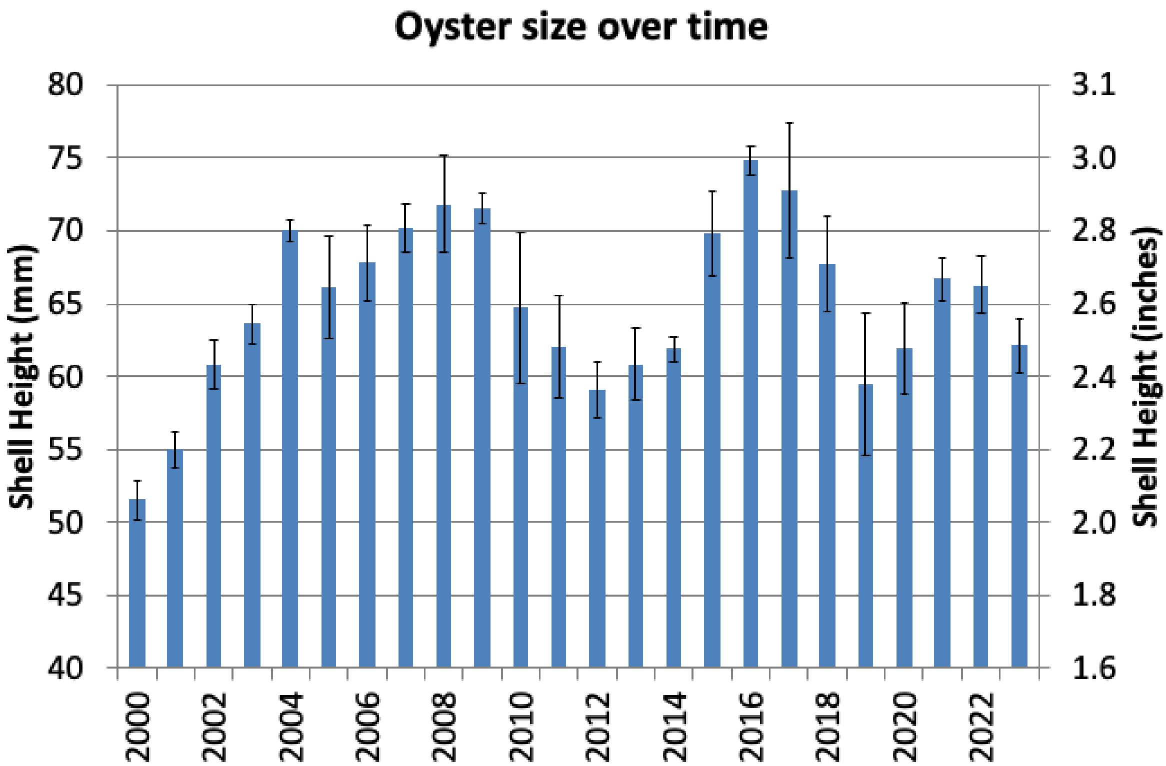

Figure 4. Interannual variation in mean shell height of oysters collected monthly from Delaware Bay NJ oyster seedbeds. Error bars represent one standard deviation of the mean of all oysters measured throughout each year. N = 50-100 oysters per month from each of the five primary long-term beds (Arnolds, Cohansey, Shell Rock, Bennies and New Beds) sampled from March to November. Samples from 2023 were collected from April to November.

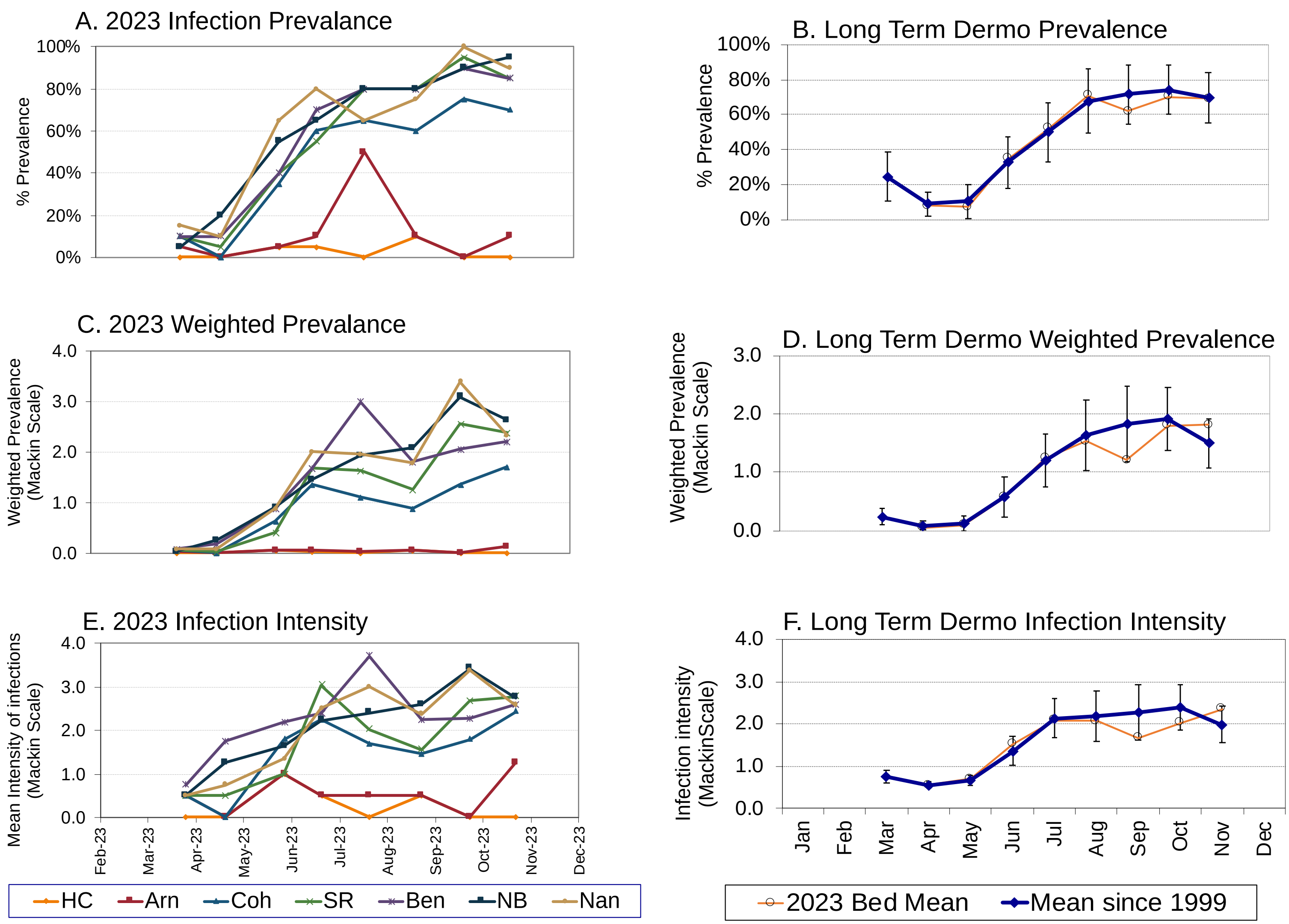

Figure 5. Results of 2023 Seed Bed Monitoring Program monthly Dermo disease prevalence (A), weighted prevalence (C) and intensity (E) compared to the long-term mean data (B, D, and F, respectively). Bed abbreviations as in Fig 3A.

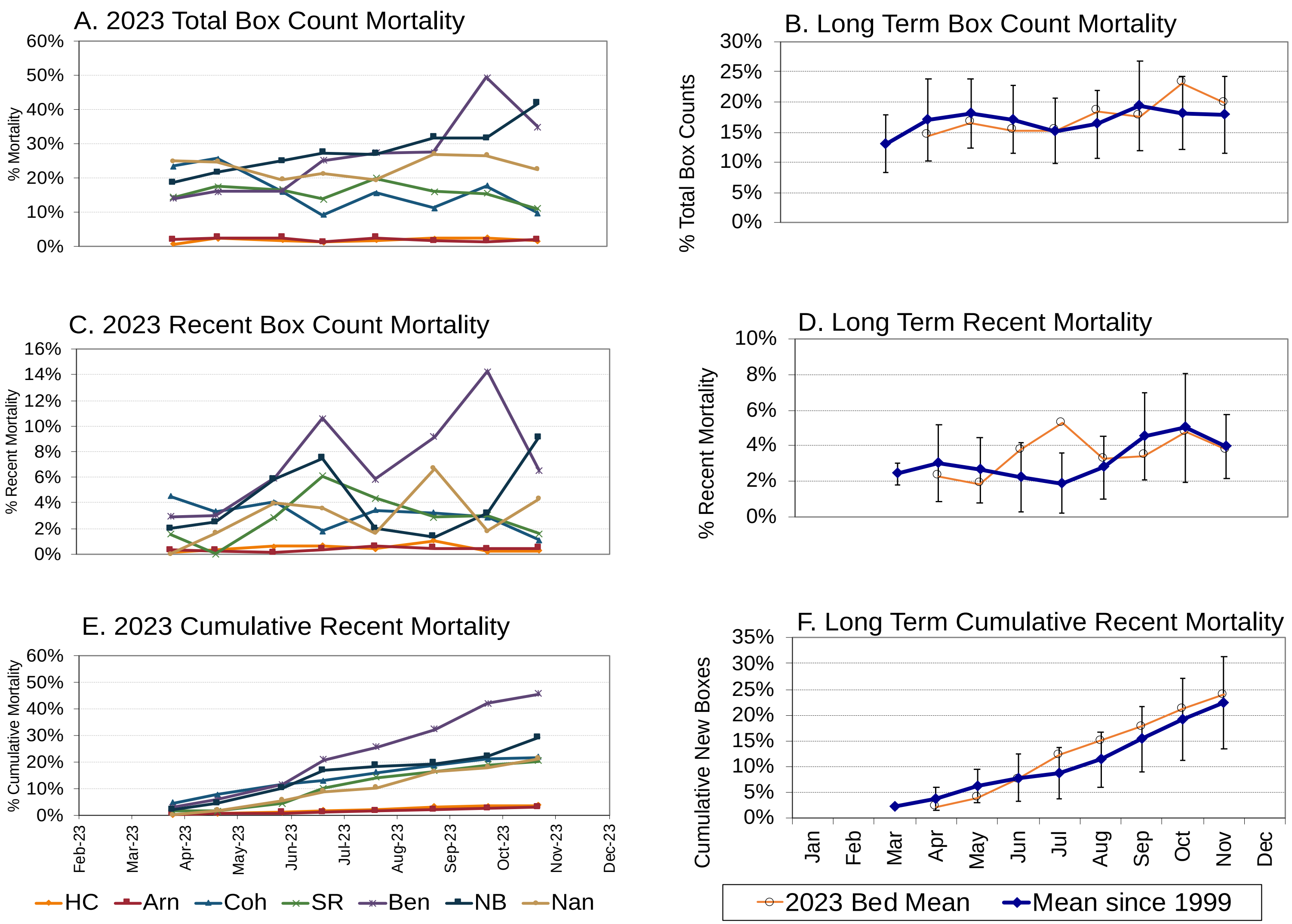

Figure 6. Results of 2023 Seed Bed Monitoring Program monthly total box count (A), recent box count (C) and cumulative mortality (E) compared to the long-term mean data (B, D, and F, respectively). Bed abbreviations as in Fig 3A.

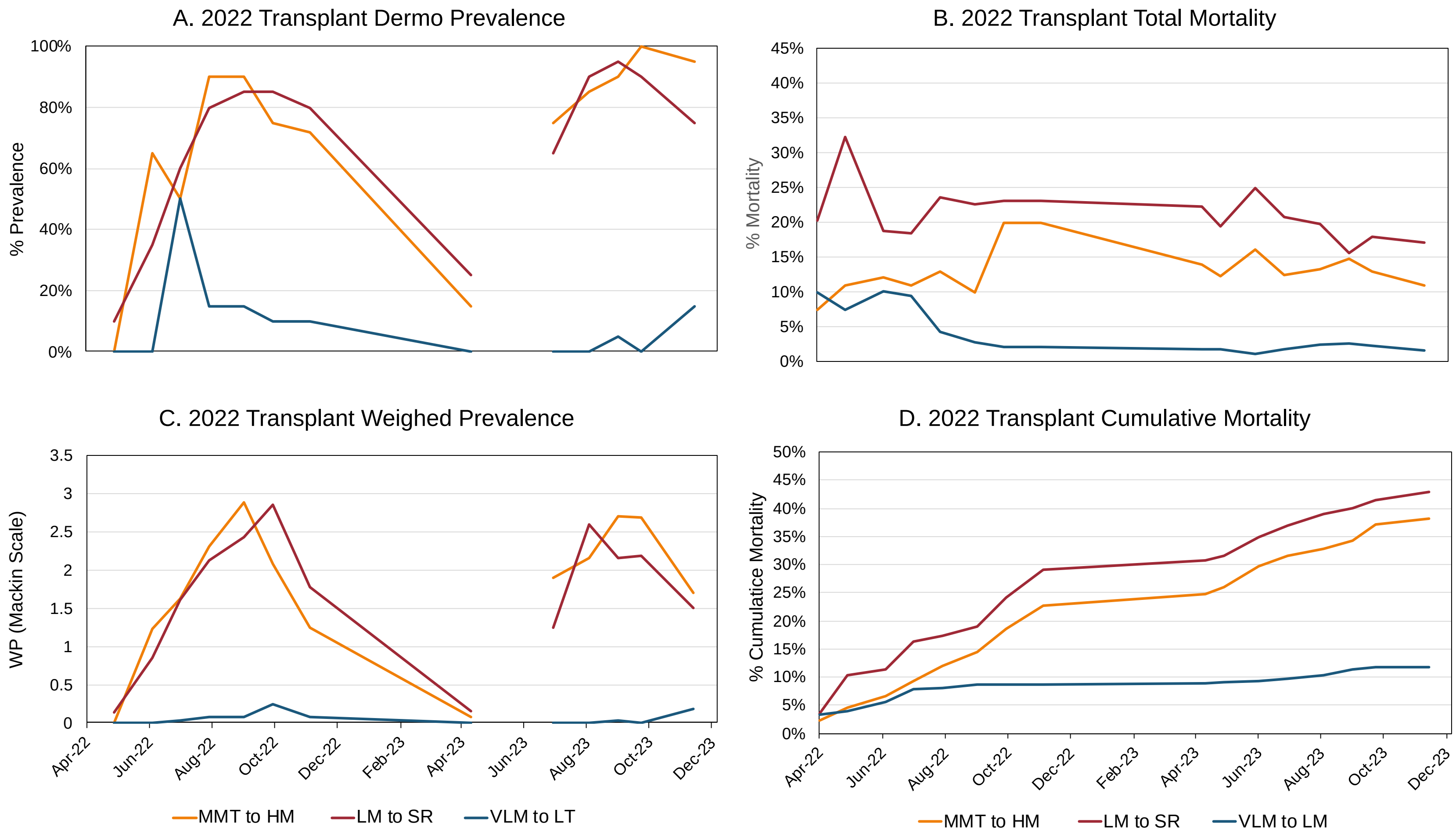

Figure 7. Dermo and mortality on the 2022 intermediate transplant sites. The 2022 donor to recipient beds were as follows: MMT to HM – Upper Middle, Middle and Sea Breeze to Bennies Sand, LM to SR - Upper Arnolds and Arnolds to Shell Rock and VLM to LM – Hope Creek to Upper Middle.

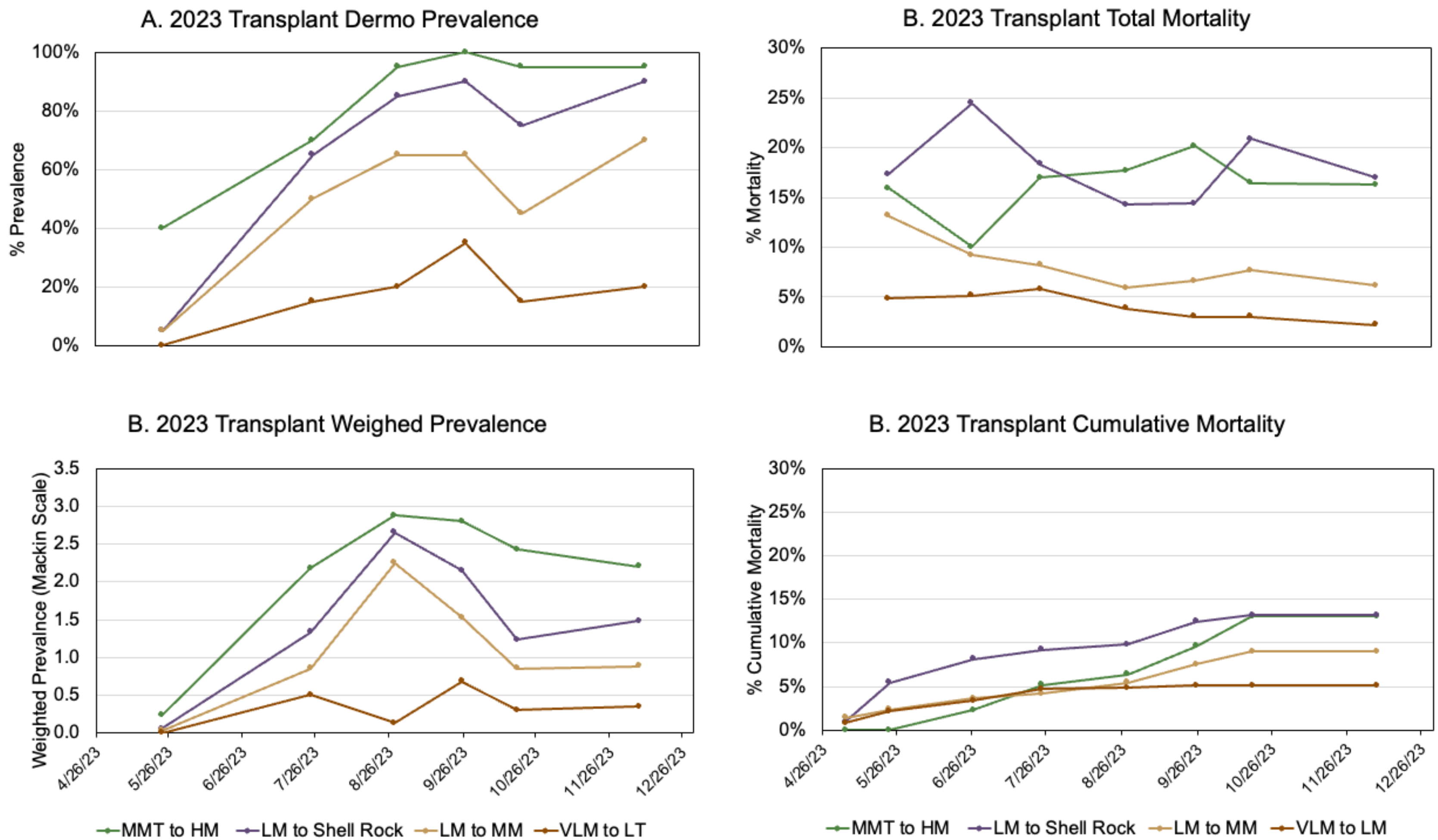

Figure 8. First year of box count and dermo disease performance of the 2023 intermediate transplants. The 2023 donor to recipient beds were as follows: MMT to HM – Upper Middle, Middle and Sea Breeze to Nantuxent, MMT to SR - Sea Breeze to Shell Rock, LM to MM, Upper Arnolds and Arnolds to Ship john and VLM – LM – Hope Creek to Upper Middle.

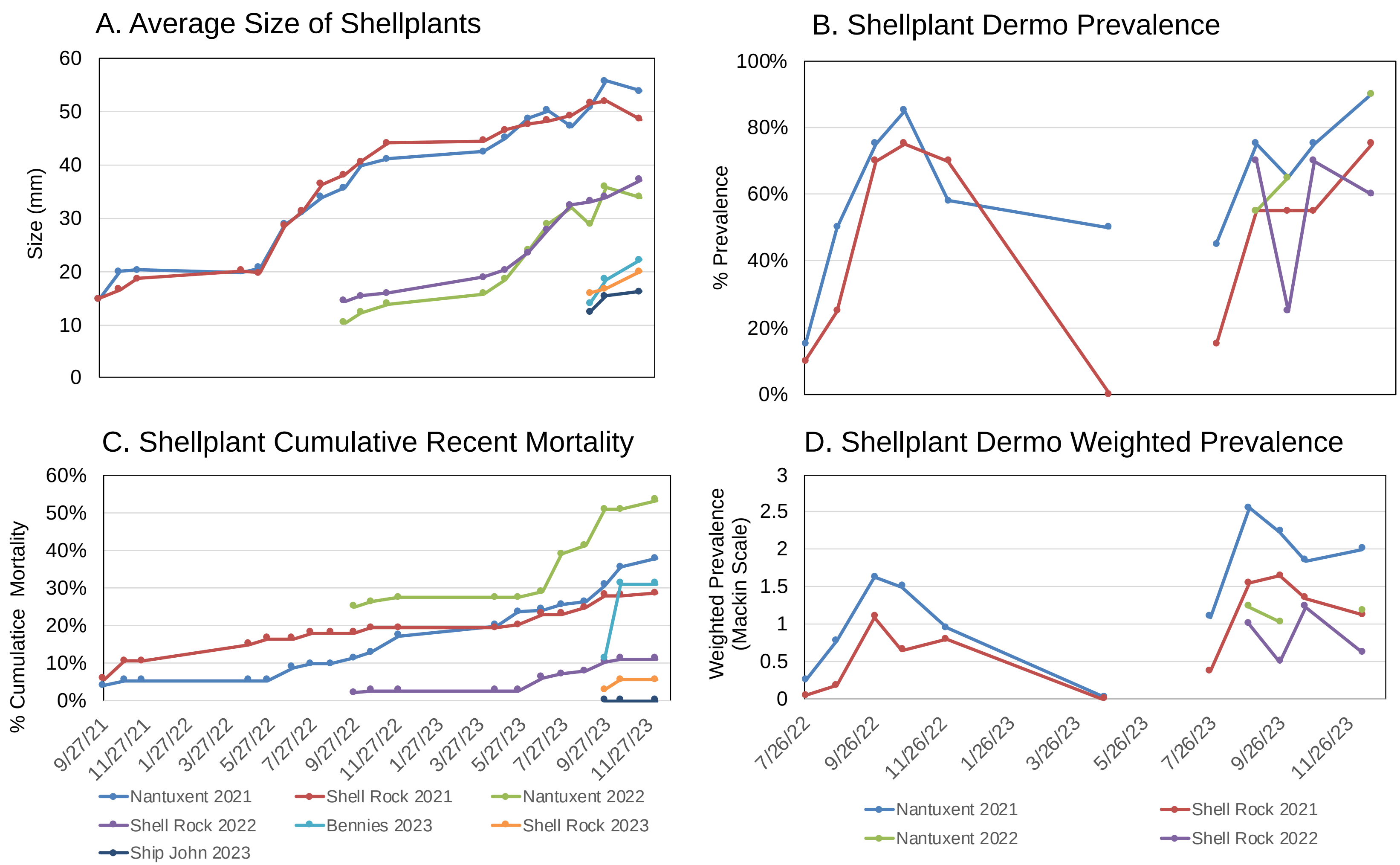

Figure 9. Performance of 2022 and 2023 shellplants. Growth and mortality monitoring began in September during the year of the plant while dermo monitoring began in August of the following year.

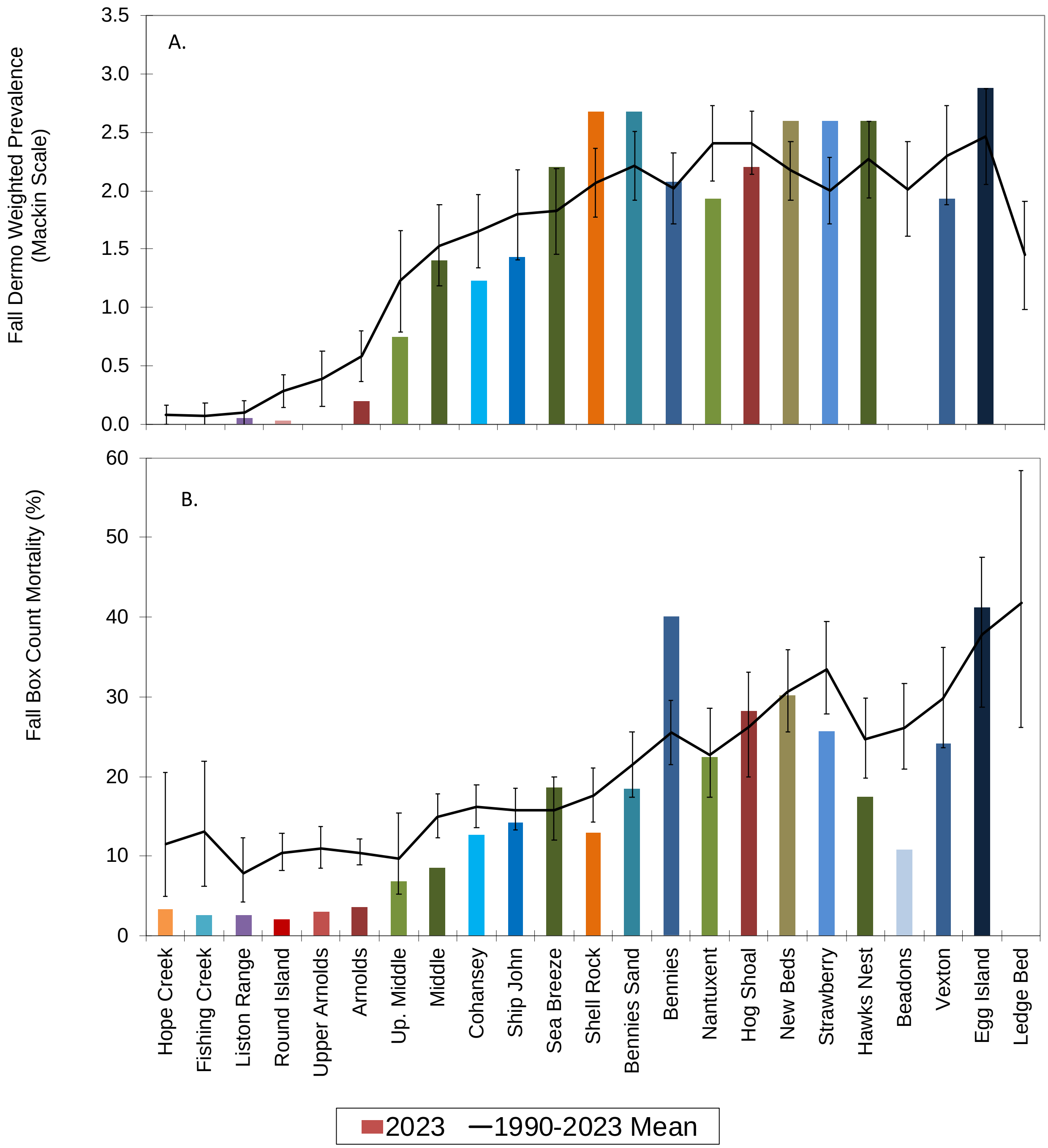

Figure 10. Long-term spatial patterns of dermo weighted prevalence (A), and natural mortality (B) across the oyster beds. From left to right, beds are listed upbay to downbay. Not all beds have been sampled every year (see Table 3). Ledge was not sampled in 2023. Bennies was sampled, but no dermo was detected. Error bars represent 95% confidence intervals.

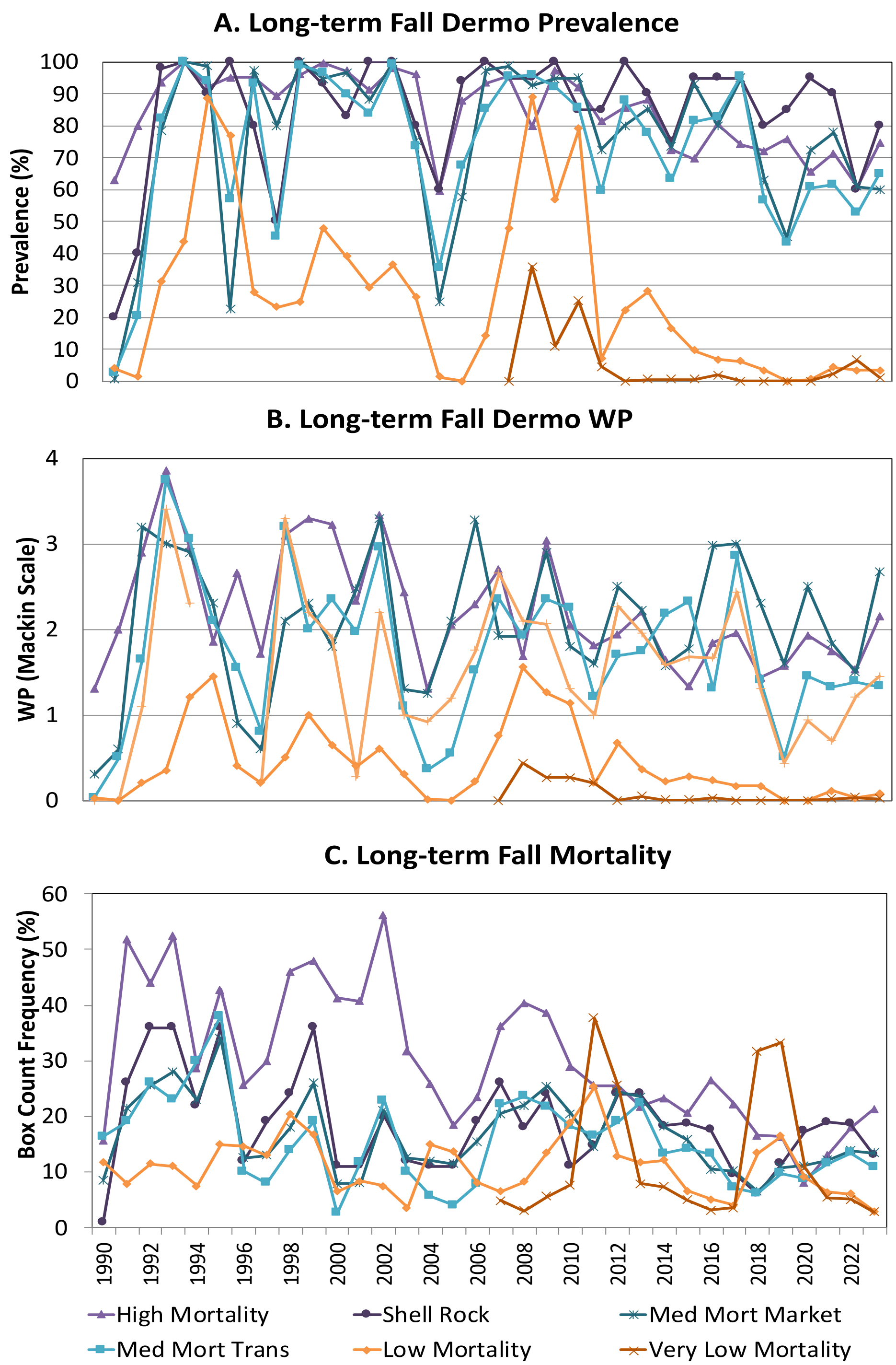

Figure 11. Annual Fall dermo prevalence (A), weighted prevalence (B) and box count mortality (C) on New Jersey Delaware Bay seedbeds by management regions shown in Figure 1.

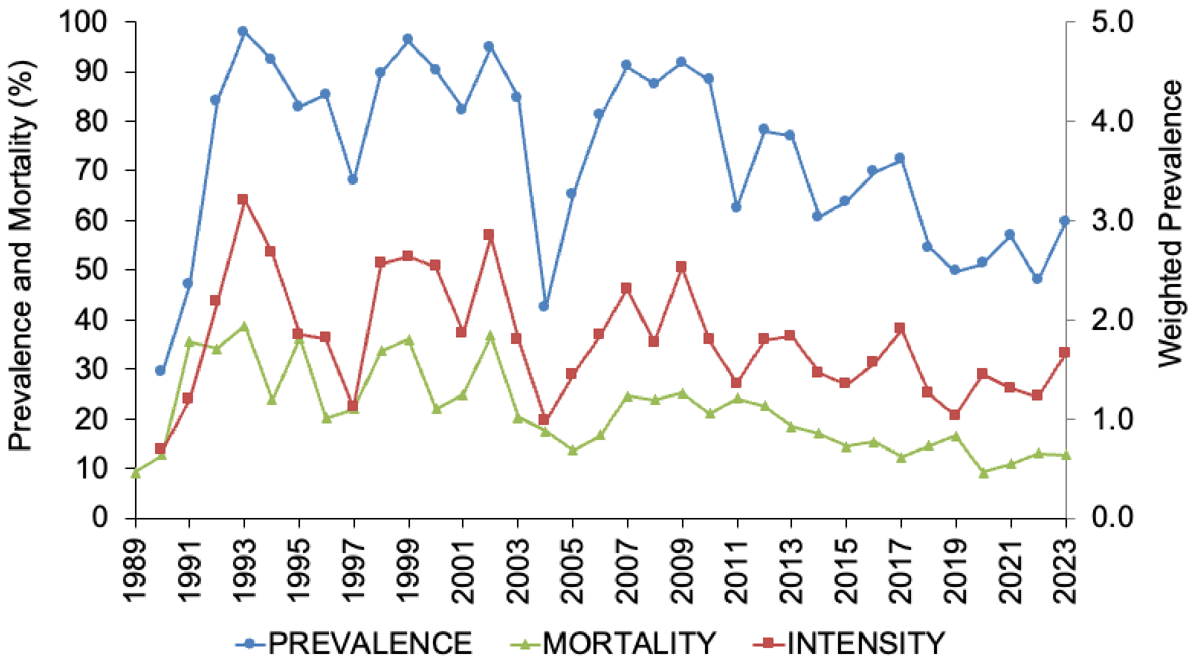

Figure 12. Long-term patterns of Fall dermo prevalence, intensity (weighted prevalence) and mortality averaged across the five beds monitored since 1990 (Arnolds, Cohansey, Shell Rock, Bennies and New Beds). These data show cycles of dermo dampening over time but with a slight increase this year.

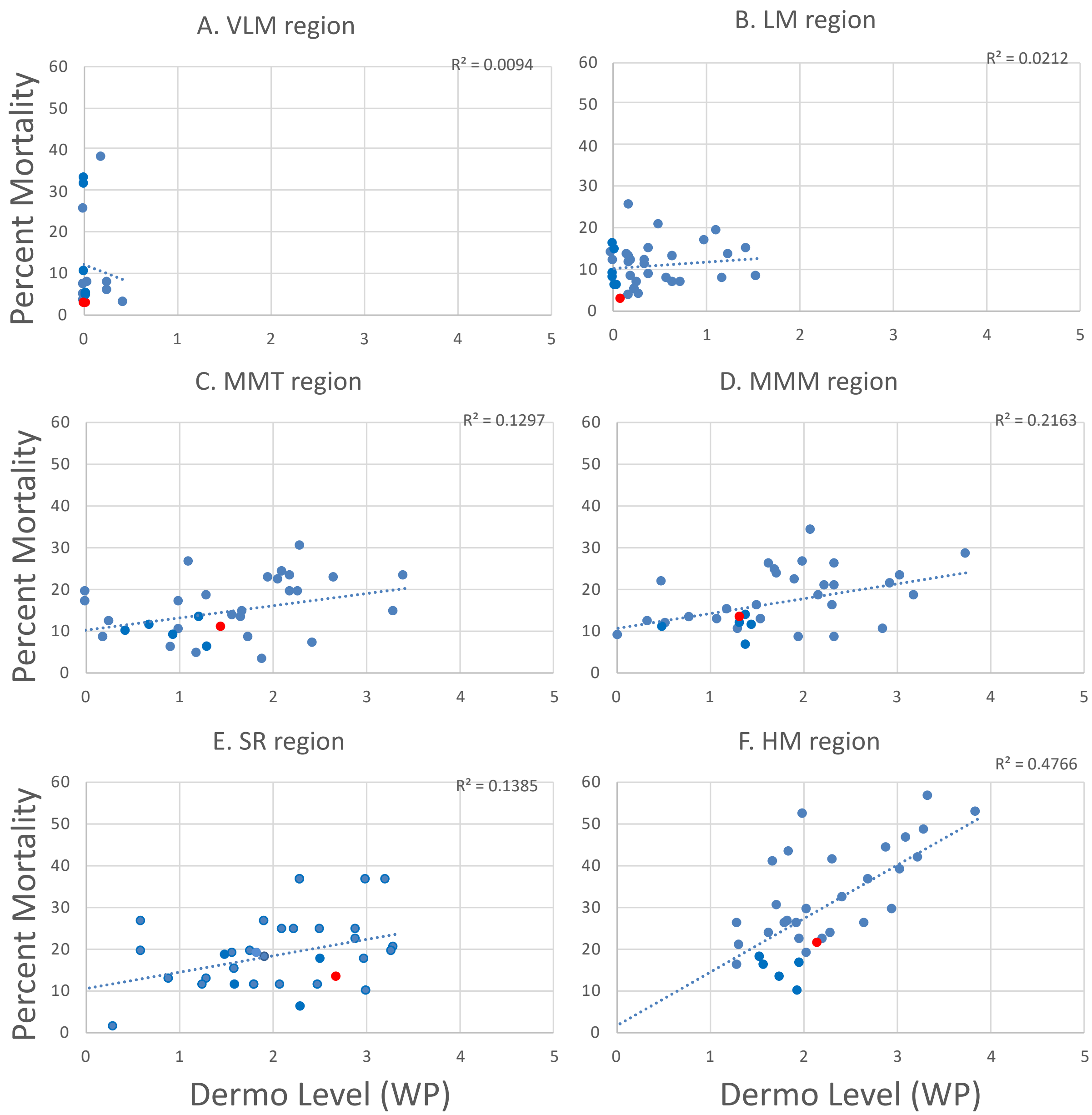

Figure 13. Region mortality as a function of dermo disease levels since 1990 (2007 for the VLM region). Red points represent 2023 data. VLM = Very Low Mortality, LM = Low Mortality, MMT = Medium Mortality Transplant, MMM = Medium Mortality Market, SR = Shell Rock, and HM = High Mortality.

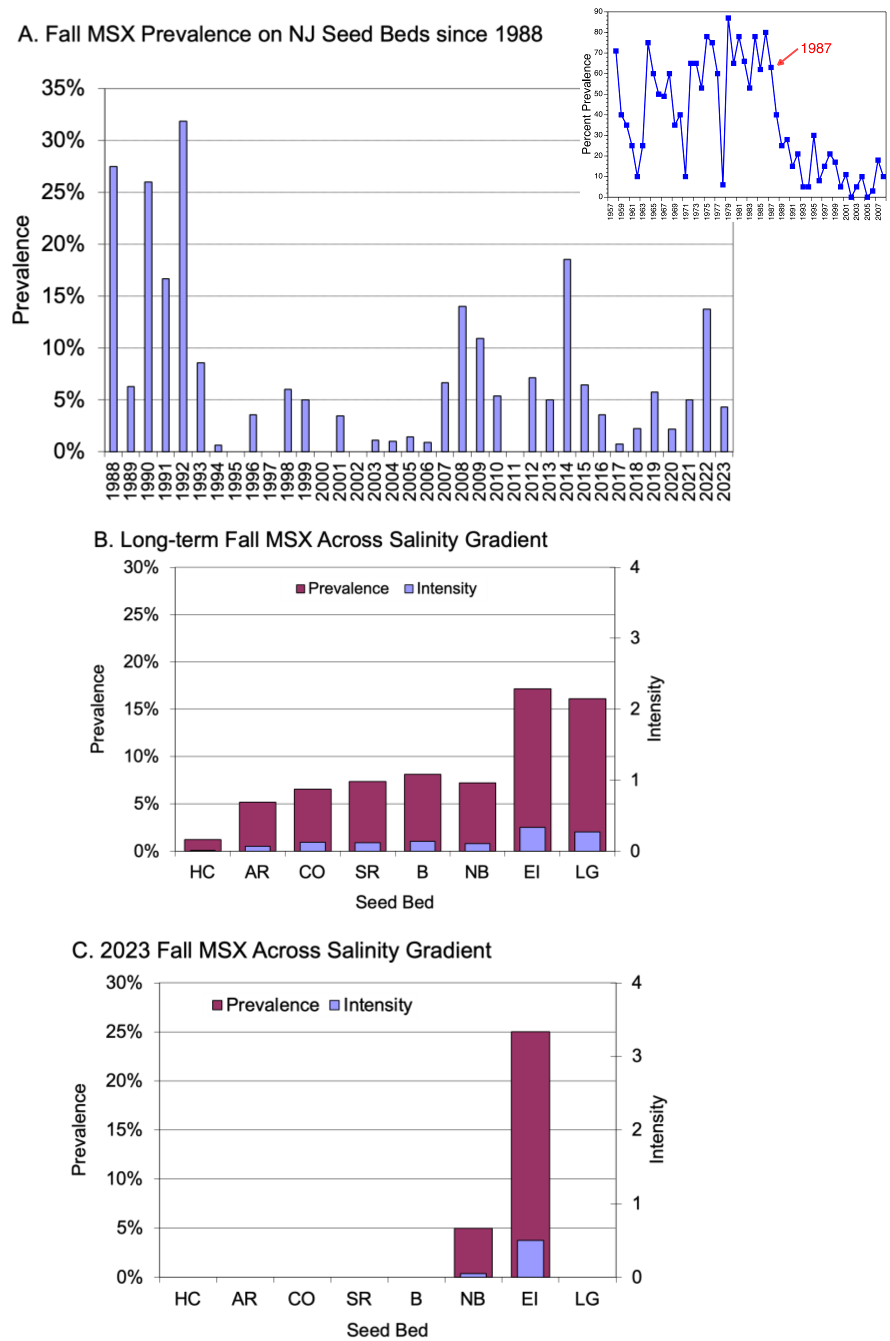

Figure 14. MSX disease on the New Jersey Delaware Bay oyster seedbeds. A. Annual Fall MSX prevalence across all beds since 1988 (2007 for HC). Inset shows lower Delaware Bay levels for comparison from Ford and Bushek (2012). B. Total fall MSX prevalence and intensity (weighted prevalence on a scale of 0 to 4) across seedbed salinity gradient since 1988. C. 2023 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.

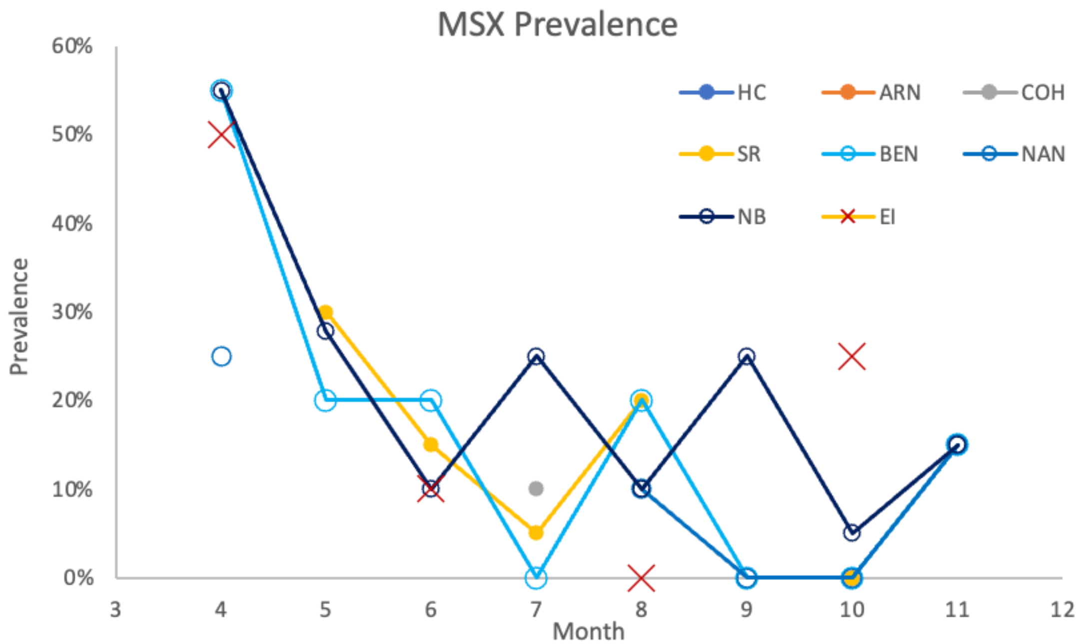

Figure 15. Seasonal prevalence of MSX during 2023