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Stock Assessment Workshop
New Jersey Delaware Bay Oyster Beds
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Final Report

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Distribution List
Delaware Bay Section of the Shellfisheries Council
NJDEP Bureau of Shellfisheries
Stock Assessment Review Committee
Oyster Industry Science Steering Committee

Abbreviations Used in this Report

BRP Biological reference point

CPUE Catch per unit effort

Dermo A parasitic oyster disease caused by the protozoan, *Perkinsus marinus*

HM High Mortality region

HSRL Haskin Shellfish Research Laboratory

LM Low Mortality region

LPUE Landings per unit effort

MMM Medium Mortality Market region

MMT Medium Mortality Transplant region

MSX A parasitic oyster disease caused by the protozoan, *Haplosporidium nelsoni*

NJDEP New Jersey Department of Environmental Protection

SARC Stock Assessment Review Committee

SAW Stock Assessment Workshop

SR Shell Rock region

SSB Spawning stock biomass

VLM Very Low Mortality region

Vp *Vibrio parahaemolyticus*

WP Weighted prevalence, a measurement of the intensity of dermo

I. HISTORICAL OVERVIEW

The Population

The natural oyster beds of the New Jersey portion of Delaware Bay stretch for about 28 miles from Artificial Island at the upper end of the Bay to Egg Island, approximately midway down the Bay, and cover approximately 16,000 acres (Figures 1 and 2). From upbay to downbay, oysters on these beds experience increasingly higher salinity that generally corresponds to higher rates of growth, predation, disease, and recruitment.

The long-term dynamics of the surveyed population can be divided into several periods of high or low relative mortality, generally corresponding to periods of high or low levels of disease intensity (Figure 3a). MSX disease, caused by the parasite *Haplosporidium nelsoni* became a significant periodic source of mortality in 1957 (Ford and Haskin 1982) but has been of little consequence following a widespread epizootic in 1986 and subsequent spread of resistance through much of the stock thereafter (Ford and Bushek 2012). From 1969-1985, MSX and mortality were low and oyster abundance was high. Around 1990, dermo disease, caused by the parasite *Perkinsus marinus* became prevalent in the Delaware Bay and effectively doubled natural mortality rates (Powell et al. 2008b). It has been a major control on the oyster population in the Delaware Bay since 1990 although mortality has been declining since 2012 (Figure 3a).

Throughout the time series, fishing has usually taken a small fraction of the stock compared to natural mortality (Figure 3b). In addition, the whole-stock fishing mortality rate has fluctuated little since the inception of the Direct Market Fishery in 1996, hovering around 2% (Figure 3b).

In addition to disease and fishing, habitat has played a key role in driving the historical population dynamics. Oysters create their own habitat. It is well understood therefore that shell, whether as natural reef or planted, is critical to oyster population stability and growth (Abbe 1988, Powell et al. 2006). Moreover, oyster shell is not a permanent resource (Mann and Powell 2007). Chemical, physical, and biological processes degrade shell over time (Powell et al. 2006). The circular nature of the relationship between oysters and the habitat they create makes monitoring and enhancement of the shell resource critical to sustainable management (Powell and Klinck 2007; Powell et al. 2012b). For this reason, shellplanting has been employed throughout the time series when funding is available to enhance recruitment (Figures 4a, b). Shellplanting is an important management activity that adds clean substrate to oyster beds. In the Delaware Bay, it has been practiced with varying regularity and intensity throughout the Assessment Survey time series with the volumes of shell planted usually dependent on available funds (Figure 4a). Earlier programs planted large volumes of oyster or clamshell on NJ oyster beds, particularly in the 1960s and 70s. Efforts since 2003 have primarily used clamshell (quahog and surf clam), a by-product of local clam processing plants.

The Fishery

From the 19th century to 1996, the natural oyster beds of New Jersey were used as a source of young oysters (seed) that were transplanted to private leases each spring; a practice called 'Bay Season' (Ford 1997). Bay Season occurred over a period of months in the earliest days but over time, it was shortened to weeks to prevent overharvesting. From about 1953 to 1996, this transplant fishery was nominally managed by a loosely applied reference point called the '40% rule' that closed beds when the percentage by volume of oysters in a dredge haul went down to 40% (Ford, 1997). Other factors such as spat set and economics were also considered in making management decisions (Fegley et al. 2003). There were years of Bay Season closures due to MSX and dermo mortality in the 1950's, 60's, 80's, and early 90's (Figure 5).

In response to the increased number of Bay Season closures and the persistent high mortality of oysters transplanted to leased grounds, a Direct Market Fishery was created for the natural oyster beds in 1996. A quota-based system designed to sustain the abundance of market-sized oysters was implemented where market-sized oysters could be harvested and marketed directly from the twenty-three natural beds (that is, they did not need to be transplanted to leased grounds for subsequent harvest). Studies indicated that the impact of dermo decreased as salinity decreased so the twenty-three beds were grouped into six Management Regions that follow the estuarine salinity gradient of the Delaware Bay. Each region was named to reflect the dermo-related mortality rates experienced by oysters there (Figure 1). Since 1996, oysters of all sizes ('seed') in the upper three regions (VLM, LM, MMT; Transplant Regions) could be transplanted to enhance abundance on the lower three regions (MMM, SR, HM; Direct Market Regions); a management activity termed 'intermediate transplant'. Market-sized oysters could then be harvested directly from the Direct Market Regions according to the recommended quota for that year. The Shell Rock bed, which otherwise would be grouped in with the other beds in the MMM region, is separated due to its consistently high productivity. The VLM, LM, and MMT became intermediate transplant regions because oysters in these regions are generally smaller and of insufficient quality to market directly. Once moved, oysters from the Transplant regions quickly attain market quality, and enhance the quota in the receiving region. This system of transplanting and area management was instituted to make use of the whole resource and to avoid overfishing of any one region (see HSRL SAW reports 2001 to 2005).

From 1996-2000, direct market harvest generally occurred in two phases, each anywhere from 7 to 15 weeks long: April-June and September-December. Since 2001, the harvest generally begins in early April and runs through late November. Transplanting from the Transplant Regions into the Direct Market Regions generally occurs in late April or early May.

The total direct market harvest quota is divided by the approximately 80 licenses held. Until 2010, each license was tied to a separate harvesting boat with a limit of one license per vessel. In 2010, rules were changed to allow a single boat to fish on up to 3 licenses. In 2014, this was changed again to allow up to 6 licenses per harvesting boat. This consolidation benefited harvesters because they no longer needed to maintain and work all boats during the season. It has also helped keep the historic, large boats maintained and working to capacity. These vessels are also needed to effectively operate the intermediate transplant program and other management activities.

The Assessment Survey

The oyster beds on the New Jersey side of Delaware Bay have been surveyed regularly since 1953, initially in response to historically low oyster abundance (Fegley et al. 2003). However, the Assessment Survey methodology, the number of beds surveyed, and their groupings have changed over the years. The history of the Assessment Survey, including changes in survey methodology, are summarized in this section and in Table 1.

Survey timing and sampling gear

From 1953 through 1988, the annual oyster Assessment Survey was conducted from a small boat using a small dredge and occurred over several months in the fall, winter, and spring. In 1989, sampling was switched to a large traditional oyster boat, the *F/V Howard W. Sockwell,* using a 1.27m commercial dredge and sampling was completed in a few days. Annual sampling now occupies up to five days (usually not consecutive) between mid-October and mid-November.

Size definitions for oyster and spat

Prior to 1990, oysters were not measured but were categorized as groups defined as 'spat', 'yearling', and 'oyster'. Post-1990 survey protocols include measurements of yearlings and oysters permitting calculation of biomass as well as abundance. Spat were still classified based on morphology and were not measured. Boxes were not measured until 1998. Also in 1998, oysters < 20 mm (¾ in or less) that had been designated 'oyster' based on morphology, were relegated to the spat category. Although counted as oyster in the assessment, the yearling category was continued until 2002. In 2003, a 20 mm 'spat cutoff' was initiated to differentiate oysters counted as a spat (young-of-the-year recruits) from the oysters included in total abundance estimates and this cutoff is still used to separate "spat" from "oysters" in all samples.

Capture efficiency and catchability coefficients

Measurement of survey swept area and experiments to determine gear efficiency began in 1998 to allow oyster density to be estimated on each sampled grid (Powell et al. 2002, 2007). Catchability coefficients calculated from these experiments began being applied to correct for dredge capture efficiency and calculate density in 1998 (Table 2). Work from 1999 to 2003 to establish catchability coefficients for the oyster beds in Delaware Bay is described in Powell et al. (2002, 2007). Briefly, analyses of these earliest data revealed a differential in dredge efficiency between the upper (above Shell Rock) and lower oyster beds. It was also found that on average, the dredge caught oysters with greater efficiency than boxes, and boxes with greater efficiency than cultch. Concerns about the effect that natural benthic changes over time might have on dredge efficiency led to the application of different sets of catchability coefficients being applied to different parts of the Assessment Survey time series (Table 3 in Ashton-Alcox et al. 2016). In September 2013, dredge efficiency experiments were again conducted using the F/V Howard W. Sockwell and a commercial dredge, but instead of divers for the 100% efficiency numbers, patent tongs on the R/V Baylor were used (Morson et al. 2018). Spatial and temporal analyses compared the 2013 patent tong experiments to the 1999, 2000, and 2003 dredge-diver experiments (Morson et al. 2018). These updated analyses showed no statistically significant temporal trend in gear efficiency. Thus, the 2016 SARC advised that data from all experiment years be averaged together within bed groups and applied to the entire time series (Ashton-Alcox et al. 2016). The 2016 SARC also advised adoption of updated bed groupings (Table 2). Finally, in addition to the influence of region, data collected during the three separate experiments suggested that capture efficiency was density-dependent (Morson et al. 2018; Figure 6). Therefore, the continued recommendation of the SARC since 2016 is to re-evaluate capture efficiency when possible, including whether other forms of sampling (e.g., patent tongs) could be used in tandem with the survey dredge during the Assessment Survey to estimate capture efficiency each year.

Retrospective reconstruction of the time series

In 2005, by request of the 6th SARC, the Assessment Survey time series from 1953 to 1997 was retrospectively reconstructed. For a complete explanation of the time series reconstruction, see Powell et al. (2008b). In brief, survey samples were divided into volumes of oysters and cultch, and oysters per bushel[1] were calculated throughout the time series. The survey was quantified in 1998 using measured tows and dredge efficiency corrections, permitting estimates of oysters and cultch per m^2. Using the assumption that cultch density is relatively stable over time, oysters per m^2 for each survey sample can be estimated using the relationship between oysters per bushel and cultch per bushel in a sample and the relationship between the cultch per bushel and the average cultch density for each bed (see equation 3 in Powell et al. 2008b). The latter estimates were obtained by using bed-specific cultch density determined empirically from the 1998-2004 quantified surveys. Comparison of retrospective estimates for 1998-2004 (obtained using the `stable cultch' assumption) with direct measurements for 1998-2004, suggests that yearly time-series estimates prior to 1997 may differ by a factor of 2 or less. Cultch varies with input rate from

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[1] The NJ bushel volume is the same as a US or DE bushel: 35 L; MD and VA bushels are larger (46 and 49 L respectively)

natural mortality and the temporal dynamics of this variation are unknown for the 1953-1997 time frame. An understanding of the shell dynamics on Delaware Bay oyster beds, however, indicates that shell is the most stable component of the survey sample supporting the assumption that a two-fold error is unlikely to be exceeded.

Survey sampling domain and strata definitions

Prior to 2005, each bed was divided into three strata based on oyster abundances. Grids of 0.2-min latitude X 0.2-min longitude were created for the primary beds and approximately 10% of them were sampled based on a stratified random sampling design (Fegley et al. 2003). On each bed, grids with 'commercial' abundances of oysters ≥ 75% of the time were called 'high'; grids with marginal or highly variable 'commercial' densities of oysters 25-75% of the time were called 'medium'; grids with abundances well below commercial densities were called 'low' (HSRL personnel; Fegley et al. 1994). Non-gridded areas between beds were never included in surveys. Information from oystermen in the early 2000's indicated that harvesting between beds was not uncommon. Therefore, from 2005 to 2008, the grid overlay was increased to cover all areas from the central shipping channel to the New Jersey Delaware Bay shoreline with every grid assigned to an existing bed. In 2007, an HSRL survey investigated the upbay extent of the New Jersey oyster resource based on bottom sediment mapping conducted by the Delaware Department of Natural Resources and Environmental Control and provided by B. Wilson (2007, personal communication). This survey resulted in the addition of three more beds termed the Very Low Mortality region (VLM) into the stock assessment (Figure 1). Earlier data for the VLM are not present in the survey database; therefore, reconstruction of its 1953-2006 time series is not possible.

From 2005-2008, all oyster beds were resurveyed except Ledge and Egg Island which have low oyster abundance with survey averages < 0.5 oysters per m^2. This resulted in a change of strata definition and survey design from that used historically (Kraeuter et al. 2006). The restratification kept the three strata system within beds and used oyster densities to determine High, Medium, and Low strata. Since 2002, a fourth 'Enhanced' stratum exists to temporarily identify grids that receive shellplants or transplants. A rotating schedule restratifies each bed approximately once per decade (Table 3, Appendix A). Analysis of many survey simulations suggested that a random survey based on High and Medium quality strata is sufficient (Kraeuter et al. 2006).

Through 2004, the Assessment Survey sampled most beds yearly although a selection of beds was sampled every other year. Since then, all beds have been sampled each year, except Egg Island and Ledge, which were sampled every other year until 2021. As of 2007, there are 23 surveyed beds grouped into six regions designated based on relative oyster mortality and the current management scheme (Figure 7). Prior to 2007, the three beds at the upbay limit of the oyster resource (VLM region) were not included in the survey, thus most of the long-term time series and all of the retrospective analyses exclude them.

The Assessment

Management of the NJ Delaware Bay oyster fishery and the annual stock assessments for the oyster resource since 1999 include the participation of scientists from Rutgers University (HSRL), the NJDEP, the NJ Bureau of Shellfisheries, members of the oyster industry, external academics, and resource managers (Table 4). The SARC is made up of nine members as follows: one member of the Delaware Bay section of the NJ Shellfisheries Council; one from the NJ oyster industry; two NJDEP members; one from the Delaware Department of Natural Resources & Environmental Control (DNREC); two outside academics; one outside resource management representative; and one non-HSRL Rutgers University representative. Appendix B lists SARC participants since the first SAW in 1999. The SAW is held over 1-2 days in the first half of February each year at HSRL following the October-November Assessment Survey and subsequent sample processing and data analyses.

Information available to the SARC to make recommendations includes reporting on the status and trends of the stock, an estimate of current abundance relative to biological reference point targets/thresholds for each region, regional summaries, and a stoplight diagram representing the overall condition by region. The latter includes abundance, mortality, an index of recruitment, and trends in oyster disease (specifically dermo) which has been the leading cause of oyster mortality since about 1990. Control rules (management guidelines) that had been implicitly used at every SAW were articulated at the 18th SAW in 2016 (Table 5).

Discussion of stock status and recommendations from the SARC regarding the assessment, resource management, and quota allocation are reported to the Delaware Bay Section of the NJ Shellfisheries Council on the first Tuesday in March. The Council then makes decisions about the direct market quota and any transplant and/or shellplant activities, the cost of which is borne by the industry via their self-imposed ‘bushel tax’. Decisions are finalized by the NJDEP, including those made about harvest dates and area management schedule.

II. CURRENT METHODOLOGY

Bed Stratification and Resurveys

Each bed that makes up the surveyed population is on a rotating schedule that results in a restratification at least once per decade (Table 3, Appendix A). This stratification map delineates the sampling domain for that bed for all years between resurvey events. The current stratification method is based on ordering grids within beds by oyster abundance. Grids with the lowest oyster densities that cumulatively contain 2% of a bed's stock are relegated to the Low Quality stratum. This includes grids with no oysters. Those that cumulatively account for the middle 48% of a bed's stock are designated `Medium Quality' and the rest that cumulatively account for the upper 50% make up the `High Quality' stratum. The temporary Enhanced stratum includes transplant- or shellplant-receiving grids.

Assessment Survey Design

The complete extent of the natural oyster resource is divided into 0.2-min latitude X 0.2-min longitude grids of approximately 25 acres that are each assigned to one of 23 beds (Figure 7). On each bed, a random subset of grids is sampled from the High and Medium quality strata during the annual Assessment Survey to estimate abundance. Prior to the 2021 Assessment Survey, to determine how many grids to sample within a given strata, a simulation was used to estimate the strata variance for a given number of sampled grids. When the reduction in variance was minimal for a given increase in grids sampled on a stratum, the sample intensity for that stratum was deemed statistically adequate to assess the abundance. However, at the 2019 SARC, a Science Recommendation was made to evaluate whether alternatives for allocating survey effort might provide a better estimate of abundance by reducing overall survey error. After alternative methods were presented to the 2020 and 2021 SARCs, the 2021 SARC recommended adopting the Neyman optimal allocation formula for allocating survey effort going forward with the stipulation that a minimum of two grids be sampled within each strata on each bed (Kimura and Somerton 2006; Morson et al. 2021). In addition, all grids that receive enhancement (shellplanting or transplanting) are sampled each year for up to three years following the enhancement activity.

The survey dredge is a standard 1.27-m commercial oyster dredge towed from either port or starboard. The on-bottom distance for each one-minute dredge tow is measured using a GPS that records positions every 2 to 5 seconds. A one-minute tow covers about 100 m^2 and usually prevents the dredge from filling completely thus avoiding the 'bulldozer' effect. The entire haul volume is recorded. If the haul is 7 bushels or larger (a full dredge), the haul is not counted, and the tow is redone at a duration of 45 seconds. Three tows are taken for each sampled grid and a $^1/_3$-bushel subsample is taken from each haul to create a composite 37-quart bushel[2].

Each composite bushel sample is processed to quantify the following: volume of live oysters, boxes, cultch, and debris; number of spat, oysters and boxes in the composite bushel; sizes of oysters and boxes from the composite bushel. Separate oyster samples are collected from each sampled grid and processed for condition index; the intensity of dermo and MSX infections is also determined. As was described in the Historical Overview section, the term oyster refers to individuals ≥ 20 mm (> ¾ in) in longest dimension while the term spat refers to those < 20 mm.

[2] The New Jersey standard bushel is 37 quarts (~35 liters).

Market-size oysters are defined as those ≥ 63.5 mm (≥ 2.5 inches). Using total counts per bushel, total bushels per tow, and swept area per tow, the density of spat, sub-market size oysters, market size oysters, and boxes are estimated for each sampled grid.

Estimating Abundance of Oysters, Boxes, and Spat

To obtain the annual estimates of abundance for each region, the randomly chosen grids from the high and medium quality strata from each bed in the region are sampled as described above to generate a relative estimate of the numbers per m^2 (or density) on each grid of spat, oysters, and boxes. Catchability coefficients (Table 2), estimated by dredge efficiency experiments (see "Capture efficiency and catchability coefficients" section above), are applied to the relative density estimates to calculate corrected-density estimates for each grid. The corrected-density estimates for all grids within a stratum on a given bed are then averaged to generate stratum-specific density estimates for each bed. These estimates are then multiplied by the area of each stratum to generate the total abundance per stratum on each bed. Strata-specific abundances are summed across beds and beds are summed across regions to generate the annual estimate of abundance in a region. The quantitative point estimates of abundance in this report include the High quality, Medium-quality, and Enhanced strata only. Low-quality areas are excluded as described earlier.

Estimating Survey Error

Two potential sources of error associated with the annual abundance estimates for each region are accounted for by estimating the uncertainty using bootstrap simulation. The first source of error is variability in oyster density within each stratum, the survey error. The second is variability in the estimate of the catchability coefficient being applied to the relative oyster density measured on each grid, the dredge efficiency error. Uncertainty around the survey point estimate is calculated by conducting 1,000 simulated surveys, each with a selection of samples from each stratum on each bed and each corrected for dredge efficiency by a randomly chosen value from all efficiency estimates available within a bed's dredge efficiency group. Error in this report is expressed as the 10^{th} and 90^{th} percentiles of these simulated distributions.

Exploitation Rate Calculations and Reference Points

Exploitation, or the fraction of the stock removed in a given year by fishing, is calculated for each region and by size (market vs. total) for each year. The calculation of exploitation for Transplant Regions is done in four steps:

1. Calculate the average number per bushel (from the transplant monitoring program) moved from each donor bed in the current year.
2. Determine the total removals from a given donor bed by multiplying the average number per bushel on that bed by the total bushels moved from each donor bed.

3. Calculate total removals by region by summing all removals from all donor beds in each region.
4. Divide the total number removed for a given region by the total abundance in that region the previous year.

The calculation for market size exploitation on Direct Market Regions is more complicated than it is on Transplant Regions because (1) an adjustment needs to be made for any region that received donor oysters from the transplant program, and (2) the calculation is based on market size oysters instead of all oysters. For the Direct Market Regions, market size exploitation rate is calculated in seven steps:

1. Calculate the average number per bushel (estimated from the Dock Monitoring Program and includes attached and smalls) from all direct market regions in the current year.
2. Multiply this average by the total catch in bushels in each market region to get total catch by region.
3. Calculate the proportion of oysters in each 0.5-inch size bin for each region from the size frequency data collected during the Dock Monitoring Program.
4. Distribute the total catch in numbers across the size frequency by region to get total numbers of oysters caught in each size bin by region.
5. Sum the numbers of oysters from all size bins 2.5 inches and above. This gets total numbers of markets removed by fishing in each region.
6. Subtract the total number of market size oysters transplanted to each region from this total number of removals. This gets total net removals by region.
7. Divide this number by the total market size abundance in each region the previous year.

The process described above was used to calculate the exploitation history for the fishery and in 2006, the SARC advised adoption of a quota system based on the 1996-2005 section of this history (later extended to 2006). These rates, herein referred to as Exploitation Reference Points, were thought to be from a period of conservative fishery management during a time of persistent, high disease pressure and were therefore deemed likely to provide conservative management goals. Initially, the 2006 SARC suggested reference points based on each Management Region's median (50^{th} percentile) exploitation rate. To provide flexibility in management, the SARC recommended using the 50^{th} percentile of exploitation as a base but to allow increasing exploitation to the 60^{th} percentile rate when the population was expanding or to reduce it to the 40^{th} percentile rate if the population was decreasing or appeared unstable.

Fishing activity during the 1996-2006 base time series was concentrated on the more downbay regions of the stock with limited data for the MMT and LM and none at all for the VLM since it did not enter the assessment until 2007. Data were so sparse for the Transplant Regions that it was decided that they should share the same set of exploitation rates. Because the exploitation percentiles were based on only eleven years of fishing data, they did not always transition linearly.

Therefore, the 2009 SARC made an adjustment to the original set of Exploitation Reference Points for the Transplant Regions in order to smooth a temporally biased change in exploitation rates at the 50th percentile that separated as high and low. The 50th and 60th percentile values from the original data were averaged. That average was used as the 50th percentile and the previous 50th percentile was then used as the 40th. Transitions between exploitation rates for the Direct Market Regions were similarly irregular. For example, in the HM, the change from the 40th to 50th percentile spanned a much larger range of exploitation rates than that of its 25th to 40th percentiles whereas SR's 40th and 50th percentiles were nearly identical. Consequently, if market-size oyster abundance was low on SR and other parameters were not promising, the choice for conservative exploitation was constrained to fishing below the 40th percentile.

The 2015 SARC specified a desire to have more regular changes between exploitation rates within each region. The 2016 SARC examined realized fishing exploitation rates since the adoption of the 1996-2006 baseline time period i.e., 2007-2015 and concluded that the median of the realized exploitation rates from 2007-2015 should be used as an exploitation target for each region going forward and that the target rate should be bounded by the range of realized rates from that period. This change from the previous Exploitation Reference Points to the new Exploitation Rate Reference Points is visualized in Figure 8. Further, the 2016 SARC agreed to allow percentage changes in either direction from no harvest up to the 2007-2015 maximum exploitation rate depending on stock status for each region.

SARC Exploitation Recommendations and Quota Projections

Each year the SARC will make a recommendation on the maximum allowable exploitation rate for each of the six Management Regions. This recommendation is presented to the New Jersey Delaware Bay Shellfish Council and the council makes the final decision about the highest allowed exploitation rate on each region. The total allowable quota is then the sum of the calculated bushels given a chosen exploitation rate for the three Direct Market Regions (plus additional quota as a result of any transplants from the Transplant Regions to the Direct Market Regions) allocated across the approximately 80 oyster licenses held. To estimate the total allowable quota from the SARC recommended exploitation rates, oysters in numbers are converted to projected catch in bushels using a grand mean of the average total oysters per landed bushel per year and the average market oysters per landed bushel per year from the Dockside Monitoring program time series (2004 to present). The rationale for using the grand mean is that the number of attached small oysters will vary between years depending on recruitment dynamics.

III. 2022 STATUS AND TRENDS

2022 Dockside Monitoring Program and Trends in Catch Composition

The Dockside Monitoring program counts and measures oysters at dockside from boats unloading direct market harvest. The results are used in the assessment to determine size frequency of the catch and harvested numbers per bushel so that beds can be appropriately debited, and exploitation rates can be determined (see section on "Exploitation Rate Calculations and Reference Points"). The overall average number of oysters per landed bushel in 2022 was 319 and the average number of market sized oysters per landed bushel was 275 (Figure 9). The proportion of small oysters attached to market-sized oysters increased in 2022, likely due to a large recruitment event (Figures 9, 4b). The grand mean for all years, used to convert targeted removals in oysters to projected quota in bushels (see section on "SARC Exploitation Recommendations and Quota Projections) was 269 oysters.

Although catch per boat day has been historically recorded for the NJ Delaware Bay oyster fishery, it has not been presented in the HSRL stock assessment reports until recently. While in previous years landings per unit effort (LPUE) were reported as bushels landed per day (based on an 8-hour day), in this document, it is reported in bushels-per-hour. The number of hours worked, beds fished, and bushels landed are calculated from the compilation of daily and weekly captain reports as well as dealer records. In this report, LPUE is reported separately for single and dual dredge boats. Single dredge LPUE increased from 19 bushels landed per hour in 2021 to 23 bushels per hour in 2022. Dual dredge LPUE decreased slightly from 31 to 30 bushels landed per hour, (Figure 10). The number of vessels of each dredge type has remained relatively unchanged since 2015 (Figure 10).

Changes in LPUE could be influenced by changes in size structure of the population. The size frequency of the surveyed population is reflected in the size frequency landed by the fishery. For example, the frequency of 2.5-3.0-inch oysters increased within 2022 fishery landings and, although decreased from 2021, remained high relative to previous years within all Direct Market Regions of the population (Figure 11). The frequency of 3.0-3.5-inch oysters within the population increased for the second year in a row. While the frequency of this size class landed by the fishery decreased from 2021, it was high relative to previous years. Although the frequency of larger oysters (≥ 3.5 inches) within the population has remained stable over the last three years, the frequency of larger individuals landed by the fishery has decreased steadily since 2017 (Figure 12). Population size structure is just one factor that could influence changes in LPUE on the direct market beds. Other factors include license consolidation, increases or decreases in market or total abundance, and seasonal limits on harvest time dictated by *Vibrio* control rules. However, it is difficult to determine which of these is having the greatest influence on catch rates, and it is most likely a combination of factors driving trends in LPUE.

2022 Catch Statistics and Fishery Exploitation

The 2022 direct market harvest occurred from April 4 to November 25 and included a period of curtailed harvest hours during summer months to comply with New Jersey's FDA-approved *Vibrio parahaemolyticus* Control Plan.[3] Sixteen vessels (4 single- and 12 dual-dredge boats) fished the quota during 2022. The total direct market harvest in 2022 was 104,264 bushels. Although the 2022 harvest represents a decrease from 2021, it is still high compared to harvest levels from the earlier part of the time series and is above the long-term average harvest of 85,000 bushels (Figure 13). The harvest from the three Direct Market Regions broke down as follows: 51% from the HM; 25% from SR; 24% from the MMM (Table 6a). Of the 14 beds in the three Direct Market Regions, only 6 were fished during the 2022 season. The HM has 11 beds, but 70% of its harvest came from just one bed, Bennies. Of the two beds in the MMM, almost the entirety of the region's harvest (99%) came from Ship John.

Table 7a describes the 2022 SARC recommendations, the Shellfish Council decisions, and the achieved exploitation rates of market-sized oysters from the Direct Market Regions. Harvest on the MMM region did not require a transplant and resulted in an achieved exploitation rate of 2.83%, lower than the median rate approved by the Shellfish Council. The achieved rates on the SR (5.09%) and HM regions (10.17%) were higher than the Council-approved maximum rates of 4.88% and 9.82%, respectively. To be harvested at their maximum rates, both the SR and HM regions required a transplant.

Table 7b describes the 2022 SARC recommendations and the Shellfish Council decisions for Transplant Region exploitation rates as well as the total oysters moved as a result of the chosen rates. A transplant took place in late April and early May 2022 from the LM region (Upper Arnolds and Arnolds) to the Shell Rock region and from the MMT region (Upper Middle, Middle, Sea Breeze) to the HM region (Bennies Sand). A small transplant from the VLM region (Hope Creek) to the LM region (Upper Arnolds) also took place. The LM transplant moved a total of 7,900 bushels, resulting in an achieved exploitation rate of 1.66% instead of the targeted 1.49% (Tables 6b, 7b). The MMT transplant moved a total of 18,900 bushels off the three beds in that region, resulting in an achieved exploitation of 2.15%, just below the chosen rate of 2.46% (Tables 6b, 7b). The 2022 SARC approved a small transplant from the VLM region, and the management decision was made to move oysters off these beds for the first time since 2011 (a small, accidental transplant occurred in 2013). The VLM transplant moved a total of 2,700 bushels from Hope Creek to Upper Arnolds and resulted in an achieved exploitation rate of 1.36%. While this transplant does not increase the direct market quota, it translates to 154 market-equivalent bushels added to the LM region. A detailed history of transplant activity can be found in Table 8 and Appendix C.

Finally, across all regions excluding the VLM, fishing mortality was 2.70% relative to total oyster

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[3] See New Jersey's FDA-approved *Vibrio parahaemolyticus* Control Plan here: https://www.nj.gov/dep/bmw/docs/nj2022vibrioplan.pdf

abundance and 3.92% relative to market-sized (≥ 2.5”) oyster abundance (Figure 14). These rates are consistent with the exploitation rates achieved since the inception of the direct market fishery in 1996 and remain low relative to natural mortality (Figure 3a).

2022 Enhancement Efforts

In 2022, there were two shell plants on NJ’s Delaware Bay oyster beds funded by the NJ oyster industry through its self-imposed ‘bushel tax’. A total of 45,049 bushels of crushed, unspatted clamshell were put directly on the High Mortality Region (Nantuxent). The Shell Rock region also received a total 67,442 bushels of clamshell. A formal evaluation of the increase in productivity that results from enhancement efforts (shellplanting and transplanting) was made in 2018 by comparing the change in oyster density on enhanced grids on Shell Rock to adjacent, non-enhanced grids on the same reef. Results from that analysis are in the 2019 SAW Report (Morson et al. 2019) and suggest that oyster density is, on average, 25 oysters per square meter higher on enhanced grids relative to adjacent, non-enhanced grids.

2022 Stock Status

At the 8th SAW in 2006, the SARC established target and threshold abundance references points based on the 1989-2005 time series for total abundance and the 1990-2005 time series for market abundance for each region (Table 9). It was concluded that this period represented the scope of oyster population dynamics in the present climate and disease regime. Targets for each region were therefore calculated as the median values of total and market-size oyster abundance and the threshold was calculated as half the target. The only exception to this was on the VLM region where the time series only just began in 2007. The 2017 SARC designated targets and thresholds for the VLM as the 75th and 50th percentiles respectively of its 2007-2016 time series (Table 9) but recommended these reference points be re-evaluated in 3-5 years.

Science Advice: Re-Evaluation of the VLM Reference Points

In 2022 a separate workshop was convened by the Oyster Industry Scientific Steering Committee (OISSC) to assess whether the reference points designated for the VLM in 2017 were still appropriate. The OISSC is made up of staff from the New Jersey Department of Environmental Protection, the Haskin Shellfish Research Lab, and members of the Fishing Industry and the Shellfish Council. A summary of the VLM Workshop can be found in Appendix I. Three important management recommendations came from the workshop:

1. *Permanently adopt the LM exploitation reference points for the VLM region.*
2. *When appropriate, consider using transplants from the VLM region to “enhance” the LM region instead of moving them to a Direct Market region.*

3. *Retain the current VLM abundance reference points (75th percentile as the Target and 50th percentile as the Threshold of the 2007-2016 time series).*

The 2023 SARC quickly suggested adopting the first two of these management recommendations but discussed the third one in great detail. Some on the SARC felt that the current reference points were not necessarily aligned with recent SARC recommendations. For example, in 2021 and 2022, the SARC recommended allowing a small transplant from the VLM region even though both the market and total abundance were well below the threshold abundance reference point. It was suggested that the other five management regions would be closed to fishing activity under the same scenario. After a long discussion on the afternoon of 2/2/23 that continued for most of the morning of 2/3/23, the SARC came to a consensus to recommend retaining the current VLM reference points. First, the SARC suggested that the reference points appeared to be appropriate. The VLM region recently demonstrated an ability to move from well below the threshold to above the target in a very short period of time (~5 years). Second, applying caution in this region by using the 50th and 75th percentiles of a time series to calculate the threshold and target seemed appropriate given the region was more prone to large, freshet mortality events than the other five management regions. Third, retaining the reference points was the consensus recommendation that came out of the workshop convened specifically to address this issue and the SARC agreed with that recommendation. Fourth, regarding recent SARC recommendations being at odds with these cautious reference points, the SARC felt that while abundance reference points are generally given primacy regarding management recommendations, and further informed by "Additional Population Indicators" and "Exploitation Rate Flexibility", both defined in Table 5 of this document, there could be extraordinary circumstances that allow harvest even when all abundance measures are below their respective threshold reference points. The SARC felt that retaining the current reference points was appropriate to provide the SARCs discretion to debate whether extraordinary circumstances exist on an annual basis, rather than lowering the reference points to conform to very recent management recommendations, and thereby enshrining that harvest is permitted.

A total of 240 grids were sampled to estimate the status of the stock in 2022 (Figure 15). The total abundance increased but was again below the target, though the market abundance remains well above the target (Figures 16a, b, 17). Spatfall increased by an order of magnitude in 2022 and was comparable to the large recruitment events estimated in 2016 and 2017 (Figure 16c). A period of above average water temperature and salinity as well as lower than average Delaware River discharge between July and September 2022 may have influenced recruitment (Bushek et al. 2023). Natural mortality increased slightly from 2021 to 2022 (Figure 16d) but remained low relative to the current decade and the 'dermo era' that began in 1990 (Figures 3a, 16.2d).

The three Intermediate Transplant Regions (VLM, LM, MMT) all have similar acreage (Figure 2). Figures 18-23 summarize the 10-year trends of the stock in these regions. The uppermost region, VLM, experienced an influx of freshwater over a long duration in both 2018 and 2019 resulting in massive die-offs (34% and 35% mortality, respectively in 2018 and 2019; Figure 18d). Total abundance fell below the threshold in the years following these back-to-back mortality events. Natural mortality continued a three-year decline in 2022 which has likely contributed to the increase in both total and market abundance between 2020 and 2022. However, both total and market abundance remain well below the threshold (Figure 18c, Table 10). Total abundance on this region has been demonstrated to increase quickly during periods of low natural mortality and high recruitment (Figure 18a, d, e; 2013-2016). However, this region also has a very slow growth rate compared to regions further downbay, and it will therefore likely take some time before the market abundance moves above the threshold again (Figures 18c, 24, Table 10). Sub-market abundance increased for a third year in a row, likely due to a very large recruitment event on the region in 2022 (Figures 18c, e). Dermo remained nearly undetectable (Figure 18b). Oysters were transplanted from the VLM region for the first time since 2013 (Figure 18f).

As was the case on the VLM region, natural mortality on the LM region declined slightly in 2022 relative to 2018-2020 (Figure 19d). This, coupled with the highest recruitment event in the long-term time series (Figure 19e), resulted in total abundance reaching the target reference point for the first time since 2019 (Figures 19a, c, d, 24). Market abundance nearly doubled relative to 2021 and remains above the target as it has been for all of the recent time series (Figure 19c, Table 10). The 2022 LM transplant resulted in an exploitation rate of 1.66%. However, because oysters were also added to the region from the VLM transplant, the realized exploitation rate for the region was -0.5% (Figure 19f).

Total abundance, market abundance, and natural mortality on the MMT region was relatively unchanged from what was observed in 2020 and 2021 (Figures 20a, c, d, e). This resulted in little change in where the stock (total abundance and market abundance) stands relative to the target and threshold reference points (Figures 20c, 24, Table 10). Spat abundance on the region was the highest since the large recruitment events in 2016 and 2017. Dermo levels increased slightly in 2022 but remained below the 1.5 threshold where natural mortality begins to increase above background levels (Figure 20b). Oysters transplanted from the MMT region in 2022, resulting in an exploitation rate of 2.15% (Figure 20f).

Direct market harvesting occurs in the two largest (HM, MMM) and the smallest (SR) regions (Figure 2). Figures 21-23 summarize the 10-year trends of the stock in these regions. Natural mortality on the MMM region remained low relative to the recent time series despite a small increase in 2022 (Figure 21d). Market abundance on this region declined to fall just below the target and although total abundance also declined, it remained above its threshold (Figures 21a, c, 24, Table 10). Recruitment on the MMM more than doubled relative to 2021 and likely led to the small increase in sub-market abundance (Figures 21e, c). The 2022 exploitation rates on the MMM region were 1.9% and 2.8% respectively on all and market sized oysters, comparable to most other years in the recent time series (Figure 21f). Dermo levels in 2022 remained relatively unchanged from the previous two years (Figure 21b).

Total abundance on the SR region increased in 2022 but remains between the threshold and target reference points (Figure 22a, 24, Table 10). Market abundance remained above the target with little change from 2021 (Figure 22c, Table 10). While natural mortality was relatively unchanged from 2021, dermo levels decreased to fall at exactly 1.5, the threshold at which mortality increases above background levels of natural mortality (Figure 22b, Table 10). As in other regions, recruitment on the SR region increased in 2022 and was the highest it has been since the 2016-2017 spatfall that led to record high numbers of sub-market and total oysters on the region (Figures 22c, e). The 2016-2017 spatfall, and subsequent increase in small oysters, was likely what led to two years of record high numbers of market-sized oysters on the SR region. The exploitation rate of market-sized oysters in 2022 in the SR region was 5.1% relative to market-sized oysters and 2.6% relative to all sizes (Figure 22f).

Although total abundance remains below the threshold on the HM region and market abundance decreased to fall below the target, there has been little change in the overall stock status relative to reference points (Figures 23a, c, 24, Table 10). Spat abundance increased on the region in 2022, but the increase was small compared to other regions (Figure 23e). Natural mortality increased while dermo levels decreased for the second year in row (Figure 23d). The exploitation rate of all oysters in 2022 was 6.4% while the exploitation of market-sized oysters was 10.1% (Figure 23f).

IV. SARC EXPLOITATION RATE AND AREA MANAGEMENT RECOMMENDATIONS

Upon review of the status of the stock, the 2023 SARC made the recommendations listed below for each management region. These recommendations are also summarized in Table 11. With the exception of the VLM region, there was very little discussion by the SARC on what exploitation rates to recommend. The general consensus was that, with the exception of the LM region where abundance increased, there was little change from the previous year in the stock status relative to the reference points. For all Direct Market Regions, the SARC therefore felt comfortable with recommending the median exploitation rate if no transplant to that region occurs and the maximum exploitation rate if a transplant to that region does occur. For the MMT and LM regions, the SARC felt comfortable recommending the maximum exploitation rate. On the VLM region, where the total abundance and market abundance remained below their respective threshold reference points, the SARC recommended allowing up to a 0.0149 exploitation rate. The SARC provided a few reasons for recommending a transplant from this region even though the region was below the threshold abundance reference points. First, the largest recruitment event ever observed on the VLM region occurred in 2022. The SARC expressed an interest in seeing some of these recruits moved downbay where they may be less prone to freshwater-induced mortality. Second, given there is some evidence that the VLM region contributes relatively little to the larger population, these recruits were thought to potentially be more valuable if moved to another management region (Appendix I). Finally, fishing industry SARC members suggested that the transplant activity that occurred on the VLM region in 2022, the first in 10 years, may have enhanced recruitment on the region and therefore expressed an interest in seeing another small transplant from the region in 2023.

- A transplant up to a 0.0149 exploitation rate could be moved from the Very Low Mortality region.
- A transplant of up to a 0.0226 maximum exploitation rate can occur on the Low Mortality region with no requirement for a transplant.
- A transplant up to a 0.0246 maximum exploitation rate could be moved from the Medium Mortality Transplant region.
- The Medium Mortality Market region can be fished up to its median exploitation rate (0.0303) with no requirement for a transplant. If a transplant occurs on the region, the exploitation rate could be increased to its maximum of 0.0370.
- The Shell Rock region can be fished up to its median exploitation rate (0.0370) with no requirement for a transplant. If a transplant occurs on the region, the exploitation rate could be increased to its maximum of 0.0488.
- The High Mortality region can be fished up to its median exploitation rate (0.0749) with no requirement for a transplant. If a transplant occurs on the region, the exploitation rate could be increased to its maximum rate of 0.0982.

V. STATEMENT OF SUSTAINABILITY

There has been general consensus by the Stock Assessment Review Committee (SARC) over recent years that the New Jersey Delaware Bay oyster fishery is being managed sustainably although there has been some debate about the language used to describe it and how it should be evaluated. A point of discussion has been the definition of sustainability used in the Magnuson-Stevens Act for federal fisheries that depends on population models and theory in the absence of strong empirical data on abundance and mortality. The Delaware Bay, NJ oyster stock assessment contains robust measures of abundance, natural mortality, and fishing mortality. Upon review of the oyster stock abundance, the exploitation time series, and management practices from 1996 to present, the 2023 SARC recommended continued acceptance of the following statement for the New Jersey Delaware Bay oyster fishery initially crafted by the 2017 SARC:

> The New Jersey Delaware Bay oyster fishery is sustainable under current fishery management strategies and prescribed exploitation rates.

VI. SARC SCIENCE ADVICE

In addition to continuing the core assessment and monitoring programs, including the Assessment Survey, the Resurvey/Restratification Program, the Dock Monitoring Program, the Dermo Monitoring Program, and the Shellplant and Transplant Monitoring Program, the 2023 SARC recommended the following list of science advice (not ordered by priority):

2023 SARC Science Advice:

- Revisit region naming conventions; consider upper, middle, lower bay
- Should the SARC consider removing the VLM from the Sustainability Statement?
- Test for correlation between seasonal fishing effort and seasonal recruitment

Unfinished SARC Science Advice:

- Plot both exploitation and market-size exploitation by bed for bed-level trends plots.
- Create a bed simulator to test impact of mis-stratification on the assessment.
- Test for autocorrelation for key stock indicators.
- Include fishing exploitation in longer-term appendices.
- For carrying capacity analyses, consider pooling beds with similar characteristics (e.g. M, growth rate) and consider using time-varying estimates of r an K.
- Coordinate with NJDEP as time and funds permit to address two items related to dredge capture efficiency:
    - Evaluate whether patent tongs are really 100% efficient on the Delaware Bay reefs.
    - Take patent tong grabs during the Assessment Survey to get annual estimates of capture efficiency on each bed.
- Survey error:
    - Report on how survey error changes if we use the combined survey and gear CVs instead of bootstrapping.

- After splitting apart survey and gear efficiency error, how much has increased sampling intensity over the last several years reduced survey error?

- Explore mechanisms (environmental, disease resistance) driving declines in natural mortality.

- Continue to explore population models using the Assessment Survey data.

- Develop specific, testable hypotheses for why Shell Rock is so productive. For example, are there synergistic effects leading to more dramatic patterns than one would expect from the gradient(s) alone.

References

Abbe, G.R., 1988. Population structure of the American oyster, *Crassostrea virginica*, on an oyster bar in central Chesapeake Bay: changes associated with shell planting and increased recruitment. *J. Shellfish Res.,* 7, 33-40.

Ashton-Alcox, K.A., E.N. Powell, J.A. Hearon, C.S. Tomlin, R.M. Babb. 2013. Transplant Monitoring for the New Jersey Delaware Bay Oyster Fishery. *J. Shellfish Res.,* 32: 2, 459-469.

Ashton-Alcox, K.A., D. Bushek, J.E. Gius, 2014. Stock Assessment Workshop New Jersey Delaware Bay Oyster Beds (16th SAW) Report. *Haskin Shellfish Res. Lab.*, Port Norris, NJ. 105pp.

Ashton-Alcox, K.A., D. Bushek, J.E. Gius, 2015. Stock Assessment Workshop New Jersey Delaware Bay Oyster Beds (17th SAW) New Jersey Delaware Bay Oyster Beds Final Report. *Haskin Shellfish Res. Lab.*, Port Norris, NJ. 117pp.

Ashton-Alcox, K.A., D. Bushek, J.E. Gius, J. Morson, D. Munroe, 2016. Stock Assessment Workshop New Jersey Delaware Bay Oyster Beds (18th SAW) New Jersey Delaware Bay Oyster Beds Final Report. *Haskin Shellfish Res. Lab.*, Port Norris, NJ. 153pp.

Ashton-Alcox, K.A., D. Bushek, J.E. Gius, J. Morson, D. Munroe, 2017. Stock Assessment Workshop New Jersey Delaware Bay Oyster Beds (19th SAW) New Jersey Delaware Bay Oyster Beds Final Report. *Haskin Shellfish Res. Lab.*, Port Norris, NJ. 120pp.

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

Bushek, D., I. Burt, E. McGurk. 2023. Delaware Bay New Jersey Oyster Seedbed Monitoring Program; 2012 Status Report. *Haskin Shellfish Res. Lab.*, Port Norris, NJ. 27pp.

Fegley, S. R., S. E. Ford, J. N. Kraeuter & D. R. Jones. 1994. *Relative effects of harvest pressure* *and disease mortality on the population dynamics of the Eastern oyster (Crassostrea virginica) in Delaware Bay*. NOAA, Final Rpt # NA26FL0588. Bivalve, NJ: Haskin Shellfish Research Laboratory, Rutgers University. 36pp text, 28 tables, 58 Figures.

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 oyster disease and harvest: the role of management. *J. Shellfish Res.* 22:451-464.

Ford, S.E. 1997. History and present status of molluscan shellfisheries from Barnegat Bay to Delaware Bay. In: *The History, Present Condition, and Future of the Molluscan Fisheries of North and Central America and Europe, Vol. 1, North America* (MacKenzie, C.L., Jr., V.G. Burrell Jr., A. Rosenfield and W.L. Hobart, Eds.) pp. 119-140. U.S. Dept. of Commerce, NOAA Tech. Report NMFS, Seattle, WA.

Ford, S.E. and H.H. Haskin. 1982. History and epizootiology of *Haplosporidium nelsoni* (MSX), an oyster pathogen in Delaware Bay, 1957-1980. *J. Invertebr. Pathol.* 40:118-141.

Ford, S.E. and D. Bushek. 2012. Development of resistance to an introduced marine pathogen by a native host. *J. Mar. Res*. 70:205-223.

Hofmann, E., D. Bushek, S. Ford, X. Guo, D. Haidvogel, D. Hedgecock, J. Klinck, C. Milbury, D. Narvaez, E. Powell, Y. Wang, Z. Wang, J. Wilkin and L. Zhang. 2009. Understanding how disease and environment combine to structure resistance in estuarine bivalve populations. *Oceanography.* 22:212-231.

Kimura, D. K. and D. A. Somerton. 2006. Review of statistical aspects of survey sampling for marine fisheries. Reviews in Fisheries Science 14: 245-283.

Kraeuter, J.N., E.N. Powell, K.A. Ashton-Alcox, 2006. Report of the 2006 Stock Assessment Workshop (8th SAW) for the New Jersey Delaware Bay Oyster Beds. *Haskin Shellfish Res. Lab.*, Port Norris, NJ. 95pp.

Kraeuter, J.N., E.N. Powell, K.A. Ashton-Alcox, 2007. Oyster growth analysis: a comparison of methods. *Journal of Shellfish Research* 26: 479-491.

Mann, R. and E.N. Powell. 2007. Why oyster restoration goals in the Chesapeake Bay are not and probably cannot be achieved. *J. Shellfish Res*. 26:4, 905-917.

Mann, R., M. Southworth, R. B. Carnegie, and R. K. Crockett. 2014. Temporal variation in fecundity and spawning in the Eastern oyster, *Crassostrea virginica*, in the Piankatank River, Virginia. *Journal of Shellfish Research* 33: 167-176.

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

Morson, J. M., D. Bushek, and J. Gius. 2019. Stock Assessment Workshop New Jersey Delaware

Bay Oyster Beds (21st SAW) Final Report. *Haskin Shellfish Res. Lab.*, Port Norris, NJ. 80pp.

Morson, J. M., D. Bushek, and J. Gius. 2021. Stock Assessment Workshop New Jersey Delaware Bay Oyster Beds (23rd SAW) Final Report. *Haskin Shellfish Res. Lab.*, Port Norris, NJ. 71pp.

Munroe, D., A. Tabatabai, I. Burt, D. Bushek, E.N. Powell & J. Wilkin. 2013. Oyster mortality in Delaware Bay: Impacts and recovery from Hurricane Irene and Tropical Storm Lee. *Estuarine, Coast. & Shelf Sci*. 135:209-219.

Munroe, D., S. Borsetti, K. Ashton-Alcox, & D. Bushek. 2017. Early post-settlement growth in wild Eastern oyster (*Crassostrea virginica* Gmelin 1791) populations. *Est. & Coasts* 40:880-888.

Powell, E.N., J.N. Kraeuter, S.E. Ford, 2001. Report of the 2001 Stock Assessment Workshop (3rd SAW) for the New Jersey Delaware Bay Oyster Beds. *Haskin Shellfish Res. Lab.*, Port Norris, NJ. 53pp.

Powell, E.N., K.A. Ashton-Alcox, J.A. Dobarro, M. Cummings, and S.E. Banta. 2002. The inherent efficiency of oyster dredges in survey mode. *J. Shellfish Res*. 21:691-695.

Powell, E.N., J.J. Gendek, K.A. Ashton-Alcox. 2005. Fisherman choice and incidental catch: Size frequency of oyster landings in the New Jersey oyster fishery. *J. Shellfish Res.* 24:469-476.

Powell, E.N., J.N. Kraeuter and K.A. Ashton-Alcox. 2006. How long does oyster shell last on an oyster reef? *Estuar. Coast. Shelf Sci.* 69:531-542.

Powell, E.N. and J.M. Klinck. 2007. Is oyster shell a sustainable estuarine resource? *J. Shellfish Res.* 26:181-194.

Powell, E.N., K.A. Ashton-Alcox, J.N. Kraeuter. 2007. Re-evaluation of eastern oyster dredge efficiency in survey mode: application in stock assessment. *N. Am. J. Fish. Manage.* 27:492-511.

Powell, E.N., J.N. Kraeuter, K.A. Ashton-Alcox, 2008a. Report of the 2008 Stock Assessment Workshop (10th SAW) for the New Jersey Delaware Bay Oyster Beds. *Haskin Shellfish Res. Lab.*, Port Norris, NJ. 131pp.

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

Powell, E.N., J.M. Klinck, K.A. Ashton-Alcox, J.N. Kraeuter. 2009. Multiple stable reference points in oyster populations: implications for reference point-based management. *Fish. Bull.* 107:133-147.

Powell, E.N., K.A. Ashton-Alcox, D. Bushek, 2012a. Report of the 2012 Stock Assessment Workshop (14th SAW) for the New Jersey Delaware Bay Oyster Beds. *Haskin Shellfish Res. Lab.*, Port Norris, NJ. 190pp.

Powell, E.N., J.M. Klinck, K.A. Ashton-Alcox, E.E. Hofmann, & J. Morson. 2012b. The rise and fall of *Crassostrea virginica* oyster reefs: The role of disease and fishing in their demise and a vignette on their management. *J. Mar. Res*., 70, 505-558.

Table 1. Timeline of surveys and monitoring programs that comprise the data presented in this report. For a detailed explanation of survey design changes see "The Assessment Survey" in the "Historical Overview" section of this report.

Annual Stock Assessment Survey – Timeline and Changes	
1953 – 1988	Small boat/dredge used for the survey; no size data collected; no sampling of VLM region; no swept area data collected; not all high/medium quality strata sampled
1989 – 1998	Changes: Commercial boat/dredge used for the survey; began collecting size data; remaining methods the same as above
1999 – 2007	Changes: Began collecting swept area; remaining methods the same as above
2008 – present	Changes: Restratified the beds; all high/medium quality strata now sampled; VLM region now sampled

Other Annual Programs	
2009 – Present	Resurvey/Restratification Program
1990 – Present	Dermo Monitoring Program
2004 – Present	Port Sampling Program

Harvest Methods	
Pre-1996	Bay Season Fishery
1996 - Present	Direct Market Fishery

Table 2. Catchability coefficients for oysters, boxes, and cultch by region. The entire time series since 1953 was reconstituted using these catchability coefficients as of 2016 SAW.

	Catchability Coefficient		
Region	**Oyster**	**Box**	**Cultch**
Very Low Mortality	2.41	6.82	9.11
Low Mortality - *Round Island*	2.41	6.82	9.11
Upper Arnolds, Arnolds	8.26	12.69	25.79
Medium Mortality Transplant	8.26	12.69	25.79
Medium Mortality Market	8.26	12.69	25.79
Shell Rock	8.26	12.69	25.79
High Mortality	2.82	5.10	8.46

Table 3. Restratification survey (resurvey) schedule. Fishing Creek, Sea Breeze, and Egg Island were resurveyed in 2022. Upper Arnolds and New Beds are scheduled for resurvey in 2023.

Region	Bed	# Grids	# Full Resurveys	Latest Resurvey	10-Year Schedule
VLM	Hope Creek	97	2	2017	2027
	Fishing Creek	67	2	2022	2032
	Liston Range	32	2	2016	2026
LM	Round Island	73	2	2018	2028
	Upper Arnolds	29	2	2013	**2023**
	Arnolds	99	2	2015	2025
MMT	Upper Middle	84	2	2020	2030
	Middle	51	2	2021	2031
	Sea Breeze	48	2	2022	2032
MMM	Cohansey	83	2	2019	2029
	Ship John	68	2	2020	2030
SR	Shell Rock	93	3	2016	2026
HM	Bennies Sand	49	3	2019	2029
	Nantuxent	68	3	2018	2028
	Bennies	171	2	2014	2024
	Hog Shoal	23	2	2016	2026
	Strawberry	29	2	2015	2025
	Hawk's Nest	28	2	2017	2027
	New Beds	112	2	2013	**2023**
	Beadons	38	3	2021	2031
	Vexton	47	3	2021	2031
	Egg Island	125	1	2022	2032
	Ledge	53	1	2021	2031

Table 4. Groups and responsibilities for managing the oyster fishery of Delaware Bay, NJ.

Group	Members	Duties
Rutgers Haskin Shellfish Research Laboratory	HSRL faculty and staff	Design/analyze stock assessment. Execute surveys with industry and NJDEP assistance. Address science needs. Host and facilitate SAW. Prepare SAW report.
Oyster Industry Science Steering Committee	HSRL Shellfish Council NJDEP	Prioritize science agenda and mgmt. strategies. Nominate SARC membership.
Stock Assessment Review Committee	Academics: RU & other Managers: NJDEP & other Industry	Peer review of assessment. Recommend harvest rates & area mgmt. by region. Provide science advice.
Shellfish Council	Industry	Select harvest rate & area mgmt. activities from SARC recommendations. Plan/approve disbursement of industry-imposed harvest taxes.
New Jersey Department of Environmental Protection	Biologists Managers Statisticians Enforcement Administrators	Approve decisions impacting public oyster resource. Lead/coordinate mgmt. activities. Monitor harvest and enforce regulations. Collect, maintain & disperse industry-imposed harvest taxes.

Table 5. Control Rules and Management Program. Control Rules were formally adopted at the 2016 SAW and contain updates from the 2017 SAW. They articulate the basic process used to manage the New Jersey Delaware Bay Oyster Fishery.

1. *Area Management*: Harvest and transplant activities are set by region (3 harvest and 3 transplant regions) to help ensure that no area receives more harvest pressure than it can sustain and enhancement efforts are appropriately directed.

2. *Baseline Abundance Targets*: The 2006 SARC set the target and threshold total abundances for each region as the median and ½ the median for the time series 1989-2005, inclusive. Those for market-size oyster (>2.5") abundances are set the same way using 1990-2005 because length measurements for oysters began in 1990. Both time series represent the beginning of the current Dermo era to the year prior to the institution of the reference points. Both periods include highs and lows of recruitment, growth, disease and mortality. For the VLM, the 2017 SARC advised use of the 75th percentile of its 2007-2016 time series as a target and the 50th percentile as the threshold for total and market-size abundance with the proviso that this be re-evaluated in three to five years.

3. *Additional Population Indicators*: Trends in abundance, recruitment, disease, mortality and other factors are examined and summarized (regional panels and stoplight table) to develop expectations of population change in the coming year(s) and to inform harvest and management decisions.

4. *Exploitation Targets*: The 2006 SARC set regional exploitation rate targets as the medians of the realized exploitation rates from the beginning of the Direct Market in 1996 to 2005 (later 2006). The 2016 SARC updated the targets as the median exploitation rate realized from 2007-2015.

5. *Exploitation rate flexibility*: The 2006 SARC set flexibility around the regional median exploitation rates (1996-2006) generally as the 40th and 60th percentiles. The 2016 SARC set flexibility between the bounds of the 2007 – 2015 max and min realized exploitation rates. Movement away from the median requires justification based upon the status of the stock, its position relative to targets and thresholds, anticipated changes to the stock, or management activities. Movement away from the median should be in percentage points, generally increments of 10% for simplicity. Strong justification is required for movement above these bounds since they have proven sustainable for the fishery.

6. *Enhancement Tools*: Shellplanting and transplanting are enhancement tools used to facilitate sustainable management. Shellplanting places non-spatted or spatted shell in areas where additional cultch can enhance recruitment. Transplanting relocates culled oysters from non-harvestable regions to Direct Market regions via the Intermediate Transplant Program.

7a. *Transplant Recipient Exploitation*: For any market region, the SARC may recommend two exploitation rates. The first would be the maximum recommended rate without a transplant. The second would be a higher rate allowed if a transplant occurs. Harvest in the region may begin at the lower rate and move to the higher rate only after a transplant has occurred. Market-size oysters that are transplanted to the region are added to the region's quota.

7b. *Transplant Donor Exploitation*: Annual exploitation rate recommendations for transplant regions are made by the SARC. Resource managers will direct transplant harvests to minimize the cultch fraction transplanted, ideally to < 25%, directing transplant vessels to new sites in the region as necessary.

Table 6. Direct market and transplant bushel summaries 2013-2022. Beds arranged upbay to downbay and color-coded by region. (a) Direct market bushels harvested, including those replanted to leases. (b) Intermediate transplant bushel removals. Sea Breeze was part of the MMM until 2011; it is now MMT. Beds without removals were omitted. A transplant did not take place in 2020.

a. Direct Market

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Sea Breeze	5,454	542								
Cohansey	10,583	8,652	10,669	12,475	20,687	8,709	7,253	12,238	3,760	242
Ship John	19,279	24,295	19,837	19,938	16,331	22,021	25,037	2,751	23,611	24,685
Shell Rock	24,280	23,589	29,629	31,794	38,189	31,872	28,761	46,765	42,033	25,707
Bennies Sand	10,841	3,038	6,301		22,339	23,395	13,911	6,014	8,145	3,311
Bennies	870	8,010	10,712	29,293	23,071	21,626	7,126	60	8,223	37,459
Nantuxent	10,218	5,154	5,267	2,101	628	11,347	17,575	26,461	28,254	12,860
Hog Shoal	2,385	3,425	103		1,756	283	9,445	2,201	758	
New Beds	226		4,912	4,494	1,143	89			1,410	
Strawberry	140									
Hawk's Nest		205								
Total	**84,276**	**76,910**	**87,430**	**100,095**	**124,144**	**119,342**	**109,108**	**96,490**	**116,194**	**104,264**

b. Transplants

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Hope Creek										2,700
Liston Range	550									
Round Island	2,250									
Upper Arnolds	15,550		10,200							2,500
Arnolds	2,700	15,500		4,800			7,200	0	5,400	5,400
Upper Middle	3,200				3,200	4,750		0	2,650	2,700
Middle	5,200	6,600	5,550	8,150	21,350	27,500	25,000	0	13,400	5,400
Sea Breeze	6,200	7,300	10,800	2,400	4,700	7,700	8,800	0	2,700	10,800
Total	**35,650**	**29,400**	**26,550**	**15,350**	**29,250**	**39,950**	**41,000**	**0**	**24,150**	**29,500**

Table 7. Council-chosen and fishery-achieved exploitation rates for 2022 for (a) Direct Market regions and (b) Transplant regions. Direct market exploitation rates include market-size (≥ 2.5”) oysters only. Transplant exploitation rates include all sizes of oysters. Small oysters and shell are culled during both transplant and harvest.

a. Direct Market

Region	Highest SARC Exploit. Option	Council Choice	Achieved Expl. Rate	Chosen Market Bushels	Add'l Quota Bushels	Achieved Total Bushels
MMM	Median 3.03% *no transplant req'd.*	3.03%	2.83%	24,960	0	24,927
SR	Max 4.88% *transplant req'd*	4.88%	5.09%	24,046	1,417	25,707
HM	Max 9.82% *transplant req'd*	9.82%	10.17%	43,025	9,040	53,630
			Totals	92,031	10,457	104,264
					Estimated Quota	**Unharvested Bushels**
					102,488	0

b. Transplant

Region	Highest SARC Exploit. Option	Council Choice	Achieved Expl. Rate	Chosen Oysters Moved	Achieved Oysters Moved	Under/Over
VLM	1.93%	1.93%	1.36%	1,484,417	1,046,387	-438,030
LM	1.49%	1.49%	1.66%	3,030,154	3,366,124	335,970
MMT	2.46%	2.46%	2.15%	5,524,254	4,837,920	-686,334

Table 8. Detailed history of transplant efforts since 2014. Due to COVID-19 restrictions, a transplant did not take place in 2020.

Year	Region	Donor Bed	Receiver Bed	Bushels Moved	Total # Oysters	Fraction Oysters < 2.5"	Number Oysters ≥ 2.5"	Added Quota Allocation	Fraction Cultch	Chosen Expl. Rate	Achieved Expl. Rate	# Oysters at Chosen (all sizes)	# Oysters at Achieved (all sizes)
2022	VLM	Hope Creek	Upper Arnolds	2,700	1,046,387	0.960	41,339	154	0.597	1.93%	1.36%	1,484,417	1,046,387
	LM	Upper Arnolds	Shell Rock	2,500	1,386,018	0.826	241,547	901	0.322	1.49%	1.66%	3,030,154	3,366,124
		Arnolds	Shell Rock	5,400	1,980,106	0.845	306,252	1,143	0.538				
	MMT	Upper Middle	Bennies Sand	2700	544,825	0.744	139,260	520	0.650	2.46%	2.15%	5,524,254	4,837,920
		Middle	Bennies Sand	5400	1,481,666	0.564	645,894	2,410	0.491				
		Sea Breeze	Bennies Sand	10800	2,811,429	0.318	1,916,946	7,153	0.292				
2021	LM	Arnolds	Shell Rock	5,400	2,601,798	0.900	260,180	974	0.472	0.76%	0.94%	2,097,973	2,601,798
	MMT	Upper Middle	Bennies	2,650	659,794	0.733	176,218	660	0.573	2.46%	2.50%	6,297,118	6,401,396
		Middle	Bennies	2,700	997,139	0.481	517,274	1,937	0.199				
		Middle	Nantuxent	10,700	3,935,479	0.535	1,829,275	6,851	0.263				
		Sea Breeze	Bennies	2,700	808,984	0.279	583,363	2,185	0.206				
2020	*NO TRANSPLANT CONDUCTED*												
2019	LM	Arnolds	Shell Rock	7,200	2,837,705	0.828	489,430	1,861	0.449	2.26%	0.70%	8,941,378	2,837,705
	MMT	Middle	Bennies Sand	25,000	9,890,349	0.748	2,496,843	9,494	0.288	2.46%	2.79%	12,158,274	13,956,501
		Sea Breeze	Bennies Sand	8,800	4,066,152	0.768	941,483	3,580	0.206				
2018	MMT	Upper Middle	Bennies	4,750	973,690	0.527	460,846	1,752	0.566	2.46%	1.76%	15,785,722	12,310,312
		Middle	Bennies	27,500	8,230,069	0.507	4,054,033	15,415	0.329				
		Sea Breeze	Bennies	7,700	3,106,553	0.759	749,703	2,851	0.290				
2017	MMT	Upper Middle	Bennies	3,200	948,685	0.365	602,546	2,282	0.408	2.46%	2.37%	8,184,564	7,887,414
		Middle	Bennies	21,350	5,625,257	0.312	3,868,205	14,652	0.299				
		Sea Breeze	Bennies	4,700	1,313,472	0.515	636,920	2,412	0.219				
2016	LM	Arnolds	Cohansey	4,800	2,168,012	0.637	787,816	2,972	0.290	0.76%	0.96%	1,712,353	2,168,012
	MMT	Middle	Shell Rock	8,150	2,556,215	0.386	1,569,932	5,925	0.280	1.49%	0.97%	3,958,253	2,979,901
		Sea Breeze	Shell Rock	2,400	426,443	0.319	290,458	1,096	0.440				
2015	LM	Upper Arnolds	Ship John	10,200	4,474,515	0.721	1,247,128	4,688	0.330	1.30%	1.30 - 1.90%	3,598,514	4,474,515
	MMT	Middle	Shell Rock	5,550	1,726,335	0.604	682,813	2,567	0.310	2.30%	> 2.30%	4,360,643	4,475,247
		Sea Breeze	Shell Rock	10,800	2,748,912	0.422	1,590,121	5,978	0.250				
2014	LM	Arnolds	Ship John	15,500	6,168,587	0.485	3,174,627	12,025	0.220	2.33%	2.25%	6,403,869	6,134,370
	MMT	Middle	Shell Rock	6,600	1,553,053	0.381	961,033	3,640	0.250	2.33%	2.41%	3,517,430	3,473,086
		Sea Breeze	Shell Rock	7,300	1,922,420	0.390	1,173,115	4,444					

Table 9. Region-specific stock performance targets and thresholds. The targets are the median of total abundance for 1989–2005 and the median of market-size (≥ 2.5”) abundance for 1990–2005. The threshold is taken as half of each target value. VLM values here represent 2017 SARC Science Advice to use the 75th percentiles of the 2007-2016 total and market-size abundance time series as targets and the 50th percentiles as thresholds with the proviso that they be re-evaluated in three to five years.

	Very Low Mortality	Low Mortality	Medium Mortality Transplant	Medium Mortality Market	Shell Rock	High Mortality
Abundance						
Target	150,632,432	391,877,696	414,560,096	747,234,944	313,595,904	438,391,488
Threshold	120,130,688	195,938,848	207,280,048	373,617,472	156,797,952	219,195,744
≥ 2.5” Abund.						
Target	32,061,787	42,075,297	46,566,027	175,051,502	72,910,219	64,446,071
Threshold	16,872,067	21,037,649	23,283,014	87,525,751	36,455,110	32,223,036

Table 10. Color coded summary status of the stock by region in 2022. See key at the bottom for definitions of what each color represents for each metric.

2022 Metrics	*Transplant* Very Low Mortality	*Transplant* Low Mortality	*Transplant* Medium Mortality	*Market* Medium Mortality	*Market* Shell Rock	*Market* High Mortality
Total Abundance						
2022 Percentile (1990-2022)	0.400	0.625	0.312	0.218	0.312	0.250
2022 vs. Target-Threshold						
Market Abundance						
2022 Percentile (1990-2022)	0.266	0.625	0.718	0.375	0.593	0.750
2022 vs. Target-Threshold						
Sub-Market Abundance (< 2.5")						
2022 Percentile (1990-2022)	0.466	0.687	0.500	0.187	0.218	0.062
Spatfall						
2022 Percentile (1990-2022)	1.000	1.000	0.812	0.562	0.600	0.031
Mortality						
2022 Percentile (1990-2022)	0.200	0.093	0.468	0.406	0.531	0.375
Dermo WP						
2022 vs. Category	0.040	0.060	1.208	1.388	1.500	1.422

	Green	**Yellow**	**Orange**
2022 Percentile (1990-2022)	Above the 60th	40th - 60th	Below the 40th
2022 vs. Target/Threshold	Above Target	b/w Target and Threshold	Below Threshold
2022 Dermo Levels	Low (<1.5)	Medium (1.5-2)	High (>2)

Table 11. 2023 SARC recommendations for maximum exploitation rates for each region and the projected quota associated with each decision. *Note that for the Medium Mortality Market, Shell Rock, and High Mortality regions two rates are listed. The first does not require a transplant while the second requires a transplant. **The estimated potential quota bushels from the transplant will always be low relative to what is achieved because the deckloads are culled (removing some of the smaller oysters) before being transplanted to the recipient region.

Transplant Regions[1]

Region	Label	Exploitation Rates of All Sizes	Regional Abundance	Removals	Oysters /Bushel	Approx. Deck Bushels	Proportion Of Oysters That Are Markets From Survey	Estimated Potential Quota Bushels**
VLM		0.0149	86,474,109	1,288,464	503	2,562	10%	256
LM	Max	0.0226	395,479,825	8,937,844	449	19,906	20%	3,981
MMT	Max	0.0246	250,596,989	6,164,686	330	18,681	42%	7,846

Direct Market Regions[2]

Region	Label	Exploitation Rates of Market Sizes	Regional Market Abundance	Removals	Oysters/ Market Bushel	Quota Bushels	Transplant Required?
MMM*	Median	0.0303	170,956,918	5,179,995	269	19,256	No
MMM*	Max	0.0370	170,956,918	6,325,406	269	23,515	Yes
SR*	Median	0.0370	118,822,930	4,396,448	269	16,344	No
SR*	Max	0.0488	118,822,930	5,798,559	269	21,556	Yes
HM*	Median	0.0749	102,176,998	7,653,057	269	28,450	No
HM*	Max	0.0982	102,176,998	10,033,781	269	37,300	Yes

[1]For transplant regions, oysters per bushel is an average from all previous transplants in that region.

[2]For each year the dock monitoring program has been in place, an average total number and an average market number are calculated per market bushel. A grand average is then calculated using all these data.

Figure 1. The natural oyster beds of Delaware Bay, NJ grouped by regional designations. The six regions are named based on long-term disease mortality patterns and management categories that follow the estuarine salinity gradient. From upbay to downbay: Very Low Mortality (dark green), Low Mortality (red), Medium Mortality Transplant (light green), Medium Mortality Market (light blue), Shell Rock (orange), High Mortality (dark blue). Black outlines indicate the complete footprint of each bed.

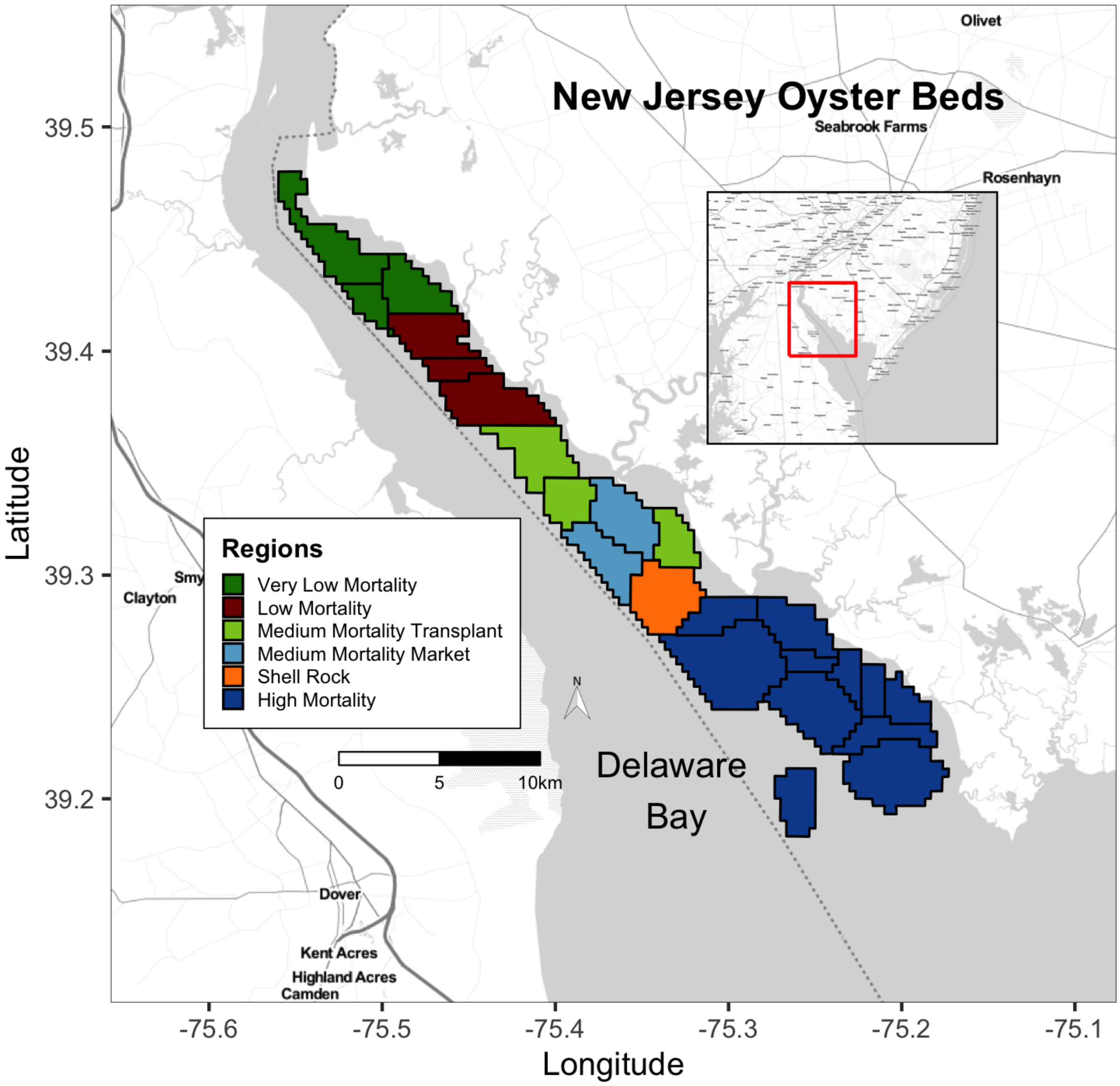


Figure 2. Regional acreage of the assessed NJ Delaware Bay oyster resource. Regions are listed upbay to downbay from left to right. The VLM, LM, and MMT contain three beds each and comprise the Transplant region. The Direct Market region includes the MMM made up of two beds, SR (one bed), and HM with eleven beds. Resource density, population characteristics and population dynamics vary among regions as described elsewhere in this document.

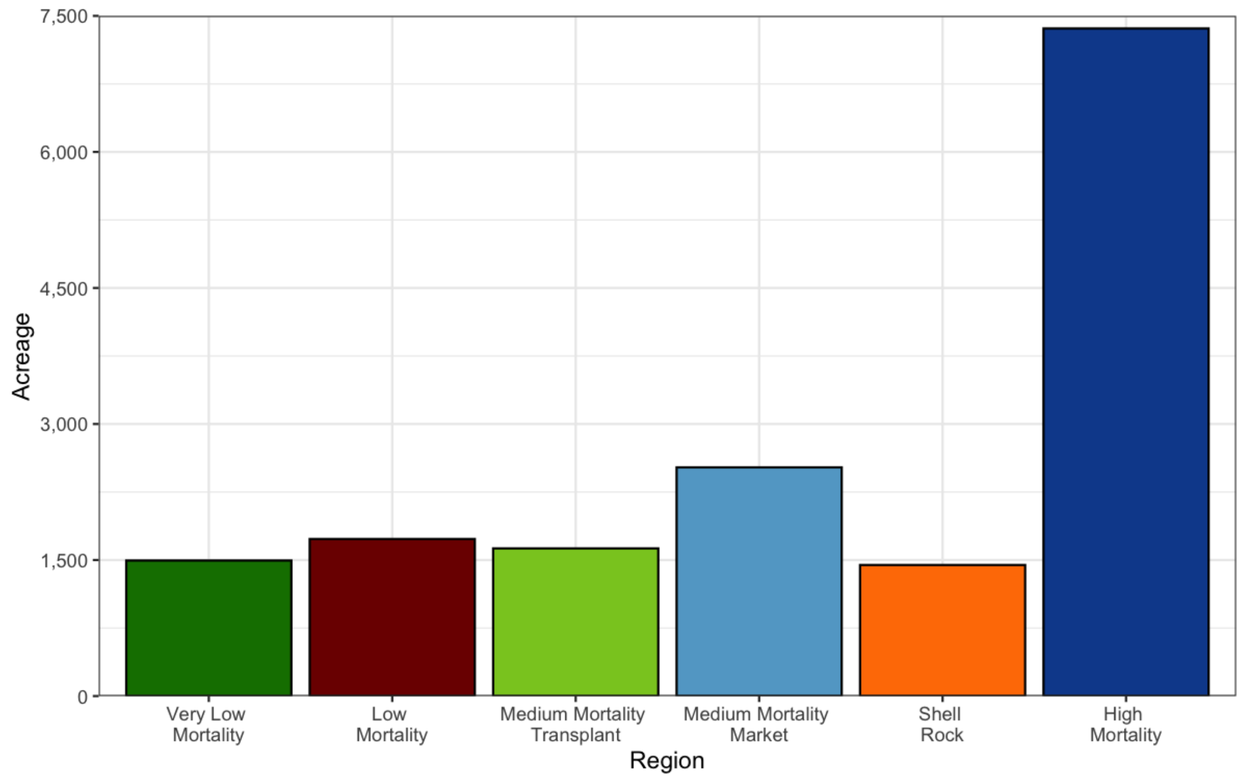
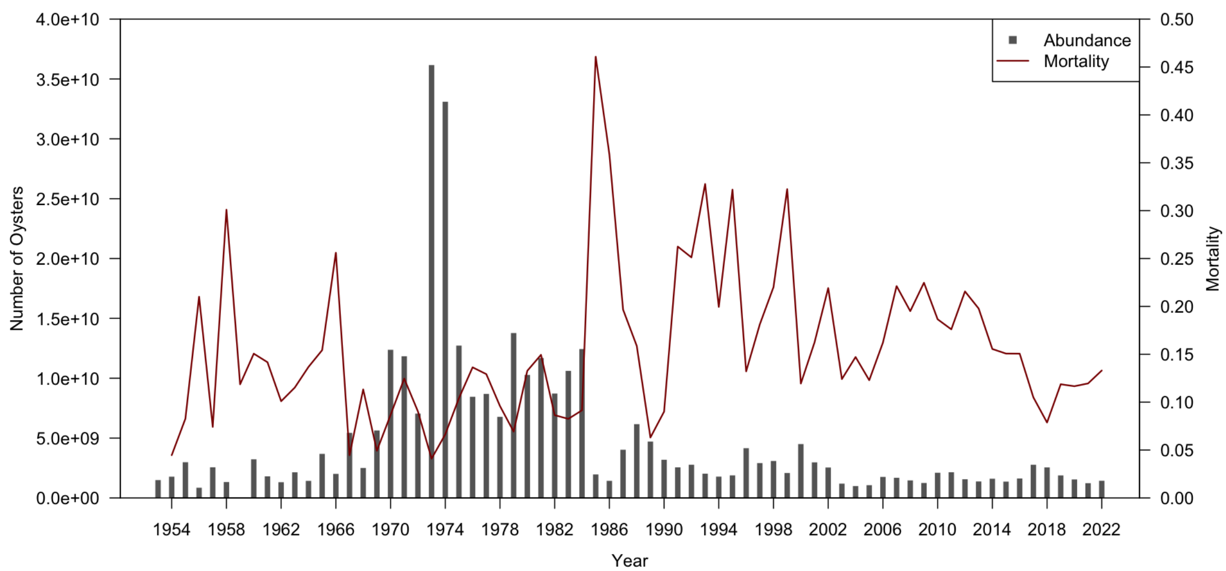


Figure 3. Time series of total oyster abundance (left axes) compared to natural mortality rate (a, right axis) and fishing mortality (b, right axis). Both figures exclude the VLM which was not quantitively surveyed until 2007.

a.



b.

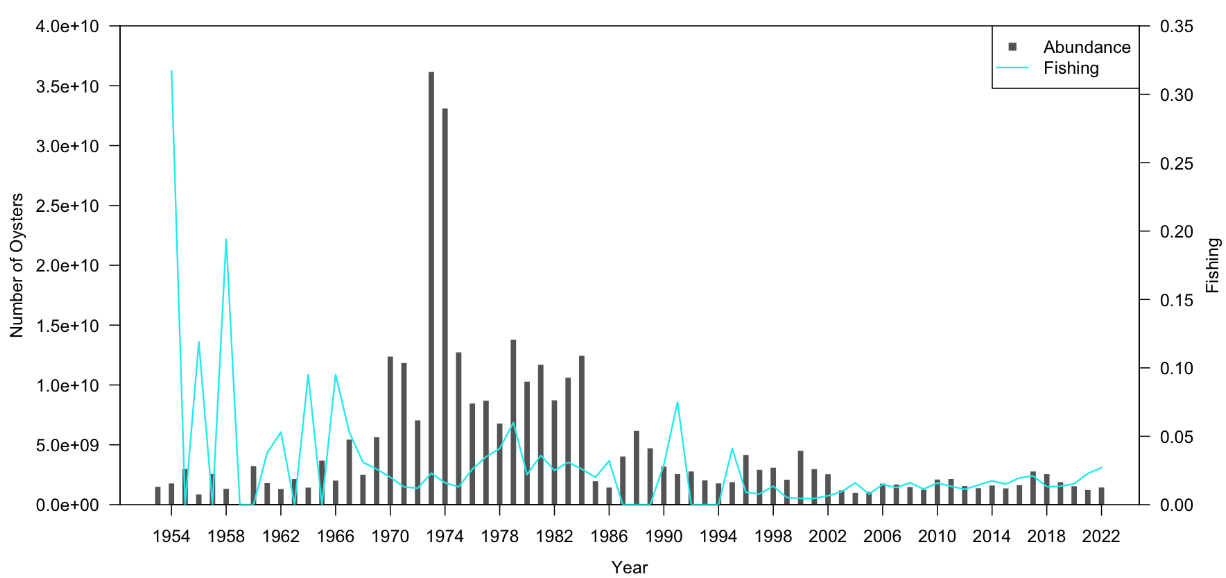
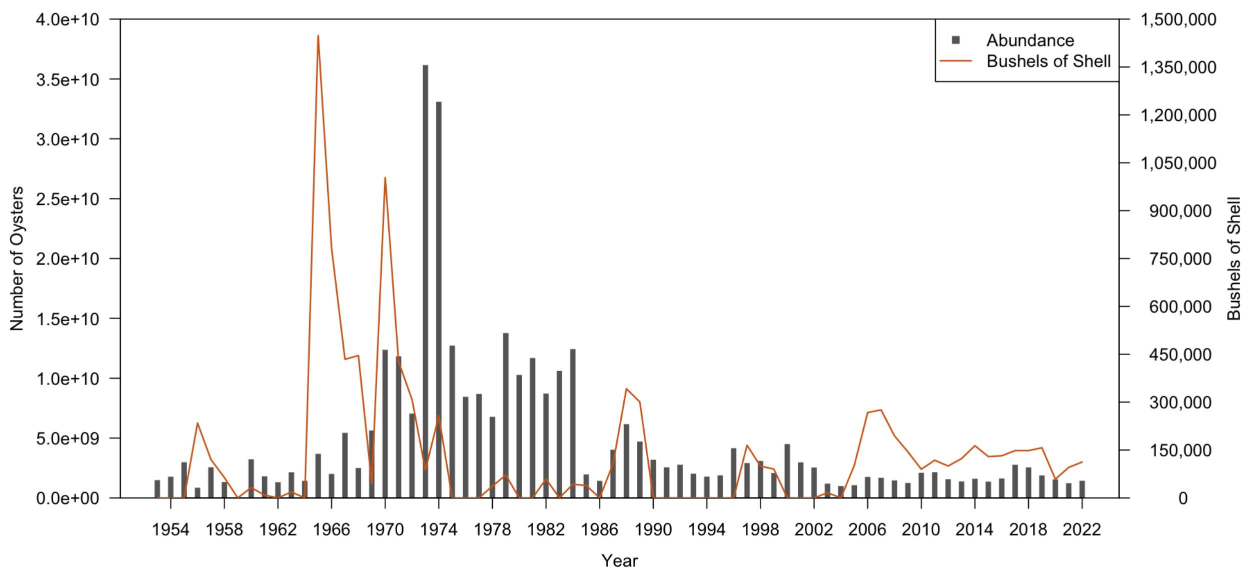


Figure 4. Time series of total oyster abundance (left axes) compared to bushels of shell planted (a, right axis) and total spat abundance from the stock assessment time series (b, right axis). Both figures exclude the VLM which was not quantitively surveyed until 2007.

a.



b.

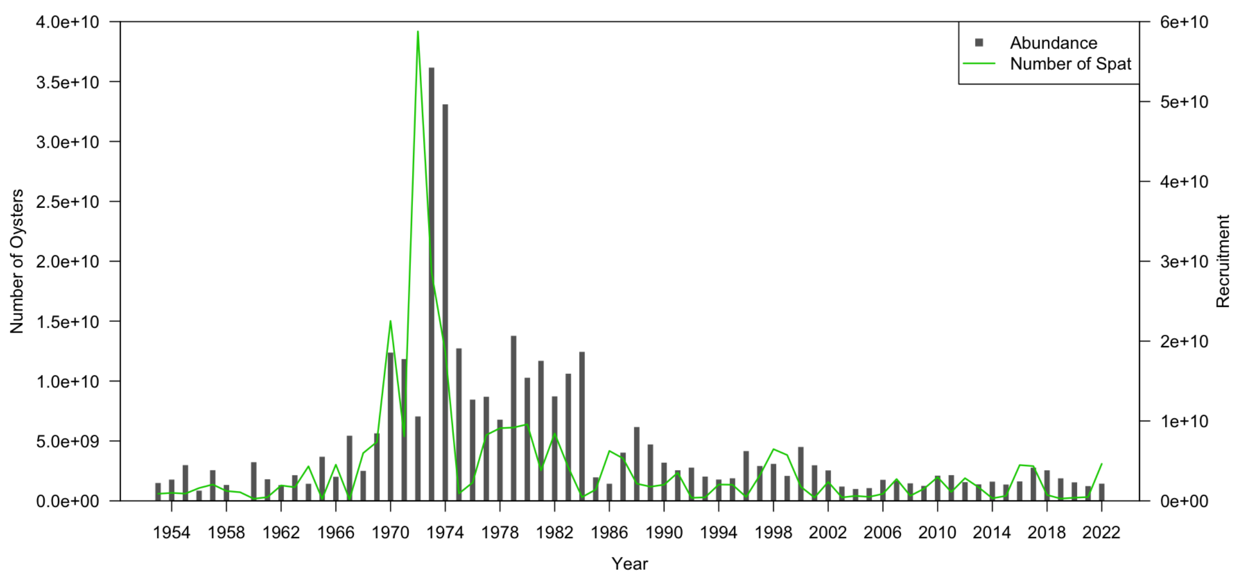


Figure 5. Number of oysters harvested from the natural oyster beds of Delaware Bay, NJ from 1953–2022. Prior to 1996, the bay-season fishery permitted removing oysters of all sizes from the natural beds and required transplanting them downbay to leased grounds for subsequent harvest. Since 1996, the direct market fishery has restricted harvest to market-size oysters without any transplant requirement. Zeros represent years of fishery closure.

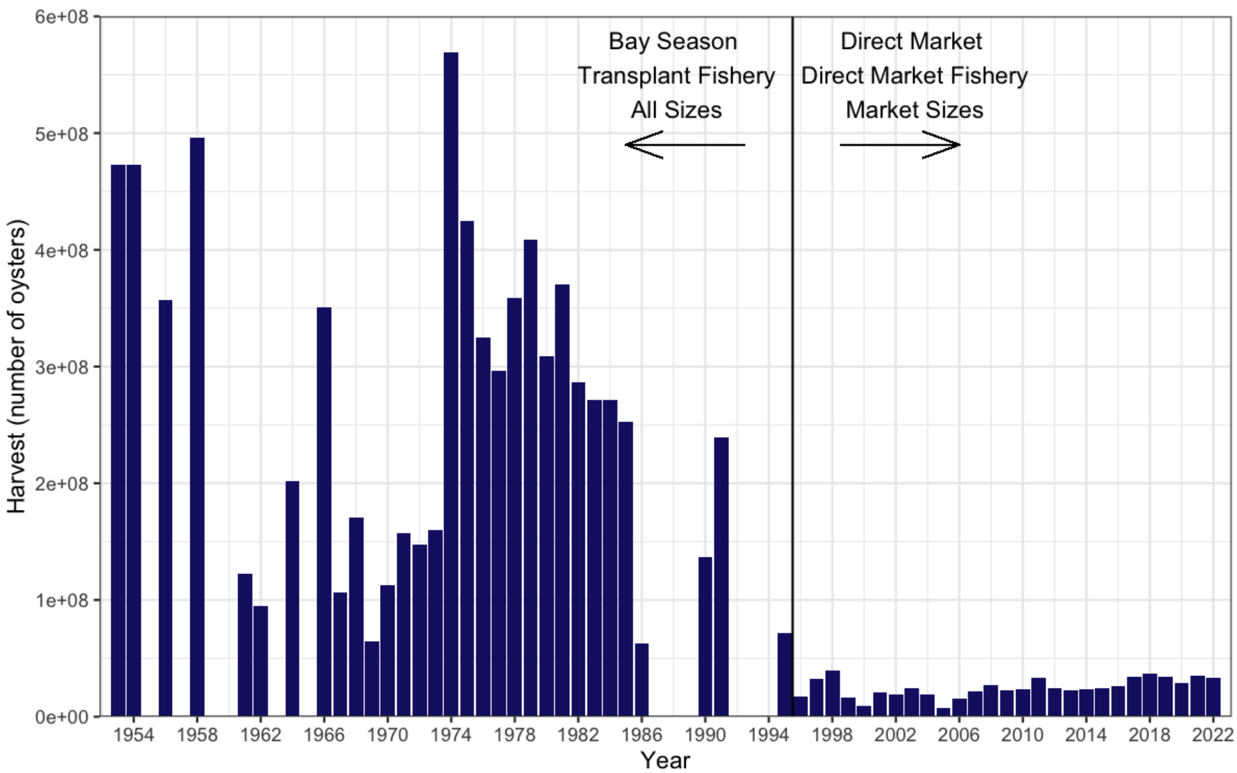


Figure 6. Survey gear capture efficiency as a function of true oyster density. Error bars represent the standard deviation from 1,000 bootstrap simulations. Line indicates the best fit power model estimated by weighted nonlinear least squares. *Adapted from Morson et al. (2018)*

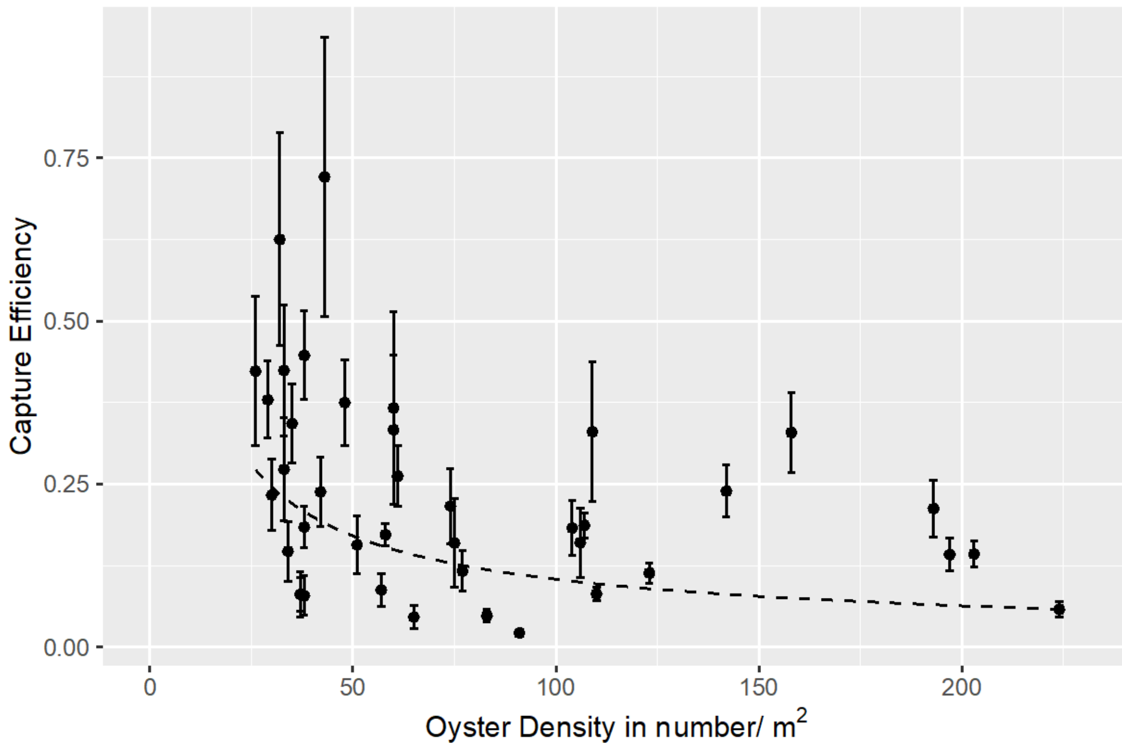


Figure 7. The assessed oyster beds of Delaware Bay, NJ colored by region (see Legend) with the 2022 strata designations. White outlines indicate the complete boundary of each bed with the high and medium quality strata grids in dark and light colors, respectively; black outlines indicate beds that were resurveyed in 2022. Strata designations are calculated within-bed not within-region. Gray areas in each bed indicate low quality strata. Annual assessments include samples from each bed's high and medium quality strata only. Each grid is 0.2" latitude x 0.2" longitude, approximately 25 acres (10.1 hectares).

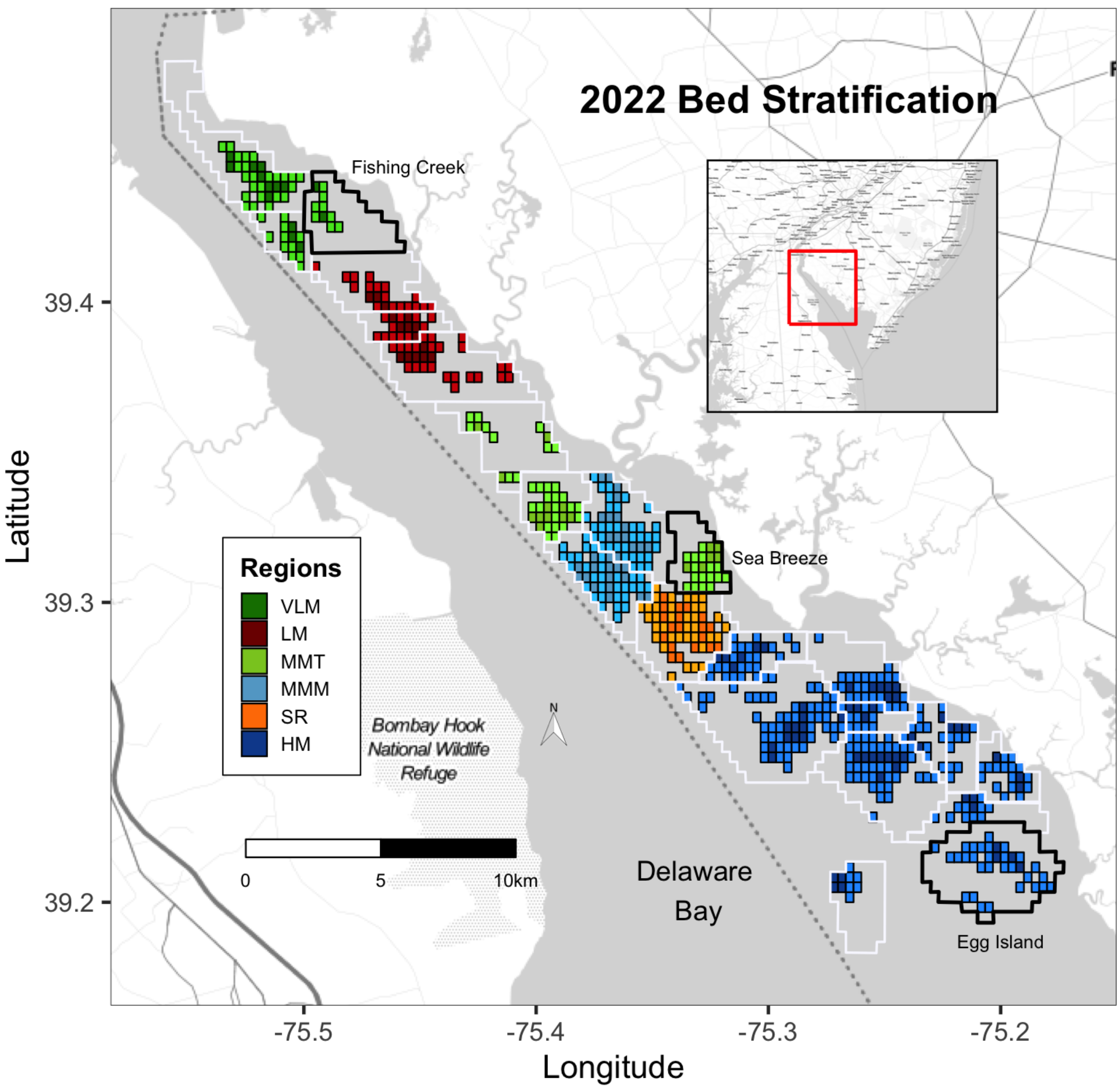


Figure 8a. Realized exploitation fractions of the >2.5" oyster stock on the Direct Market regions in Delaware Bay NJ for two time periods: 1996-2006 and 2007-2015. The 2007-2015 median (dotted line) is based on the realized exploitation values with shading indicating the range. Negative values reflect oysters added through intermediate transplanting.

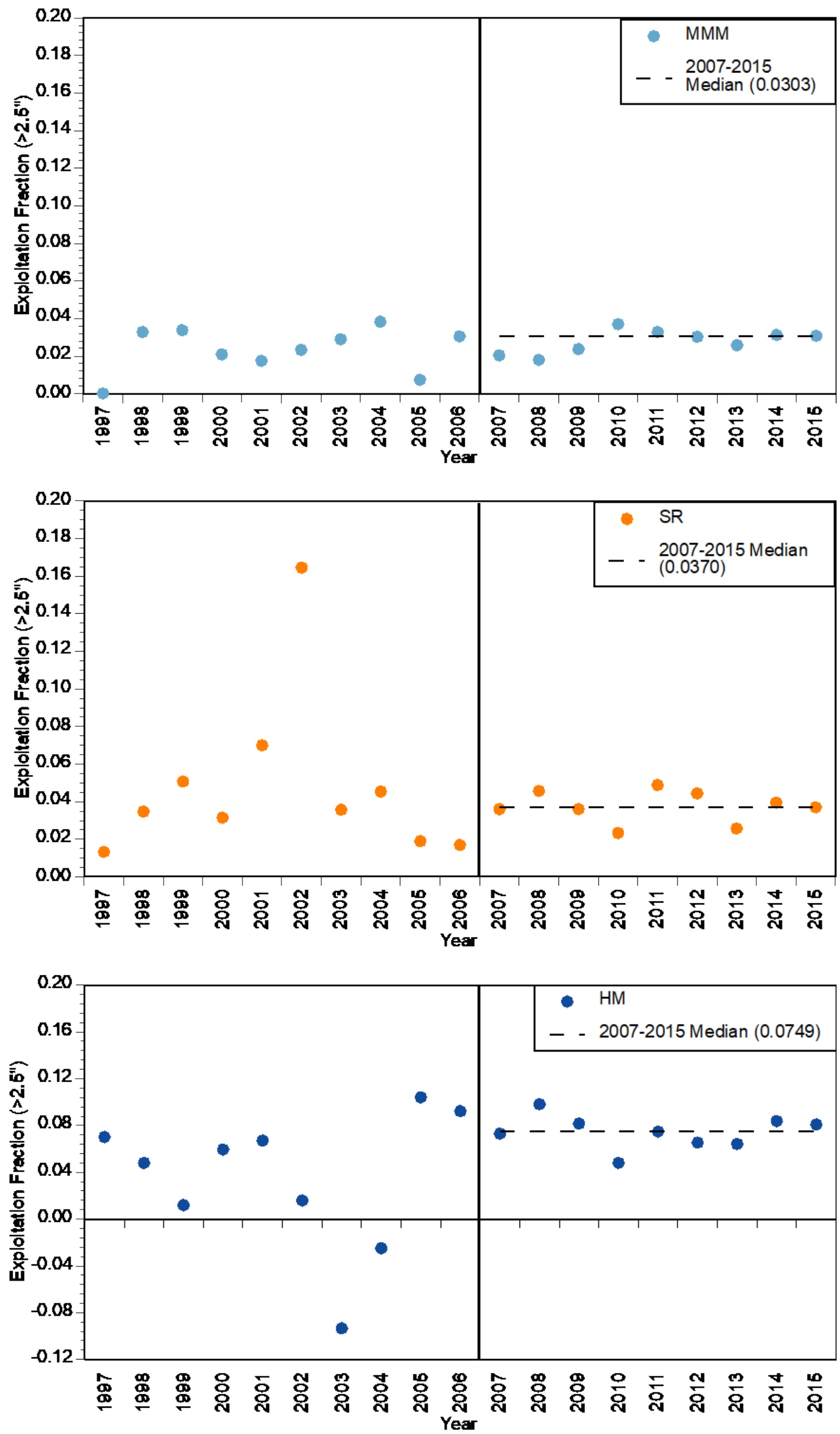


Figure 8b. Realized exploitation fractions of the whole oyster stock, excluding spat, on the Transplant regions in Delaware Bay NJ for two time periods: 1996-2006 and 2007-2015. The 2007-2015 median (dotted line) is based on the realized exploitation for each region with shading indicating the range. The VLM abundance time series began in 2007 and the region has only 3 years of exploitation. Due to sparse data in the earlier time series, the LM and MMT share the same set of data.

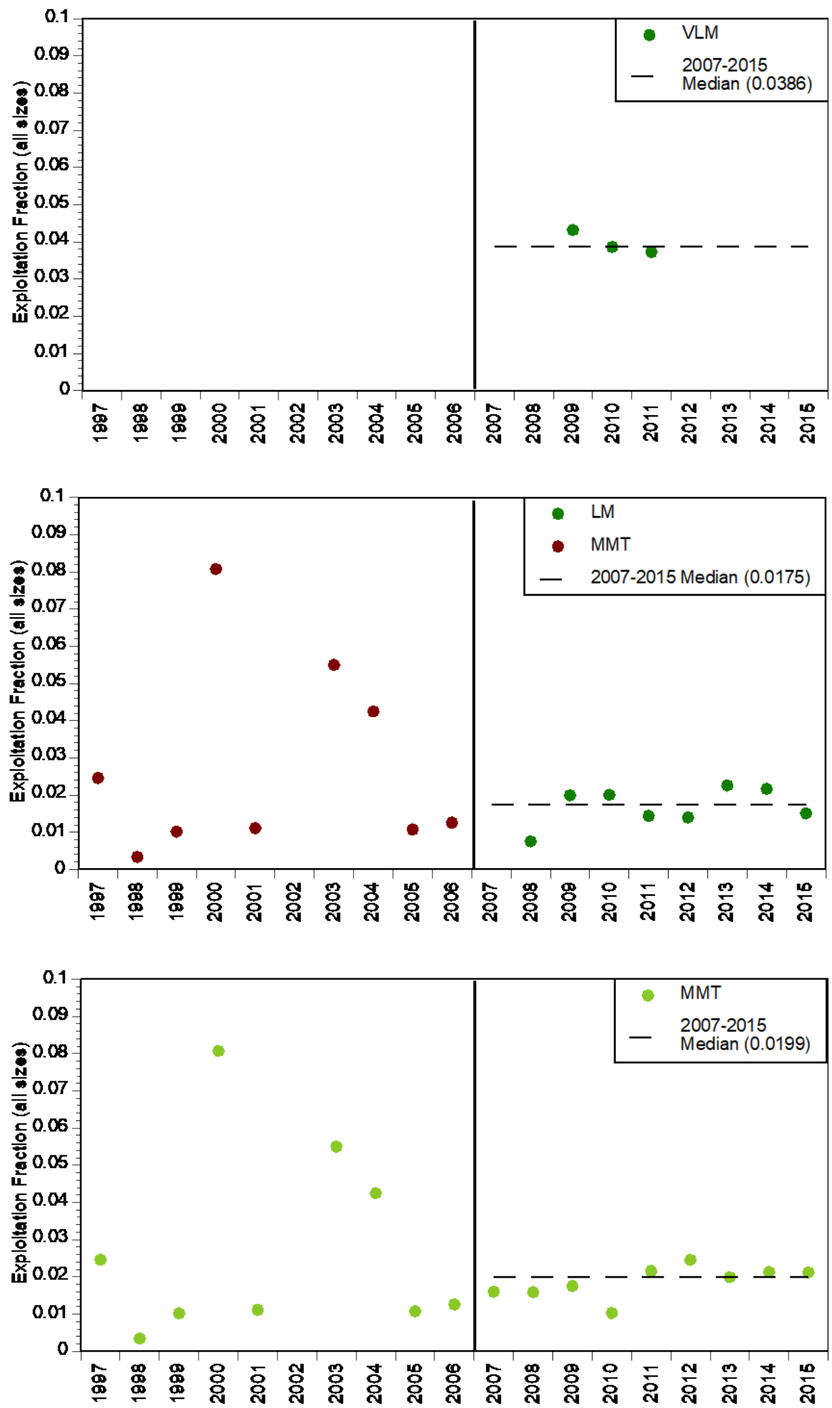


Figure 9. Landed oysters per bushel in three groups: market-size (≥2.5"), smaller attached oysters, and smaller unattached oysters. The number of market-size oysters per landed bushel in 2022 averaged 275, while the total oysters per landed bushel averaged 319. The long-term mean of all oysters and market oysters per landed bushel (269) is shown as an orange line.

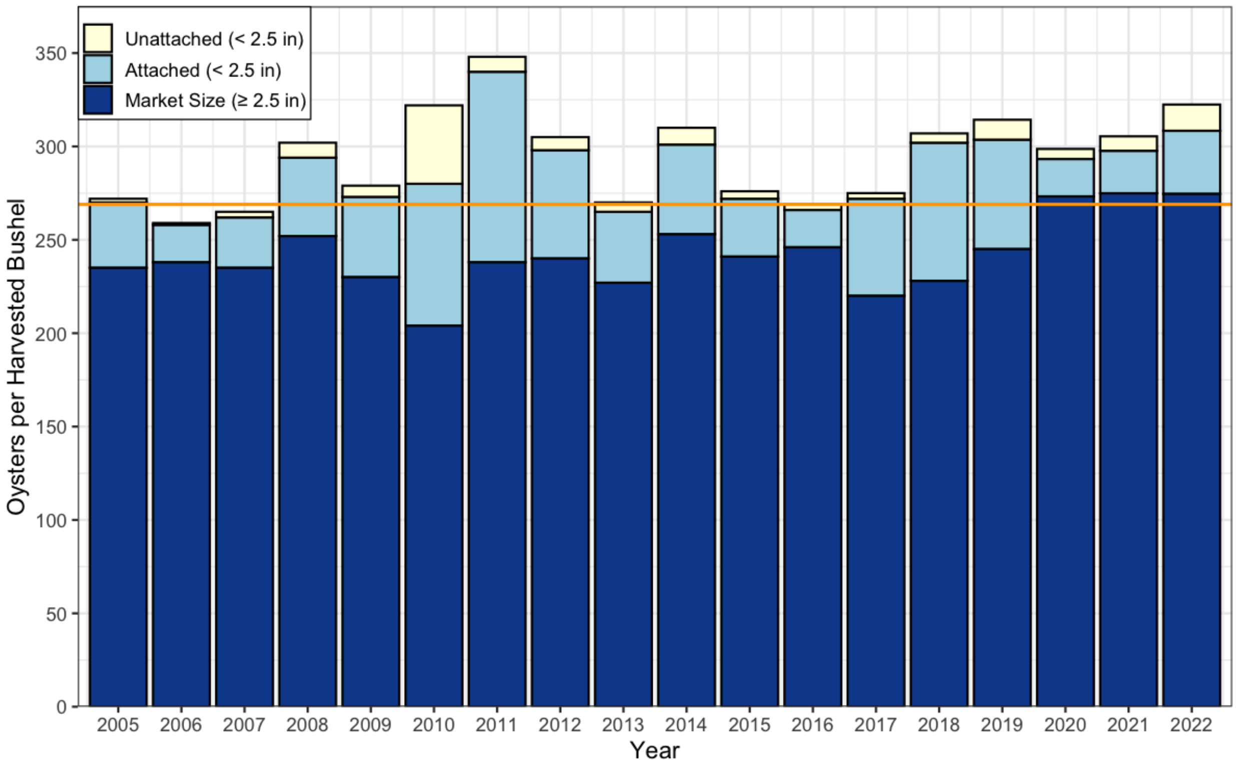


Figure 10. Numbers of single and dual dredge boats (stacked bars) participating in the NJ Delaware Bay oyster harvest overlaid with LPUE (total number of harvested bushels/total hours worked) for each dredge type.

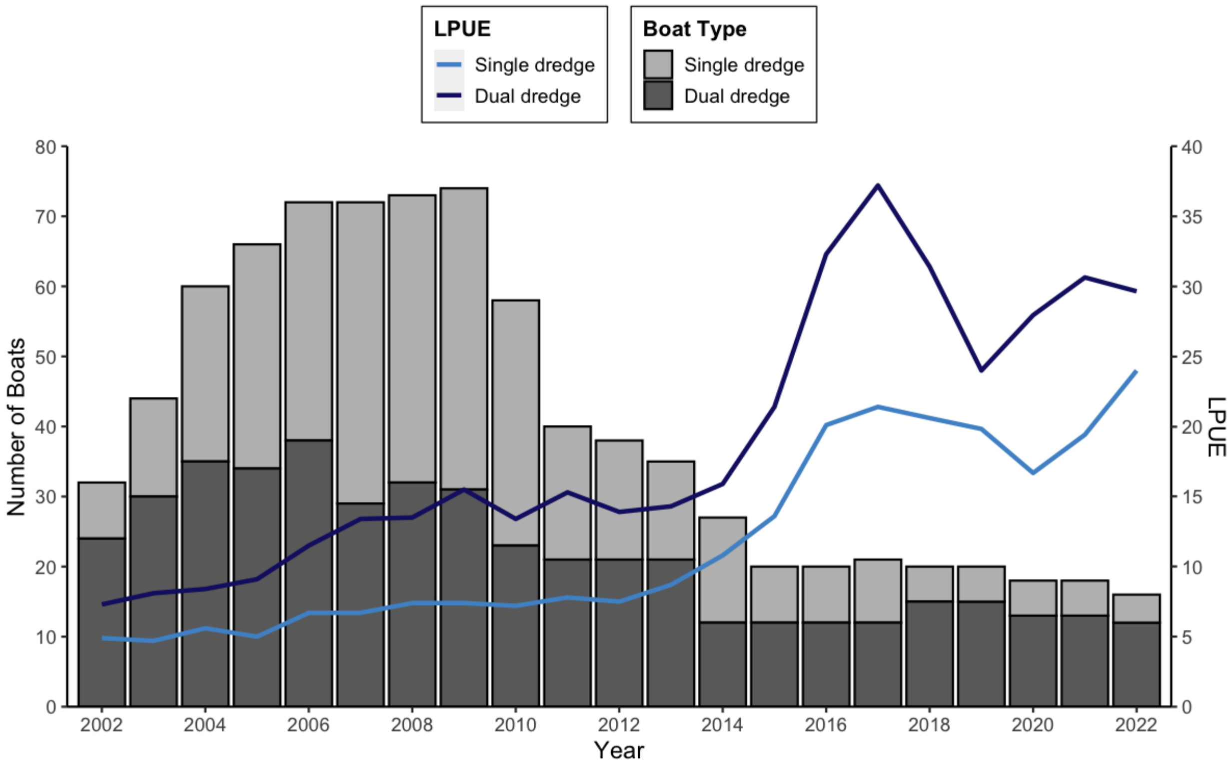


Figure 11. Size frequency of oysters landed by the fishery in direct market regions (top panel) and within the direct market regions of the surveyed population (bottom panel). Vertical line indicates the market-size cutoff (≥ 2.5 inches).

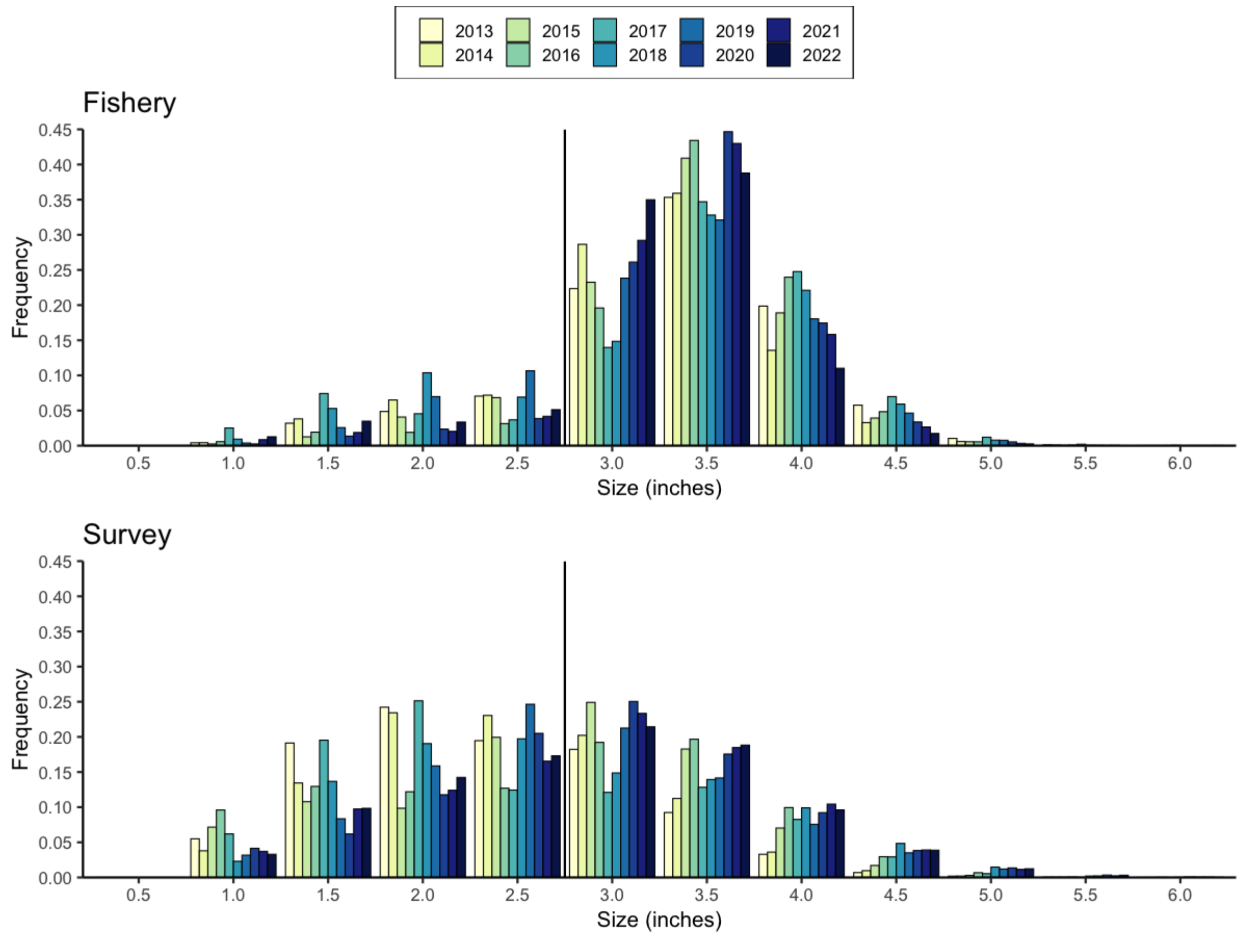


Figure 12. Frequencies of large (≥ 3.5 inches) oysters landed by the fishery in direct market regions (top panel) and within the surveyed population (bottom panel).

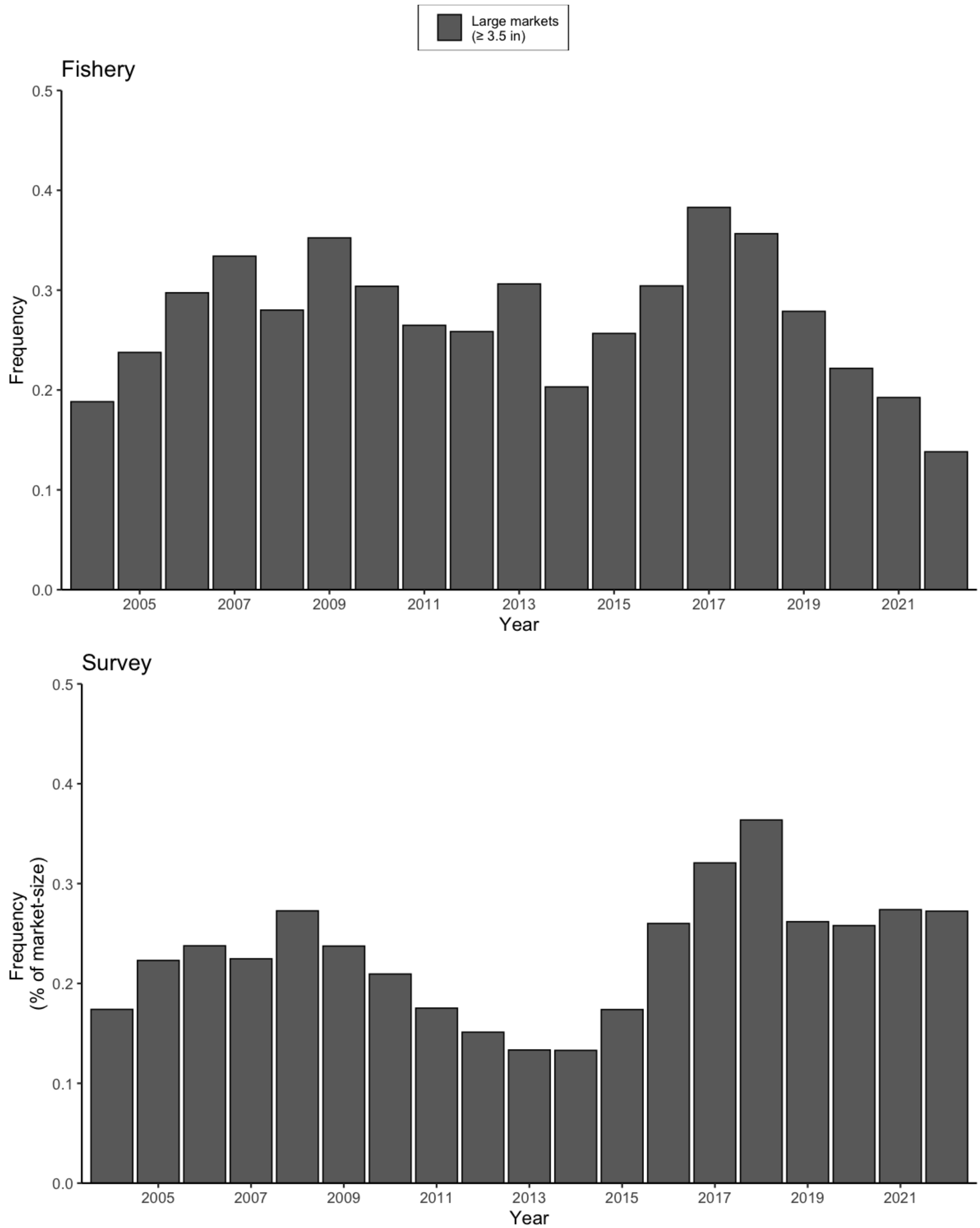


Figure 13. Number of bushels harvested from the natural oyster beds of Delaware Bay since the inception of the direct-market program in 1996. The 26-year average harvest is 84,876 bushels. The vertical line shows the beginning of the current exploitation and management strategy in 2007. The projected quota for 2022 was ~102,500 bushels after transplant (orange line).

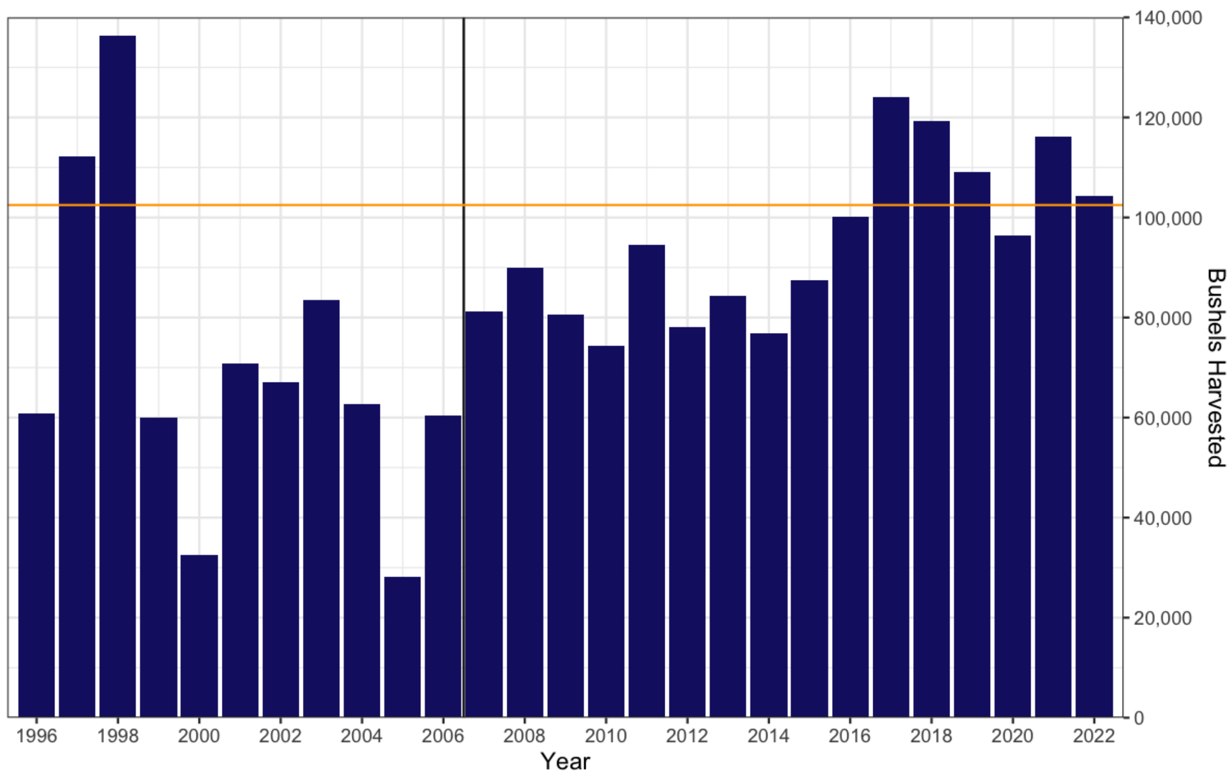
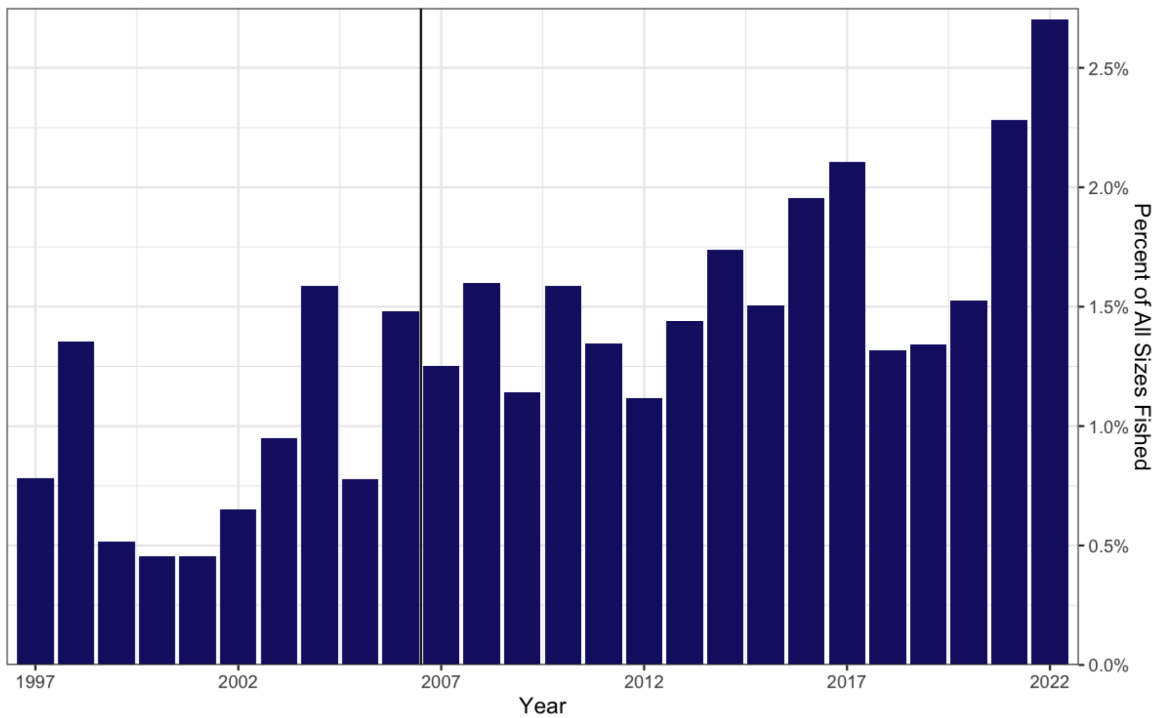


Figure 14. Fishing mortality as a percentage of (a) total oyster abundance and (b) the market-sized oyster abundance (≥2.5”) over all regions excluding the VLM. Regional abundance-based quotas began in 2007 (vertical line).

a.



b.

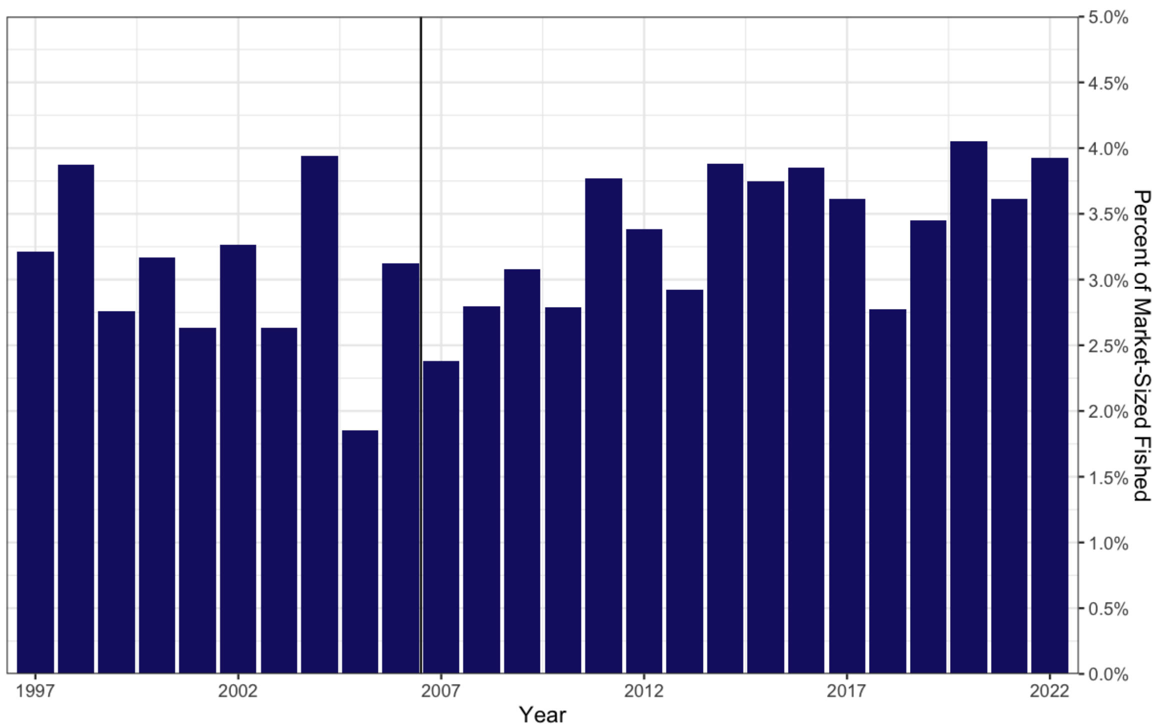


Figure 15. Map of the 2022 oyster stock assessment sample sites. Black dots are sites from high quality stratum on each bed and white dots are sites from medium quality stratum on each bed. X's indicate transplant enhancement sites and triangles indicate shellplant enhancement sites.

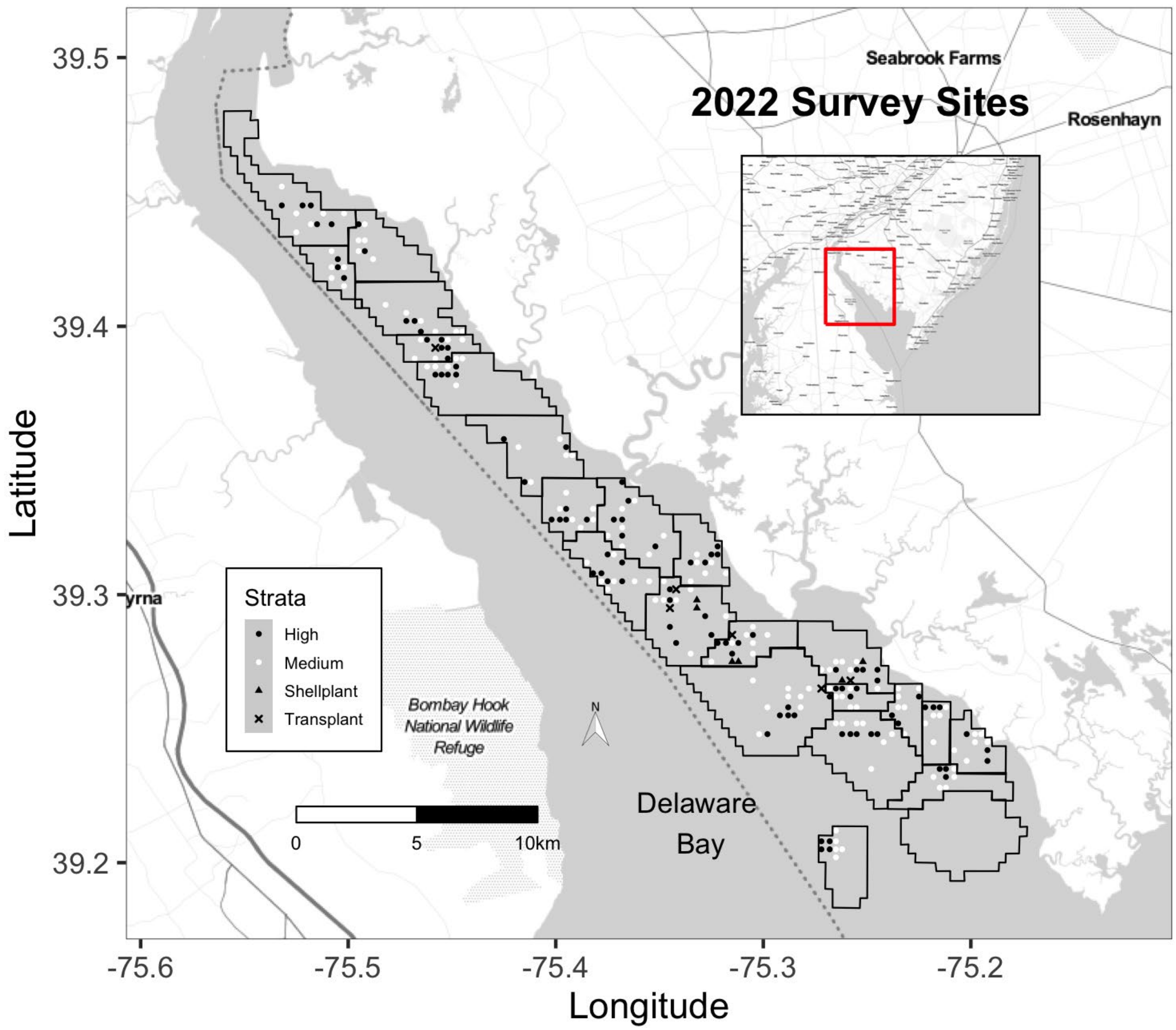


Figure 16.1. Ten-year time series summary for the population, excluding the VLM. Top panels: total abundance (≥ 20 mm) and size class abundances (≥ 20 mm). Bottom panels: spat abundance and mortality rate (< 20 mm). Dashed horizontal lines represent the threshold and solid horizontal lines represent the target for abundance in panel A and for market abundance in panel B.

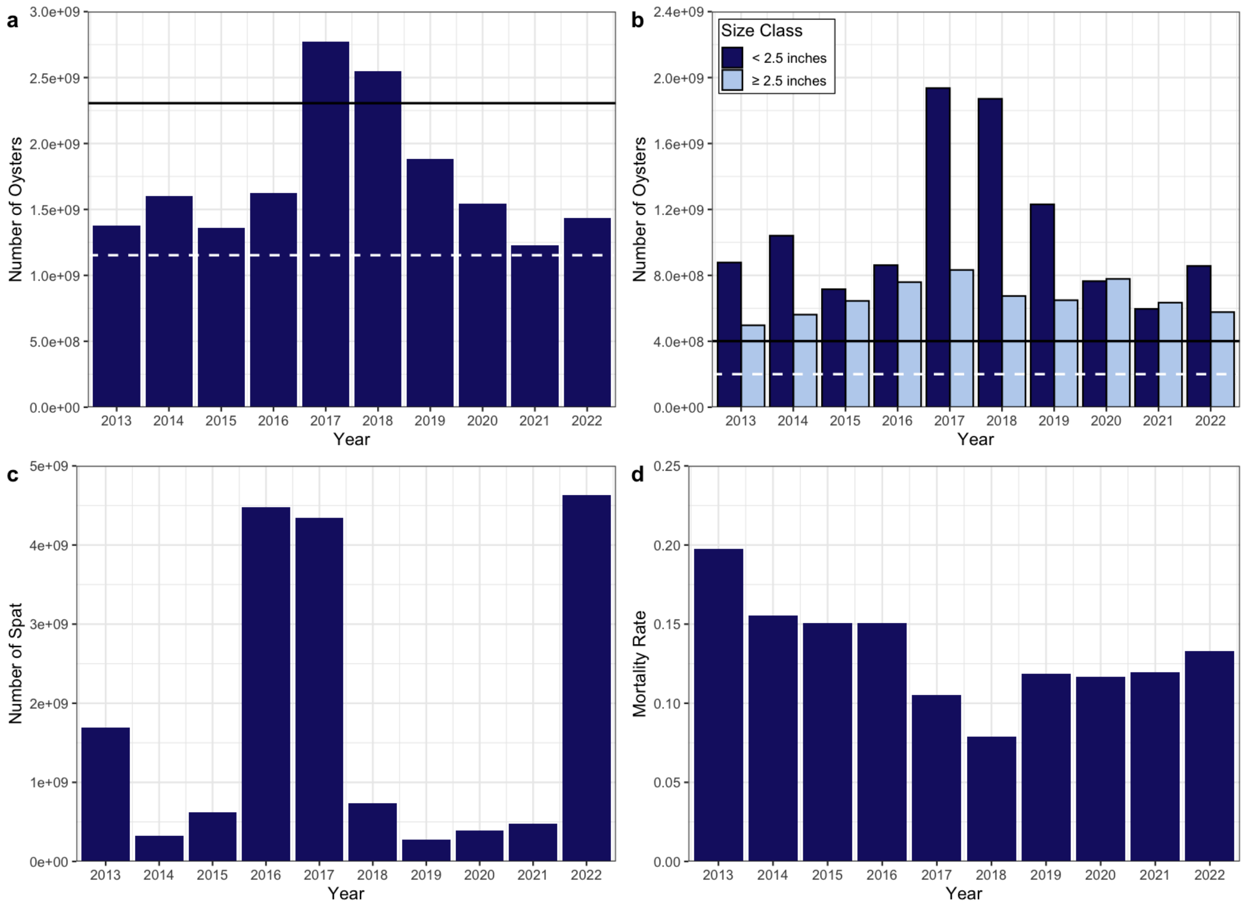


Figure 16.2. Long-term time series summary for the population, excluding the VLM. Top panels: total abundance (≥ 20 mm) and size class abundances (≥ 20 mm). Bottom panels: spat abundance and mortality rate (< 20 mm). Dashed horizontal lines represent the threshold and solid horizontal lines represent the target for abundance in panel A and for market abundance in panel B.

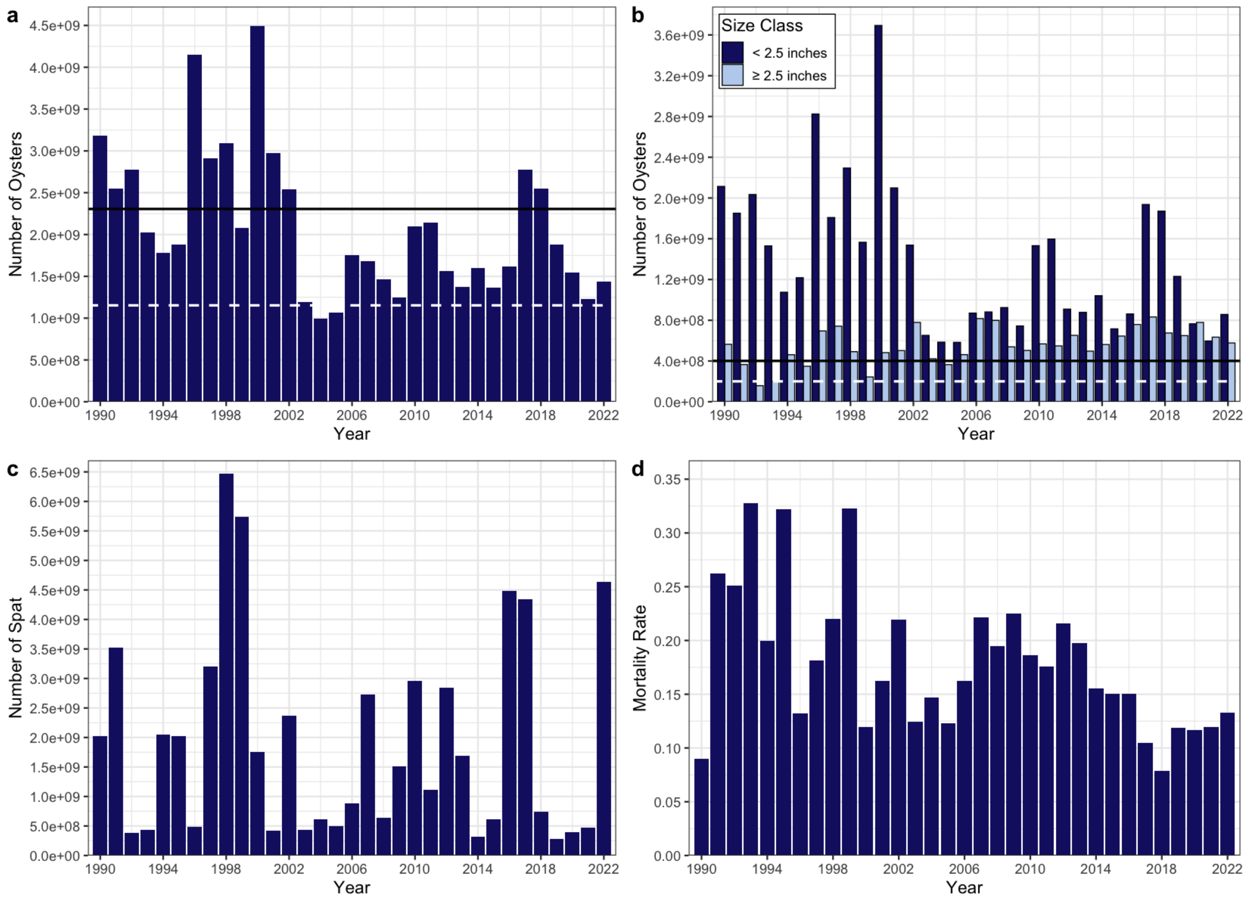
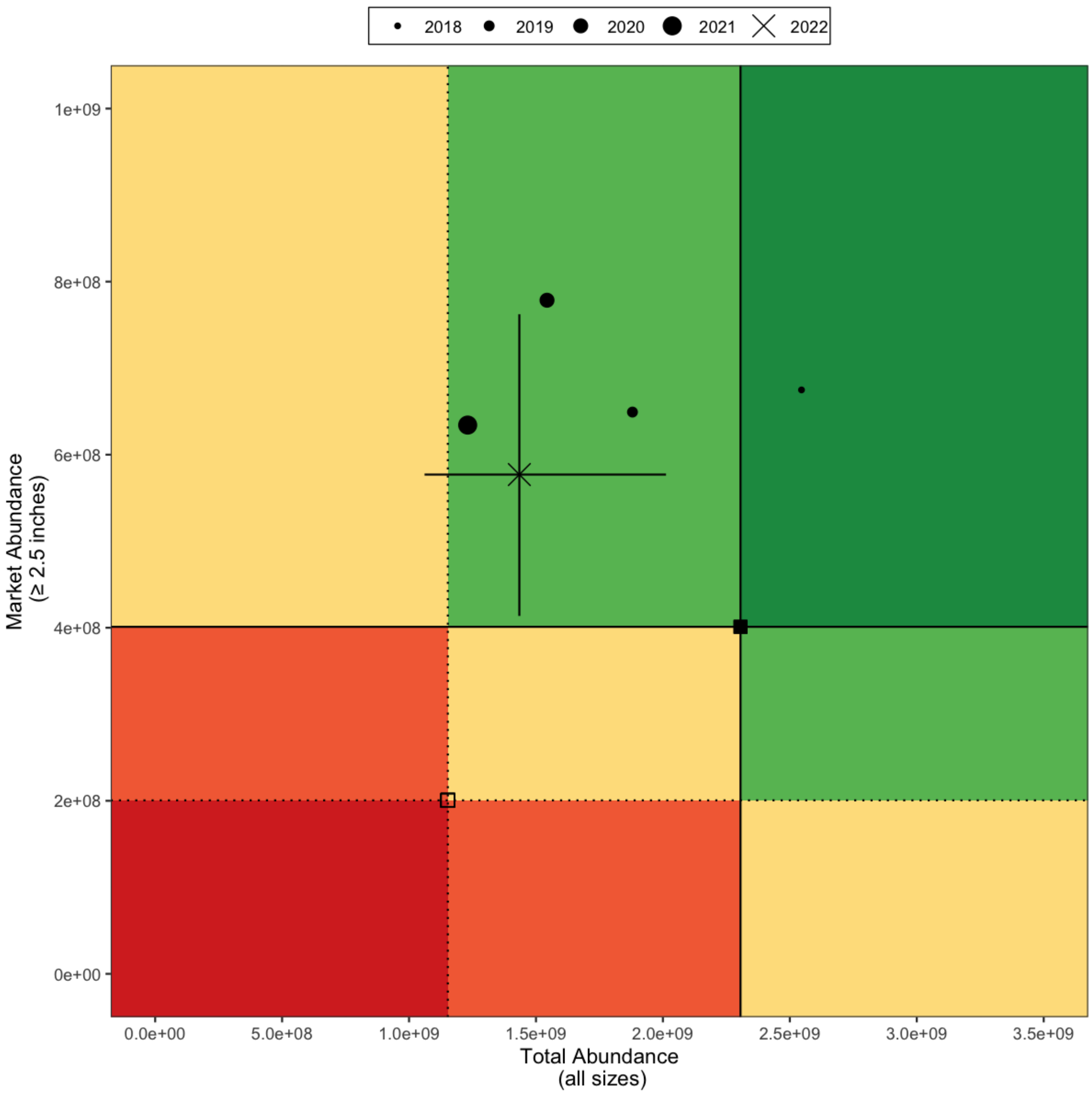


Figure 17. Position of the oyster stock 2018–2022 with respect to abundance and market abundance (≥ 2.5") targets and thresholds, excluding the VLM. Targets and thresholds are defined in Table 9. Error bars on the 2022 values are the 10th and 90th percentiles of 1,000 simulations of estimates incorporating both survey error and gear efficiency error. *Shading: Green, above all 4 cutoffs*; *Light green, above 3 cutoffs*; *Yellow, above 2 cutoffs*; *Orange, above 1 cutoff*; *Red, below all 4 cutoffs.*



Figures 18 – 23. Ten-year and long-term time series summaries by region. Left panels: a) total abundance (≥ 20 mm), c) size class abundances (≥ 20 mm), and e) spat abundance (< 20 mm). Spat abundance does not include spat recruited to planted clamshell. Solid and dashed horizontal lines demarcate target and threshold abundances, respectively (a, c). Target and threshold lines on size class abundance plots (c) refer to market-sized oysters only. Right panels: b) Dermo levels, d) box-count mortality rate and f) fishing mortality rate relative to both total (≥ 20 mm) and market-size (≥2.5") abundance. Horizontal line on Dermo plots (b) indicates threshold above which natural mortality begins to increase due to Dermo.

Figure 18.1. Ten-year time series summary for the VLM. Targets are the 75th percentiles and the thresholds are the 50th percentiles of the 2007-2016 total and market abundance time series.

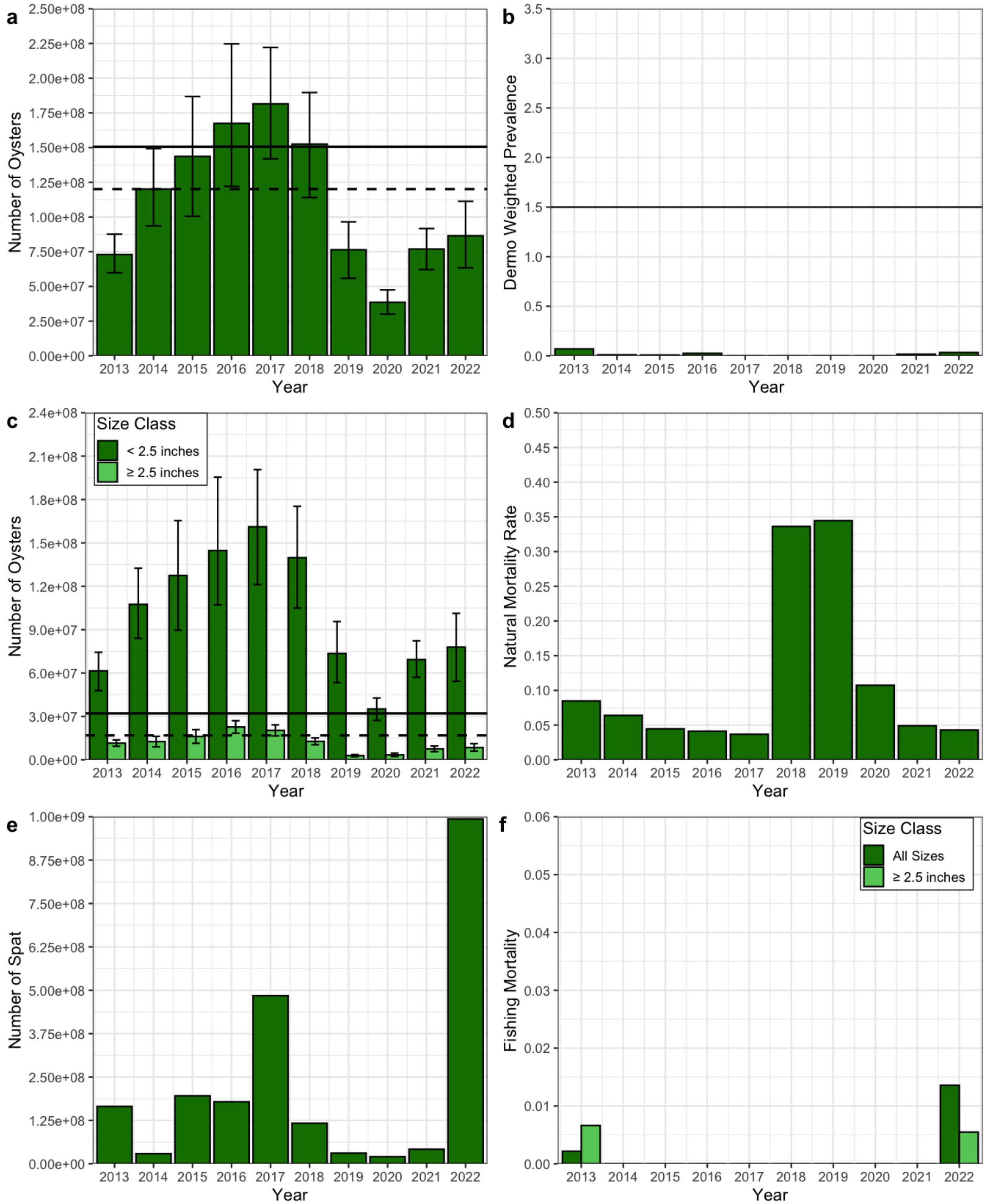


Figure 18.2. Long-term time series summary for the VLM. Targets are the 75th percentiles and the thresholds are the 50th percentiles of the 2007-2016 total and market abundance time series.

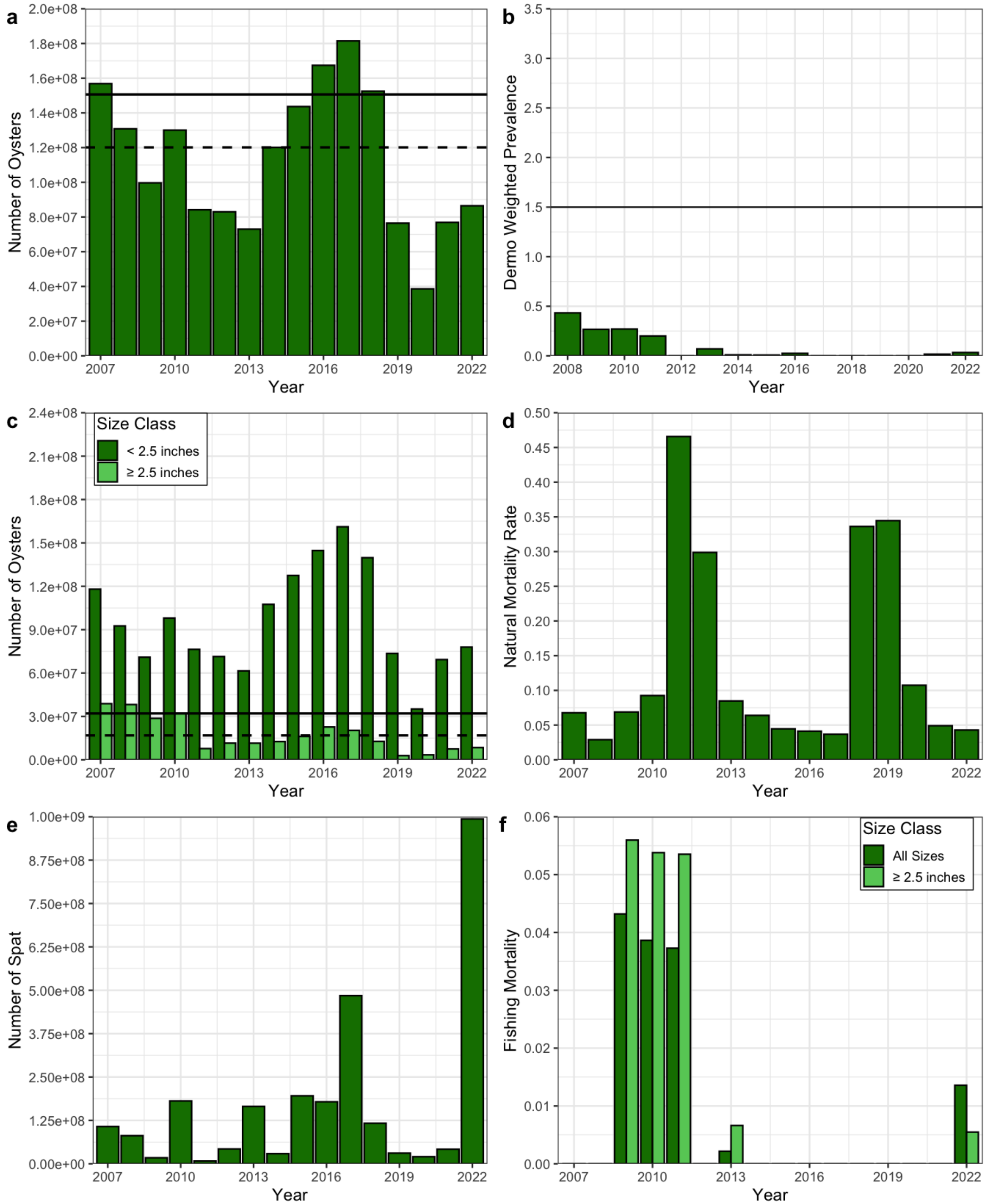


Figure 19.1. Ten-year time series summary for the LM. Targets are the median of the total abundance for 1989-2005 and the median of market-size (≥ 2.5”) abundance for 1990-2005. Thresholds are half the target value.

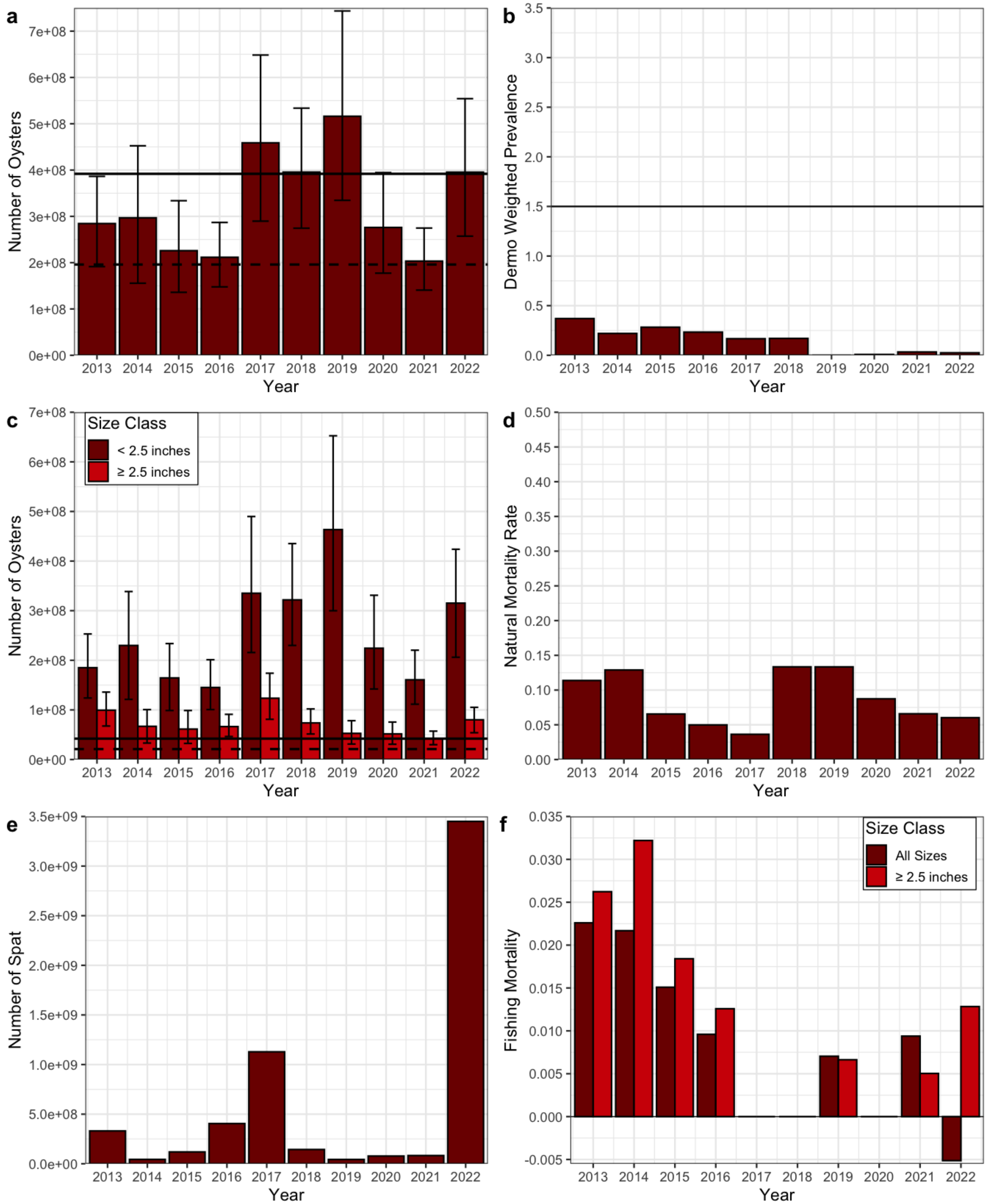


Figure 19.2. Long-term time series summary for the LM. Targets are the median of the total abundance for 1989-2005 and the median of market-size (≥ 2.5") abundance for 1990-2005. Thresholds are half the target value.

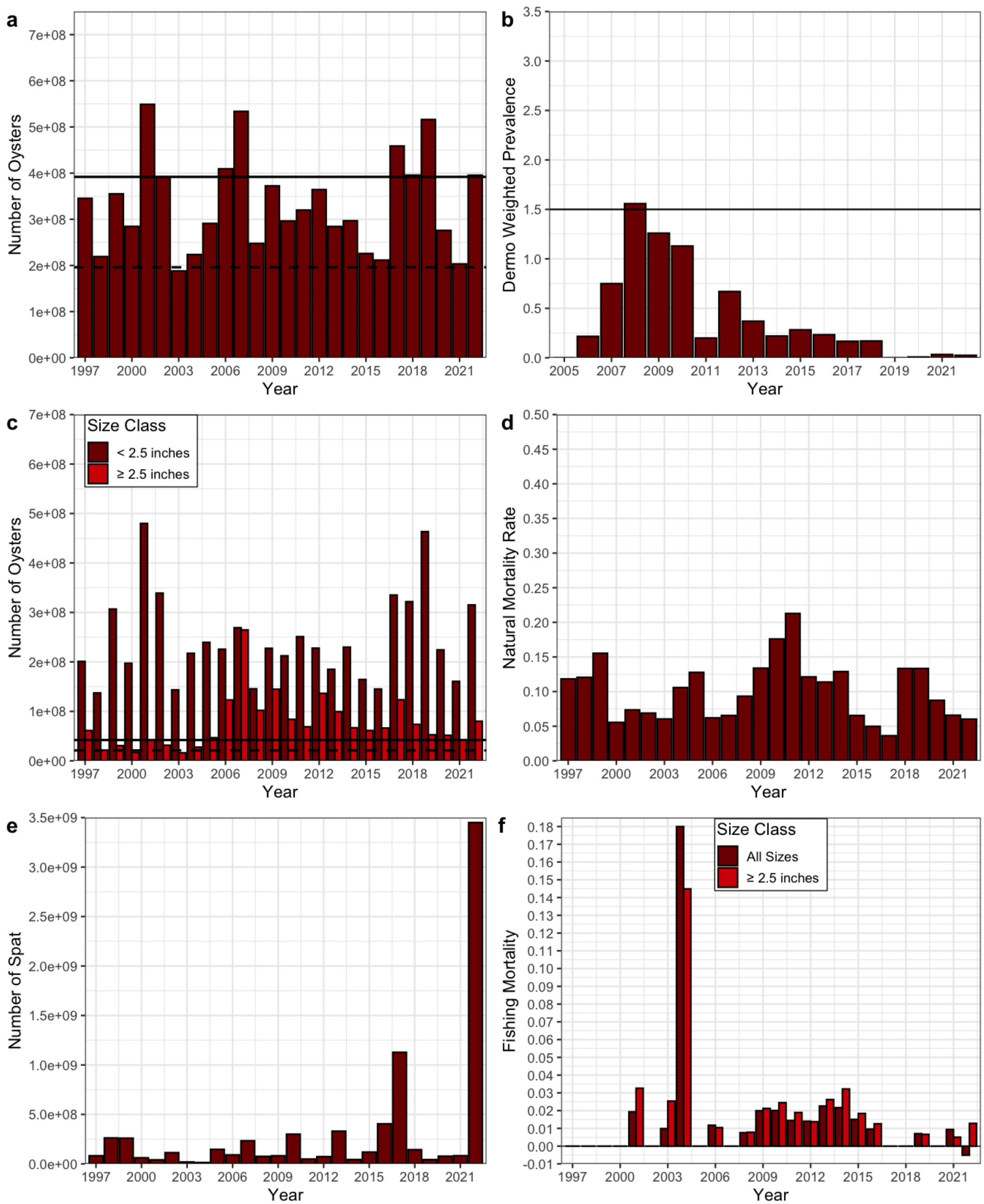


Figure 20.1. Ten-year time series summary for the MMT. Targets are the median of the total abundance for 1989-2005 and the median of market-size (≥ 2.5”) abundance for 1990-2005. Thresholds are half the target value.

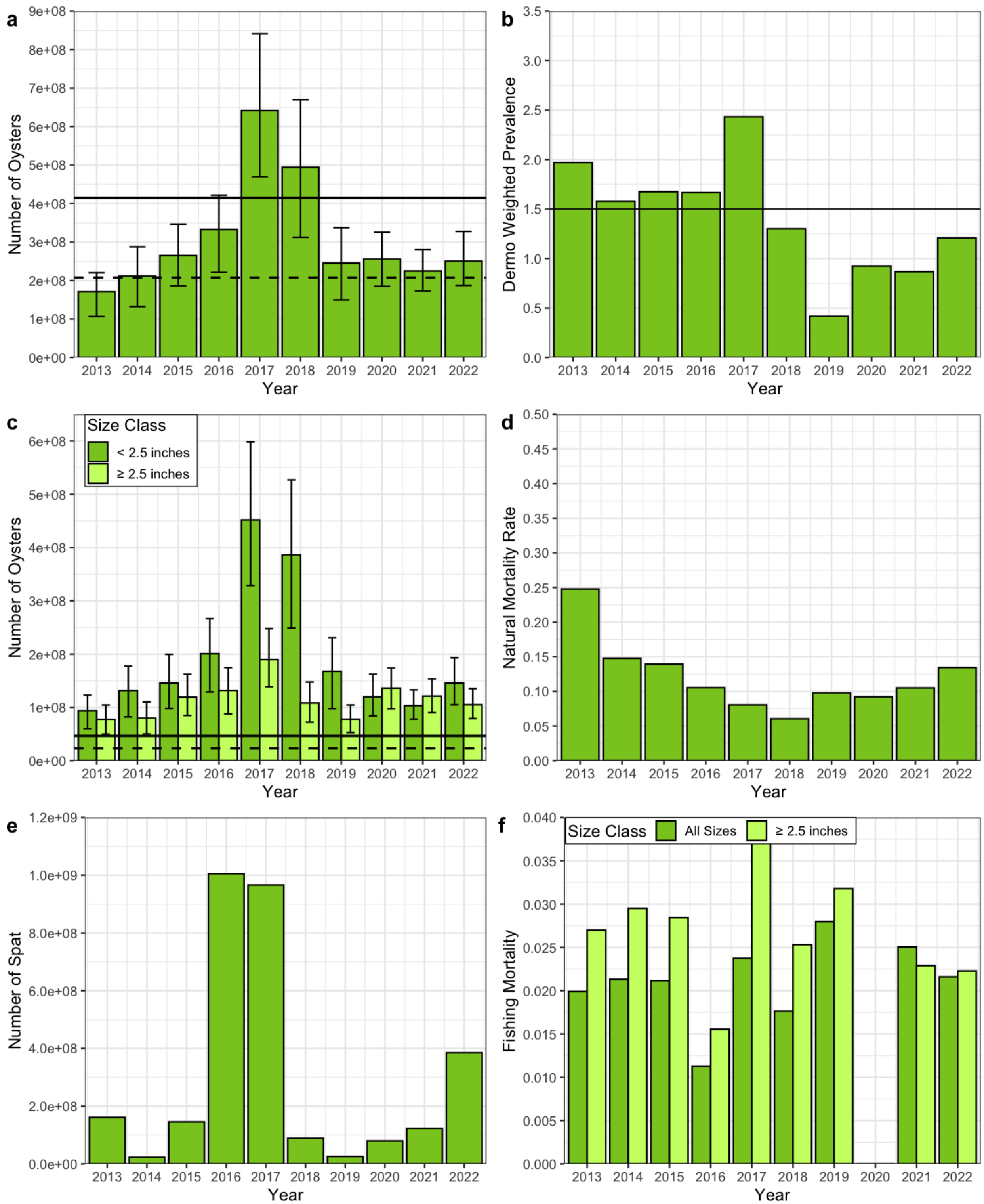


Figure 20.2. Long-term time series summary for the MMT. Targets are the median of the total abundance for 1989-2005 and the median of market-size (≥ 2.5”) abundance for 1990-2005. Thresholds are half the target value.

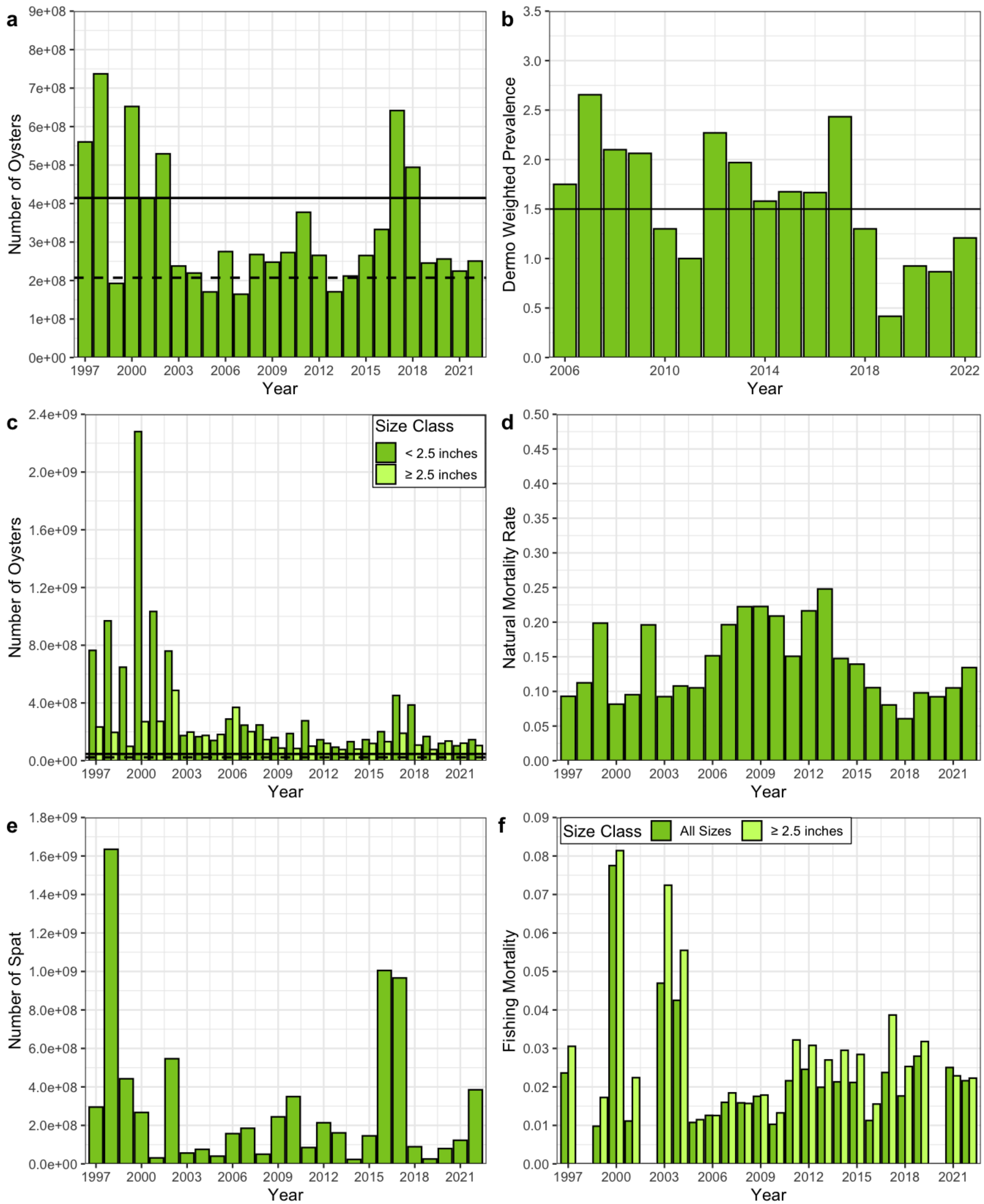


Figure 21.1. Ten-year time series summary for the MMM. Targets are the median of the total abundance for 1989-2005 and the median of market-size (≥ 2.5”) abundance for 1990-2005. Thresholds are half the target value.

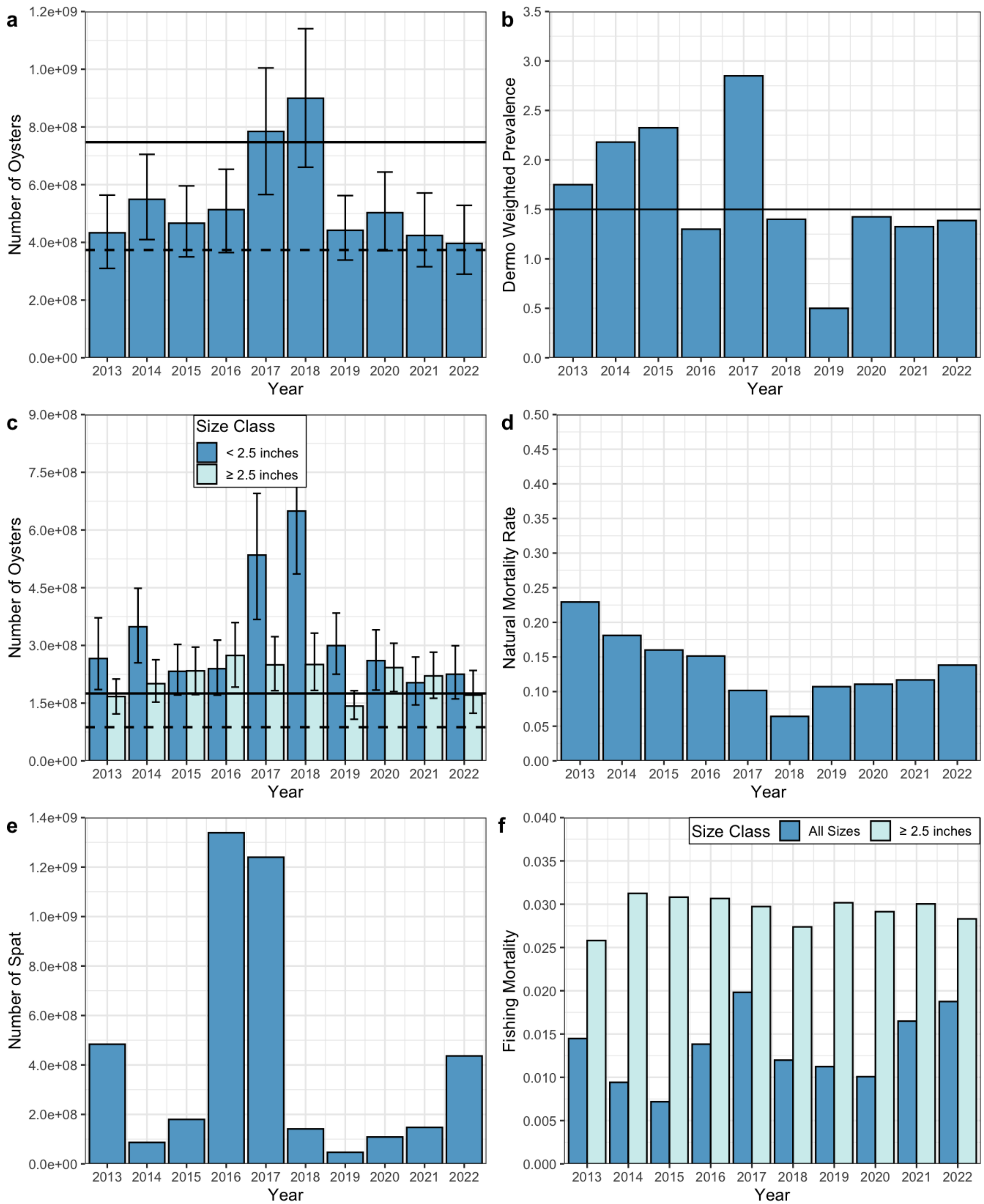


Figure 21.2. Long-term time series summary for the MMM. Targets are the median of the total abundance for 1989-2005 and the median of market-size (≥ 2.5”) abundance for 1990-2005. Thresholds are half the target value.

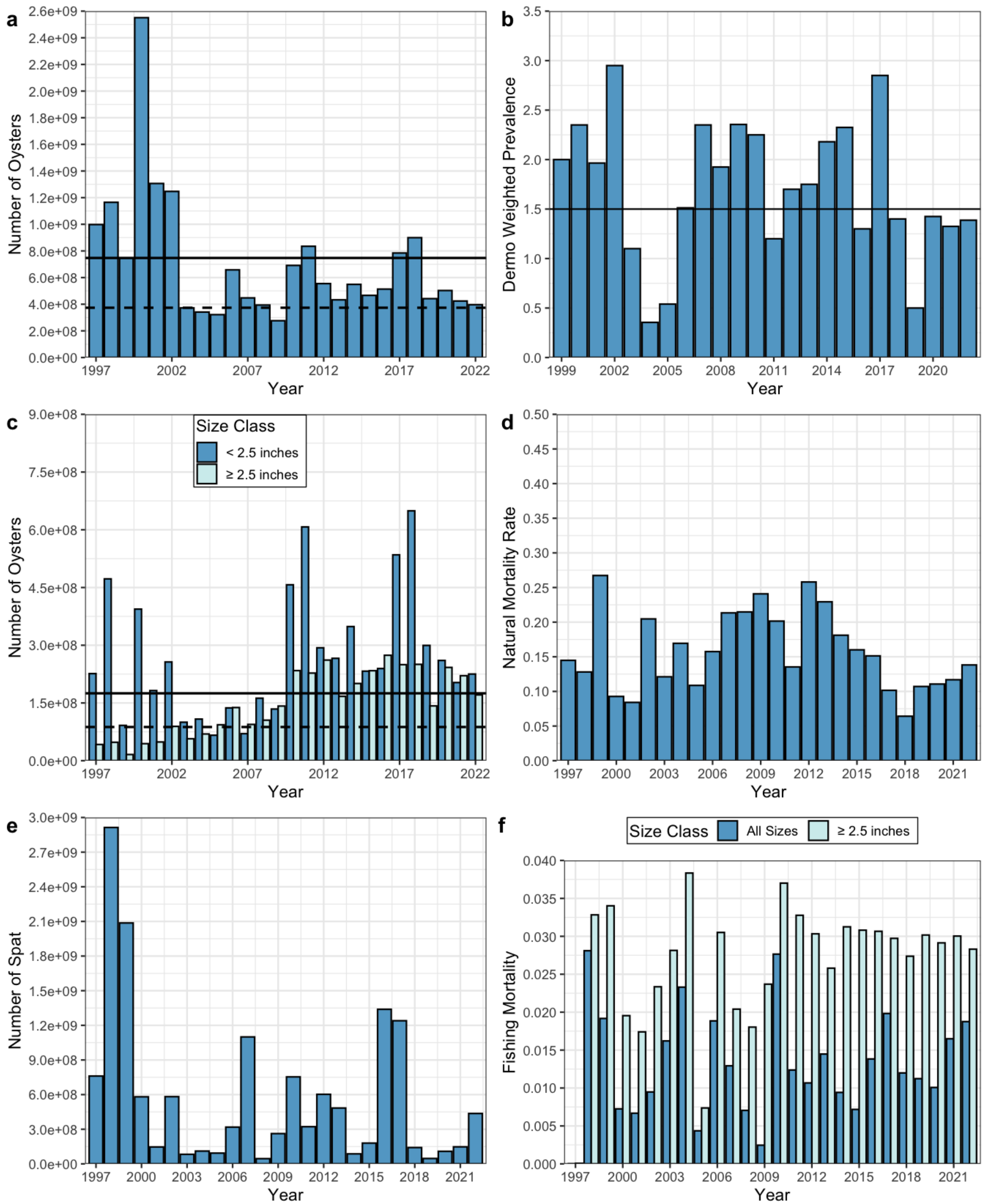


Figure 22.1. Ten-year time series summary for the SR. Targets are the median of the total abundance for 1989-2005 and the median of market-size (≥ 2.5") abundance for 1990-2005. Thresholds are half the target value.

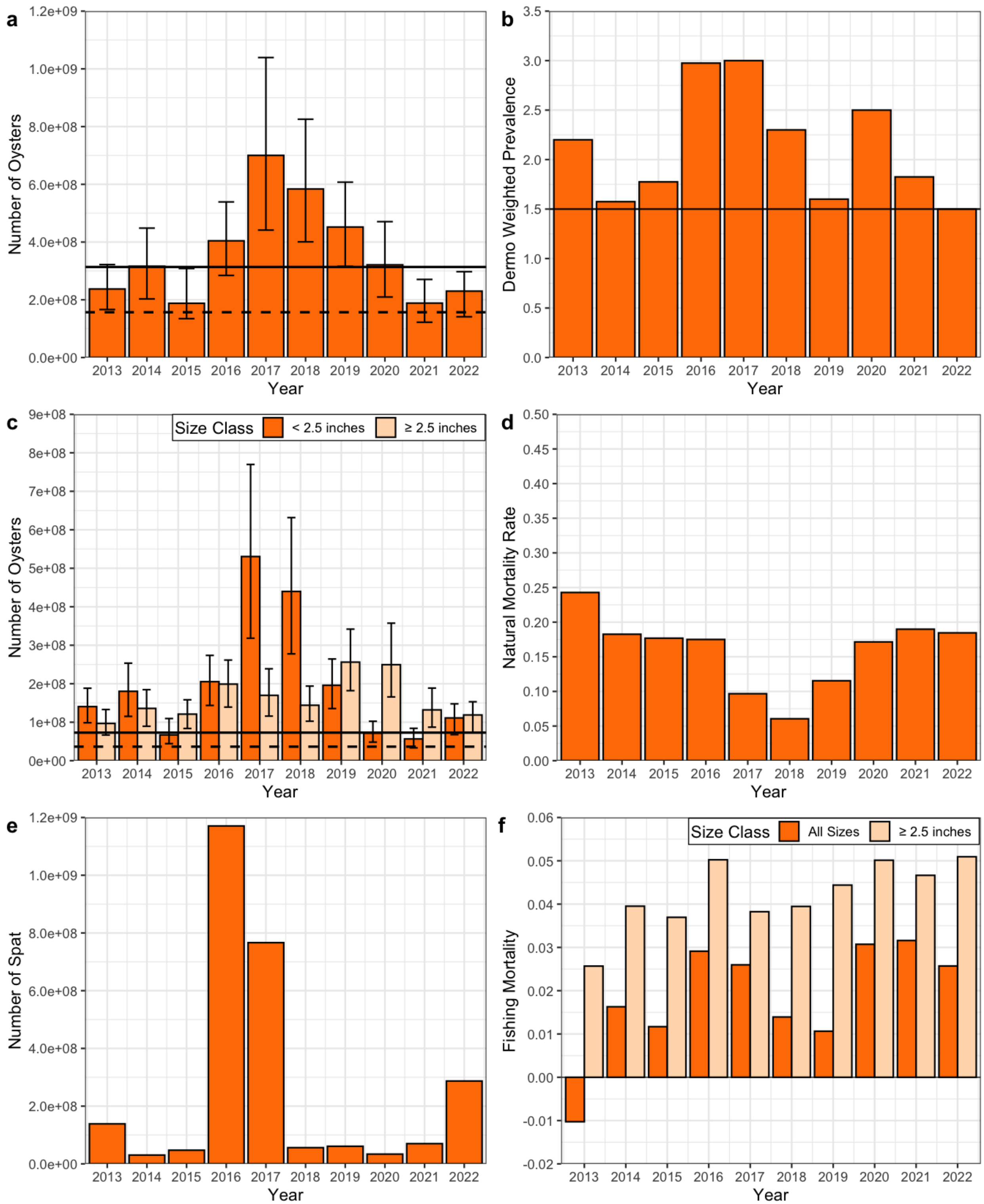


Figure 22.2. Long-term time series summary for the SR. Targets are the median of the total abundance for 1989-2005 and the median of market-size (≥ 2.5") abundance for 1990-2005. Thresholds are half the target value.

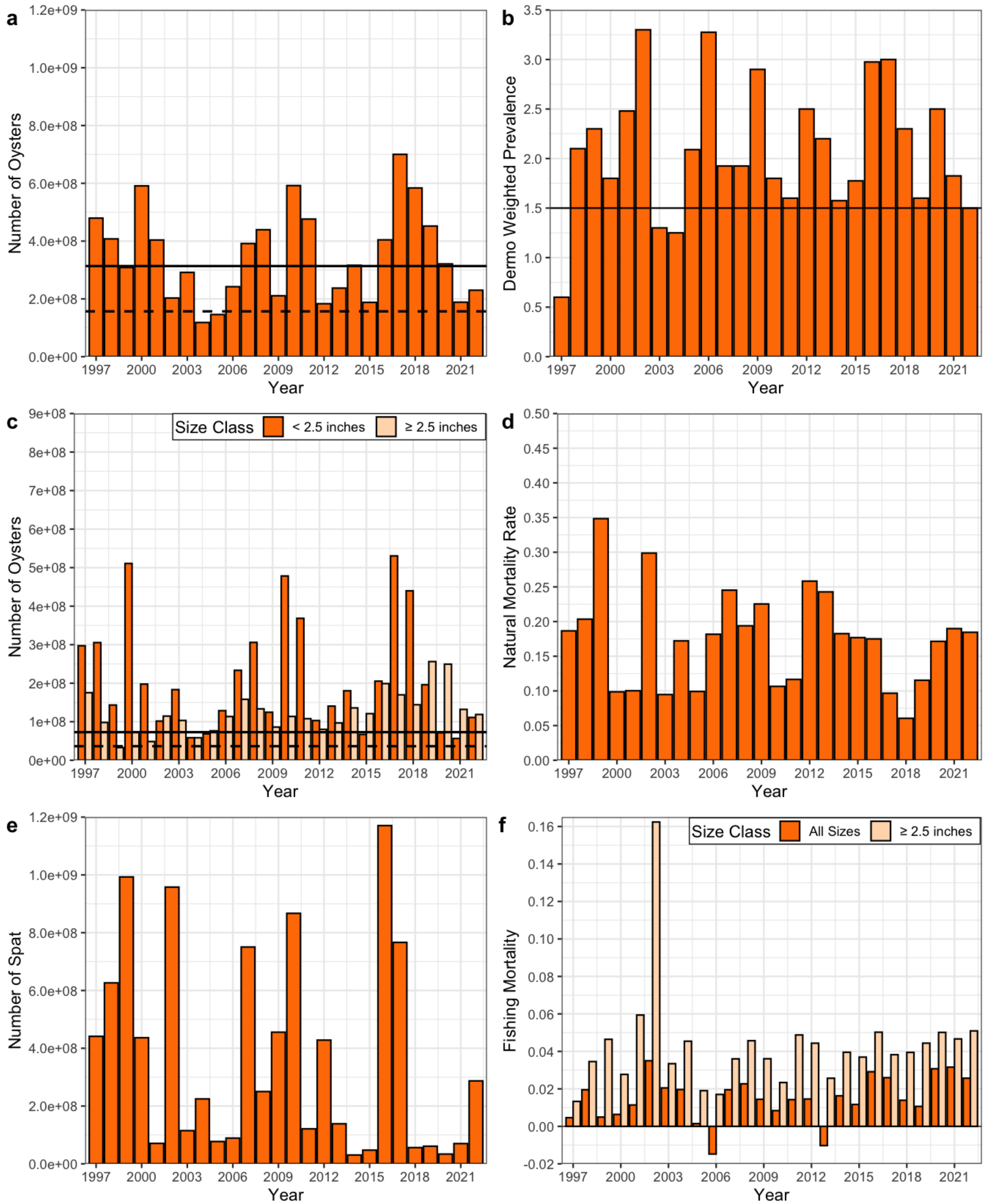


Figure 23.1. Ten-year time series summary for the HM. Targets are the median of the total abundance for 1989-2005 and the median of market-size (≥ 2.5”) abundance for 1990-2005. Thresholds are half the target value.

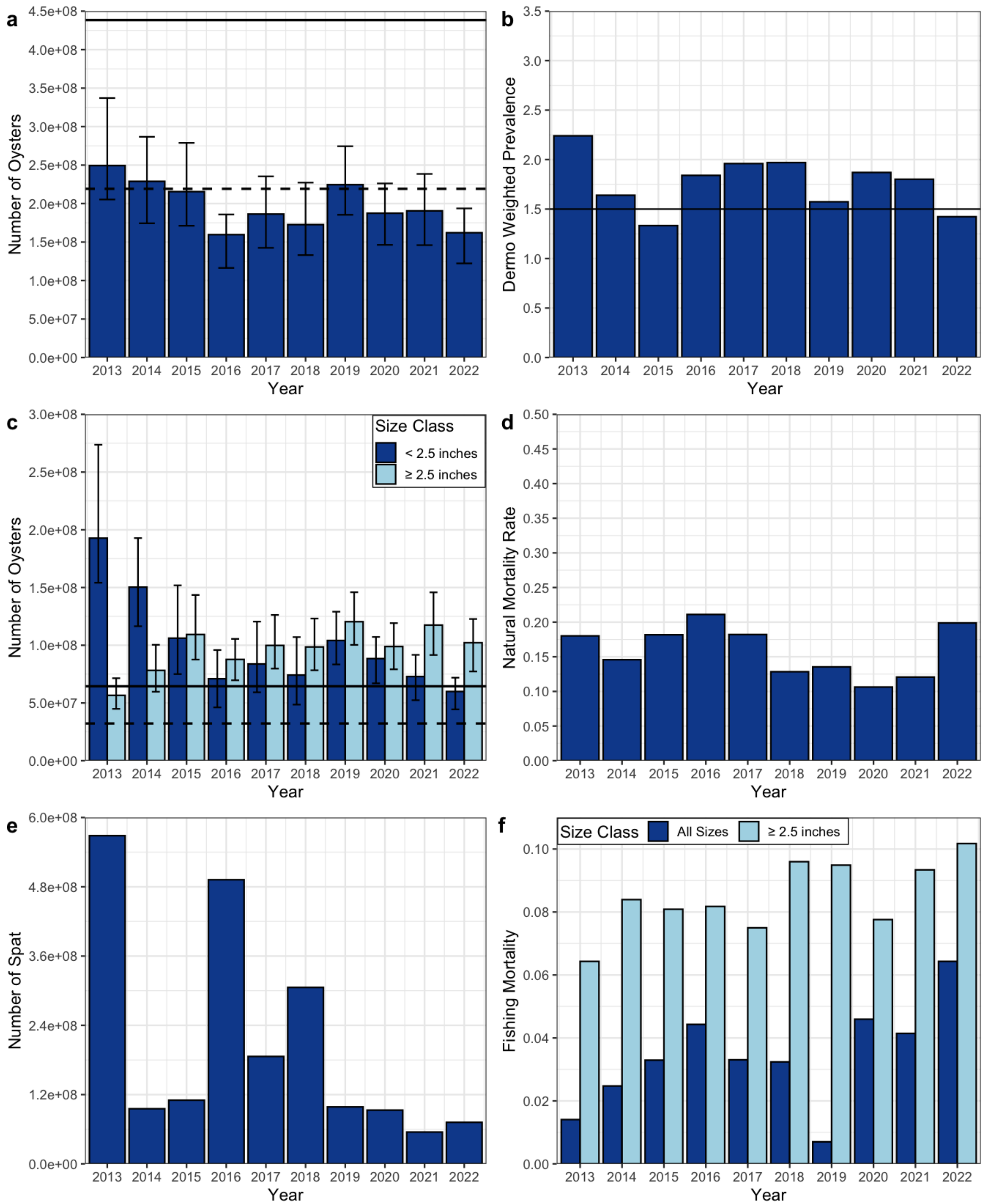


Figure 23.2. Long-term time series summary for the HM. Targets are the median of the total abundance for 1989-2005 and the median of market-size (≥ 2.5") abundance for 1990-2005. Thresholds are half the target value.

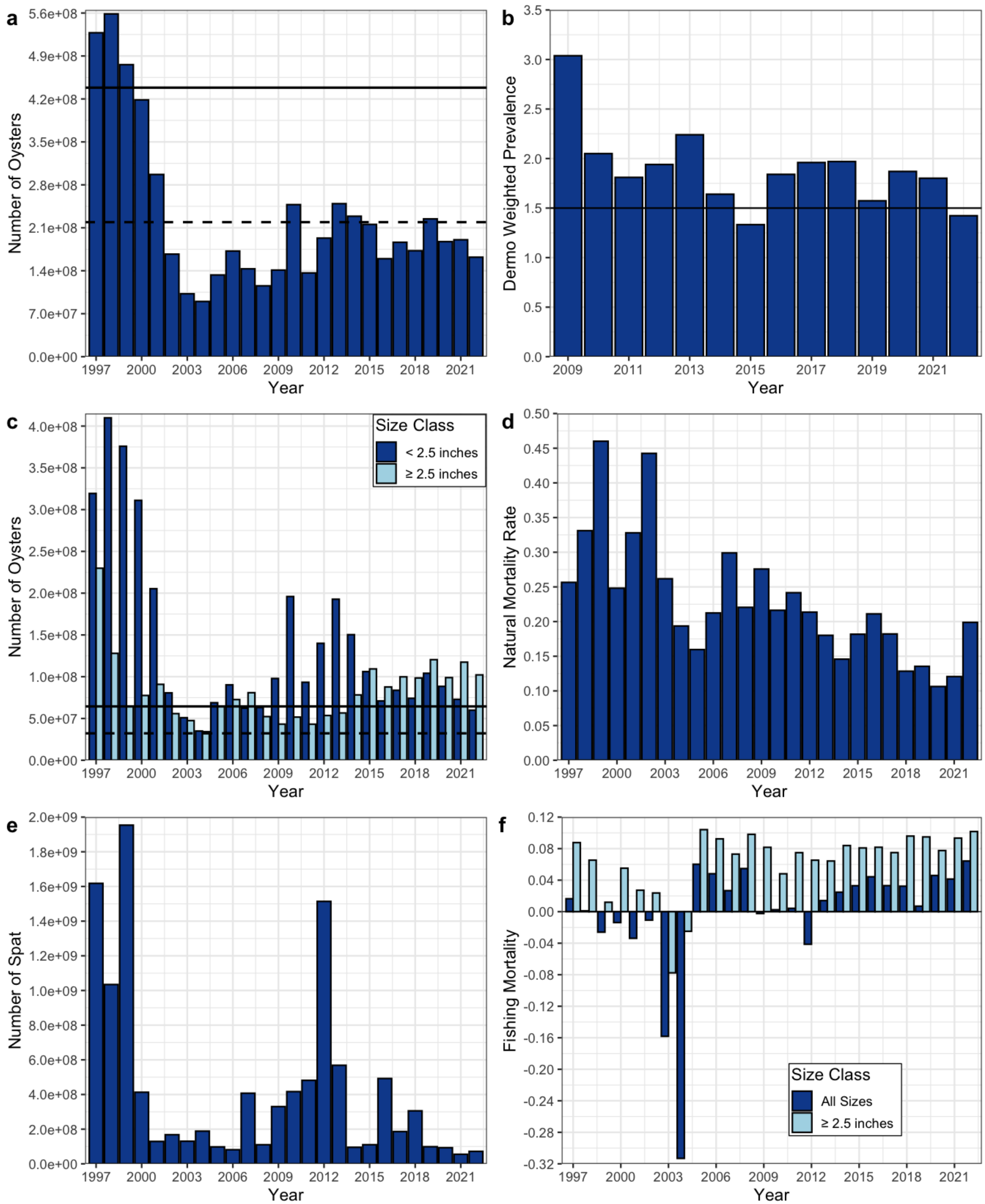
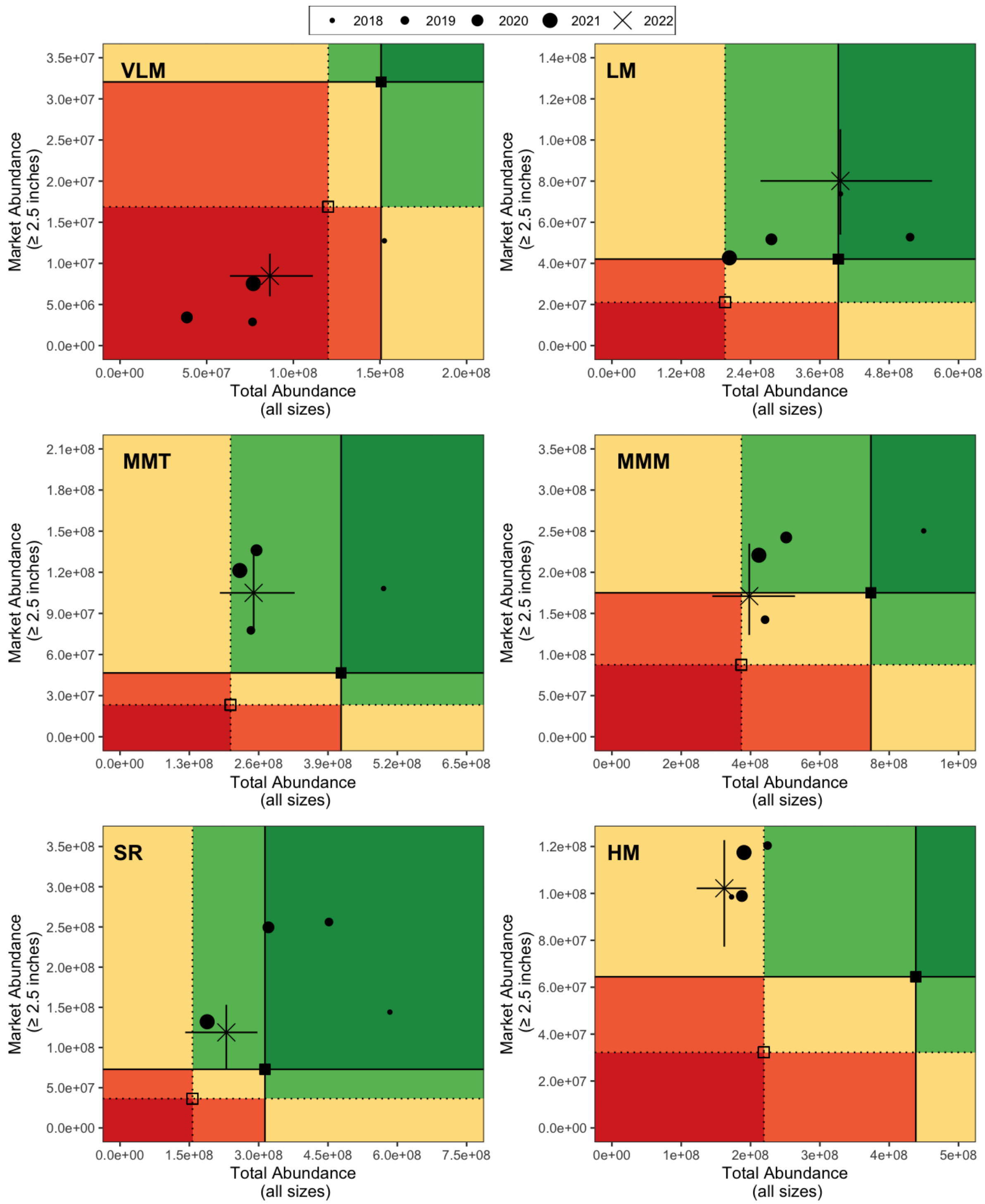


Figure 24. Position of the oyster stock 2018–2022 with respect to abundance and market abundance (≥ 2.5”) targets and thresholds for each region. Targets (solid lines) and thresholds (dashed lines) are defined in text. Error bars on the 2022 values are the 10th and 90th percentiles of 1,000 simulations of estimates incorporating both survey error and gear efficiency error. *Shading: Green, above all 4 cutoffs*; *Light green, above 3 cutoffs*; *Yellow, above 2 cutoffs*; *Orange, above 1 cutoff*; *Red, below all 4 cutoffs.*



Appendix A. History of partial (P) and full (F) resurveys for all beds, grouped by region. The entire resource was gridded and stratified between 2005 and 2008. The current 10-year resurvey schedule was implemented in 2009.

Region	Bed	# Grids	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16	'17	'18	'19	'20	'21	'22
VLM	Hope Creek	97			P	P									F					
VLM	Fishing Creek	67			P	P														F
VLM	Liston Range	32			P	P								F						
LM	Round Island	73			F											F				
LM	Upper Arnolds	29			F						F									
LM	Arnolds	99			F								F							
MMT	Upper Middle	84			F													F		
MMT	Middle	51	P						F										F	
MMT	Sea Breeze	48	P							F										F
MMM	Cohansey	83	P				F										F			
MMM	Ship John	68	P					F										F		
SR	Shell Rock	93	P			F				F				F						
HM	Bennies Sand	49	P	P			F										F			
HM	Nantuxent	68	P	F				F								F				
HM	Bennies	171	P	F								F								
HM	Hog Shoal	23	P	F										F						
HM	Strawberry	29		F									F							
HM	Hawk's Nest	28		F											F					
HM	New Beds	112			F						F									
HM	Beadons	38		F					F										F	
HM	Vexton	47		F					F										F	
HM	Egg Island	125																		F
HM	Ledge	53																	F	

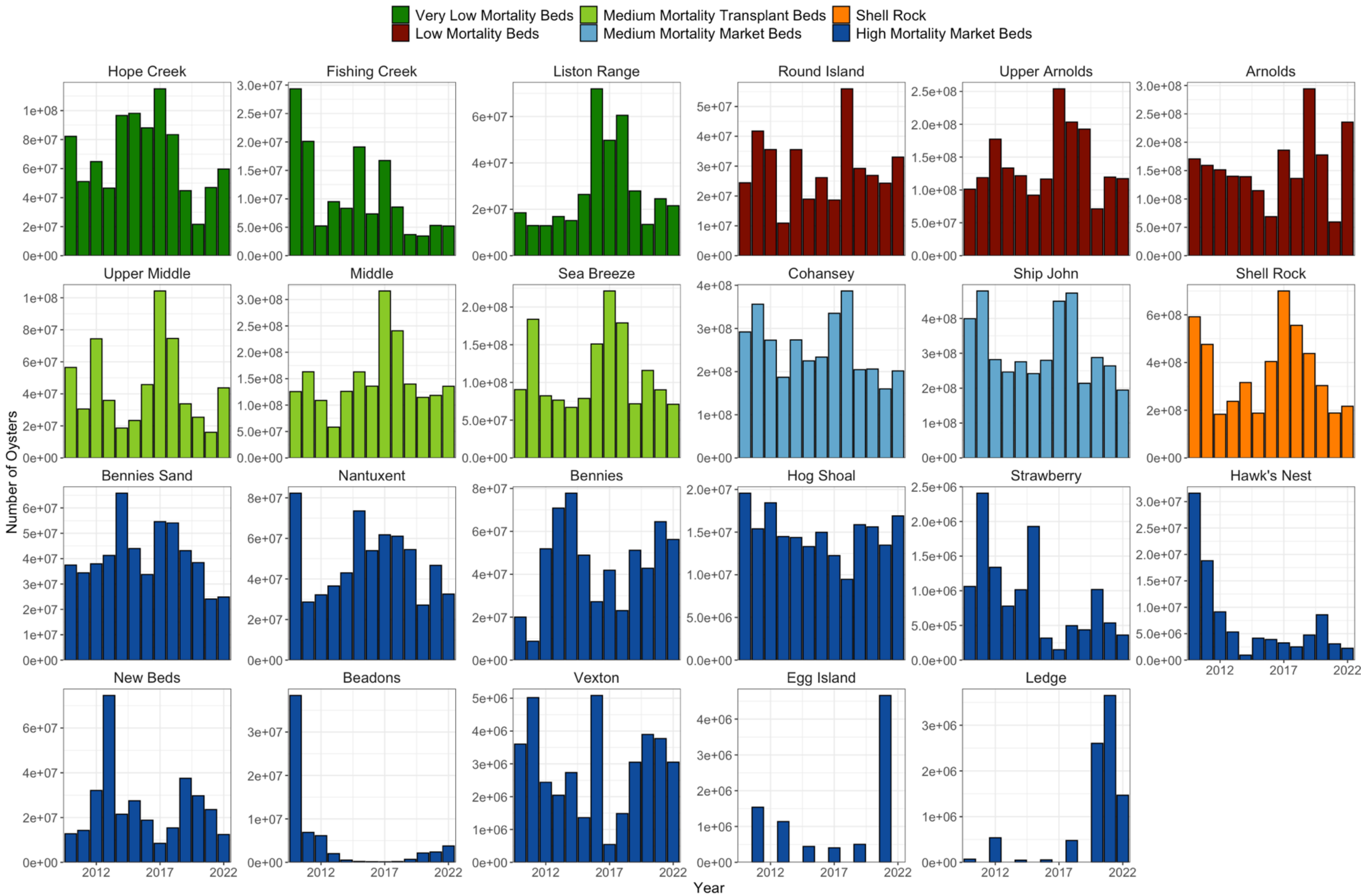
Appendix B. SARC members listed by affiliation. SAW year refers to when the February workshop was held to discuss the previous year's data. Names in parentheses indicate that the appointed member did not attend the meeting.

SAW Year	Council	Industry	NJDEP	NJDEP	Academic	Academic	Management	Rutgers (non-HSRL)	DNREC
1999			Don Byrne	Jim Joseph	Eleanor Bochenek	Judy Grassle	Paul Rago	Joe Dobarro	
2000			Paul Scarlett	Jim Joseph	Steve Jordan		Paul Rago	Joe Dobarro	
2001	Scott Bailey		Bruce Halgren	Jim Joseph	Steve Jordan	Roger Mann	Jim Weinberg	Joe Dobarro	
2002	Scott Bailey	Steve Fleetwood	Bruce Halgren	Jim Joseph	Tom Soniat	Roger Mann	Larry Jacobsen	Joe Dobarro	
2003	Scott Bailey	Scott Sheppard	Tom McCloy	Jim Joseph	Tom Soniat	Joe DeAlteris		John Quinlan	Desmond Kahn
2004	Scott Bailey	Scott Sheppard	Russ Babb	Jim Joseph	Ken Paynter	Joe DeAlteris		John Quinlan	Desmond Kahn
2005	Scott Bailey	Steve Fleetwood	Russ Babb	Brandon Muffley	Ken Paynter	Joe DeAlteris	Jim Weinberg	John Quinlan	Desmond Kahn
2006	Scott Bailey	Steve Fleetwood	Russ Babb	Brandon Muffley	(Ken Paynter)	Roger Mann	Larry Jacobsen	Joe Dobarro	Desmond Kahn
2007	Barney Hollinger	Steve Fleetwood	Russ Babb	Mike Celestino	Steve Jordan	Roger Mann	Tom Landry	Joe Dobarro	Rich Wong
2008	Barney Hollinger	Steve Fleetwood	Russ Babb	Mike Celestino	Steve Jordan	Roger Mann	Tom Landry	Gef Flimlin	
2009	Scott Bailey	Steve Fleetwood	Russ Babb	Mike Celestino	Steve Jordan	Ken Paynter	Tom Landry	Francisco Werner	
2010	Barney Hollinger	Steve Fleetwood	Russ Babb	Mike Celestino	Ken Paynter	(Roger Mann)	Tom Landry	Francisco Werner	Rich Wong
2011	Barney Hollinger	Bill Riggin	Russ Babb	Mike Celestino	Danielle Kreeger	Roger Mann	Patrick Banks	Olaf Jensen	Rich Wong
2012	Barney Hollinger	Bill Riggin	Jason Hearon	Mike Celestino	Steve Fegley	Roger Mann	Patrick Banks	Olaf Jensen	Rich Wong
2013	Barney Hollinger	Bill Riggin	Jason Hearon	Mike Celestino	Steve Fegley	Juli Harding	Patrick Banks	Olaf Jensen	Rich Wong
2014	Barney Hollinger	Scott Bailey	Jason Hearon	Mike Celestino	(Steve Fegley)	(Juli Harding)	Mitch Tarnowski	John Wiedenmann	Rich Wong
2015	Steve Fleetwood	Scott Bailey	Jason Hearon	Mike Celestino	Pat Sullivan	Juli Harding	Mitch Tarnowski	John Wiedenmann	Rich Wong
2016	Steve Fleetwood	Scott Bailey	Jason Hearon	Mike Celestino	Pat Sullivan	(Jerry Kauffman)	Mitch Tarnowski	John Wiedenmann	Rich Wong
2017	Steve Fleetwood	Barney Hollinger	Craig Tomlin	Mike Celestino	Pat Sullivan	Jerry Kauffman	Missy Southworth	John Wiedenmann	Rich Wong
2018	Barney Hollinger	Scott Sheppard	Craig Tomlin	Mike Celestino	Mike Wilberg	Jerry Kauffman	Missy Southworth	John Wiedenmann	Rich Wong
2019	Barney Hollinger	Scott Sheppard	Craig Tomlin	Mike Celestino	Mike Wilberg	Matthew Hare	Missy Southworth	John Wiedenmann	Rich Wong
2020	Steve Fleetwood	Scott Sheppard	Craig Tomlin	Mike Celestino	Mike Wilberg	Matthew Hare	Carolina Bourque	John Wiedenmann	Rich Wong
2021	Steve Fleetwood	Tim Reeves	Craig Tomlin	Mike Celestino	Daniel Hennen	Matthew Hare	Carolina Bourque	John Wiedenmann	Rich Wong
2022	Barney Hollinger	Tim Reeves	Craig Tomlin	Mike Celestino	Daniel Hennen	Dave Eggleston	Carolina Bourque	John Wiedenmann	Rich Wong
2023	Barney Hollinger	Tim Reeves	Craig Tomlin	Mike Celestino	Daniel Hennen	Daniel Bowling	Christine Jensen	John Wiedenmann	Rich Wong

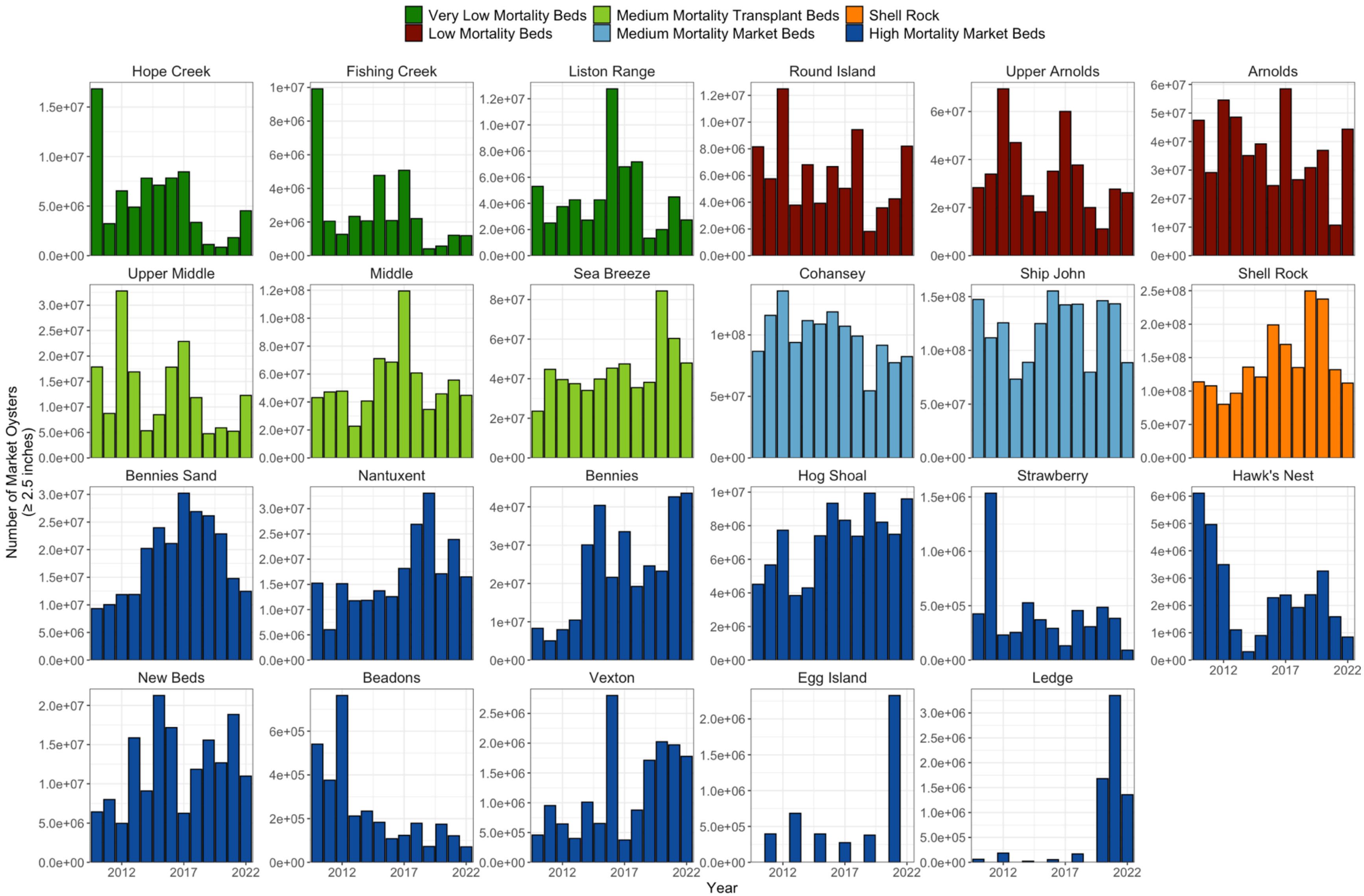
Appendix C. Detailed history of transplant efforts since 2007. A transplant was initially planned for 2020, but due to the COVID-19 pandemic and associated impacts on the market the transplant program was canceled.

Year	Region	Donor Bed	Receiver Bed	Bushels Moved	Total # Oysters	Fraction Oysters < 2.5"	Number Oysters ≥ 2.5"	Added Quota Allocation	Fraction Cultch	Chosen Expl. Rate	Achieved Expl. Rate	# Oysters at Chosen (all sizes)	# Oysters at Achieved (all sizes)
2022	VLM	Hope Creek	Upper Arnolds	2,700	1,046,387	0.960	41,339	154	0.597	1.93%	1.36%	1,484,417	1,046,387
	LM	Upper Arnolds	Shell Rock	2,500	1,386,018	0.826	241,547	901	0.322	1.49%	1.66%	3,030,154	3,366,124
		Arnolds	Shell Rock	5,400	1,980,106	0.845	306,252	1,143	0.538				
	MMT	Upper Middle	Bennies Sand	2,700	544,825	0.744	139,260	520	0.650	2.46%	2.15%	5,524,254	4,837,920
		Middle	Bennies Sand	5,400	1,481,666	0.564	645,894	2,410	0.491				
		Sea Breeze	Bennies Sand	10,800	2,811,429	0.318	1,916,946	7,153	0.292				
2021	LM	Arnolds	Shell Rock	5,400	2,601,798	0.900	260,180	974	0.472	0.76%	0.94%	2,097,973	2,601,798
	MMT	Upper Middle	Bennies	2,650	659,794	0.733	176,218	660	0.573	2.46%	2.50%	6,297,118	6,401,396
		Middle	Bennies	2,700	997,139	0.481	517,274	1,937	0.199				
		Middle	Nantuxent	10,700	3,935,479	0.535	1,829,275	6,851	0.263				
		Sea Breeze	Bennies	2,700	808,984	0.279	583,363	2,185	0.206				
2020	*NO TRANSPLANT CONDUCTED*												
2019	LM	Arnolds	Shell Rock	7,200	2,837,705	0.828	489,430	1,861	0.449	2.26%	0.70%	8,941,378	2,837,705
	MMT	Middle	Bennies Sand	25,000	9,890,349	0.748	2,496,843	9,494	0.288	2.46%	2.79%	12,158,274	13,956,501
		Sea Breeze	Bennies Sand	8,800	4,066,152	0.768	941,483	3,580	0.206				
2018	MMT	Upper Middle	Bennies	4,750	973,690	0.527	460,846	1,752	0.566	2.46%	1.76%	15,785,722	12,310,312
		Middle	Bennies	27,500	8,230,069	0.507	4,054,033	15,415	0.329				
		Sea Breeze	Bennies	7,700	3,106,553	0.759	749,703	2,851	0.290				
2017	MMT	Upper Middle	Bennies	3,200	948,685	0.365	602,546	2,282	0.408	2.46%	2.37%	8,184,564	7,887,414
		Middle	Bennies	21,350	5,625,257	0.312	3,868,205	14,652	0.299				
		Sea Breeze	Bennies	4,700	1,313,472	0.515	636,920	2,412	0.219				
2016	LM	Arnolds	Cohansey	4,800	2,168,012	0.637	787,816	2,972	0.290	0.76%	0.96%	1,712,353	2,168,012
	MMT	Middle	Shell Rock	8,150	2,556,215	0.386	1,569,932	5,925	0.280	1.49%	0.97%	3,958,253	2,979,901
		Sea Breeze	Shell Rock	2,400	426,443	0.319	290,458	1,096	0.440				
2015	LM	Upper Arnolds	Ship John	10,200	4,474,515	0.721	1,247,128	4,688	0.330	1.30%	1.30 - 1.90%	3,598,514	4,474,515
	MMT	Middle	Shell Rock	5,550	1,726,335	0.604	682,813	2,567	0.310	2.30%	> 2.30%	4,360,643	4,475,247
		Sea Breeze	Shell Rock	10,800	2,748,912	0.422	1,590,121	5,978	0.250				
2014	LM	Arnolds	Ship John	15,500	6,168,587	0.485	3,174,627	12,025	0.220	2.33%	2.25%	6,403,869	6,134,370
	MMT	Middle	Shell Rock	6,600	1,553,053	0.381	961,033	3,640	0.250	2.33%	2.41%	3,517,430	3,473,086
		Sea Breeze	Shell Rock	7,300	1,922,420	0.390	1,173,115	4,444					
2013	VLM	Liston Range	Shell Rock	550	*VLM CLOSED in 2013, accidental transplant from this region*								
	LM	Round Island	Shell Rock	2,250	888,151	0.535	412,848	1,552	0.280	2.33%	< 2.33%	9,962,070	8,459,940
		Upper Arnolds	Shell Rock	15,550	6,238,792	0.553	2,787,160	10,478					
		Arnolds	Shell Rock	2,700	1,109,073	0.609	433,783	1,631					
	MMT	Upper Middle	Bennies Sand	3,200	890,008	0.338	588,950	2,214	0.270	2.33%	< 2.33%	5,465,140	3,798,531
		Middle	Bennies Sand	5,200	1,346,337	0.423	777,424	2,923					
		Sea Breeze	Bennies Sand	6,200	1,587,589	0.268	1,161,796	4,368					
2012	LM	Arnolds	Nantuxent	7,650	4,489,153	0.790	942,900	3,558	0.280	1.27%	< 1.27%	4,730,022	4,469,068
	MMT	Upper Middle	Nantuxent	2,100	797,489	0.648	280,788	1,060	0.260	1.88%	> 1.88%	7,245,772	9,221,809
		Middle	Bennies Sand	11,200	4,406,878	0.602	1,755,084	6,623					
		Sea Breeze	Bennies Sand	5,425	2,563,782	0.751	638,647	2,410					
		Sea Breeze	Nantuxent	3,100	1,463,987	0.733	391,610	1,478					
2011	VLM	Hope Creek	Cohansey	6,150	3,766,429	0.658	1,289,314	4,940	0.180	1.27%	< 1.27%	5,003,664	4,871,104
		Liston Range	Cohansey	1,800	1,085,283	0.615	417,586	1,600					
	LM	Round Island	Bennies	3,350	1,630,191	0.603	646,914	2,479	0.270	1.27%	> 1.27%	3,991,178	4,252,834
		Upper Arnolds	Bennies	2,800	1,008,104	0.608	394,902	1,513					
		Arnolds	Bennies	4,000	1,638,736	0.665	549,631	2,106					
	MMT	Middle	Bennies	17,750	5,900,036	0.533	2,753,351	10,549	0.250	1.88%	> 1.88%	5,255,322	5,848,372
2010	VLM	Hope Creek	Bennies	1,200	NA	NA	NA	1,232	0.400	1.27%	~1.27%	3,833,693	NA
		Fishing Creek	Bennies	200	NA	NA	NA						
		Fishing Creek	Shell Rock	1,800	NA	NA	NA						
		Liston Range	Shell Rock	4,750	NA	NA	NA	4,839					
	LM	Upper Arnolds	Shell Rock	1,200	NA	NA	NA	839	0.250	2.33%	< 2.33%	8,587,511	NA
		Upper Arnolds	Bennies	17,050	NA	NA	NA	14,814					
	MMM	Sea Breeze	Bennies	11,050	NA	NA	NA	5,502	0.390	1.88%	< 1.88%	4,155,570	
		Cohansey	Bennies	1,500	NA	NA	NA			NA	NA	NA	NA
2009	VLM	Hope Creek	Ship John	9,100	5,780,080	0.651	2,017,030	7,699	0.240	1.27%	> 1.27%	5,032,780	5,722,475
	LM	Arnolds	Bennies	10,400	4,942,416	0.485	2,544,755	9,713	0.250	1.88%	> 1.88%	4,621,870	4,946,939
	MMT	Upper Middle Middle	Bennies	14,100	4,559,705	0.548	2,060,715	7,865	0.270	2.33%	> 2.33%	4,716,070	4,566,296
2008	LM	Arnolds	Cohansey	9,450	4,089,861	0.483	2,113,742	8,161	0.350	1.27%	> 1.27%	3,664,083	4,012,758
	MMT	Middle	Bennies Sand	8,200	2,577,406	0.363	1,641,413	6,337		2.33%	> 2.33%	2,291,480	2,553,726
2007	MMT	Middle	Nantuxent	12,982	3,819,176	0.460	2,064,242	7,849	0.360	1.48%	~1.48%	NA	3,819,176

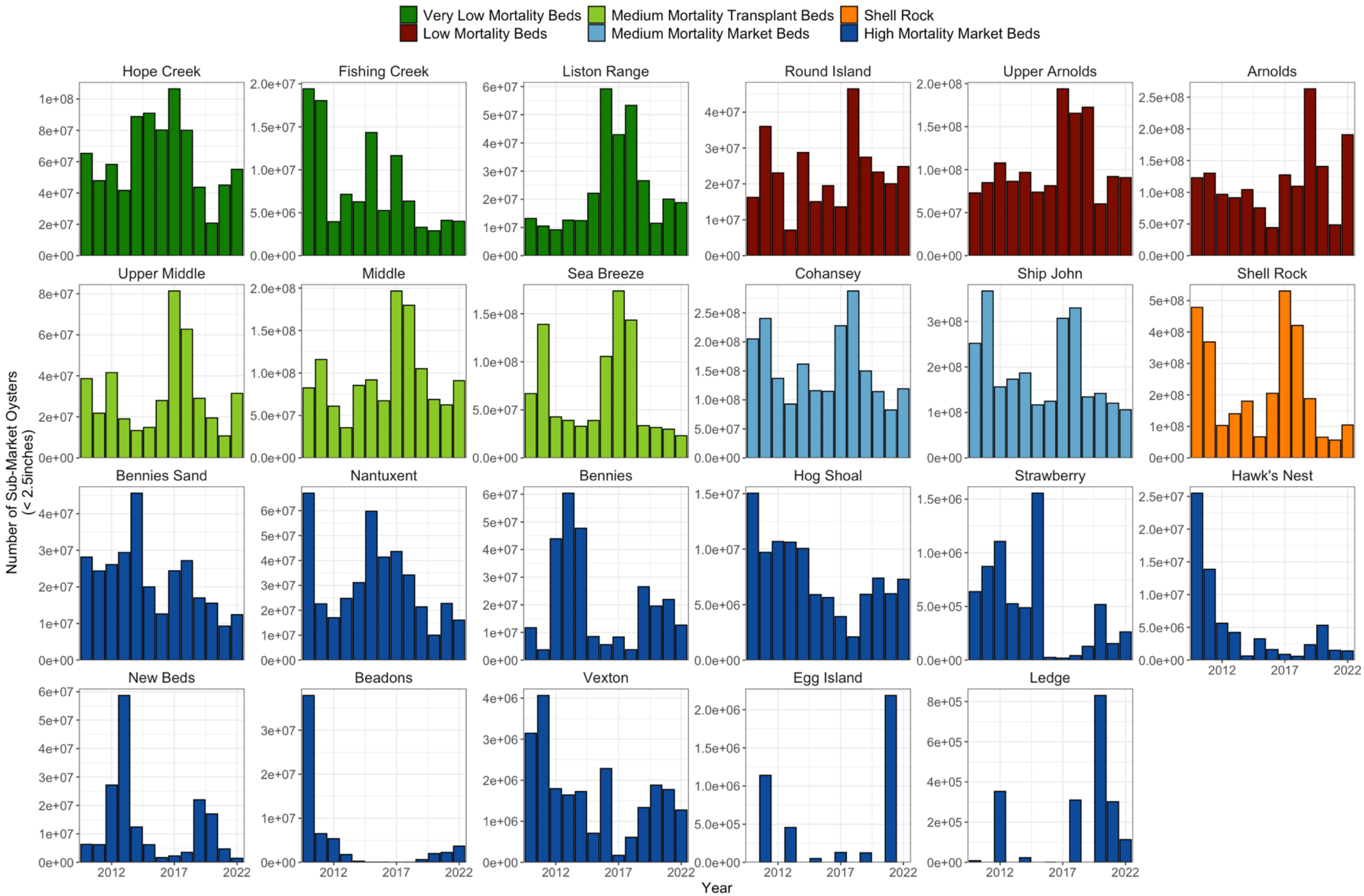
Appendix D. Bed-level oyster abundance for each region. Note y-scale varies.



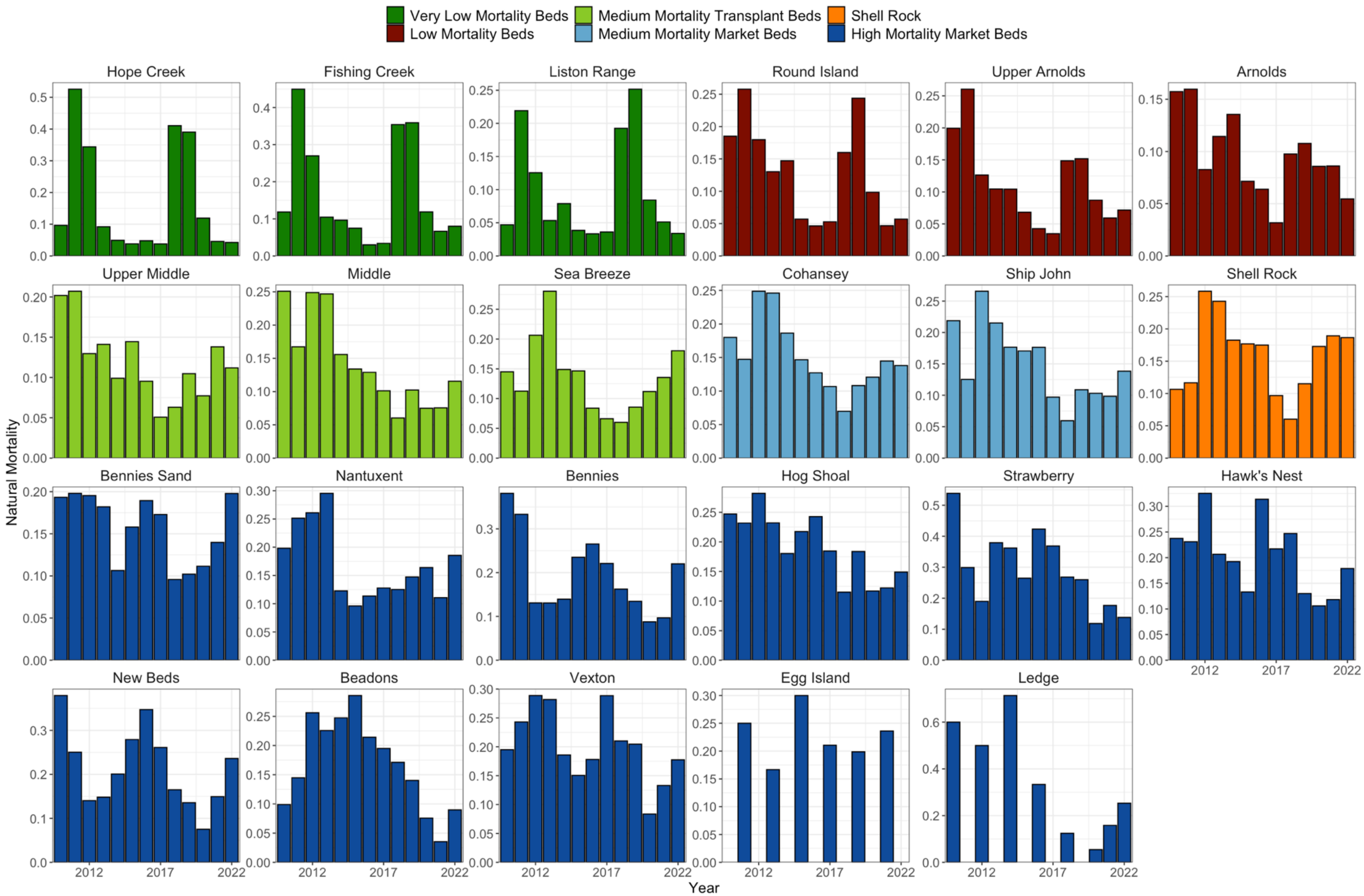
Appendix E. Bed-level market abundance for each region. Note y-scale varies.



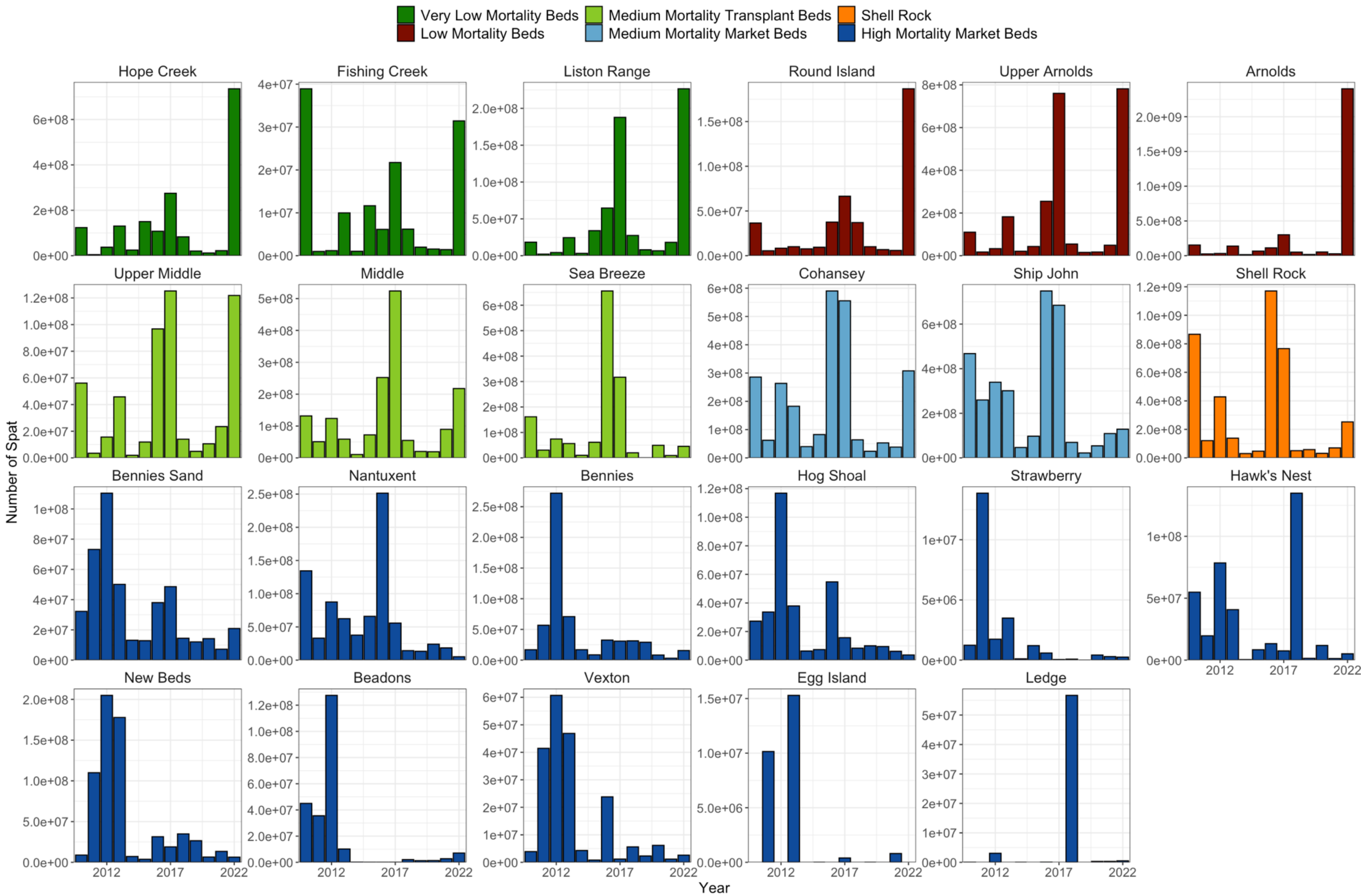
Appendix F. Bed-level sub-market abundance for each region. Note y-scale varies.



Appendix G. Bed-level mortality for each region. Note y-scale varies.



Appendix H. Bed-level spat abundance for each region. Note y-scale varies.



Appendix I. Very Low Mortality Workshop Summary

<u>1. Workshop Participants:</u>

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New Jersey Department of Environmental Protection (NJDEP)

Steve Fleetwood, Barney Hollinger, Bill Riggin
Oyster Industry and Shellfish Council

Iris Burt, Dave Bushek, Jennifer Gius, Jason Morson, Daphne Munroe
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<u>2. Background:</u>

The following is an excerpt from the 2017 Stock Assessment Workshop Final Report (Ashton-Alcox et al. 2017):

When the Very Low Mortality Region (VLM) entered the assessment in 2007, there was no history on which to base biological reference points. At the 2012 SAW, an assumption was made that this region mimicked the Low Mortality Region (LM) well enough to adjust the LM targets for acreage and apply them to the VLM (see p. 34, Ashton-Alcox et al. 2012). Catchability coefficients from the LM were also applied to the VLM. Upon analyzing the results of the 2013 dredge calibration experiments, it became apparent that catchability coefficients for the VLM differed from those of the LM and thus, the biological reference point targets being used for the VLM were similarly suspect. The 2016 SARC advised the development of region-appropriate targets and thresholds for the VLM. The VLM assessment time series now has 10 years of observations that include a wide range of population influences. The first two years had high abundance with no exploitation; the next three included transplant exploitation after which there was a severe freshwater mortality event followed by a three-year fishery closure. Since then, there has been a continuing recovery period without exploitation. The SARC debated various applications of the 10-year time series values as potential targets and thresholds. Ultimately, the SARC advised use of the 75th percentile of the VLM 2007-2016 abundance time series as a target and the 50th percentile as the threshold with the proviso that this be re-evaluated in three to five years.

In 2022 a separate workshop was therefore convened by the Oyster Industry Scientific Steering Committee (OISSC) to assess whether the abundance and fishing exploitation reference points designated for the VLM in 2017 were still appropriate. The OISSC is made up of staff from the New Jersey Department of Environmental Protection, the Haskin Shellfish Research Lab, and members of the Fishing Industry and the Shellfish Council. This report summarizes some of the key findings from the workshop.

3. Exploitation Reference Points

As was described in the background section above, the VLM region only entered the assessment in 2007. As a result, there was no exploitation history on which to base or calculate a range of sustainable exploitation rates. Therefore, exploitation reference points in the region were initially modeled after the Low Mortality region (Powell et al. 2009). However, the SARC recommendation to apply a single set of catchability coefficients in 2015, and subsequent reconstruction of the entire time series, resulted in a shift in abundance and exploitation rates on every region. These changes are detailed in the 2016 SAW final report (Ashton-Alcox et al. 2017). One unintended consequence of this change was an increase in the exploitation rate reference points for the VLM region. This occurred because the catchability on the VLM region was adjusted higher, which in turn adjusted the abundance lower, which in turn adjusted the exploitation rate higher (Ashton-Alcox et al. 2017). This change received little attention between 2016 and 2021 because there were no recommendations from any SARC during this time to transplant from the region. However, in 2021, when a SARC recommended a small transplant be allowed, the SARC also requested to recommend a rate lower than the minimum rate available on the VLM region, and a rate more in line with the LM region. Since it was the original intent of the SARC in 2009 to have the exploitation reference points on the VLM match those from the LM, the LM exploitation rates were provided as an alternative option to the SARC in 2021 and again in 2022.

After some discussion amongst workshop participants about the VLM exploitation reference points, participants unanimously supported permanent adoption of the LM exploitation reference points for the VLM region.

4. How Much Does the VLM Region Contribute to Recruitment Bay-Wide

A management approach that applies more conservative abundance and exploitation reference points may be warranted on the VLM region if we know it contributes a disproportionately large amount of recruitment to the rest of the bay. However, hydrodynamics models of oyster larvae dispersal in Delaware Bay suggest simulated larvae released from the VLM region tend to grow more slowly than those released from other regions and that they tend to be retained in the upper part of the bay (Narvaez et al. 2012; Figure 1). This results in simulated larvae from this region surviving to settlement, on average, just 7% of the time, whereas larvae from other regions can survive to settlement upwards of 50% of the time. It should be noted however, that a simulated population, based in part on the recruitment dynamics described in Narvaez et al. 2012, estimated a much slower recovery of the VLM population between 2011 and 2018 (Munroe et al. 2013), suggesting some uncertainty in these larval survival estimates.

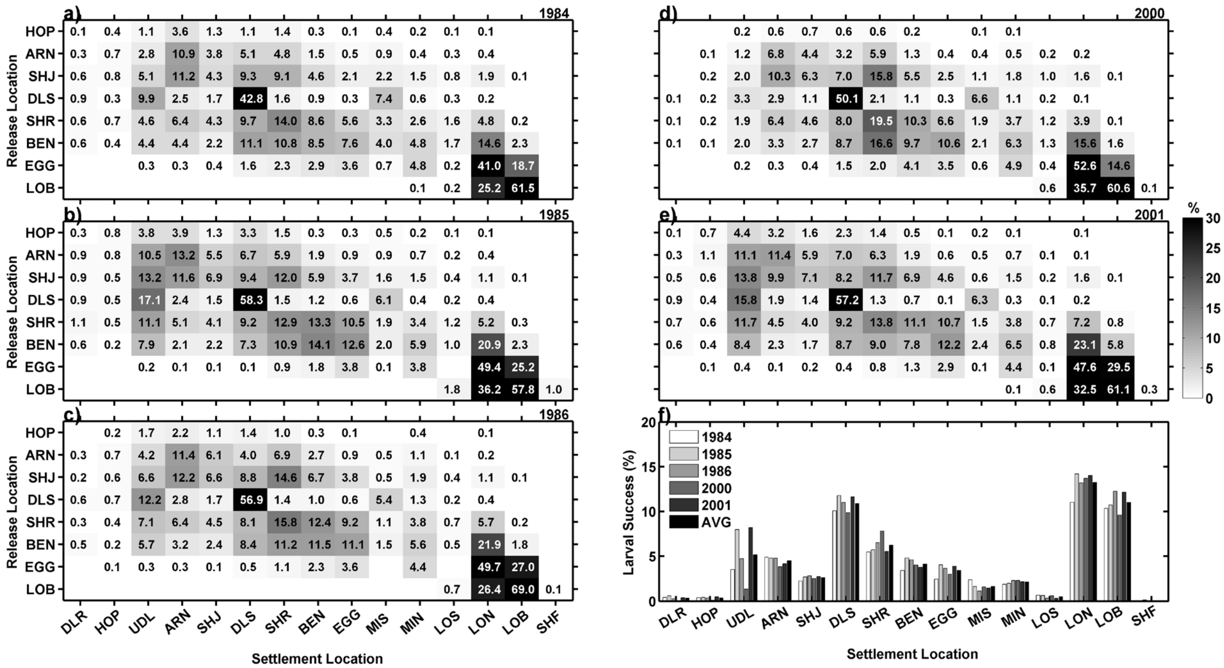

Figure 1. Proportion of larvae surviving to settlement for five test years after being released from different regions of the Delaware Bay. HOP = Hope Creek, which is a bed on the Very Low Mortality region (Adapted from Narvaez et al. 2012).

Since simulated larvae released from the VLM rarely survive long enough to settle, a more cautious approach to management in the VLM region may not be warranted if based only on the contribution of this region to population-wide recruitment.

5. Impact of Low Salinity on the VLM Region

A more precautionary approach to management of the VLM region may also be warranted if the region appears to be affected more frequently and more drastically by changes in the environment. In 2011 and again in 2018, lower than average salinity in the upper Delaware Bay resulted in large mortality events on the Very Low Mortality region (Figure 2).

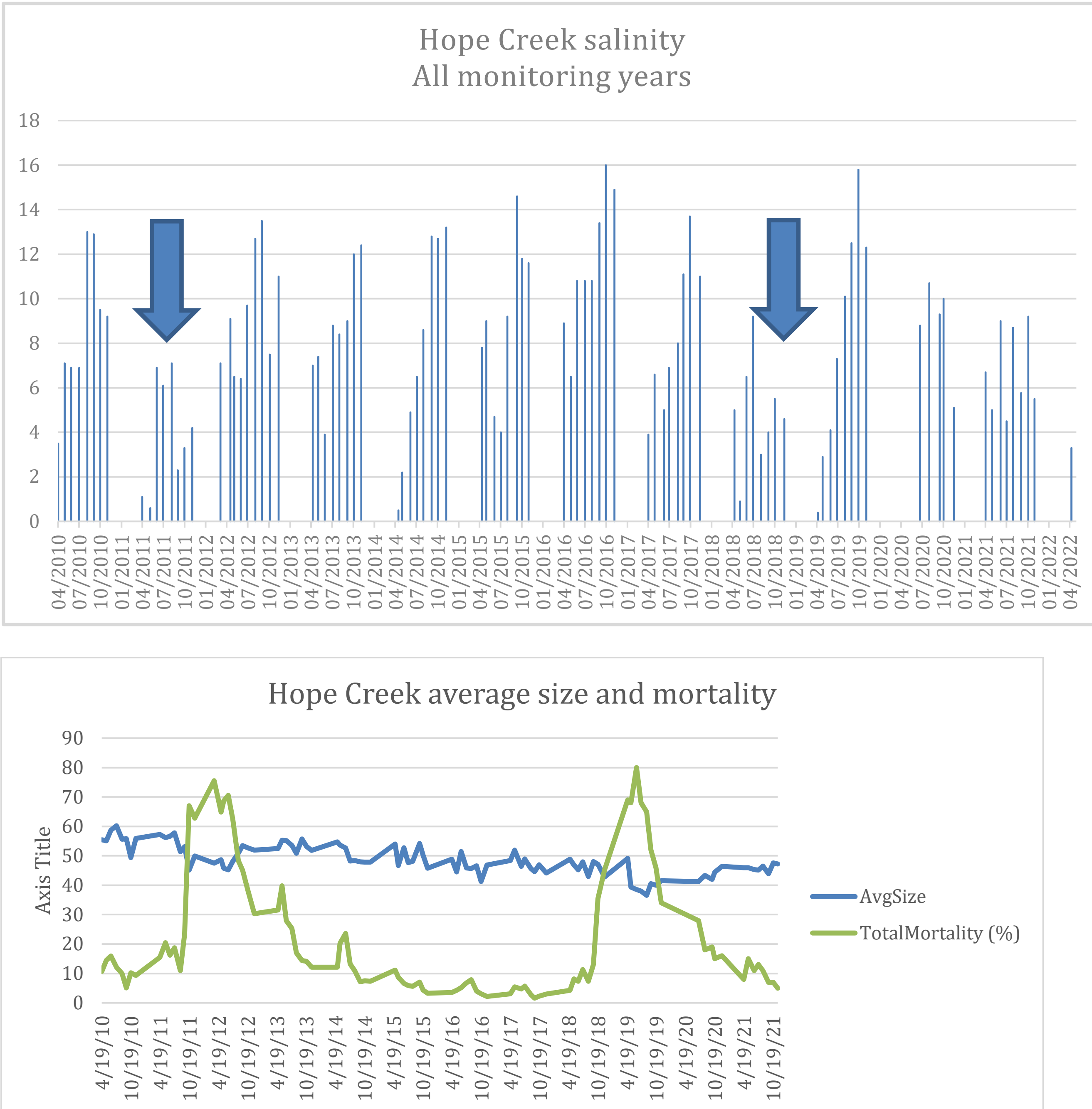

Figure 2. Salinity measured at Hope Creek (VLM Region) (top panel) and the total mortality and average size at Hope Creek (bottom panel).

Since the VLM region clearly experienced two large mortality events associated with lower-than-average salinity during the short time period over which the region has been assessed, a more precautionary approach to management is likely warranted if there is concern that additional low salinity events may be observed in the future.

6. Is There Evidence the VLM Region Is Being Managed Sustainably?

A population viability analysis (PVA) is a simple tool that simulates future population size based on observed population growth rates during application of a given management strategy. PVA applied to data collected since 2007 (the first year the VLM was assessed) from each of the management regions in Delaware Bay suggests the VLM total and market population size is likely to change very little ten years from now (Figure 3).

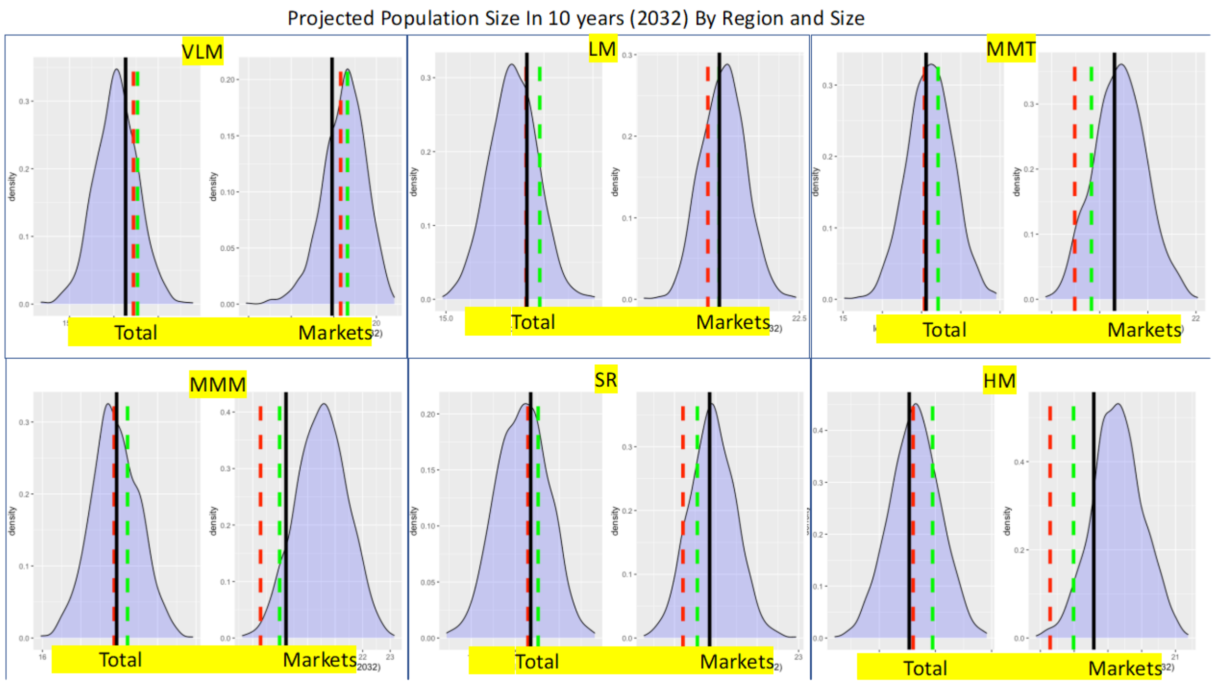

Figure 3. Population viability analysis applied to population growth rate data (2007-2022) from each management region. A probability plot is included of simulated population size (x axis) for Total and Market abundance for each management region in 2032. The solid black line represents the current (2022) population size and the green (Target) and red (Threshold) dashed lines represent the current reference points for each region.

The current management approach on the VLM region appears to be sustainable and simulated population projections on this region fit within the range of projections on the other management regions. This suggests a change to the management approach and reference points may not be warranted.

7. Enhancement of the Low Mortality Region

In discussing reference points for the VLM region, a discussion topic came up that is worth reporting/summarizing. Several workshop participants expressed concern that some portion of the oysters being moved from the VLM region to the lower parts of the bay might die. In addition, there was recognition that recent declining abundance trends on the LM region suggest it could benefit from enhancement activity (transplants and shellplants) that have proven successful in increasing productivity in regions lower in the bay. Finally, there was recognition that a transplant from the VLM region to the LM region in 2022, the first transplant to ever go to the LM region, experienced low mortality and high recruitment relative to other transplants conducted in 2022.

Workshop participants agreed that there should be regular discussion/consideration for taking any approved transplants from the VLM region and putting them on the LM region where they may survive better even if they won't increase the harvest/quota on the Direct Market regions.

8. Potential Alternative Reference Points

The committee explored several potential alternative reference points and these alternatives are summarized below.

Towards the development of alternative reference points, and in search of finding some natural breakpoints in the VLM region abundance timeseries, we explored a variety of quantitative methods including regression trees and changepoint analyses. Neither approach produced usable results, we suspect, in part, because of the limited length of the VLM timeseries and lack of underlying differences.

We therefore employed more qualitative methods. The VLM timeseries is relatively short (15 years). Both total abundance and market abundance have generally trended downwards over time, save the period between 2014-2016/17 (Figure 4). In the absence of a quantitative statistic breaking the timeseries into 'regimes,' the limited length of the timeseries, and the range of abundance observed over this time, we chose to use all years in development of candidate reference points.

There are limited biological models available to inform a biological basis for selecting reference points, and so we explored empirical reference points. The methods employed included (Figure 5):

1. Status quo – the 75th and 50th percentiles of the 2007-2016 timeseries as the target and threshold, respectively.

2. The 75th and 50th percentiles of the 2007-2021 timeseries as the target and threshold, respectively.

3. The 50th percentile of abundance of the 2007-2021 timeseries as the target, and 1⁄2 of this value as the threshold (Feb 2022 SAW proposal).

4. The average of the 3 lowest abundances above the median level of abundance as the target, and the average of the 3 highest abundances below the median as the threshold.

5. The 25th percentile of abundances above the median level of abundance as the target, and the 75th percentile of abundances below the median level of abundance as the threshold.

6. The 60th and 40th percentiles as the target and threshold, respectively.

Alternatives 4 and 5 were broadly modelled after American lobster reference points.

In terms of answering whether there is a level of abundance below which the resource should never drop, we didn't have any quantitative guidance (other than obvious values) and so have avoided that question. Though a guiding principle to development of reference points might be to have as many data points below the selected threshold as practicable, in recognition that the fewer points below, the greater the uncertainty about stock dynamics at low levels of abundance (e.g., risk of depensatory dynamics?). There is of course a tradeoff between maximizing the number of observed data points below a threshold and forgoing yield.

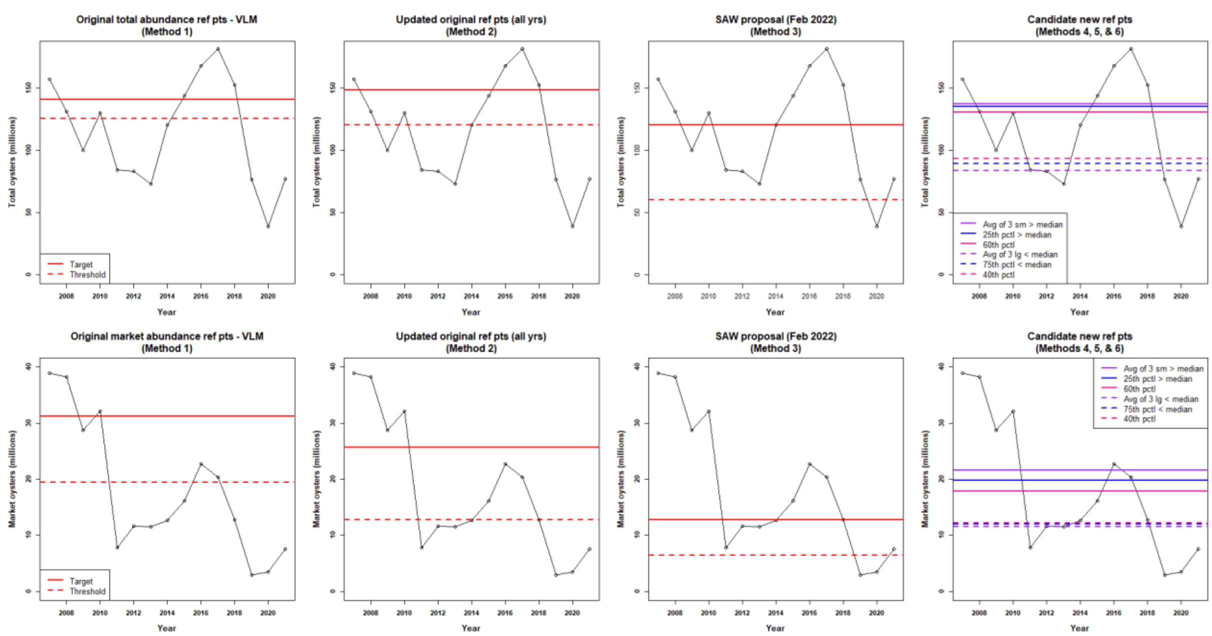

Figure 4. Depiction of various iterations of existing and candidate reference points for total (top row) and market (bottom row) abundance of the VLM region.

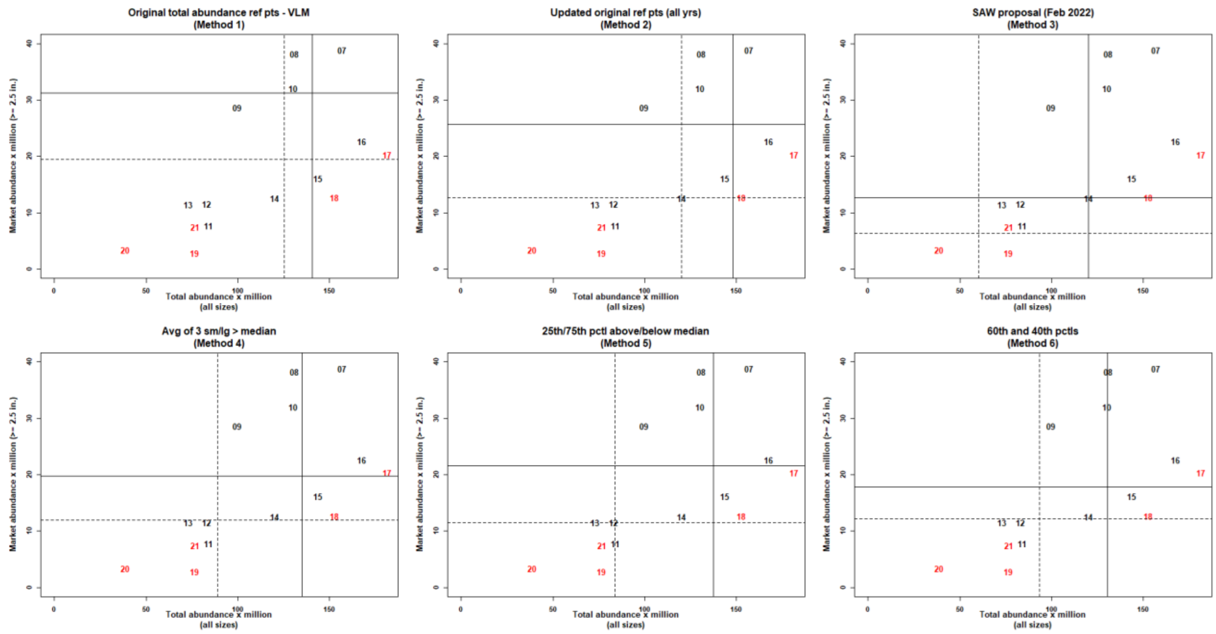

Figure 5. Total abundance versus market abundance for the VLM region with 6 different reference point methods superimposed to demonstrate stock status. The plot depicts the last 2 digits of each year. Dotted lines = thresholds, solid lines = targets. The most recent 5 years are plotted in red font.

5. Consensus Recommendations:

After reviewing each of the key workshop findings above, three important management recommendations came out of the workshop:

1. Permanently adopt the LM exploitation reference points for the VLM region.

2. When appropriate, consider using transplants from the VLM region to "enhance" the LM region instead of moving them to a Direct Market region.

3. Retain the current VLM abundance reference points (75th percentile as the Target and 50th percentile as the Threshold of the 2007-2016 time series).

6. References:

Ashton-Alcox, K.A., D. Bushek, J.E. Gius, 2012. Stock Assessment Workshop New Jersey Delaware Bay Oyster Beds (14th SAW) Report. *Haskin Shellfish Res. Lab.*, Port Norris, NJ. 105pp.

Ashton-Alcox, K.A., D. Bushek, J.E. Gius, J. Morson, D. Munroe, 2017. Stock Assessment Workshop New Jersey Delaware Bay Oyster Beds (19th SAW) New Jersey Delaware Bay Oyster Beds Final Report. *Haskin Shellfish Res. Lab.*, Port Norris, NJ. 120pp.

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

Narvaez, D. A., J. Klinck, E. N. Powell, E. E. Hoffmann, J. Wilkin, and D. Haidvogel. 2012. Modeling dispersal of easter oyster (*Crassostrea virginica*) larvae in Delaware Bay. Journal of Marine Research 70: 381-409.

Powell, E., and K. A. Ashton-Alcox. 2009. Stock Assessment Workshop New Jersey Delaware Bay Oyster Beds (11th SAW) Report. *Haskin Shellfish Res. Lab.*, Port Norris, NJ. 116pp.