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Stock Assessment Workshop
New Jersey Delaware Bay Oyster Beds
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Final Report

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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 mid-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. 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 and 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 throughout a number of 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 four 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 with the exception of Egg Island and Ledge. The survey alternates sampling of these two beds each year due to their consistently low abundance. As of 2007, there are 23 surveyed beds grouped into six regions designated on the basis of 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 Shell Fisheries, 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 Shell Fisheries Council; one from the NJ oyster industry; two NJDEP members; one from 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 Oct-Nov 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 Shell Fisheries 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 approximately 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. To determine how many grids to sample within a given strata, a simulation is used to estimate the strata variance for a given number of sampled grids. When the reduction in variance is minimal for a given increase in grids sampled on a stratum, the sample intensity for that stratum is deemed statistically adequate to assess the abundance. However, a large number of samples is never dedicated to a bed known to have very low abundance. Grids that receive enhancement (shellplanting or transplanting) are sampled each year for up to three years following the enhancement activity.

Science Advice: Formalize Allocation of Survey Effort

There is subjectivity in the approach for allocating survey effort described above for two reasons. First, the meaning of "when a reduction in variance is minimal" can vary from one person to the next, and second, what constitutes a "large number of samples" can vary from one person to the next. Therefore, an ongoing Science Recommendation since the 2019 SAW has been, "an evaluation of alternative methods for allocating survey effort." Three alternatives were presented and discussed at the SAW this year. In the first application, an exponential decay model was fit to a plot of sample number (x) and variance (y) and the sample number associated with the slope at 20% of the slope at the origin was identified as the required number of samples (Figure 8a). In the second application, the sample allocation was identified by the number that resulted in a CV of 20% (0.2) or less (Figure 8b). The third application made use of the Neyman optimal allocation formula applied to a stratified random survey design (Kimura and Somerton 2006) with the stipulation that a minimum of two grids from each strata must be sampled. Figure 8c shows the distribution of samples across the sample domain using the status quo method on the left and the Neyman allocation formula on the right. Sampling effort is more heavily allocated on high density areas under the Neyman allocation formula.

The 2021 SARC indicated a preference for the Neyman optimization method so we will use that moving forward.

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; condition index; and the intensity of dermo and MSX infections. 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. 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

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

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.

Science Advice: How does increased sampling intensity affect survey error?

A Science Recommendation from the 2018 SARC suggested an evaluation of ways to reduce assessment uncertainty. To address this, an audit of all sample processing methodology, described above, was conducted to determine if there were opportunities to increase sample processing efficiency and thus increase the number of samples that could be collected in a given sampling season. Adjustment to survey protocols to increase processing efficiency are summarized in the final report from the 2019 SAW (Morson et al. 2019). The 2019 and 2020 SARCs subsequently recommended an evaluation of how the increased efficiency, and subsequent increase in sampling intensity, during the 2019 and 2020 Assessment Survey affected survey error.

As a result of increased sample processing efficiency, a total of 25 more grids were added to the standard 175 grids for the 2019 Assessment Survey (200 total) and an additional 27 more grids were added for the 2020 Assessment Survey (227 total). To evaluate the effect these added samples had on survey error, total abundance survey CV was evaluated for all three surveys (2018-2020; Figure 9). The added samples did not have a large influence on the total abundance error. However, the total abundance error is a combination of both survey error, which would be affected by increased sample intensity, and gear efficiency error, which would not be affected. The 2021 SARC therefore requested that the influence of only the survey error be evaluated and reported on at the next SAW.

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 (50th percentile) exploitation rate. To provide flexibility in management, the SARC recommended using the 50th percentile of exploitation as a base but to allow increasing exploitation to the 60th percentile rate when the population was expanding or to reduce it to the 40th 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 10. 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.

Science Advice: Is There a Tendency to "Over" or "Under-Harvest" In Any One Direct Market Region?

As described above, quota projections are made using a grand mean from all market regions. The 2020 SARC suggested this may mean there could be a tendency to over- or under-harvest on a given region if that region consistently has more or less markets per bushel than the grand mean calculated from all market regions. To evaluate this, the difference between the targeted and *achieved exploitation rate was plotted for each market region (Figure 11). The plot suggests there is a tendency across all direct market regions to "under-harvest". However, when "Achieved Exploitation (F)" is calculated, the total number of market size oysters transplanted to the region is debited from the removals for that region (see "Exploitation Rate Calculations and Reference Points" section). Therefore, any time there is a transplant to a market region, which happens frequently, the expectation should be that the "Achieved F" will be lower than the "Targeted F".*

III. 2020 STATUS AND TRENDS

2020 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 2020 was 297 and the average number of market sized oysters per landed bushel was 273 (Figure 12). The proportion of small oysters attached to market size oysters declined in 2020 likely due to the low spatfall events in both 2019 and 2020 (Figure 12). 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 267 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. While LPUE for single dredge boats continued a slight downward trend in 2020, dual dredge LPUE increased from 24 to 28 bushels landed per hour (Figure 13). The number of vessels of each dredge type, single and dual, has remained mostly unchanged since 2015 (Figure 13).

Changes in LPUE on the direct market beds could be influenced by several factors: license consolidation, shifts in population size structure, increases or decreases in market or total abundance, and seasonal limits on harvest time dictated by *Vibrio* control rules. It is difficult to determine which of these is having the greatest influence on catch rates. For example, if changes in LPUE were influenced by oyster size alone, we would expect LPUE to reflect trends in size distribution, with the number of bushels landed per hour increasing along with the fraction of oysters in the larger size bins. This is not always the case. Although there was a decrease in the frequency of large oysters (≥ 3.5 inches) during 2010 and 2011 within both fishery landings and the population as a whole (Figure 14), LPUE remained stable in those years for both dredge types (Figure 13). And while increases in LPUE do track with increases in large oysters for 2012-2016, it is important to note that license consolidation during this time would have allowed the most effective combinations of captains, crews, and boats to land oysters more efficiently. Looking more closely at the size frequency of market-size animals, the frequency of large oysters (≥ 3.5 inches) landed by the fishery has decreased in tandem with that of the population since 2018 (Figure 15). Rather than any single factor, it is most likely a combination of license consolidation, changes in the size of the population and the size structure, and stricter seasonal limits on harvest times that is driving trends in LPUE. Regardless of landings, it is important to note that the size structure landed by the fishery has consistently mirrored the size structure observed in the surveyed population.

2020 Catch Statistics and Fishery Exploitation

The 2020 direct market harvest occurred from April 6 to November 27 and included a period of curtailed harvest hours during summer months to comply with New Jersey's FDA-approved *Vibrio parahaemolyticus* Control Plan[3]. Eighteen vessels (5 single- and 13 dual-dredge boats) fished the quota during 2020. The total direct market harvest in 2020 was 96,490 bushels, a decline from the 109,108 harvested in 2019 (Figure 16). This decline in catch was not a management decision. In fact, the total harvest for 2020 was originally projected to be near 115,000 bushels based on the exploitation rates recommended by the 2020 SARC and selected by the Shellfish Council along with various transplant and enhancement efforts. However, the early part of the 2020 fishing season saw a substantially reduced market for oysters due to the COVID-19 pandemic that resulted in a large reduction in effort and catch during this time. As a result, the Shellfish Council decided to forgo transplanting any oysters off of the Transplant Regions in 2020 reducing the TAC to only that existing on the Direct Market Regions (97,103 bushels). Had a transplant happened in 2020, an additional 20,000 bushels may have been available to harvest within the total approved TAC.

The harvest from the three Direct Market regions broke down as follows: 36% from the HM; 48% from SR; 16% from the MMM (Table 6). Of the 14 beds in the three Direct Market regions, only 7 were fished during the 2020 harvest season. The HM has 11 beds, but 76% of its harvest came from just one bed, Nantuxent, which happens to be nearest to the primary landing port. Of the two beds in the MMM, 82% of its harvest came from Cohansey and 12% from Ship John.

Table 7 represents the 2020 SARC recommendations, the Shellfish Council's choices, and the achieved exploitation rates of ≥2.5" oysters from the Direct Market regions. Note the Shellfish Council did approve going to the maximum rate on Shell Rock without a transplant and also on

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[3] See New Jersey's FDA-approved *Vibrio parahaemolyticus* Control Plan here: http://www.nj.gov/dep/bmw/docs/nj2020vibrioplan.pdf

the Medium Mortality Market and High Mortality regions had a transplant to those regions occurred. As noted above, however, the Shellfish Council subsequently decided to cancel the intermediate transplant program in 2020 due to the COVID-19 pandemic and associated impacts on the market. Finally, the total stock (excluding the VLM region) achieved exploitation rate of market-sized oysters (>2.5") was 4.05% (Figure 17). This level of exploitation is within the range of low exploitation rates achieved since initiating the direct market fishery.

2020 Enhancement Efforts

In 2020, 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 58,697 bushels of unspatted clamshell were put directly on the High Mortality Region (Benny Sand 21 and 22). While no transplant program was conducted in 2020, a detailed history of the transplant program now exists in Table 8 as requested by the 2020 SARC. 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.

2020 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 time 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 ½ 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.

A total of 227 grids were sampled to estimate the status of the stock in 2019 (Figure 18). The total abundance was again below the target, though the market abundance remains well above the target (Figures 19a, b and 20). Natural mortality was relatively unchanged from 2019 to 2020 (Figure 19c) and remained low relative to the current decade and the 'dermo era' that began in 1990 (Figure 3). Spatfall was low for the third consecutive year relative to the large spatfall estimated in 2016 and 2017 (Figure 19d).

The three intermediate transplant regions (VLM, LM, MMT) all have similar acreage (Figure 1). Figures 21-23 (a-f) summarize the 10-year trends of the stock in these regions. The uppermost region, VLM, was at its highest abundance in 2017 since first surveyed in 2007 (Figure 21a), however, two consecutive years (2018 and 2019) of persistently high freshwater inflow resulted in massive die-offs (34% and 35% mortality, respectively) substantially reducing abundance (Figure 21d). As freshwater killed oysters, it also drove dermo to undetectable levels for the fourth consecutive year (Figure 21b). While natural mortality declined considerably in 2020 relative to the previous two years, total abundance has continued to decline and is now the lowest it has been in the last 10 years. Market abundance also remains well below the threshold and since this region has a very slow growth rate compared to regions further downbay, it will likely take some time before the market abundance moves above the threshold again (Figures 21c, 27). In addition, the 2020 spat set in the VLM region was at only the 15th percentile for the 2007-2020 times series (Figures 21e, Table 10), suggesting the abundance of small oysters may continue to decline in the future. No oysters have been transplanted from the VLM region since 2013 (Figure 21f).

Natural mortality on the LM region fell to nearly 8% in 2020 from about 13% in 2018 and 2019, and dermo was nearly undetectable (Figure 22d,b). Nevertheless, a significant decline in sub-market abundance resulted in total abundance falling below the target (Figures 22c and a, 27). Market abundance remained relatively unchanged from 2019 and continues to be above the target as it has been for all of the recent time series (Figures 22c and 27). Recruitment in the LM region was low again in 2020 (Figure 22e, Table 10) and, as was indicated earlier, while the 2020 SARC recommended allowing up to a 2.26% exploitation rate on the LM region, the Shellfish Council decided not to conduct a transplant this year due to impacts from the COVID-19 pandemic (Figure 22f).

Natural mortality in the MMT region was about 9%, remaining well below levels observed in the first half of the 2010s (Figure 23d). Dermo levels increased slightly from 2019 but remained below 1.5 (Figure 23b), a threshold above which the disease begins increasing natural mortality (Bushek et al. 2012). A decline in sub-market oysters was offset by an increase in market-sized oysters resulting in little change in the total abundance or where the stock stands relative to target and threshold reference points (Figures 23c and a, 27; Table 10). Recruitment on the MMT region in 2020 was, once again, low (30th percentile; Table 10) for a third consecutive year (Figure 23e). As indicated previously, no transplant was taken from the MMT region due to impacts of the pandemic even though a 2.46% exploitation rate had been recommended and selected at the start of the season (Figure 23f).

The direct market harvest regions vary in size, but the regional acreage does not reflect the distribution of the oyster stock. For instance, in 2020, HM made up nearly 50% of all oyster acreage but contained only about 12% of the total stock from all six regions while SR and MMM that together make up approximately 25% of the total oyster acreage, made up 52% of the total oyster abundance. In 2020, SR, the smallest region, contained 1.7 times as many oysters as HM, the largest region. Figures 24-26 (a-f) summarize the 10-year trends of the stock in these regions.

Natural mortality on the MMM region continues to be low relative to the recent time series (Figure 24d). Dermo was below but near the 1.5 threshold (Figure 24b). Market abundance on this region increased to return above the target in 2020 and this resulted in a small increase in total abundance as well, though total abundance remains between the target and threshold (Figures 24c and a, 27; Table 10). Recruitment increased slightly relative to 2019, but was low again relative to the recent time series 2020 (23rd percentile; Figure 24e; Table 10). The 2020 exploitation rates on the MMM region were 1.0% and 2.9% respectively on all and market sized oysters, similar to most other years in the recent time series (Figure 24f).

After three years of lower than average natural mortality on SR, an increase in dermo weighted prevalence may have caused an increase in mortality in 2020 relative to 2019 (Figure 25b). Nevertheless, mortality remains low (36th percentile, Table 10; Figure 25d) relative to the 1990 to 2020 time series. Total abundance and sub-market abundance declined for the third consecutive year (Figures 25a,c) and total abundance remains just slightly above the target for this region (Figures 25, 27). While small oysters appear to be declining rapidly in recent years, market abundance is unchanged from 2019 to 2020 and remains well above the target (Figures 25c, 27). The 2020 abundance is average (50th percentile), while the 2020 market abundance is extremely high (97th percentile) relative to the 1990 to 2020 time series (Table 10). Recruitment, as in other regions, was very low (3rd percentile; Table 10) again in 2020 on the SR region (Figure 25e). Exploitation rate of market sized oysters in the SR region was 5% in 2020, an increase for the third consecutive year (Figure 25f). Exploitation rate of all sizes increased from 2019 as well to a value of 3.1% in 2020 (Figure 25f).

Finally, the HM region continued a declining trend of low levels of natural mortality in 2020 (Figure 26d) even though dermo levels have remained above the threshold level of 1.5 (Figure 26b). Declines in both market and sub-market abundance from 2019 led to total abundance (Figure 26a) falling back below the threshold reference point in 2020; however, market abundance remained above the target reference point (Figures 26c, 27). Recruitment on the HM region was extremely low (3rd percentile; Table 10; Figure 26e) again in 2020, as it was in the rest of the regions (Figures 21-25). The exploitation rate of all oysters was 4.5% while the exploitation of market-sized oysters was 7.8% (Figure 26f).

IV. SARC EXPLOITATION RATE AND AREA MANAGEMENT RECOMMENDATIONS

Upon review of the status of the stock, the 2021 SARC made the following recommendations that are summarized in Table 11.

- A transplant up to a 0.0193 exploitation rate could be moved from the Very Low Mortality region to the Middle bed on the Medium Mortality Transplant region.

- A transplant up to a 0.0076 exploitation rate could be moved from the Low Mortality region to the Shell Rock region.
- A transplant up to a 0.0246 exploitation rate could be moved from the Medium Mortality Transplant region with 50% of the resultant transplant going to the Shell Rock region and the other 50% going to either Bennies or Benny Sand on the High Mortality region.
- The Medium Mortality Market region can be fished up to its median exploitation rate (0.0303) with no requirement for a transplant.
- The Shell Rock region can be fished up to its median exploitation rate (0.0370) with no requirement for a transplant. If a transplant to Shell Rock occurs, the exploitation rate could be increased to 0.0426.
- The High Mortality region can be fished up to its median exploitation rate (0.0749) with no requirement for a transplant. If a transplant to the High Mortality region occurs, the exploitation rate could be increased to its maximum rate (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 2021 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 Dockmonitoring Program, the Dermo Monitoring Program, and the Shellplant and Transplant Monitoring Program, the 2021 SARC recommended the following list of science advice (not ordered by priority):

- Continue to estimate intra-grid variability during the Resurvey program

- Report how survey error changed after adding additional grids in 2019 and 2020.

- 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? How has this varied across the management regions?

- 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.

- Evaluate alternative methods for sub-sampling spat, including collecting a sub-sample of cultch from each sample.

- Evaluate interactions between spatfall and fishing at local (bed-level) scales.

- Examine bed-level exploitation rate data to see if there is a level of fishing where a measurable impact (ex. recruitment, fecundity, oyster condition, etc.) is detected.

- Include more evaluation of longer-term trends (beyond the most recent 10 years) in the "recent trends" sections of the presentation and report.

- Continue growth experiments and analysis for one more year

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

- Continue to evaluate the influence of enhancement program efforts. More specifically, are there factors (environment, initial oyster density, initial shell density, etc.) that increase likelihood of a positive enhancement?

- Continue to explore population models using the Assessment Survey data

- Re-evaluate application of current reference points on the VLM region.

- 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.

- Explore the idea that carrying capacity could play a role in current stable market abundance.

- Continue to explore alternatives for allocating survey samples (neyman vs. status quo vs. other alternatives).

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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. Upper Middle and Ship John were resurveyed in 2020. Middle, Beadons, and Vexton are scheduled for resurvey in 2021. Egg Island and Ledge have never been resurveyed.

Region	Bed	# Grids	# Full Resurveys	Latest Resurvey	10-Year Schedule
VLM	Hope Creek	97	2	2017	2027
	Fishing Creek	67	1	2007-2008	2022
	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	1	2020	2030
	Middle	51	1	2011	**2021**
	Sea Breeze	48	1	2012	2022
MMM	Cohansey	83	1	2019	2029
	Ship John	68	1	2020	2030
SR	Shell Rock	93	3	2016	2026
HM	Bennies Sand	49	1	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	2	2011	**2021**
	Vexton	47	2	2011	**2021**
	Egg Island	125	0	-	-
	Ledge	53	0	-	-

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 bushels harvest, including those replanted to leases for 2011-2020. Beds arranged upbay to downbay and color-coded by region.

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Middle										
Sea Breeze		170	5,454	542						
Cohansey	19,074	11,288	10,583	8,652	10,669	12,475	20,687	8,709	7,253	12,238
Ship John	19,212	17,755	19,279	24,295	19,837	19,938	16,331	22,021	25,037	2,751
Shell Rock	24,112	22,628	24,280	23,589	29,629	31,794	38,189	31,872	28,761	46,765
Bennies Sand	8,825	5,836	10,841	3,038	6,301		22,339	23,395	13,911	6,014
Bennies	4,997	2,155	870	8,010	10,712	29,293	23,071	21,626	7,126	60
NantuxentP	5,467	14,332	10,218	5,154	5,267	2,101	628	11,347	17,575	26,461
Hog Shoal	9,049	1,965	2,385	3,425	103		1,756	283	9,445	2,201
New Beds	1,778	443	226		4,912	4,494	1,143	89		
Strawberry			140							
Hawk's Nest	1,954	1,568		205						
Beadons										
Vexton	2									
Total	94,470	78,140	84,276	76,910	87,430	100,095	124,144	119,342	109,108	96,490

Table 7. Council-chosen and fishery-achieved exploitation rates for 2020 for (a) Transplant regions and (b) Direct Market regions. Direct market exploitation rates include market-size oysters only. Transplant exploitation rates include all sizes of oysters. Small oysters and shell are culled during both transplant and harvest. No intermediate transplants occurred due to COVID-19 impacts.

a. Transplant

b. Direct Market

Table 8. Detailed history of transplant efforts since 2014. 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	Number Oysters ≥ 2.5"	Chosen Expl. Rate	Achieved Expl. Rate	# Oysters at Chosen (all sizes)	# Oysters at Achieved (all sizes)	Added Quota Allocation
2019	LM	Arnolds	Shell Rock	7,200	489,430	2.26%	0.70%	8,941,378	2,837,705	1,861
	MMT	Middle	Bennies Sand	25,000	2,496,843	2.46%	2.79%	12,158,274	13,956,501	9,494
		Sea Breeze	Bennies Sand	8,800	941,483					3,580
2018	MMT	Upper Middle	Bennies	4,750	460,846	2.46%	1.76%	15,785,722	12,310,312	1,752
		Middle	Bennies	27,500	4,054,033					15,415
		Sea Breeze	Bennies	7,700	749,703					2,851
2017	MMT	Upper Middle	Bennies	3,200	602,546	2.46%	2.37%	8,184,564	7,887,414	2,282
		Middle	Bennies	21,350	3,868,205					14,652
		Sea Breeze	Bennies	4,700	636,920					2,412
2016	LM	Arnolds	Cohansey	4,800	787,816	0.76%	0.96%	1,712,353	2,168,012	2,972
	MMT	Middle	Shell Rock	8,150	1,569,932	1.49%	0.97%	3,958,253	2,979,901	5,925
		Sea Breeze	Shell Rock	2,400	290,458					1,096
2015	LM	Upper Arnolds	Ship John	10,200	1,247,128	1.30%	1.30 - 1.90%	3,598,514	4,474,515	4,688
	MMT	Middle	Shell Rock	5,550	682,813	2.30%	> 2.30%	4,360,643	4,475,247	2,567
		Sea Breeze	Shell Rock	10,800	1,590,121					5,978
2014	LM	Arnolds	Ship John	15,500	3,174,627	2.33%	2.25%	6,403,869	6,134,370	12,025
	MMT	Middle	Shell Rock	6,600	961,033	2.33%	2.41%	3,517,430	3,473,086	3,640
		Sea Breeze	Shell Rock	7,300	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 2020. See key at the bottom for definitions of what each color represents for each metric.

2020 Metrics	*Transplant* Very Low Mortality	*Transplant* Low Mortality	*Transplant* Medium Mortality	*Market* Medium Mortality	*Market* Shell Rock	*Market* High Mortality
Total Abundance						
2020 Percentile (1990-2020)	0.000	0.200	0.333	0.433	0.500	0.400
2020 vs. Target-Threshold						
Market Abundance						
2020 Percentile (1990-2020)	0.076	0.300	0.933	0.733	0.966	0.700
2020 vs. Target-Threshold						
Sub-Market Abundance (< 2.5")						
2020 Percentile (1990-2020)	0.000	0.333	0.333	0.300	0.100	0.300
Spatfall						
2020 Percentile (1990-2020)	0.153	0.400	0.300	0.233	0.033	0.033
Mortality						
2020 Percentile (1990-2020)	0.692	0.400	0.166	0.266	0.366	0.000
Dermo WP						
2020 vs. Category	0.000	0.008	0.925	1.425	2.500	1.870

	Green	**Yellow**	**Orange**
2020 Percentile (1990-2020)	Above the 60th	40th - 60th	Below the 40th
2020 vs. Target/Threshold	Above Target	b/w Target and Threshold	Below Threshold
2020 Dermo Levels	Low (<1.5)	Medium (1.5-2)	High (>2)

Table 11. 2021 SARC recommendations for maximum exploitation rates for each region and the projected quota associated with each decision. *Note that for the Medium Mortality Market and the 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		0.0193	38,583,170	744,655	503	1,480	8.00%	118
LM	Min	0.0076	276,049,021	2,097,973	447	4,693	18.00%	845
MMT	Max	0.0246	255,980,418	6,297,118	329	19,140	53.00%	10,144

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	242,329,738	7,342,591	267	27,500	No
SR*	Median	0.0370	249,480,213	9,230,768	267	34,572	No
SR*		0.0426	249,480,213	10,627,857	267	39,805	Yes
HM*	Median	0.0749	98,901,130	7,407,695	267	27,744	No
HM*	Max	0.0982	98,901,130	9,712,091	267	36,375	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 complete footprint of each bed including grids in the High, Medium, and Low oyster density strata.

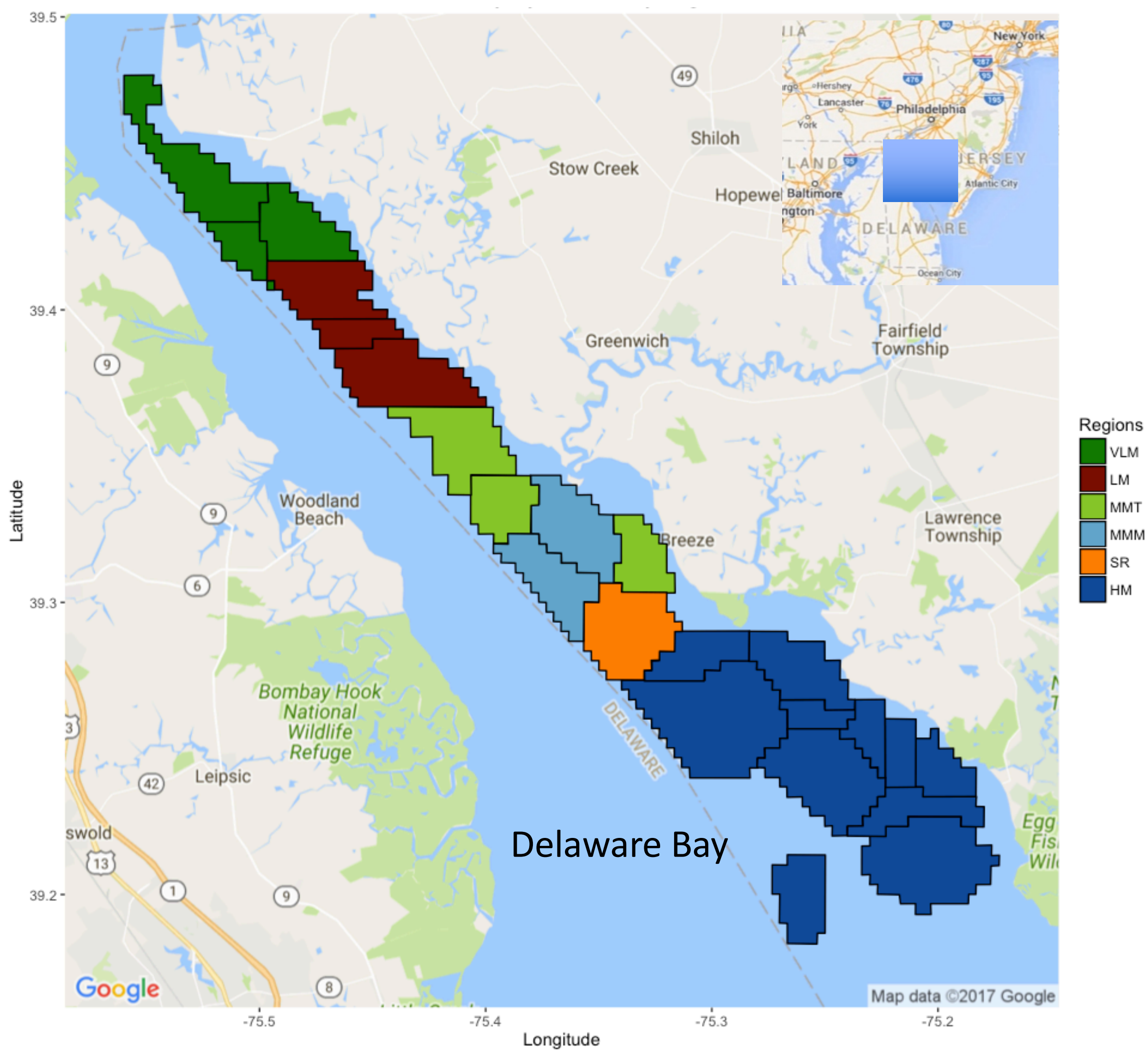


Figure 2. Regional acreage of the assessed NJ Delaware Bay oyster resource. Regions are listed upbay to downbay from left to right. The VLM, LM, and MMT contain three beds each and comprise the Transplant region. The Direct Market region includes the MMM made up of two beds, SR (one bed), and HM with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

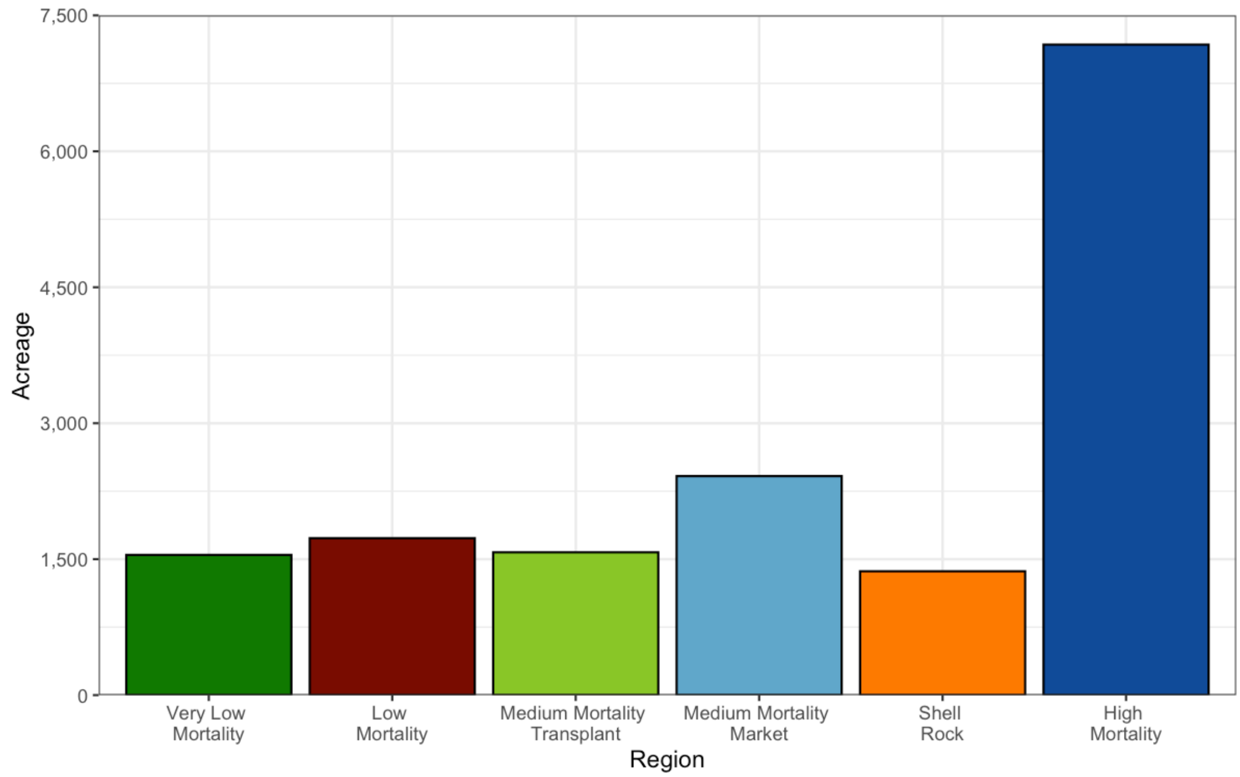
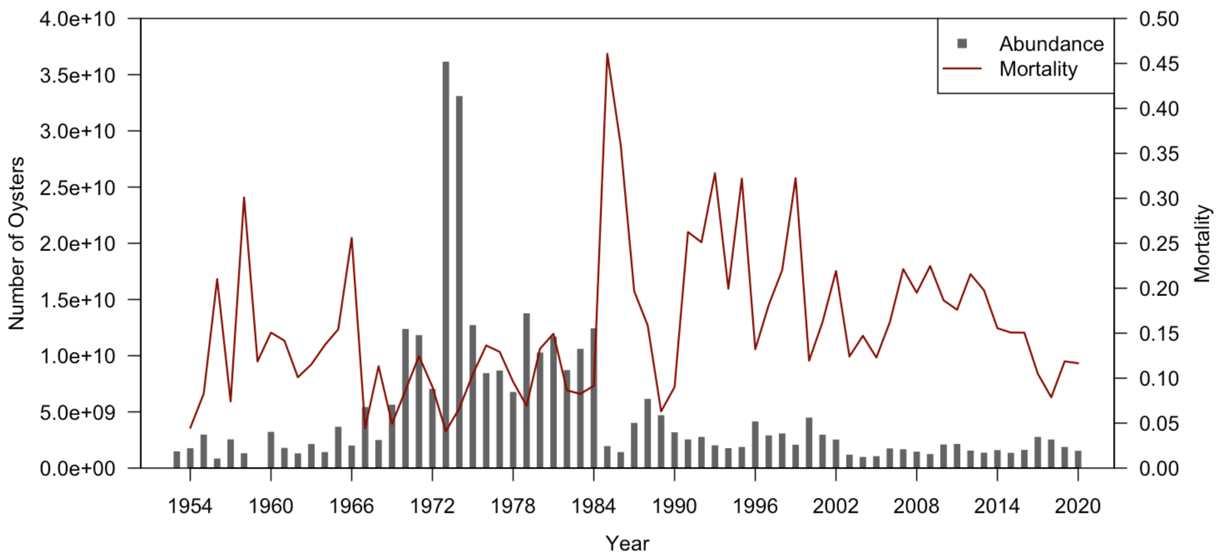


Figure 3. Time series of total oyster abundance (left axes) compared to natural mortality rate (a, right axis) and fishing mortality (b, right axis). Both figures exclude the VLM which was not quantitively surveyed until 2007.

a.



b.

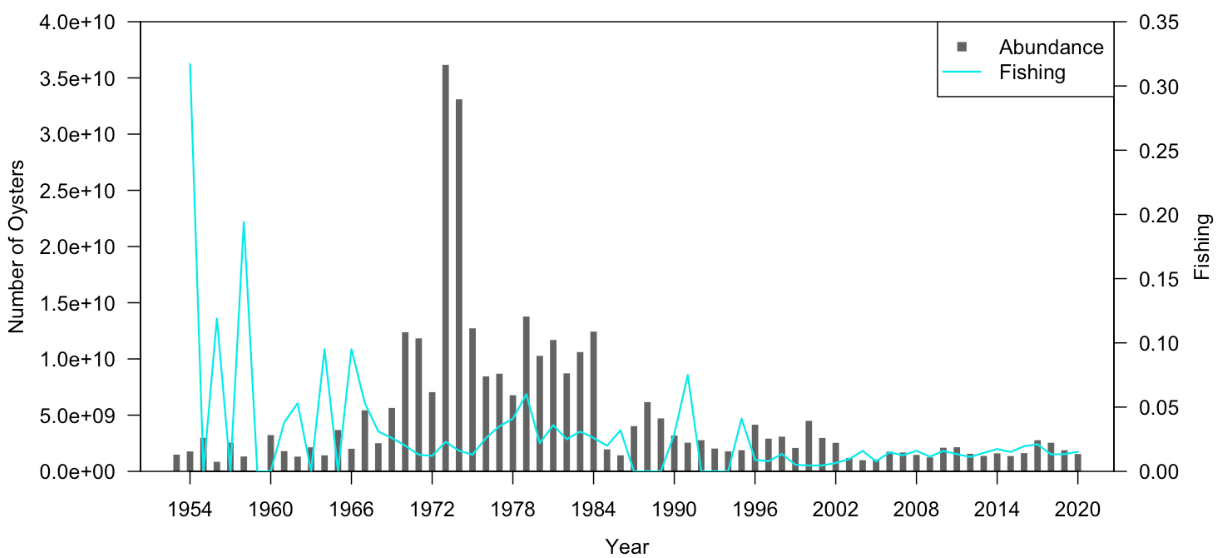
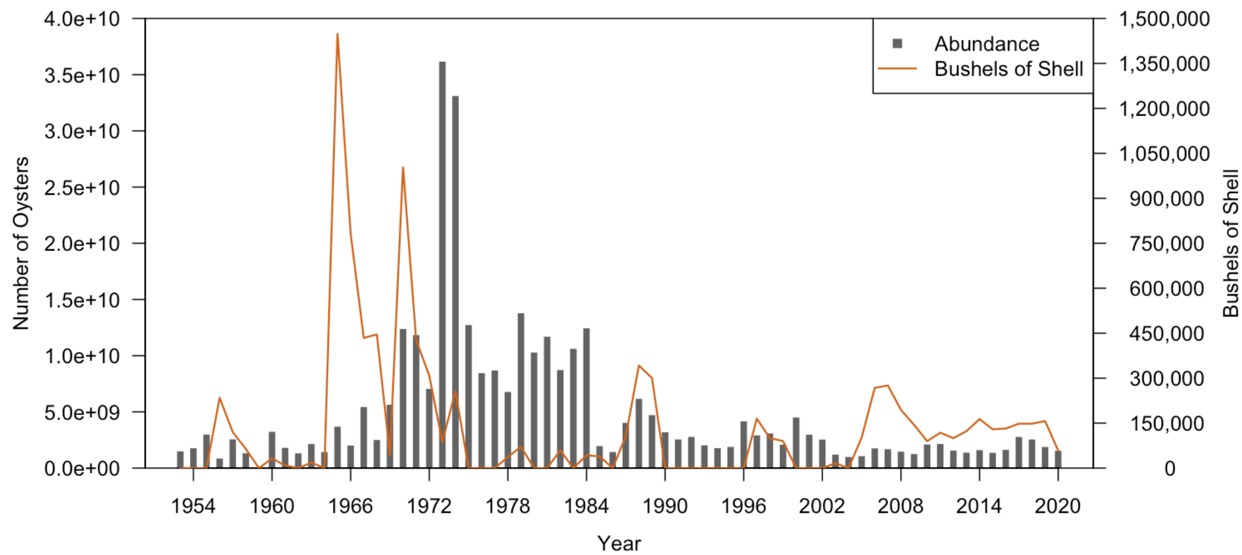


Figure 4. Time series of total oyster abundance (left axes) compared to bushels of shell planted (a, right axis) and total spat abundance from the stock assessment time series (b, right axis). Both figures exclude the VLM which was not quantitively surveyed until 2007.

a.



b.

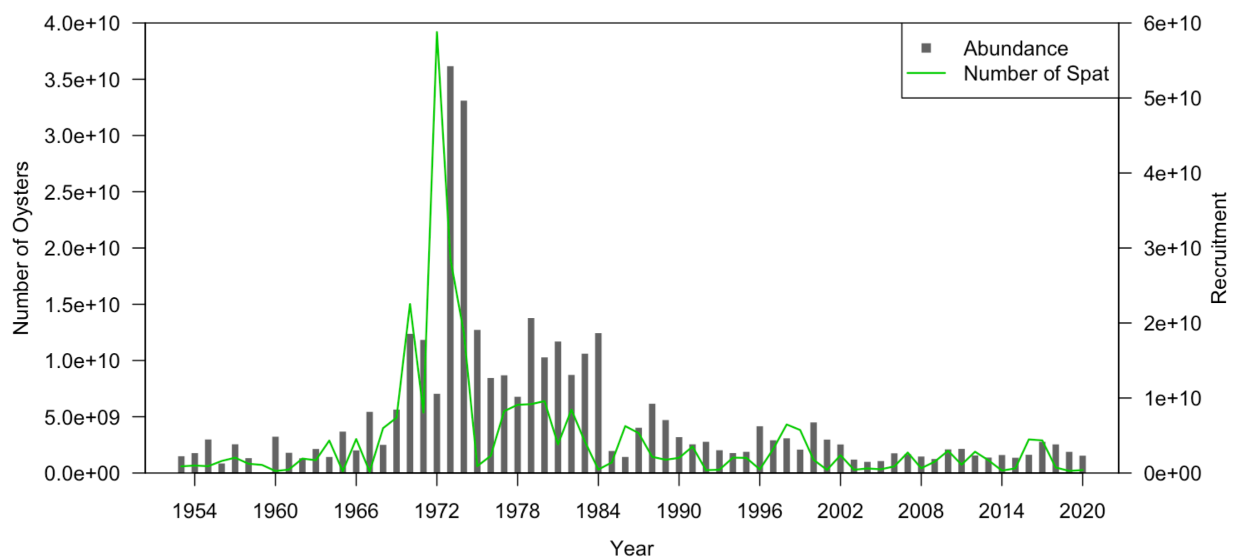


Figure 5. Number of oysters harvested from the natural oyster beds of Delaware Bay, NJ from 1953–2020. Prior to 1996, the bay-season fishery permitted removed oysters of all sizes from the natural beds and required transplanting them downbay to leased grounds for subsequent harvest. Since 1996, the direct market fishery has restricted harvest to market-size oysters without any transplant requirement. Zeros represent years of fishery closure.

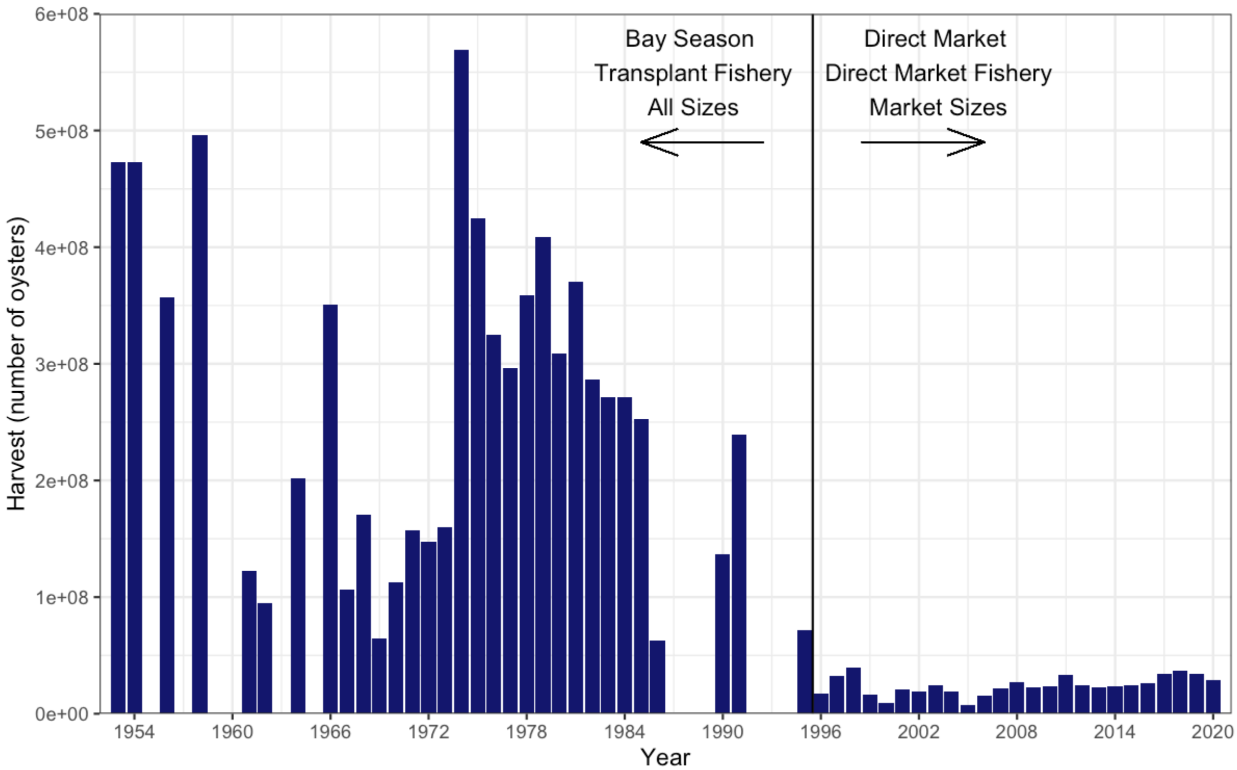


Figure 6. Survey gear capture efficiency as a function of true oyster density. Error bars represent the standard deviation from 1,000 bootstrap simulations. Line indicates the best fit power model estimated by weighted nonlinear least squares. *Adapted from Morson et al. (2018)*

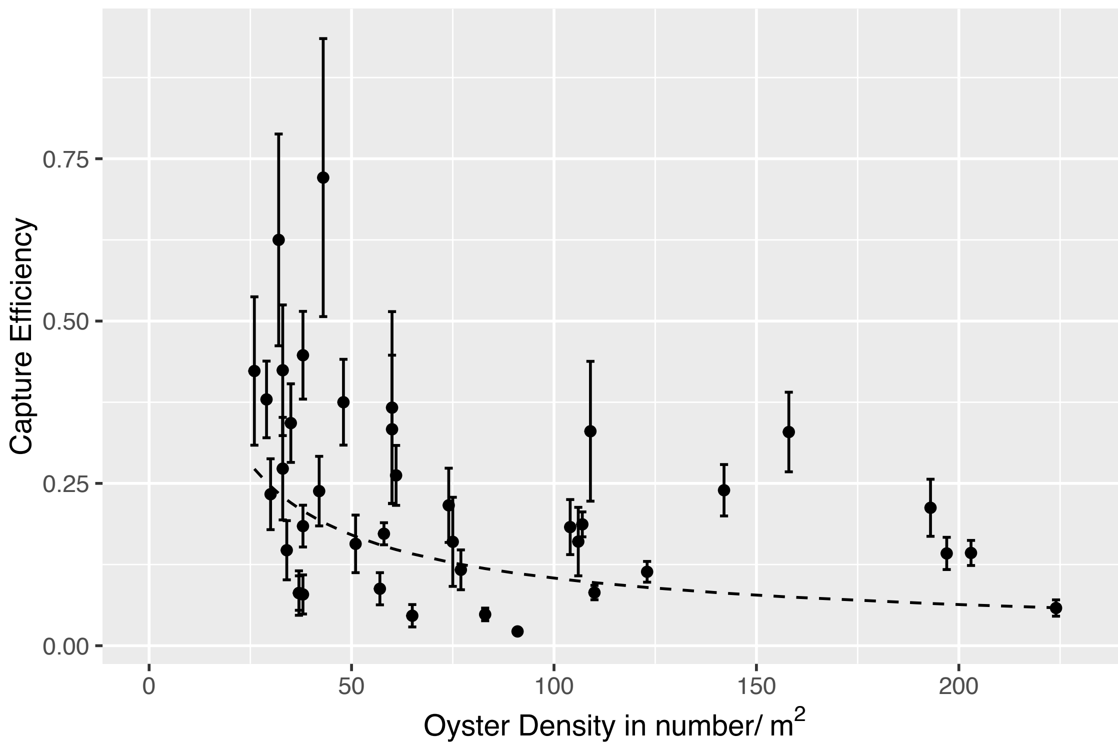


Figure 7. The assessed oyster beds of Delaware Bay, NJ colored by region (see Legend) with the 2020 strata designations. White outlines indicate the complete boundary of each bed with the high and medium quality strata grids in dark and light colors, respectively; black outlines indicate beds that were resurveyed in 2020. 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).

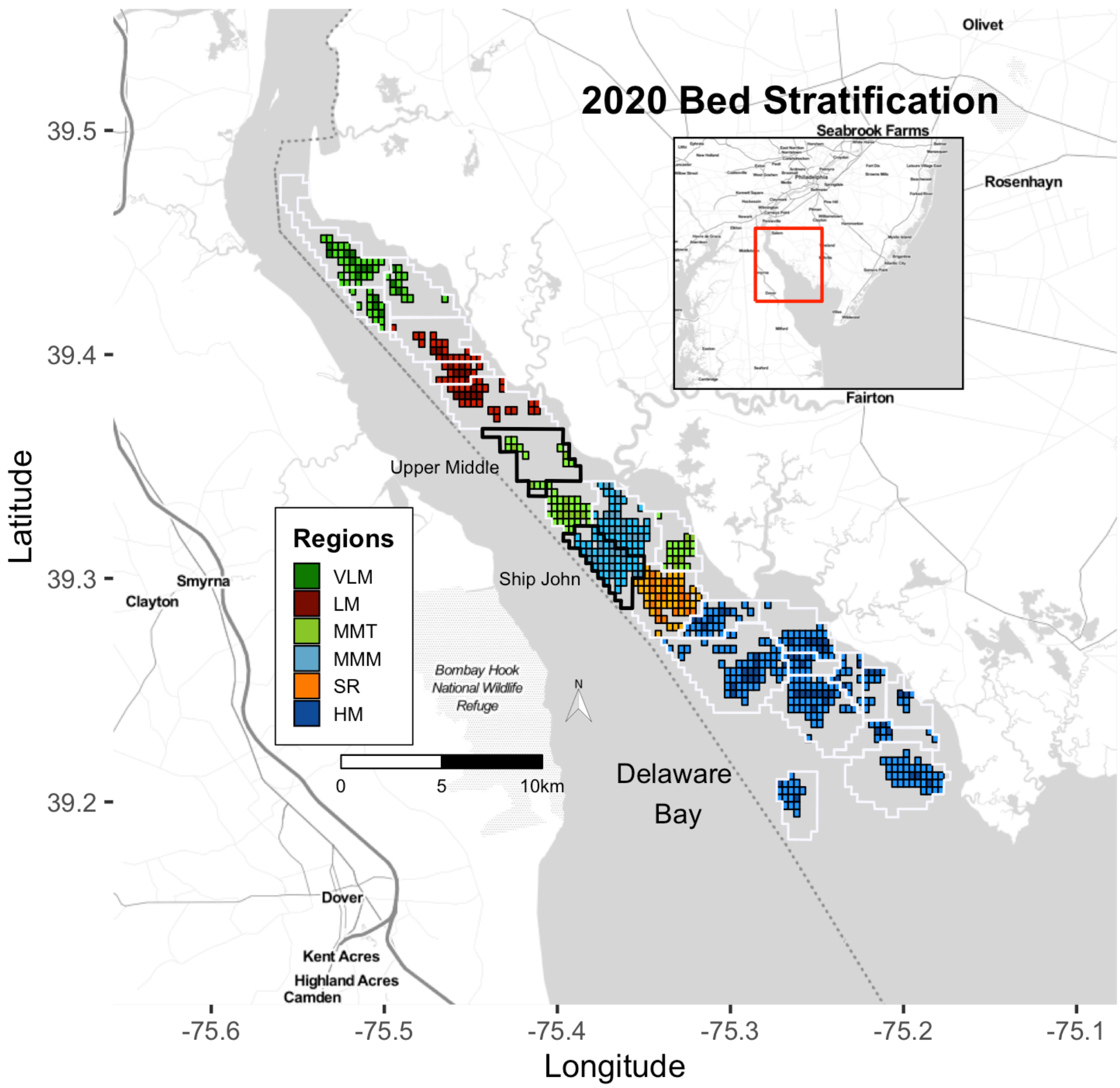
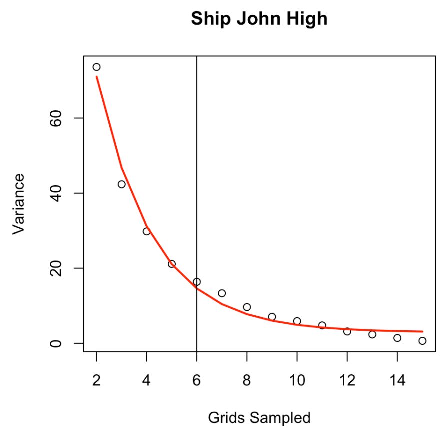
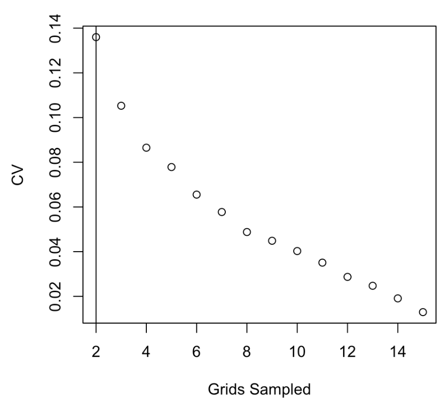


Figure 8. Three alternatives for allocating survey effort: a. benchmark reduction in variance; b. benchmark reduction in coefficient of variation (CV); c. status quo/ "eyeball" allocation method described in the methodology (left) and Neyman's optimal allocation formula with a minimum of two grids per strata (right). Black dots on panel c. represent allocated samples and the varying color shades on each grid represent high (dark) to low (light) density. See "Science Advice: Formalize Allocation of Survey Effort" under "Assessment Survey Design" for additional details.

a.



b.



c.

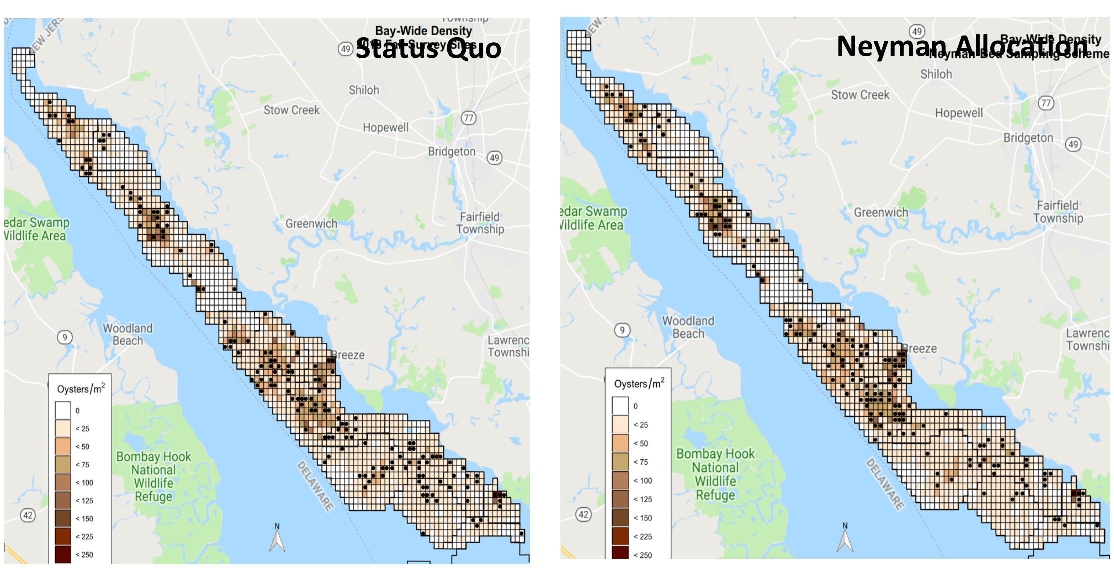


Figure 9. Total abundance survey CV calculated for each of 2018, 2019, and 2020 when a total of 171, 200, and 227 grids were sampled respectively.

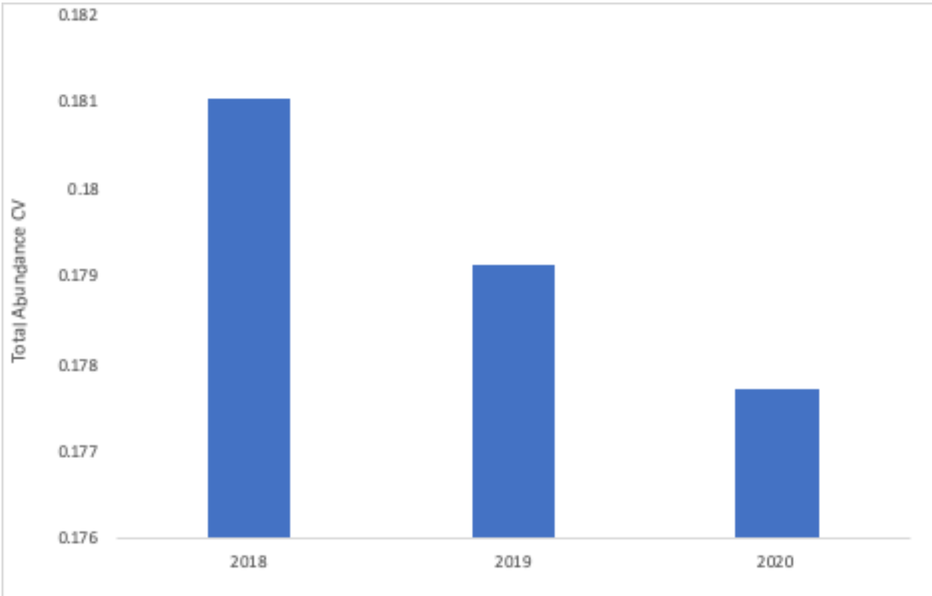


Figure 10a. Realized exploitation fractions of the >2.5” oyster stock on the Direct Market regions in Delaware Bay NJ for two time periods: 1996-2006 and 2007-2015. The 2007-2015 median (dotted line) is based on the realized exploitation values with shading indicating the range. Negative values reflect oysters added through intermediate transplanting.

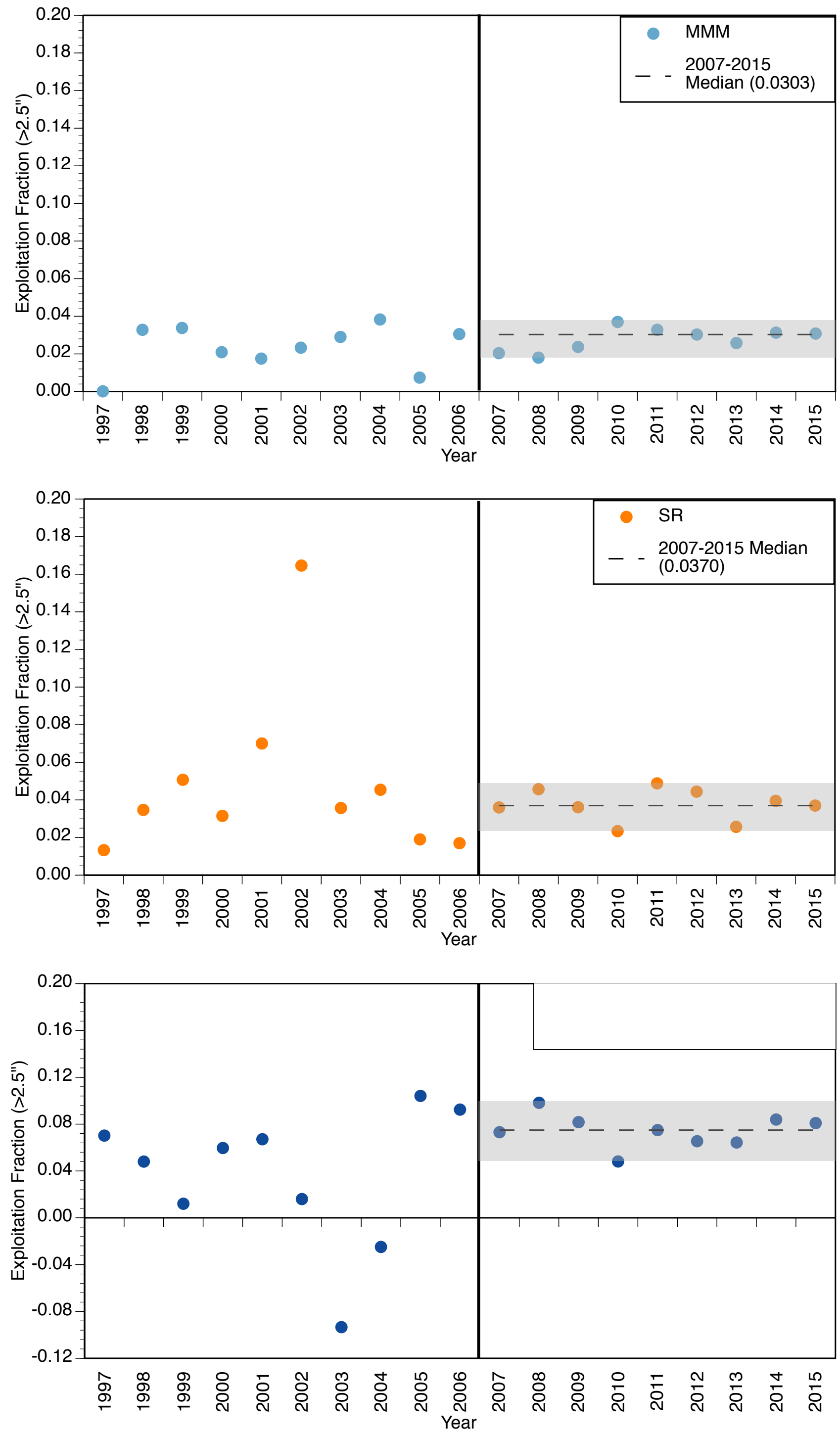


Figure 10b. Realized exploitation fractions of the whole oyster stock, excluding spat, on the Transplant regions in Delaware Bay NJ for two time periods: 1996-2006 and 2007-2015. The 2007-2015 median (dotted line) is based on the realized exploitation for each region with shading indicating the range. 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.

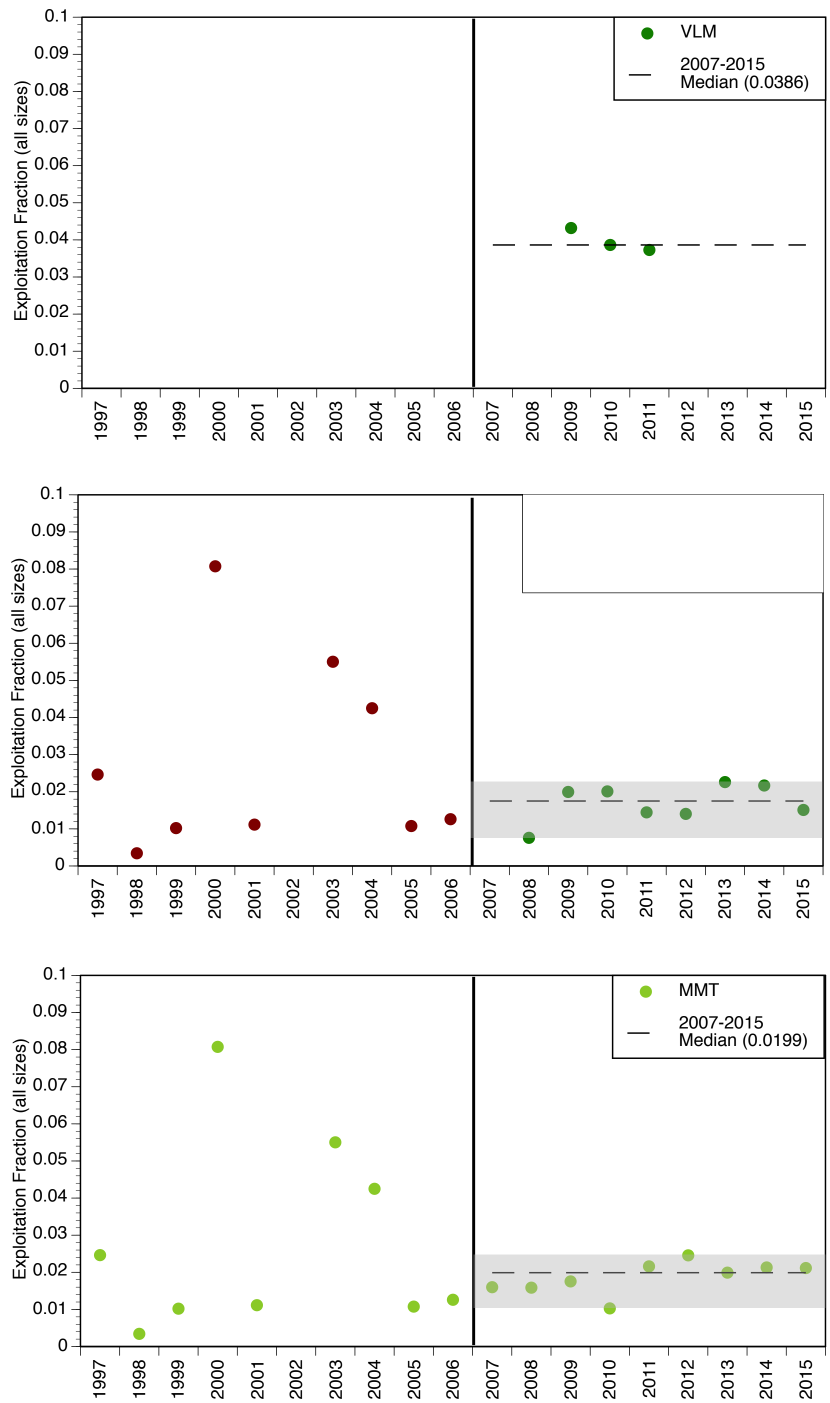


Figure 11. Boxplot showing achieved – targeted exploitation rate (F) for each of the three direct market regions over the ten years (2009-2019). Values less than 0 indicate harvests below the total allowable whereas values above 0 indicate harvests that exceeded the total allowable catch. Boxes bound the 25th and 75th quartiles with the median shown as a horizontal line and the whiskers representing one standard deviation.

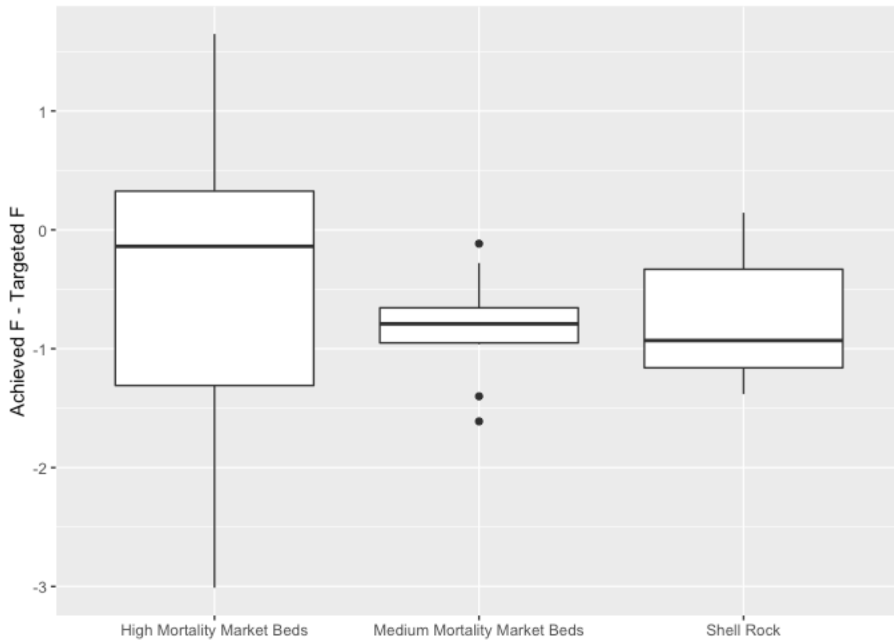


Figure 12. Landed oysters per bushel in three groups: market-size (≥2.5"), smaller attached oysters, and smaller unattached oysters. The number of market-size oysters per landed bushel in 2020 averaged 273, while the total oysters per landed bushel averaged 297. The long-term mean of all oysters and market oysters per landed bushel (267) is shown as an orange line.

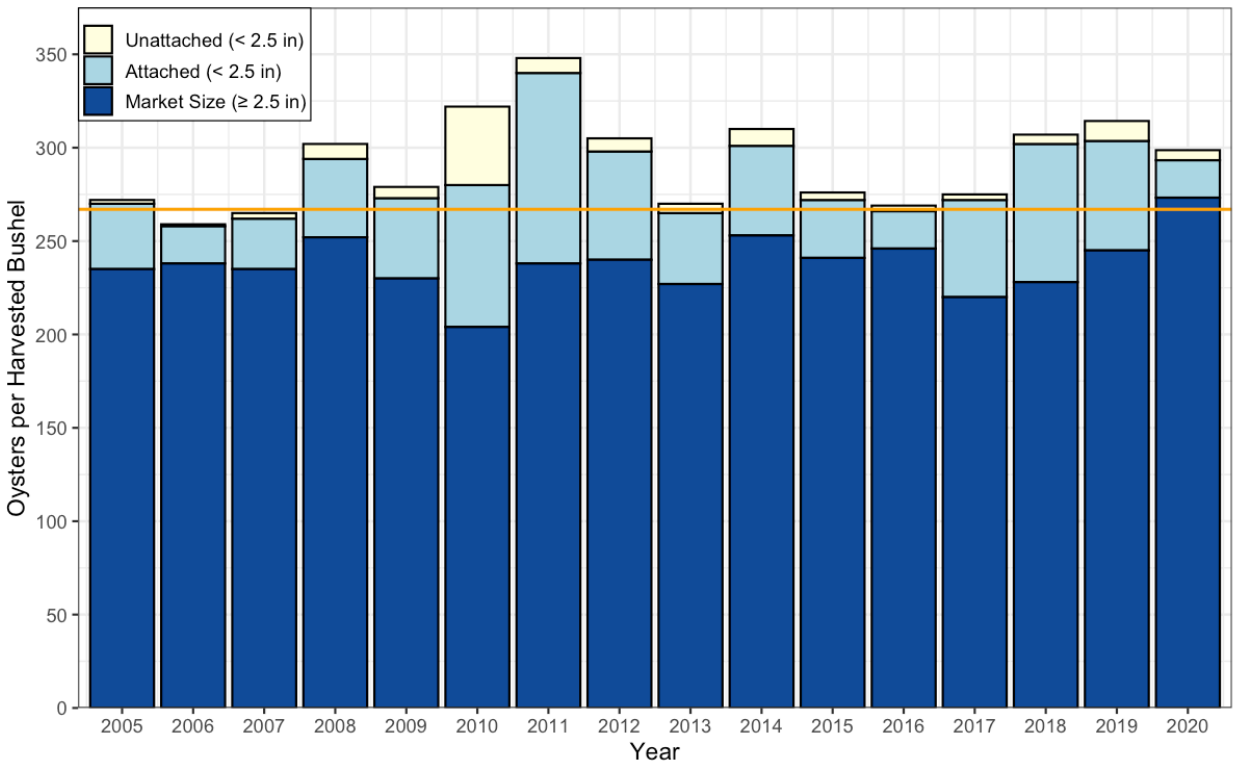


Figure 13. Numbers of single (light bar) and dual (dark bar) dredge boats participating in the NJ Delaware Bay oyster harvest overlaid with LPUE (total number of harvested bushels/total hours worked) for single (light blue) and dual (dark blue) dredge boats.

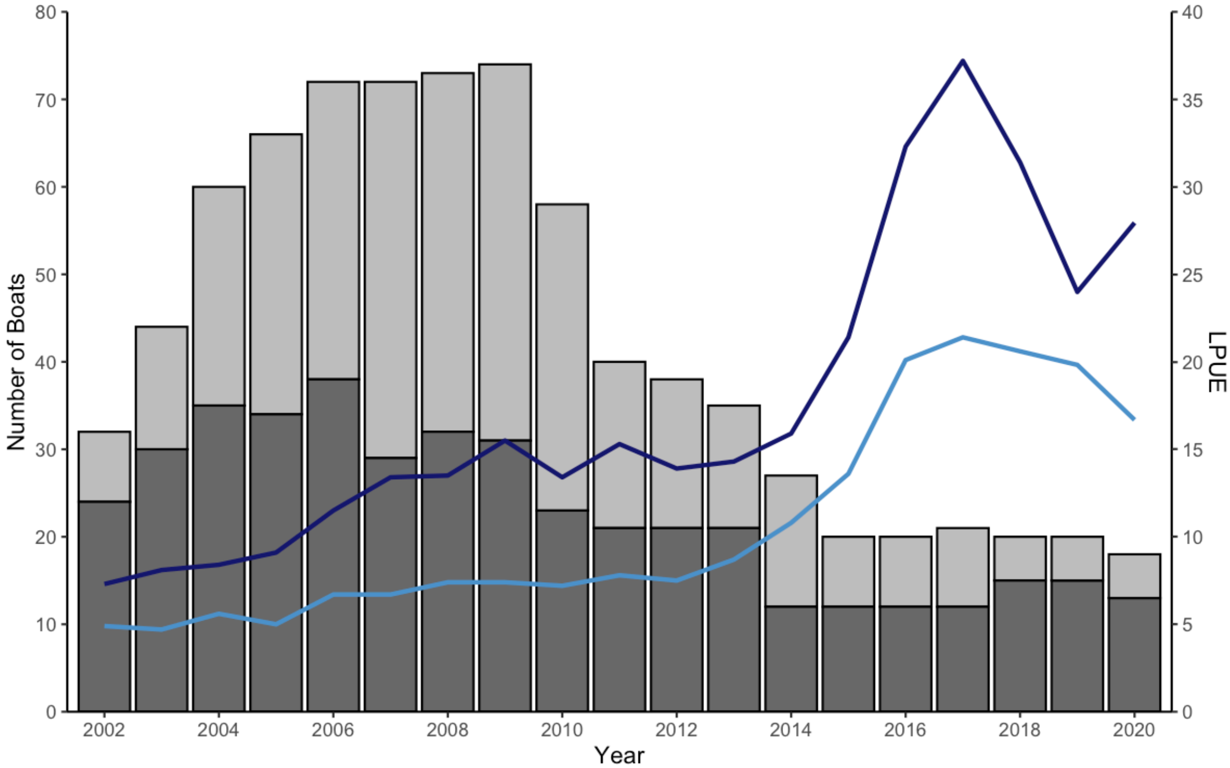


Figure 14. Size frequency of oysters landed by the fishery in direct market regions (top panel) and within the direct market regions of the surveyed population (bottom panel). Vertical line indicates the market-size cutoff (≥ 2.5 inches).

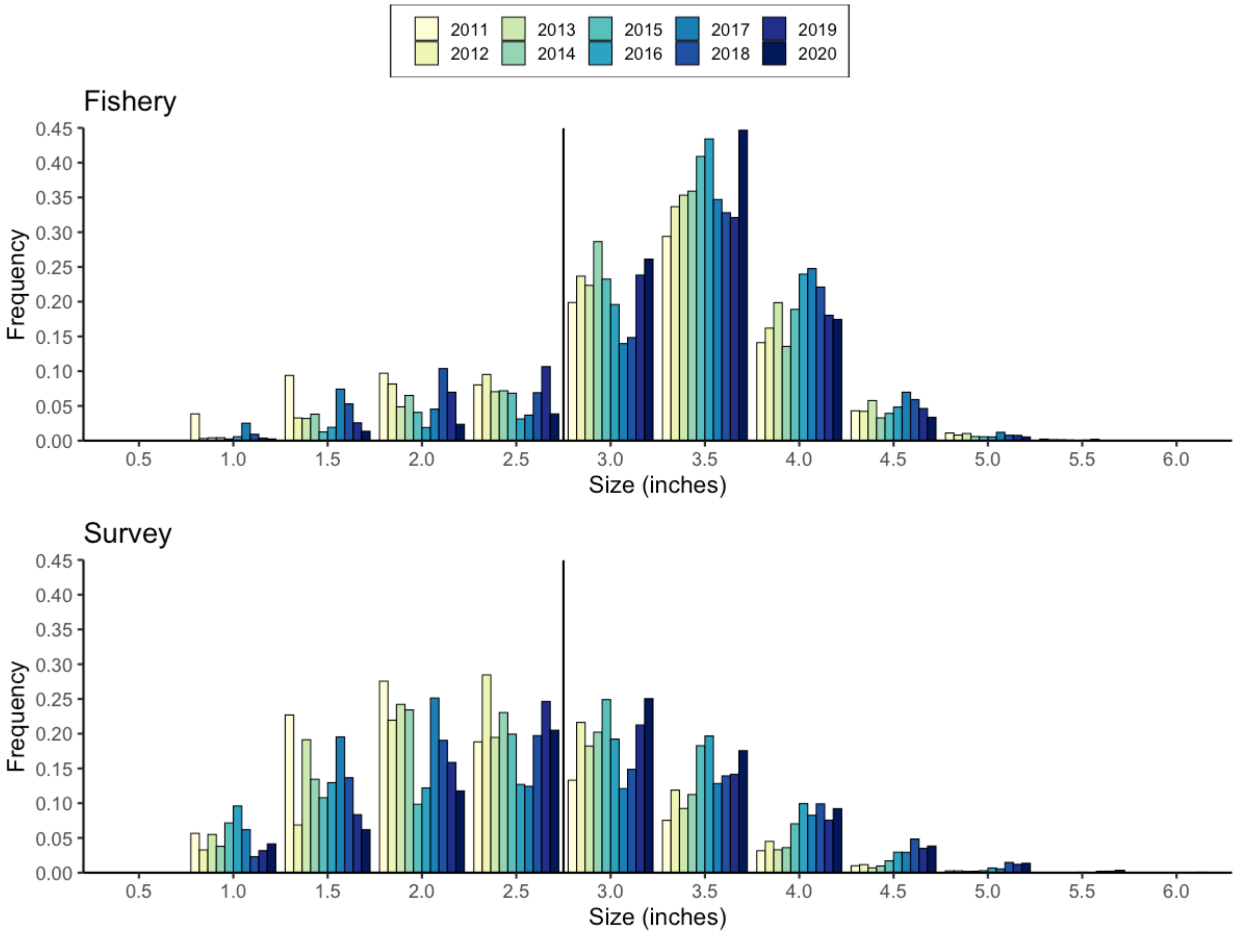


Figure 15. Frequencies of large (≥ 3.5 inches) oysters landed by the fishery in direct market regions (top panel) and within the surveyed population (bottom panel).

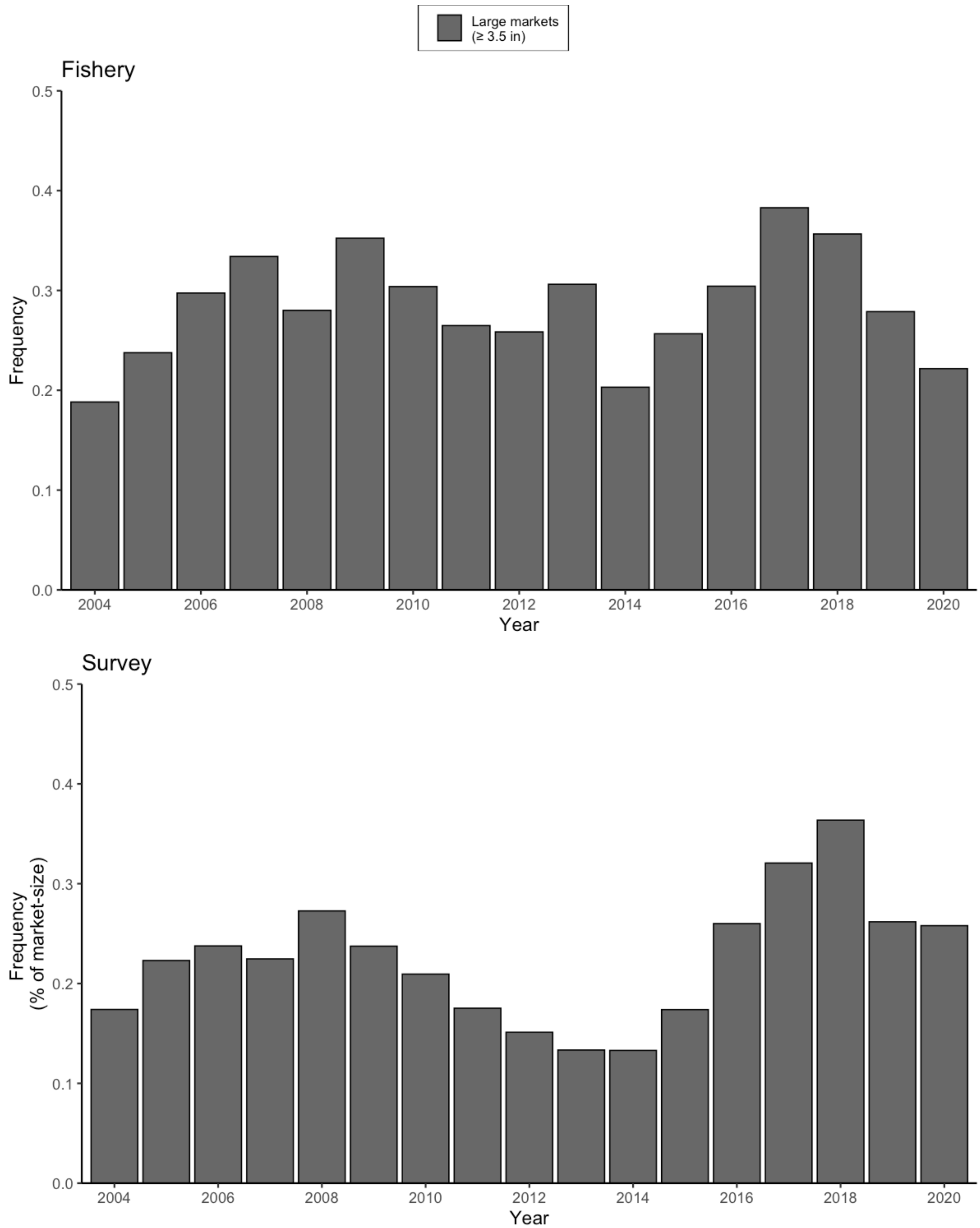


Figure 16. Number of bushels harvested from the natural oyster beds of Delaware Bay since the inception of the direct-market program in 1996. The 24-year average harvest is 82,279 bushels. The vertical line shows the beginning of the current exploitation and management strategy in 2007. With an intermediate transplant, the projected quota for 2020 was ~115,000 bushels (orange line).

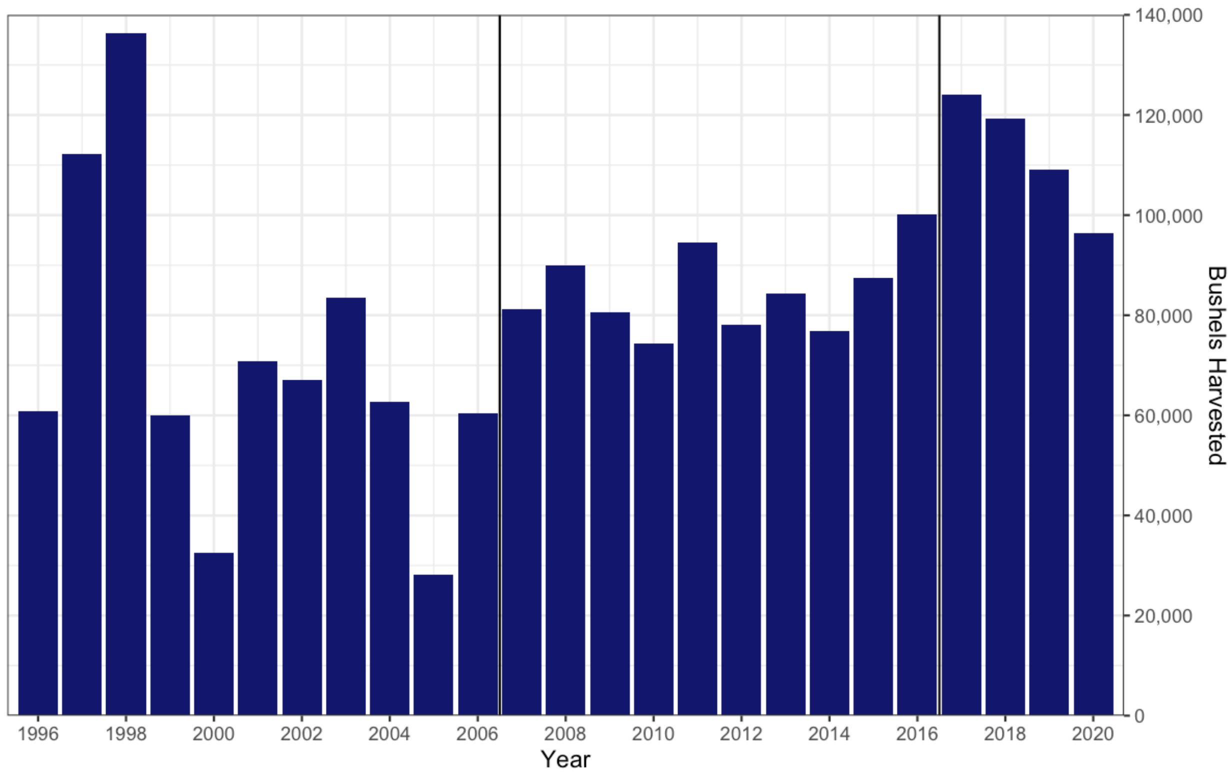
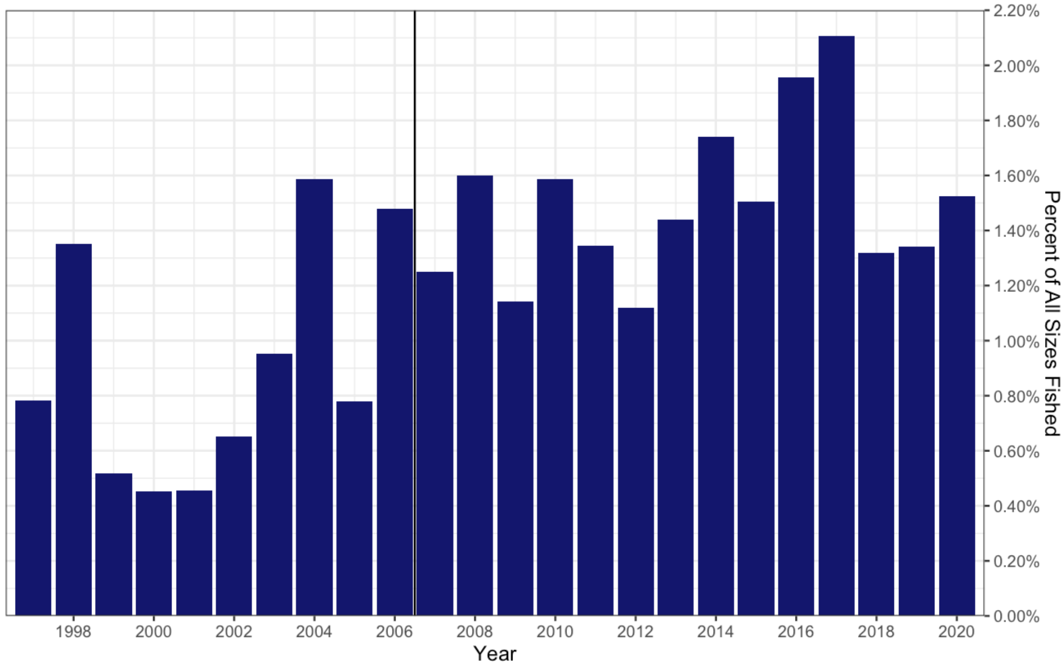


Figure 17. Fishing mortality as a percentage of (a) total oyster abundance and (b) the market-sized oyster abundance (≥2.5”) over all regions excluding the VLM. Regional abundance-based quotas began in 2007 (vertical line).

a.



b.

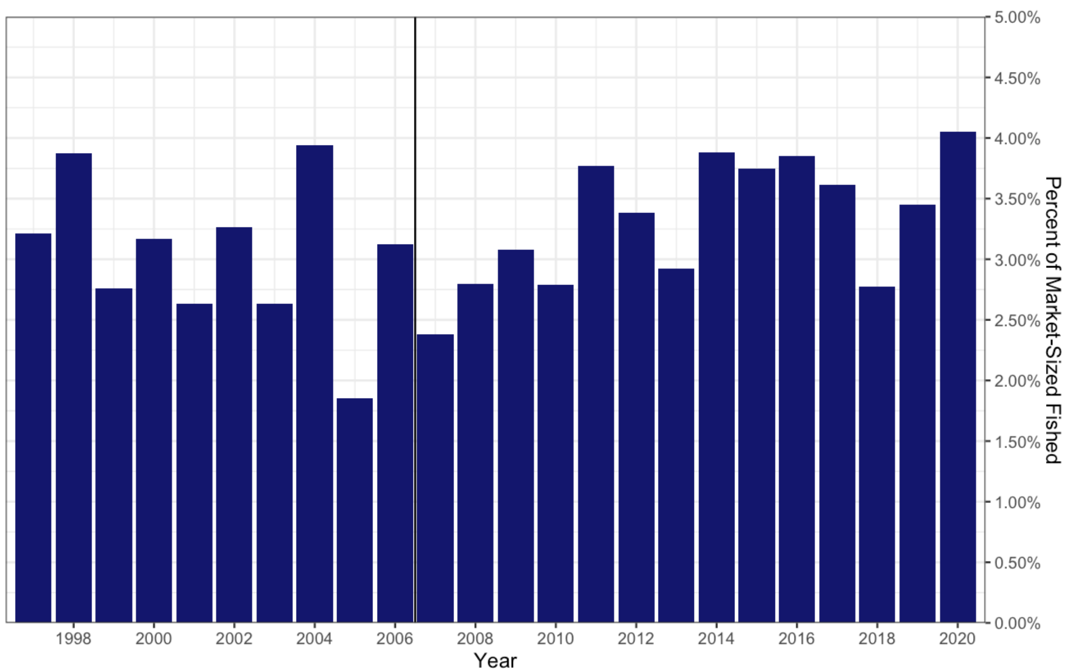


Figure 18. Map of the 2020 oyster stock assessment sample sites. Black dots are sites from high quality stratum on each bed and white dots are sites from medium quality stratum on each bed. Black x's indicate transplant enhancement sites and black triangles indicate shellplant enhancement sites.

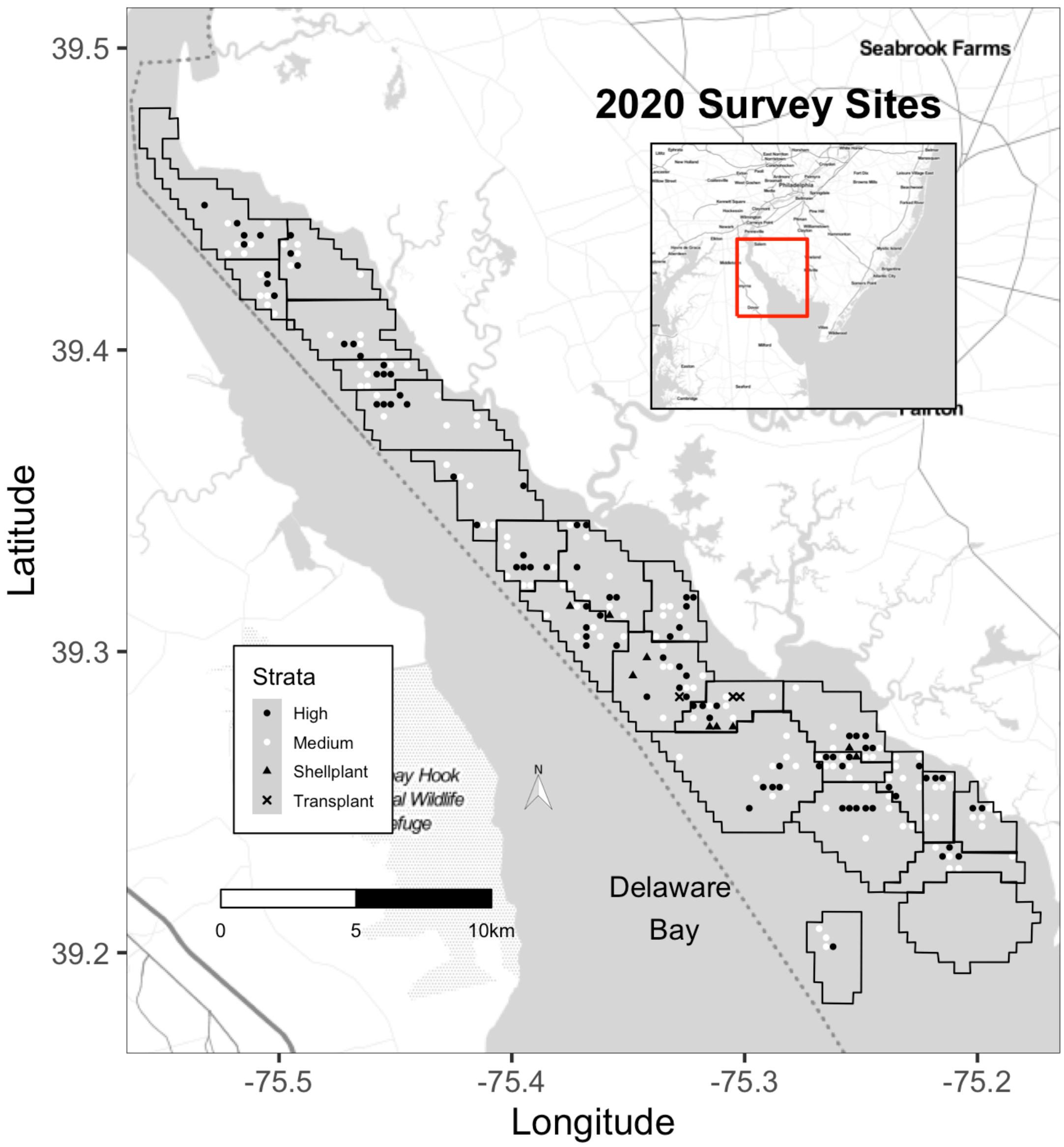


Figure 19. Ten-year time series summary for the population, excluding the VLM. Top panels: total abundance (≥ 20 mm) and size class abundances (≥ 20 mm). Bottom panels: mortality rate and spat abundance (< 20 mm). Dashed horizontal lines represent the threshold and solid horizontal lines represent the target for abundance in panel A and for market abundance in panel B.

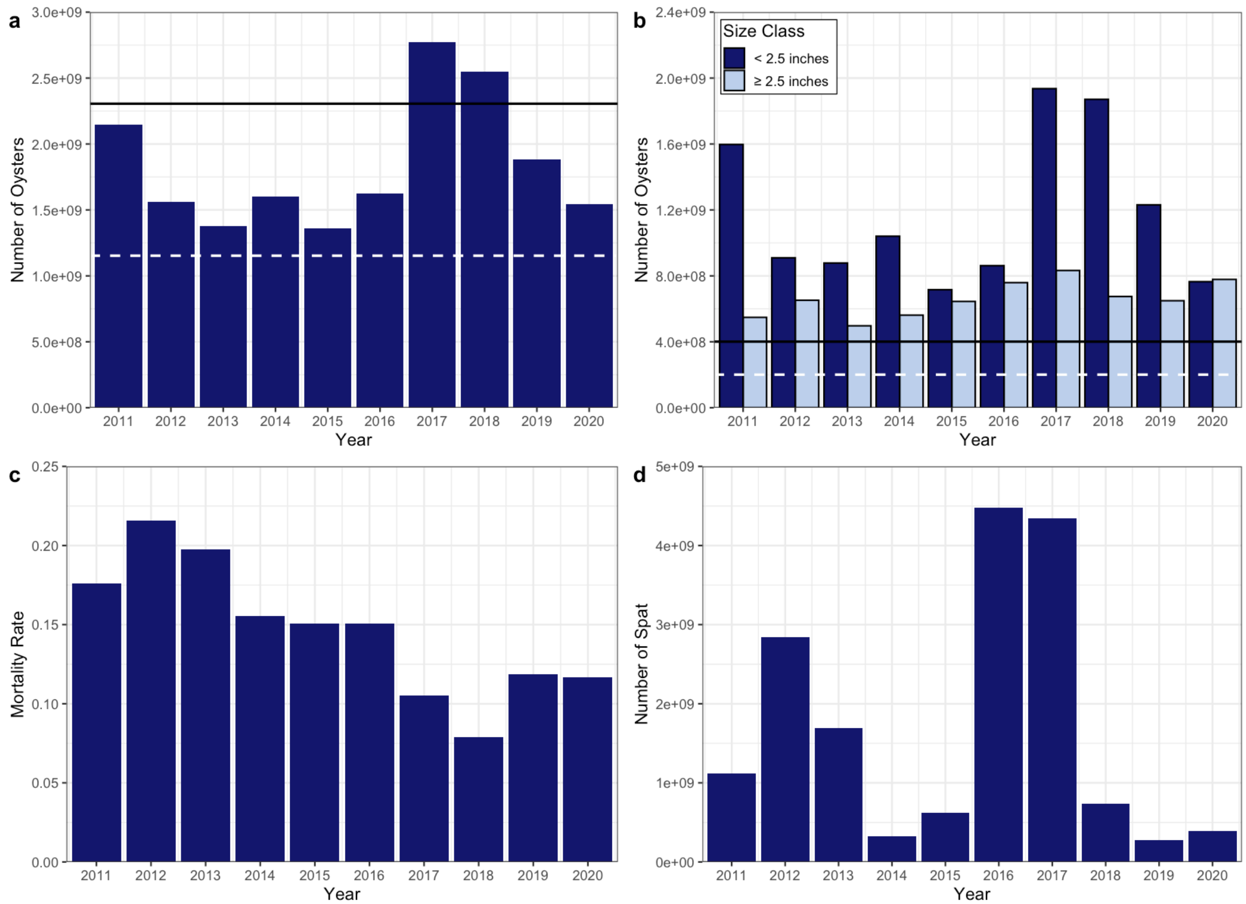
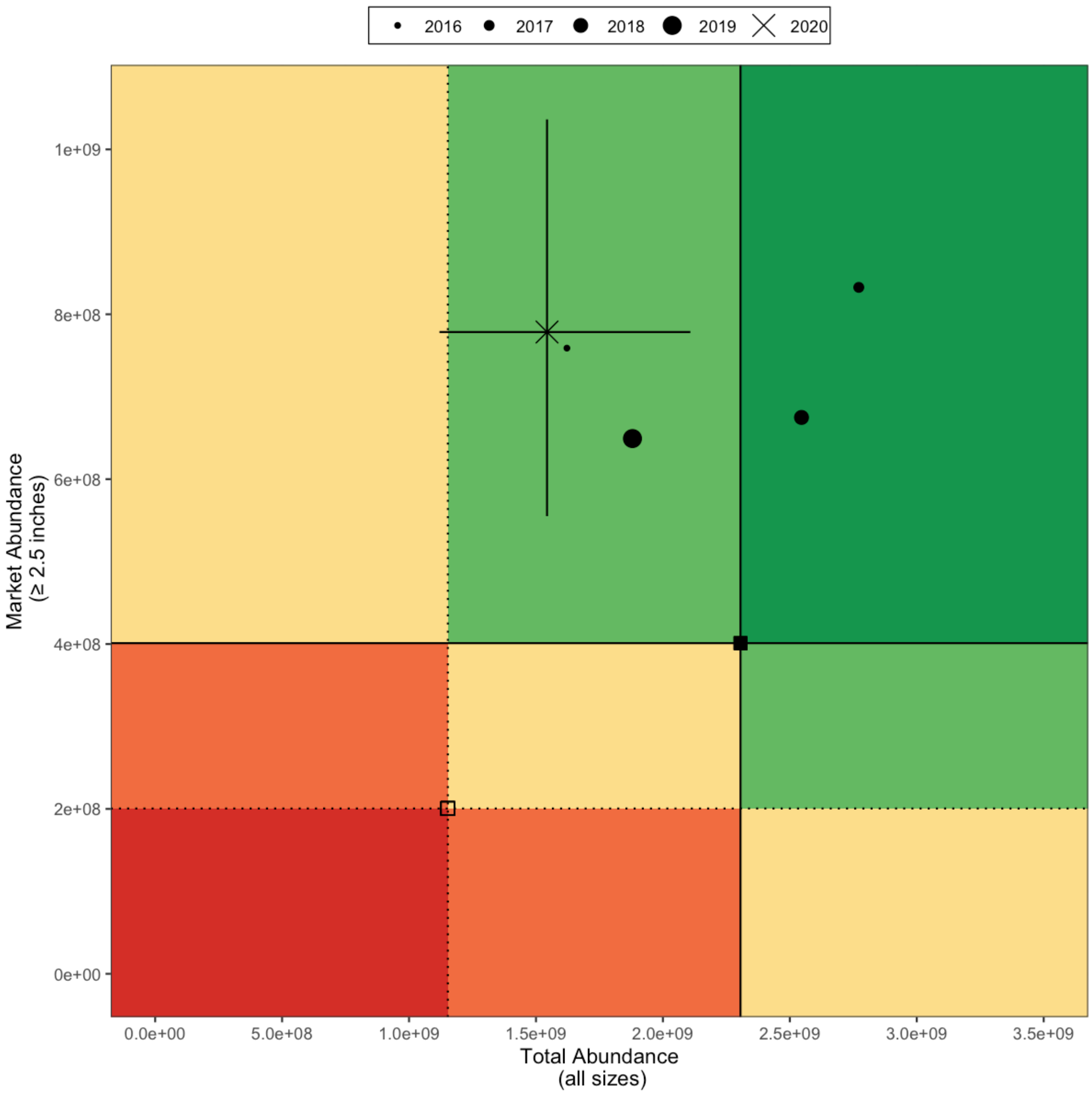


Figure 20. Position of the oyster stock 2016–2020 with respect to abundance and market abundance (≥ 2.5") targets and thresholds, excluding the VLM. Targets and thresholds are defined in Table 9. Error bars on the 2020 values are the 10th and 90th percentiles of 1,000 simulations of estimates incorporating 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 21 – 26. Ten-year 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 21. Ten-year time series summary for the VLM.

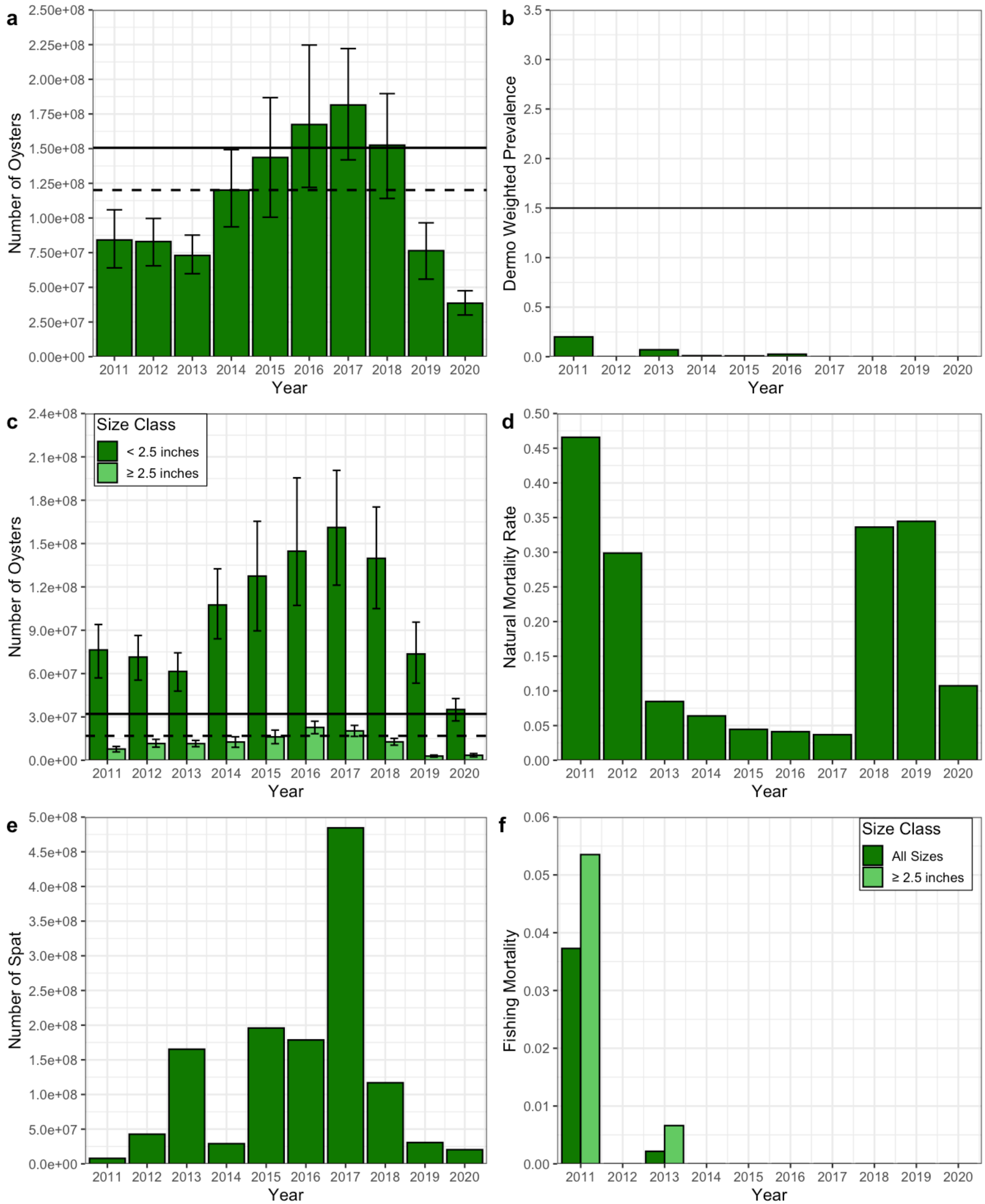


Figure 22. Ten-year time series summary for the LM.

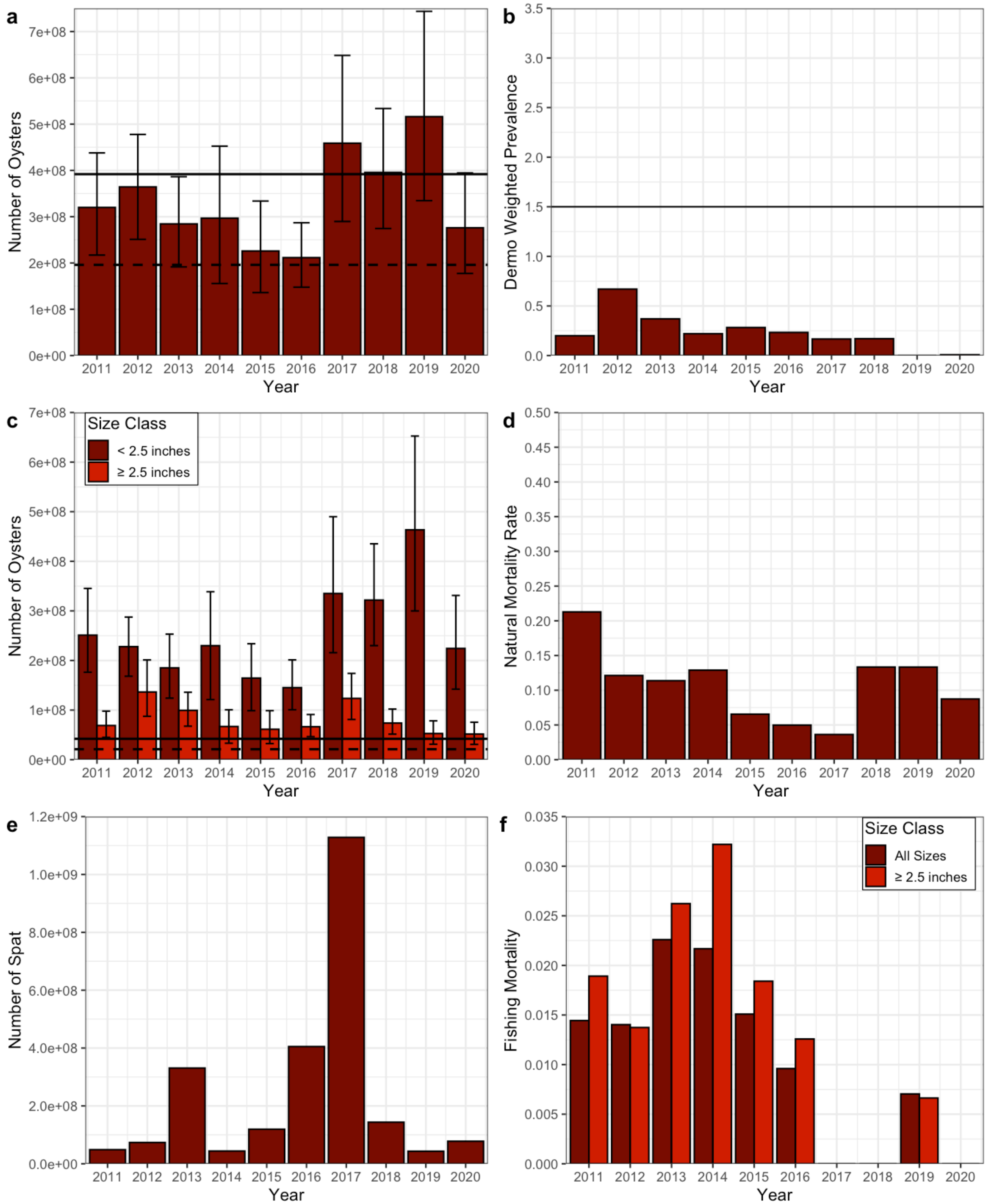


Figure 23. Ten-year time series summary for the MMT.

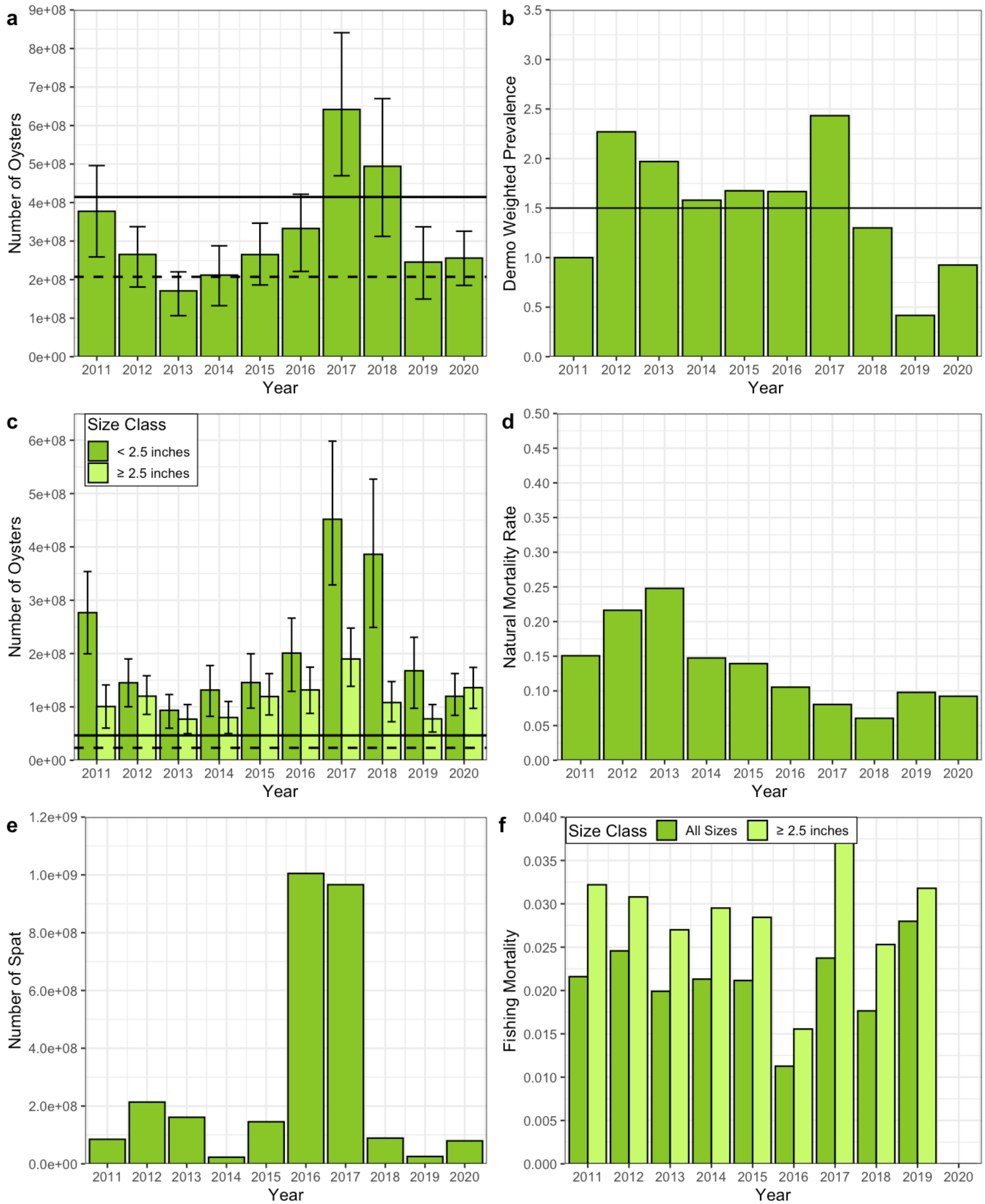


Figure 24. Ten-year time series summary for the MMM.

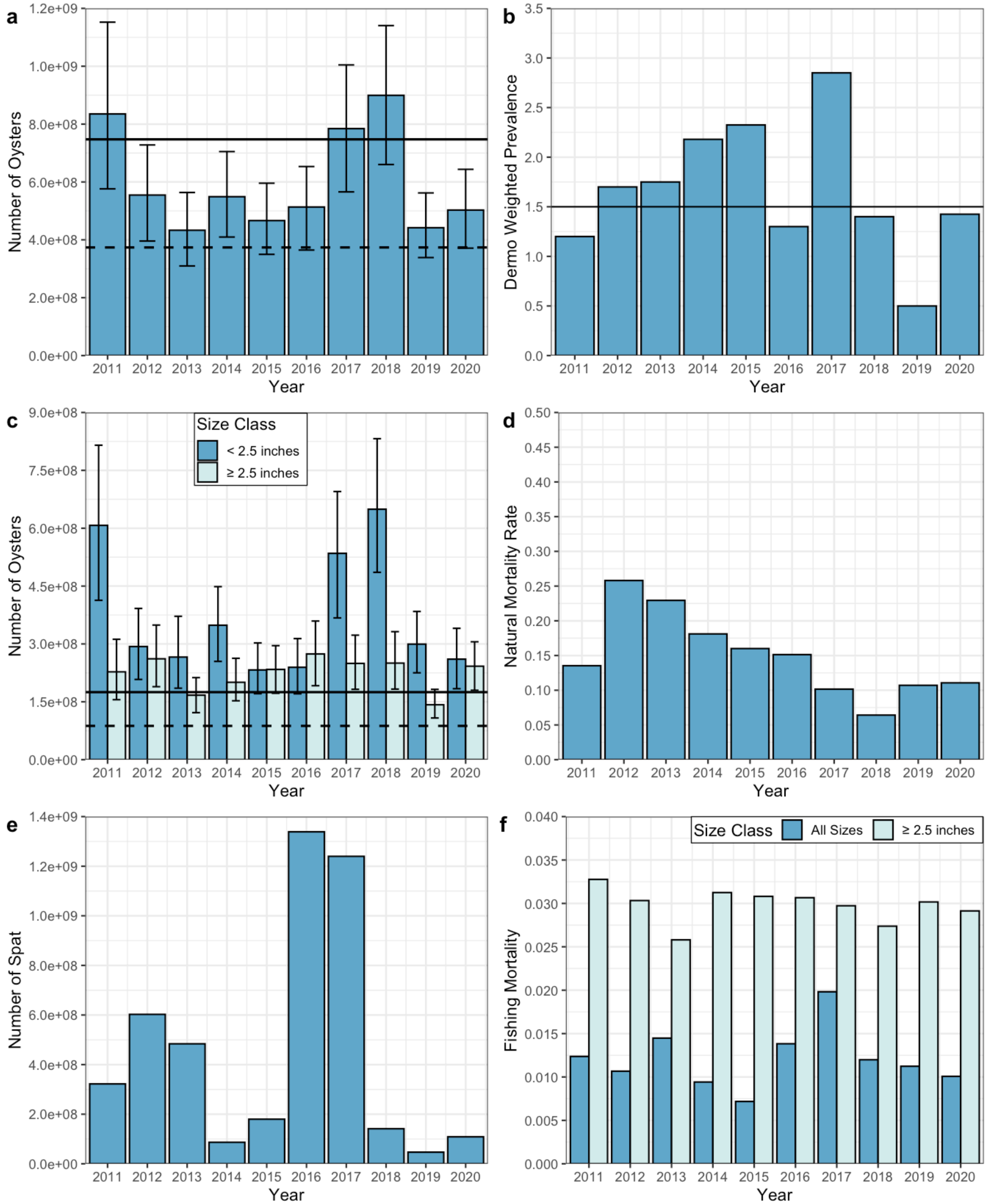


Figure 25. Ten-year time series summary for the SR.

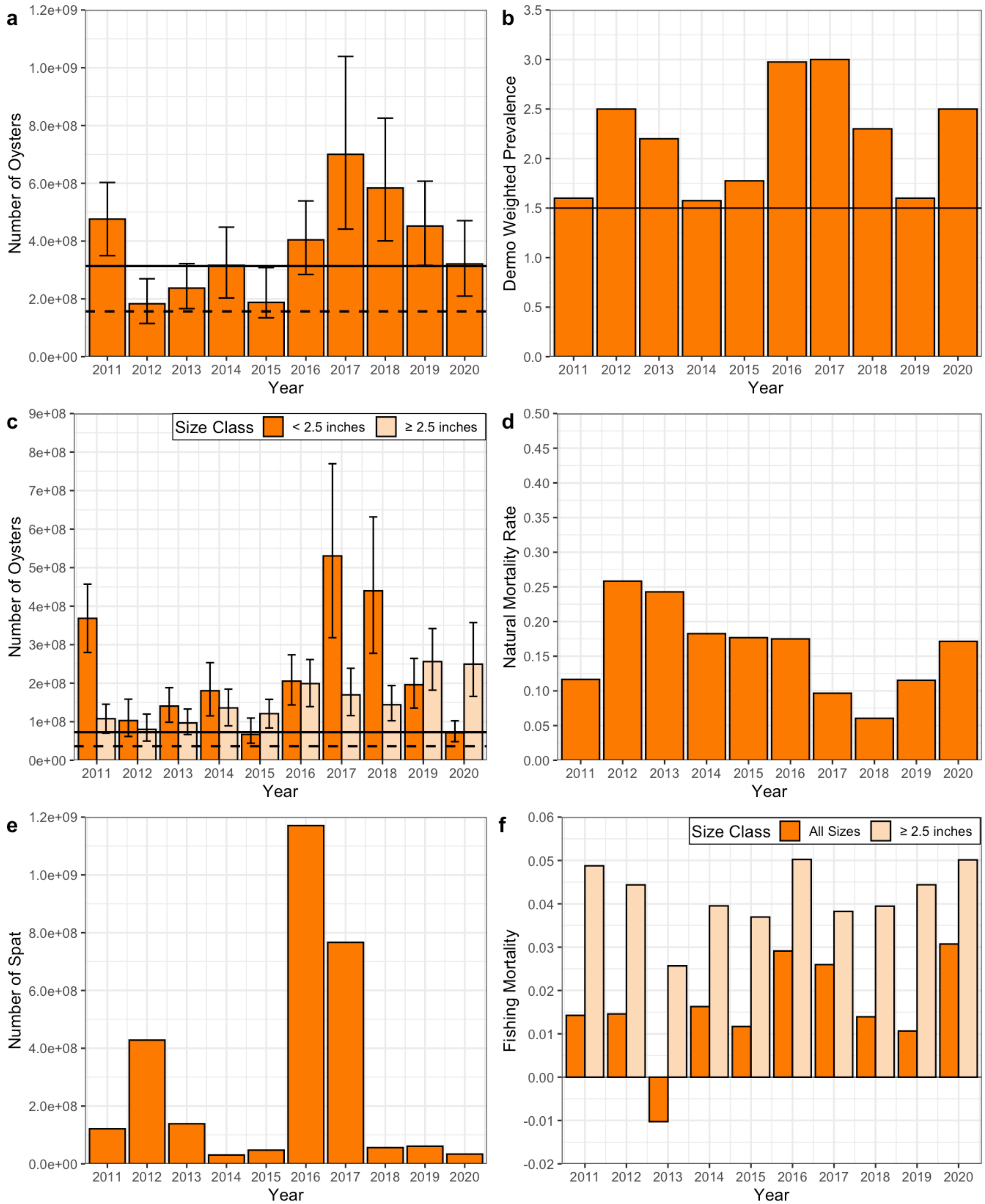


Figure 26. Ten-year time series summary for the HM.

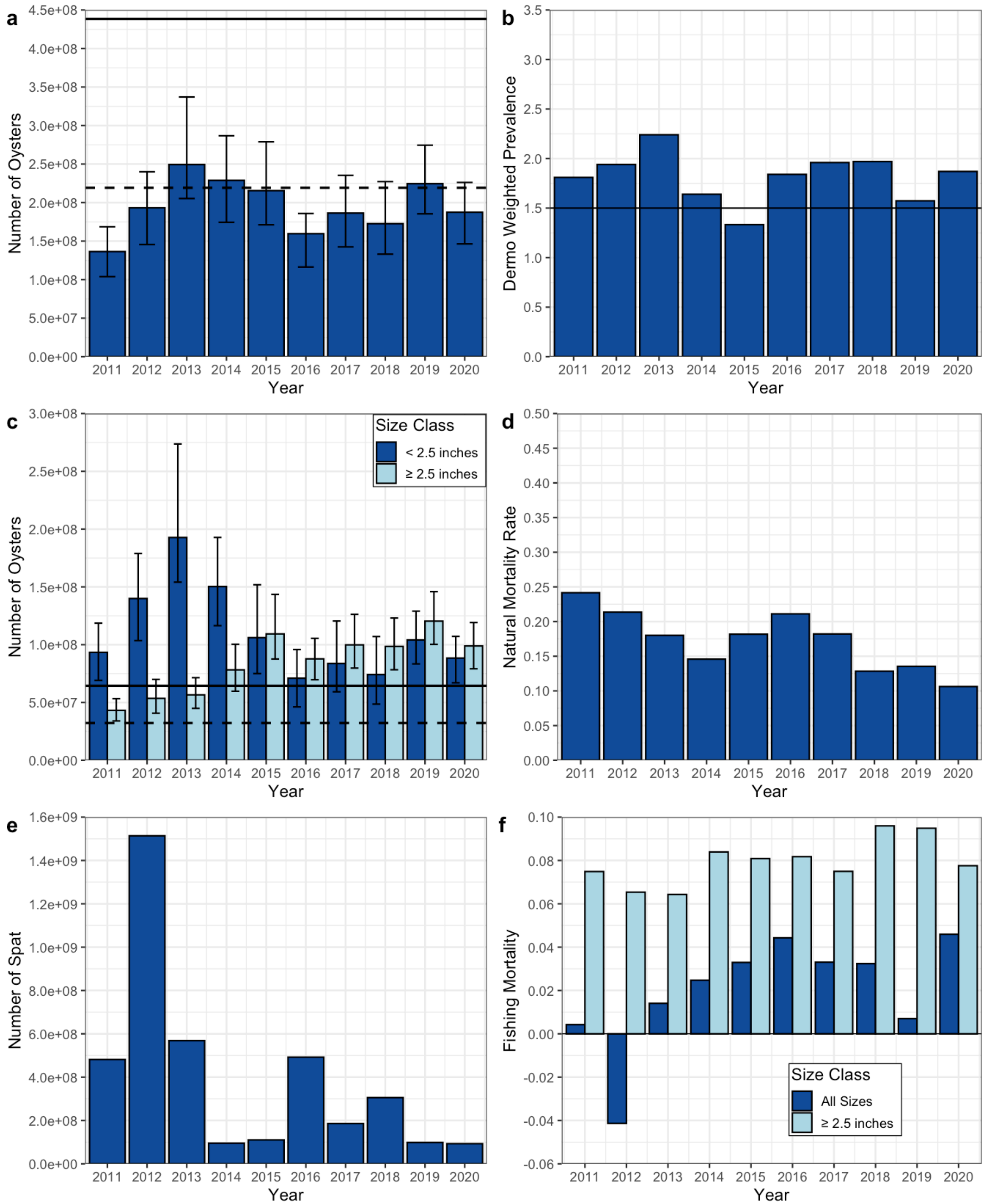
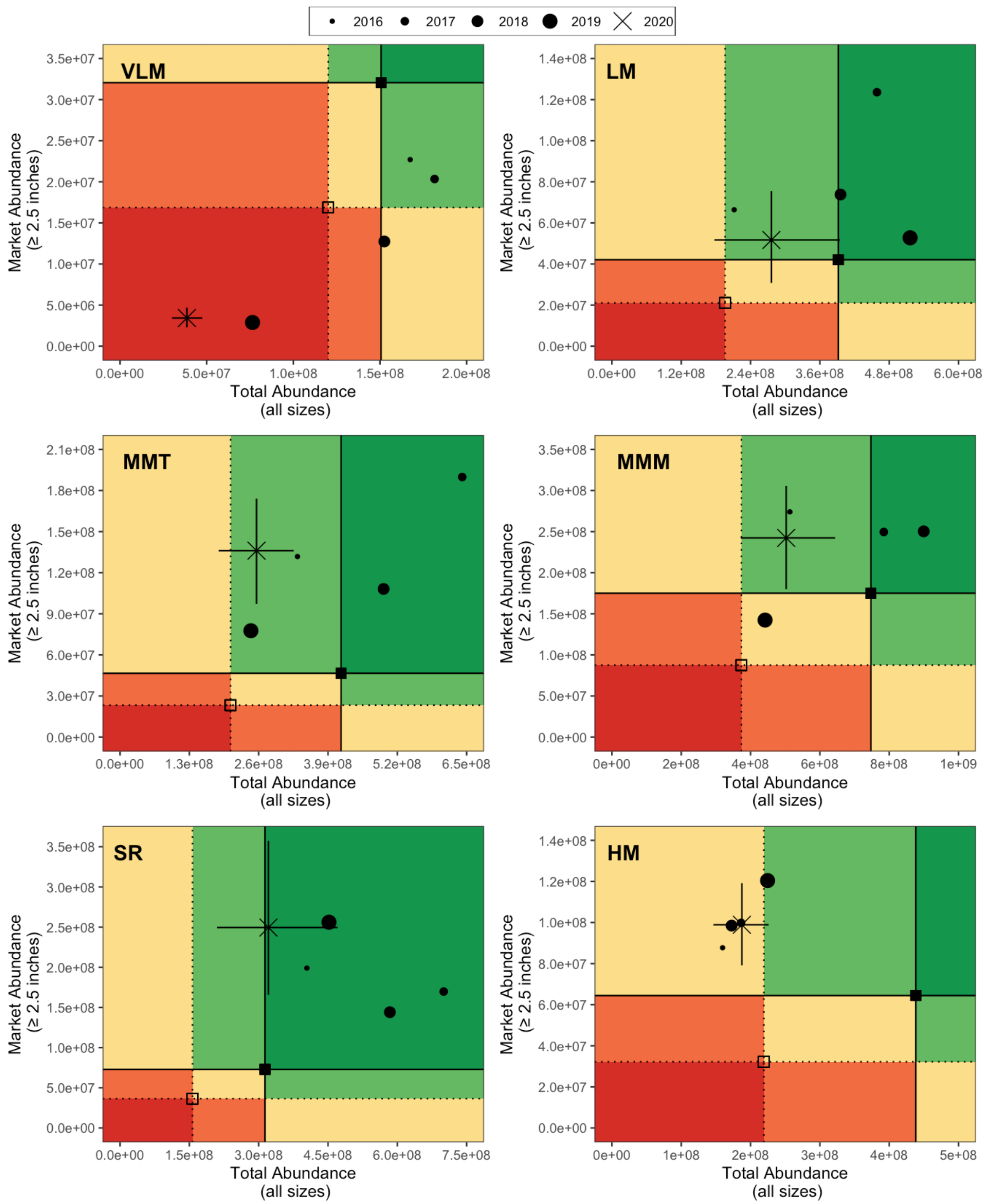


Figure 27. Position of the oyster stock 2016–2020 with respect to abundance and market abundance (≥ 2.5”) targets and thresholds for each region. Targets (solid lines) and thresholds (dashed lines) are defined in text. Error bars on the 2020 values are the 10th and 90th percentiles of 1,000 simulations 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*.

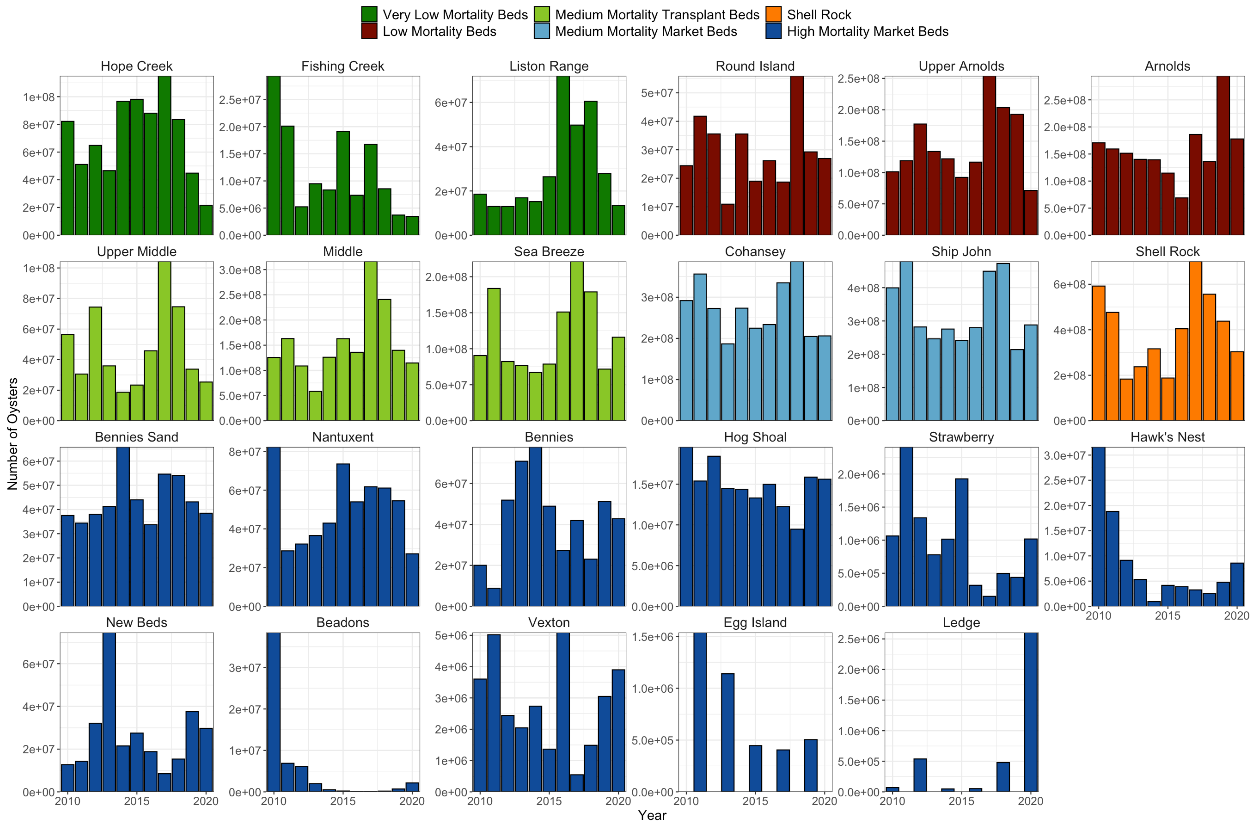


Appendix A. History of partial (P) and full (F) resurveys for all beds, grouped by region. The entire resource was gridded and stratified between 2005 and 2008. The current 10-year resurvey schedule was implemented in 2009.

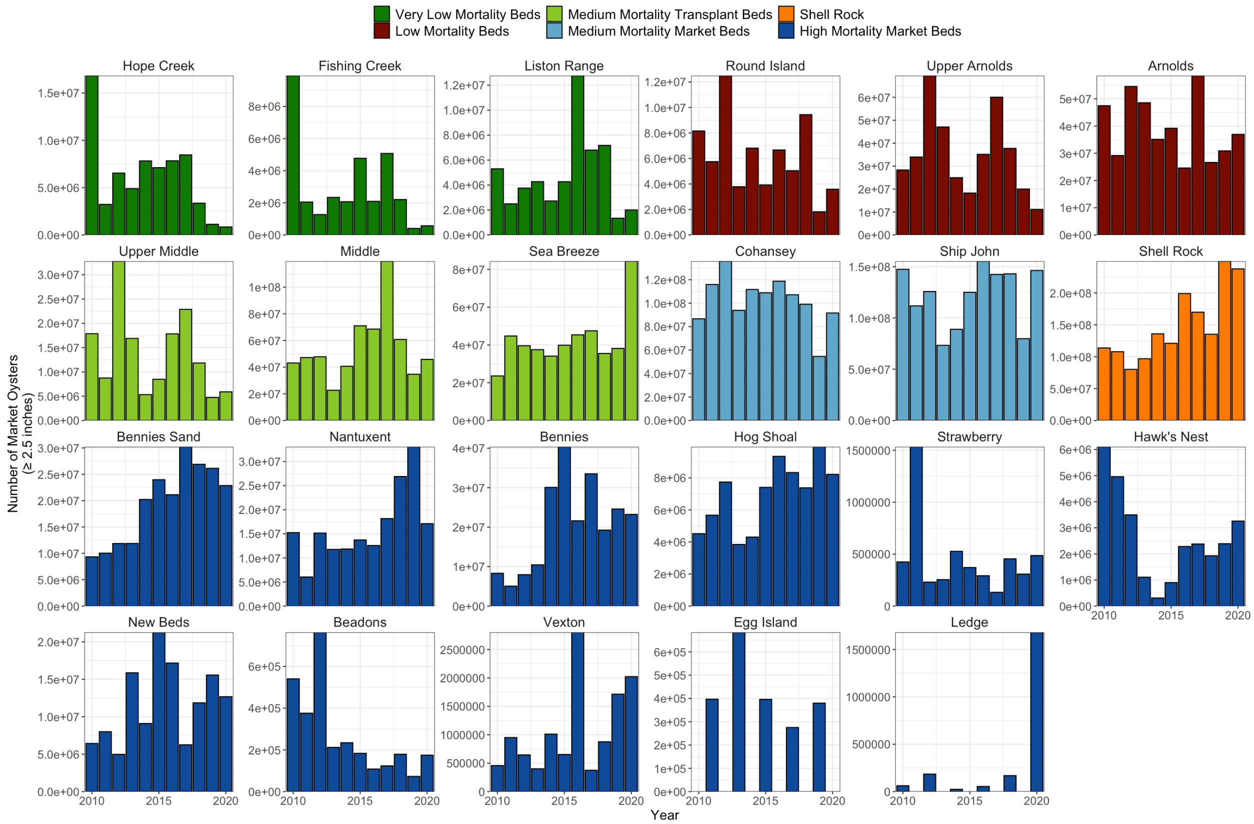
Appendix B. SARC members listed by affiliation. SAW year refers to when the February workshop was held to discuss the previous year's data. Names in parentheses indicate that the appointed member did not attend the meeting.

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

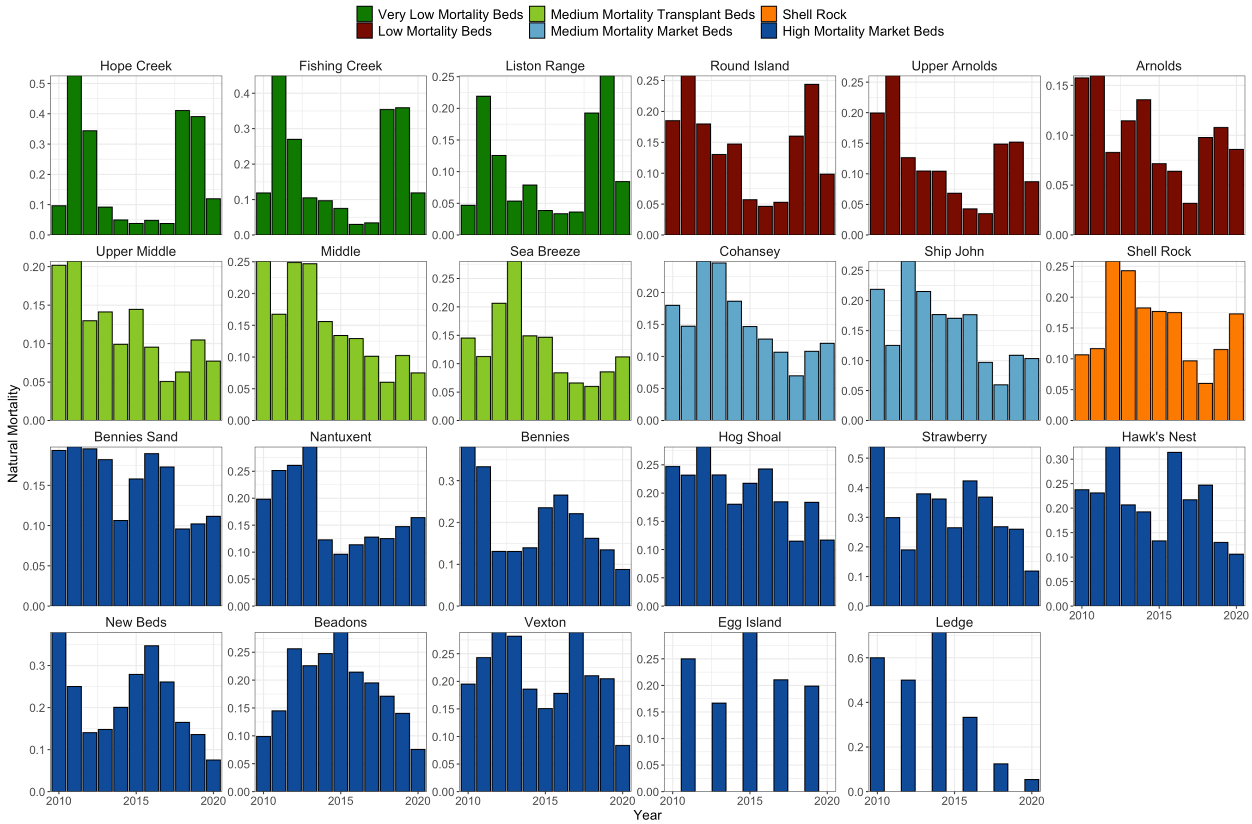
Appendix C. Bed-level oyster abundance for each region. Note y-scales varies.



Appendix D. Bed-level market abundance for each region. Note y-scales varies.



Appendix E. Bed-level mortality for each region. Note y-scales varies.



Appendix F. Bed-level spat abundance for each region. Note y-scales varies.