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Final Report

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Distribution List
Delaware Bay Section of the Shell Fisheries Council
NJDEP Bureau of Shell Fisheries
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

TABLE OF CONTENTS

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, mortality, 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 abundances were high. Circa-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 this relationship has not been as strong in recent years.

Throughout the time series, fishing has usually taken a small fraction of the stock compared to disease (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 or 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 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, the 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, a system called the Direct Market Fishery was adopted 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 were to be harvested directly from the twenty-three natural beds. This resulted in the twenty-three beds being grouped into six management regions that follow the estuarine salinity gradient of the Delaware Bay with each region named to reflect the 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 the lower three regions (MMM, SR, HM; Direct Market Regions) to enhance abundance there. 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 on the beds in these regions are generally smaller and of insufficient quality to market directly. Use of them by intermediate transplanting helps alleviate harvest pressure on the direct market regions when natural mortality has been high and recruitment has been low in those regions. In addition, once moved, oysters from the Transplant regions quickly depurate, 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. Each oyster license must be associated with a boat. Until 2010, the licensed boat had to be the harvesting boat. 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.

The 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). The survey methodology and the number of beds surveyed and their groupings have changed over the years (Table 1), but as of 2007, there are 23 surveyed beds grouped into six regions designated on the basis of relative magnitude of average oyster mortality and the current management scheme (Figure 6). Prior to 2007, the three beds at the upbay limit of the oyster resource (VLM) were not included in the survey, thus most of the long-term time series and all of the retrospective analyses exclude them.

From 1953 through 1988, the annual oyster survey was conducted from a small boat using a small dredge and occurred throughout a number of months in the fall, winter, and spring. Over time, 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). In 1989, sampling was switched to a large traditional oyster boat, the *F/V Howard W. Sockwell,* using a 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. Through 2004, the stock survey assessed 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 that continue to alternate due to their consistent low abundance.

Prior to 1990, oysters were not measured but were categorized as groups defined as ‘spat’, ‘yearling’, and ‘oyster’. Post-1990 survey protocols included 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 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.

Measurement of survey swept areas and experiments to determine gear efficiency began in 1998 allowing estimates of oyster density (Powell et al. 2002, 2007). Catchability coefficients calculated from these experiments began being applied to survey dredge hauls to correct for dredge efficiency and calculate density in 1998 (Table 2).

In 2005 by request of the 6th SARC, the survey time series from 1953 to 1997 was retrospectively quantitated. 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 natural mortality and the temporal dynamics of this variation are unknown for the 1953-1997 time frame. Understanding of 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. Accordingly, the quantitative time-series estimates are considered the best for 1953 to 1997.

Prior to 2005, each bed was divided into three strata based on oyster abundances. On each bed, grids with ‘commercial’ abundances of oysters ≥ 75% of the time were called ‘high’ (or ‘test’); grids with marginal or highly variable ‘commercial’ densities of oysters 25-75% of the time were called ‘medium’ (or ‘high’); 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

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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)

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 (Appendix A). 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).

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 Dept. 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. stock 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 indicators, spat settlement success (recruitment potential for the following year), 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 NJDEP acceptance and also include those made about harvest dates and area management schedule.

II. CURRENT METHODOLOGY

Bed Stratification and Resurveys

As described in the Historical Overview section, each bed 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. Initial analyses of restratification surveys (resurveys) showed that this stratum could be deleted from the fall stock assessment survey to focus on the grids that support 98% of the stock on each bed. To test how many strata should define the remaining 98% of the stock, the remaining grids were input into a Monte Carlo model in which they were subsampled repeatedly without replacement. The mean abundance estimated from the subsample was compared to the mean abundance obtained from the average of all grids. Analysis of many simulations suggested that a random survey based on two further strata would suffice. These are defined by ordering the remaining grids by increasing abundance. 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. Transplant grids were sampled only in the year they receive a transplant. At the 19th SAW (2017), this was increased to two years. Shellplant grids are sampled for three years after a shellplanting effort. Beginning in 2018, and on a Science Recommendation from the 2018 SARC, enhanced grids were reassigned to a stratum by re-evaluating where the most recent abundance for those enhanced grids sits on the cumulative curve for the most recent resurvey for that bed. Prior to 2018, these grids were placed back in their previous stratum (which sometimes meant returning to a low quality stratum where they would no longer be sampled).

A random subset of grids is sampled from each stratum (High and Medium quality) for each bed during the annual survey to estimate abundance. To determine how many grids to sample within a given strata, a Monte Carlo 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 should not be dedicated to a bed known to have very low abundance (ex. Vexton in 2018).

Science Advice: Evaluate Alternative Methods For Allocating Survey Effort

There is subjectivity in the approach for allocating survey effort described above for two reasons. First, 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. For this reason, the 2018 SARC made the following Science Recommendation, "an evaluation of alternative methods for allocating survey effort." A formal evaluation of three alternatives were presented at the 2019 SAW, each with a total sampling effort equal to that used during the 2018 survey. Each alternative made use of the Neyman optimal allocation formula (NF) applied to a stratified random survey design (Kimura and Somerton 2006). The first applied NF to the current stratification map. The second allocated a minimum of two samples to each stratum first, then applied NF to the remaining available samples. The third approach restratified all grids in the entire Bay by Region instead of by Bed and then applied the NF to allocate samples. In each instance the concentration of survey effort when compared to status quo moved away from lower density grids and toward higher density grids (Figure 7). Under all three alternative scenarios, beds like Shell Rock, Cohansey, and Arnolds would receive more of the total sampling effort and beds like New Beds, Strawberry, and Fishing Creek would receive less of the total sampling effort (Table 6). The 2019 SARC recommended no change to the current allocation strategy because the subjectivity built into the strategy was deemed important. For example, under two of the alternative strategies, entire beds would be unsurveyed given the current restratification map. Retaining the ability to allocate effort to these beds was deemed important. The 2019 SARC also recommended an evaluation of how added survey effort would affect uncertainty on regions receiving more/less effort (see "Science Advice" section of this report).

Science Advice: Evaluate How Stratification Changes If Done On Market Abundance

As described above, the strata on each bed are defined based on total oyster abundance. Since market abundance is sometimes deemed a less uncertain and more stable index, the 2018 SARC made a Science Recommendation to evaluate how the stratification maps would change if the strata were defined by market abundance instead of total abundance. Figure 8 demonstrates that most grids would remain in the same strata for most resurvey events. The exceptions to this included only those beds with very low abundance and patchy oyster distribution. Given these results, the 2019 SARC recommended continuing to define strata based on total abundance instead of market abundance.

Survey Design

The natural oyster beds of the New Jersey portion of Delaware Bay have been surveyed yearly since 1953 using a stratified random sampling method. 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. Each grid on a bed is assigned to a stratum (Low, Medium, or High quality) based on its relative density of oysters (see section above on "Bed Stratification and Resurveys"). A subset of grids from the High and Medium quality strata on each bed is randomly selected each year for the survey (Egg Island and Ledge are sampled in alternate years). Grids that received 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[3], oysters, and boxes per composite bushel; sizes of spat, oysters, and boxes from the composite bushel; condition index; and the intensity of Dermo and MSX infections.

Science Advice: Evaluate Ways To Reduce Assessment Uncertainty

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 processed in a given sampling season. This evaluation focused on two particularly laborious tasks associated with sample processing: 1) measuring every oyster and 2) counting every spat in each sample.

To evaluate whether it was necessary to measure every oyster in a sample, all size frequency data collected from 1999-2017 were first broken up into three groups: ~200 oysters, ~300 oysters, ~400 oysters. The size data in each group was then binned at 5mm intervals. A random set of oysters was drawn from each sample from 1:max (oysters in the sample) and the mean squared error of (true proportion in a bin – random draw proportion in a bin), was plotted against the number of oysters measured (Figure 9). An exponential decay model was then fit to each plot and the sample number associated with the slope at 10% and 5% of the slope at the origin was

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

[3] Beginning in 2003, oyster spat are defined based on size (< 20 mm, the average first-season size on the Delaware Bay natural oyster beds). Prior to 2003, oysters were classified as spat based on morphology.

identified. In no instance did even the more conservative benchmark (5%) occur above 100 oysters.

To test whether a 100 random draw of oysters was sufficient to describe the length frequency distribution, a random subset of 100 oysters was pulled aside during the 2018 survey for one grid on each high quality strata and the size frequency created from this subset was compared to one created from measuring all oysters in the sample (Figure 10). No statistical difference was found between the subsample l-f distribution and the full sample l-f distribution on any of the beds evaluated.

To evaluate whether it was necessary to count every spat in a composite bushel, we evaluated several "sub-sampling" methods. The most promising method focused on counting the number of spat on oysters, given oysters already need to be measured. This count was used to calculate a spat per volume on oyster. A regression equation was then used to scale "spat/volume of oyster" to "spat/volume of everything". The relationship between these two is plotted in Figure 11 and the results of using this method are plotted in Figure 12. Figures 11 and 12 suggest in combination that subsampling spat using this method provides total spatfall estimates similar to what was observed when spat were counted on everything in a sample. However, there was a follow up Science Recommendation to evaluate whether the agreement in Figure 12 is as tight if a subset of the data is used as a training data set for the model and a separate subset of data are used to test the model performance (see "Science Advice" section of this report).

Given the results of these findings, beginning in 2018, only 100 random oysters are drawn from each sample to estimate the size frequency and only spat on oysters are counted and then scaled to the rest of the sample to estimate the total spatfall in sampled strata. These two changes resulted in an enormous increase in sample processing efficiency in 2018. Therefore, the 2019 survey will include an initial 33% increase (approximately 50 more sampled grids) in sampling effort. The reduction in survey error gained from these added samples will be evaluated by resampling using the grid density data collected during the 2019 survey.

Estimating Abundance of Oysters, Boxes, and Spat

To obtain the annual estimates of abundance for each region, grids from the high and medium quality strata are chosen randomly from each bed in the region and sampled as described above to generate a relative estimate of the numbers per m^2 on each grid. Catchability coefficients estimated by dredge efficiency experiments (see "Capture Efficiency and Catchability" section below) 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.

Throughout this report, 'oyster' refers to individuals ≥ 20 mm (0.8") in longest dimension while 'spat' refers to those < 20 mm. The 20 mm cutoff was chosen as the average spat size through the estuarine gradient of beds in the Delaware Bay. The result of this is that in upbay regions, e.g. Low Mortality, the < 20 mm size class may include oysters that are older than their first season while in the High Mortality region (HM), oysters in their first season may be > 35 mm (1.4"). Analyses have shown that using the 20mm spat size cutoff as opposed to physical morphology for region-specific spat sizes did not yield a statistically significant difference in spat vs oyster abundance estimates for any of the regions (Ashton-Alcox et al., 2017). In this report, market-size oysters are defined as those ≥ 63.5 mm (2.5").

Capture Efficiency and Catchability

Densities of oysters, boxes, and cultch from each survey sample are calculated from the area swept by the dredge, the total haul from which the sample was taken, and the appropriate catchability coefficients (q) to correct for dredge efficiency. Work from 1999 to 2003 to establish these coefficients for the oyster beds in Delaware Bay is described in Powell et al. (2002, 2007) and more recently in Morson et al. (2018). Briefly, differences between bottom samples from parallel transects of measured tows by a commercial dredge from the *F/V Howard W. Sockwell* and quadrat samples collected by divers presumed to be 100% efficient were calculated. Analyses of the 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 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). Parallel transects were sampled to compare numbers of oysters caught in measured tows versus those collected by the tongs. 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 (Ashton-Alcox et al. 2016). The spatial analyses showed that the original Upbay dredge efficiency bed group should be further divided for a total of three catchability coefficient groups (Table 2; Figure 13). This result is due to the 2013 dredge-tong comparisons on Hope Creek and Round Island. These beds are farther upbay than Arnolds, the previous most upbay bed used for gear efficiency experiments. The spatial analyses also indicated that Shell Rock should be included with the Upbay group of beds rather than the Downbay group (Figure 13). The 2016 SARC advised adoption of the updated bed groupings for gear efficiency applications presented in Figure 13 and listed in Table 2. Finally, in addition to influence of region, it was clear from the data collected during the three separate experiments that capture efficiency was density-dependent (Morson et al. 2018 and Figure 14). In other words, the regional variation in efficiency is likely a proxy for variation in true oyster density. Efficiency is high in the lower bay where oyster density is low and low in the middle and upper bay where oyster density is high (Figure 13).

Science Advice: Re-Evaluate Capture Efficiency Of The Survey Gear

Given how important it is to have accurate estimates of survey gear efficiency and given that efficiency is likely density-dependent, the 2017 SARC made a Science Recommendation to re-evaluate the capture efficiency of the survey dredge whenever funding is available to do so. In September of 2018, the experiments conducted in 2013 were repeated at the same locations using the same protocol with one exception: at locations where dredge efficiency was highly variable in the lower bay (Figure 13), the total number of tong grabs was increased from six to twelve.

The results suggested that capture efficiency measured in 2018 in both the "downbay" and "upbay" regions did not vary from the distribution of efficiency values measured in 2003 and 2013 (Figure 15). However, in the "far upbay" region, the capture efficiency estimates measured during the 2018 experiment were much lower than those measured in 2013 (Figure15). The lack of any change in efficiency on the "downbay" and "upbay" regions is likely due to the lack of any change in average true oyster density there (Figure 15), while the large differences in efficiency observed on the "far up bay" region could likely be attributed to the large change in oyster density on that region between the two experiments. In 2013, during the first experiment, the population in the far up bay region had, just a couple of years earlier, experienced a freshet even that killed 40% of the population. This resulted in low oyster density in this region when the 2013 experiments were conducted. In 2018, the population in that region had recovered to reach its highest level of abundance in the previous 10 years, which resulted in a large increase in density and likely an associated large decrease in gear efficiency.

The 2019 SARC discussed the ramifications of the most recent dredge efficiency experiment results. The major issue discussed was that to estimate capture efficiency of the survey gear accurately, one needs to know the true density of oysters on the bottom. However, if one knew the true density of oysters on the bottom, it would not be necessary to estimate capture efficiency. As a result, the 2019 SARC made a Science Recommendation to evaluate the application of alternative survey gears that could be used in tandem with the survey dredge so that spot estimates could be made of true oyster density along the sampled domain and this information could then be used to adjust the catchability coefficients accordingly.

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. Step one is to calculate the average number per bushel (from the transplant monitoring program) moved from each donor bed in the current year. Step two is to 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. Step three is to calculate total removals by region by summing all removals from all donor beds in each region. Finally, step four is to 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. Step one is to 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. Step two is to multiply this average by the total catch in bushels in each market region to get total catch by region. Step three is to 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. Step four is to distribute the total catch in numbers by region across the size frequency by region to get total numbers of oysters caught in each size bin by region. Step five is to 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. Step six is to 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. Finally, step seven is to 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 16. 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. 2018 STATUS AND TRENDS

2018 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 2018 was 306 and the average number of market sized oysters per landed bushel was 228 (Figure 17). The proportion of small oysters attached to market size oysters increased in 2018 likely due to the large spatfall events in 2016 and 2017 (Figure 17). 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 263 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 both dredge types has steadily increased since 2012, 2018 catch rates remained constant at 21 bushels-per-hour for single dredge boats and decreased to 31 bushels-per-hour for dual dredge boats (Figure 18). The number of vessels of each dredge type, single and dual, has also remained relatively constant at 8 and 12, respectively, since 2015. However, the number of single dredge boats decreased to 5 and the number of dual dredge boats increased to 15 in 2018 (Figure 18).

Increases in LPUE on the direct market beds could be influenced by several factors: license consolidation, shifts in population size structure 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 greater influence on catch rates. Within both fishery landings and the population as a whole, there was a decrease in the frequency of large oysters (≥ 3.5 inches) during 2010 and 2011 (Figure 19). If changes in LPUE were influenced by oyster size alone, we would expect LPUE to closely mirror trends in size distribution. This is not always the case; LPUE remained stable in 2010 and 2011 for both dredge types (Figure 18). 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 landed by the fishery has been increasing in tandem with that of the population since 2014, with the exception of a slight decrease in large oysters landed in 2018 (Figure 20). 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.

Science Advice: Determine If Growth Rates Have Changed In Recent Years

One potential explanation for the change in size structure of the catch and the population described above and apparent in Figures 19 and 20 is that oysters are growing at faster rates in recent years. Therefore, a Science Recommendation from the 2018 SARC was to evaluate whether growth rates have changed recently. To address this, experiments were conducted in 2018 to monitor incremental growth of oysters on five reefs (Hope Creek, Cohansey, Shell Rock, Bennies, and New Beds). The methods for monitoring monthly and annual growth increments were first described in Kraeuter et al. (2007) for an experiment conducted in 2001. The same methodology was repeated in 2018, but briefly, 10 oysters were collected in each of ten 10mm size bins from each reef in late May 2018. These oysters were numbered with a unique ID, tethered to fishing leader, and tied off to a rack that could be placed on the bottom. Three days after collection, oysters were returned to the reef where they came from and each oyster was measured monthly from June through November 2018. While several experiments were lost, experiments on two of the reefs where the same experiment was conducted in 2001 were monitored for all 7 months. Growth rates may have increased from 2001 to 2018 (Figure 21). However, additional experiments will be conducted in 2019 and results from those experiments, along with the data collected in 2018, should provide more conclusive evidence for whether oyster growth rates have changed throughout the Bay since 2001.

Science Advice: Evaluate Changes In Population Fecundity Over Time

Given the recent shift in population size structure presented in Figures 19 and 20, and the increasing fishery practice of "high grading" (throwing larger oysters back in favor of collecting smaller, more marketable oysters), the 2018 SARC made a science recommendation to evaluate how these changes in size structure have influenced population fecundity. To estimate population fecundity, the power function published in Mann et al. (2014) was used to convert numbers of oysters at size to fecundity at size for the last 19 years of data (2000-2018; Figure 22). Over the last six years there has been a steep incline in population fecundity that has coincided with the change in population size structure (Figures 19, 20, 22).

2018 Catch Statistics and Fishery Exploitation

The 2018 direct market harvest occurred from April 2 to November 16 and included a period of curtailed harvest hours during summer months to comply with New Jersey's FDA-approved *Vibrio parahaemolyticus* Control Plan[4]. A total of 20 vessels including 5 single- and 15 dual-dredge boats were in operation. The number of boats has declined since 2009 when 74 boats harvested oysters. As described above, this is a result of a legislation change to allow license consolidation so boats can now harvest multiple quotas rather than one quota per boat. The total direct market harvest in 2018 was 119,342 bushels, a slight decline from the 124,144 harvested in 2017, but the third straight year the total quota was over 100,000 (Figure 23). The harvest from the three Direct Market regions broke down as follows: 47% from the HM; 27% from SR; 26% from the MMM (Table 7a). Of the 14 beds in the three Direct Market regions, 8 were fished during the 2018 harvest season. The HM has 11 beds and 79% of its harvest came from Bennies and Bennies Sand. Of the two beds in the MMM, 28% of its harvest came from Cohansey and 72% from Ship John.

Table 8a describes the exploitation rates chosen by the SARC and approved by the Shellfish Council in 2018 for the Direct Market regions. The 2018 harvest on the Medium Mortality Market region resulted in an exploitation rate of 2.74%, less than the 3.70% maximum rate proposed by the 2018 SARC and approved by the Shellfish Council. On the Shell Rock region, the 2018 harvest resulted in an exploitation rate of 4.10%, also less than the 4.88% maximum

[4] See New Jersey's FDA-approved *Vibrio parahaemolyticus* Control Plan here: http://www.nj.gov/dep/bmw/docs/nj2017vibrioplan.pdf

rate proposed by the 2018 SARC and approved by the Shellfish Council. Finally, on the High Mortality region the 2018 harvest resulted in an exploitation rate of 9.66%. This achieved rate was higher than the 8.99% maximum rate proposed by the 2018 SARC and approved by the Shellfish Council.

Tables 8b and 9 describe the exploitation rates chosen by the SARC and approved by the Shellfish Council in 2018 for the Transplant regions and the total bushels and oysters moved as a result of those chosen rates. While the SARC approved exploitation up to the rate of 2.32% and 2.01%, respectively, on the Very Low and Low Mortality regions, no oysters were moved from these regions in 2018. The intermediate transplant program moved 39,950 bushels of culled material from Middle, Upper Middle, and Sea Breeze (Table 7b) onto Bennies in the HM in Spring 2018 (Table 9). The total transplant contained 12.3 million oysters of all sizes, the market-size fraction of which provided 16.6% of the total direct market quota (20,017 bushels).

Finally, the exploitation rate of the total stock (excluding the VLM region) was approximately 1.35% (Figure 24a) while the achieved exploitation rate of market-sized oysters (>2.5") was 2.78% (Figure 24b). This level of exploitation is consistent with low exploitation rates achieved since initiating the direct market fishery.

2018 Enhancement Efforts

In 2018, there were three shell plants on NJ's Delaware Bay oyster beds, all funded by the NJ oyster industry through its self-imposed 'bushel tax'. Unspatted clamshell was put directly on one grid in each of three regions: 42,184 bushels on HM (Hog Shoal); 63,276 bushels on SR (Shell Rock); and 42,705 bushels on MMM (Ship John). A formal evaluation of the increase in productivity that results from enhancement efforts (shellplanting and transplanting) was conducted in 2018 by comparing the change in oyster density on enhanced grids on Shell Rock to adjacent, non-enhanced grids on the same reef (Figure 25). Results from that analysis suggest that enhancement efforts clearly increase productivity on enhanced grids relative to adjacent, non-enhanced grids (Figure 25). Efforts are underway in 2019 to evaluate the duration of this effect using a wider distribution of beds and grids.

2018 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. It was concluded that this time period represented the scope of oyster population dynamics in the present climate and disease regime (aka the 'Dermo Era'). Targets for each region were therefore calculated as the median (middle) 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. Targets and thresholds for each region are presented in Table 10 and reference will be made to the current stock status relative to these targets and thresholds throughout the description of the status of the stock below.

A total of 171 grids were sampled to estimate the status of the stock in 2018 (Figure 26). For the second year in a row the total abundance and market abundance are both above the target (Figures 27 and 28). Natural mortality has been in decline for seven years and declined again from 2017 to 2018 (Figure 27c). Spatfall declined sharply in 2018 relative to the large spatfall estimated in 2016 and 2017 (Figure 27d).

Transplant Regions
The three intermediate transplant regions (VLM, LM, MMT) all have similar acreage (Figure 2). Figures 29-31 summarize the 10-yr trends of the stock in these regions. The uppermost region, VLM, was at the highest abundance last year (2017) since it was first surveyed in 2007 (Figure 29). The region had been rebuilding with good spat sets and increased survival since a late 2011 freshwater event that caused 47% mortality. A similar influx of freshwater over a longer duration occurred in 2018 and resulted in another massive die-off (34% mortality; Figure 29). This event resulted in the market abundance falling below the threshold for the first time since 2015 (Figures 29 and 35). Since this region has a very slow growth rate compared to regions further downbay, it will likely take some time before the market abundance reaches the target again. While the total abundance declined since last year, it remains just above the target (Figures 29 and 35). The 2018 spat set in the VLM region was right at the 50th percentile for the 2007-2018 times series (Figure 29, Table 11). Dermo remained undetectable indicating the increased mortality shown in Figure 29 was likely a result of the persistent freshet during the latter half of 2018 (see Dermo monitoring report, Bushek et al. 2019). Oysters have not been transplanted from the VLM region since 2011 (Table 7b).[5]

Though not as extreme, the LM region also experienced an elevated rate of natural morality in 2018 (13% = the highest natural mortality since 2011; Figure 30). Given the low levels of dermo in the LM region in 2018 (Figure 30), it is likely the influx of freshwater accounted for the spike in natural morality. While natural mortality increased, there was only a small decline in the number of oysters on the LM region, likely resulting from high levels of spat in 2017 (Figure 30). Total abundance remains slightly above the target and the market abundance remains well above the target (Figures 30 and 35). Though recruitment did decline a great deal from 2017 to 2018, the 2018 recruitment is above the 60th percentile of the 1990-2018 time series (Figure 30, Table 11). No oysters were transplanted from the LM region for the second consecutive year

[5] In 2013, one boat strayed from LM transplanting for part of a day and dredged 550 bu from the VLM.

even though the 2018 SARC had recommended allowing a transplant from this region (Table 7b).

The MMT region had the lowest levels of natural mortality in the recent time series, continuing a steady decline since 2013 (Figure 31). While the total abundance of oysters declined relative to 2017, 2018 is the second highest abundance in the recent (last ten years) time series (Figure 31). Both the total and market abundance remain above the target and both are near the 80th percentiles from the 1990-2018 time series (Figure 31 and 35, Table 11). Recruitment in 2018 was below the 40th percentile of the 1990-2018 time series and declined dramatically relative to the large sets in 2016 and 2017 (Figure 31, Table 11); 2018 represents the second lowest recruitment event in the past decade. Approximately 40,000 bushels of culled material were transplanted from the MMT region to the HM region (Table 9), representing exploitation rates of 1.7% and 2.5% on total and market sized oysters, respectively; both reductions from 2017 (Figure 31).

Direct Market Regions

Direct market harvesting occurs in the two largest (HM, MMM) and the smallest (SR) regions (Figure 2). However regional acreage does not reflect the distribution of the oyster stock. For instance, in 2018, the HM made up nearly 50% of all oyster acreage but contained only about 7% of the total stock of all six regions while the SR and MMM that together make up approximately 25% of the total oyster acreage, made up 58% of the total oyster abundance. In 2018, SR contained nearly 3.5x as many oysters as HM. Figures 32-34 summarize the 10-yr trends of the stock in these regions.

Similar to what was observed on the MMT region, the MMM region saw the lowest rate of natural mortality in the recent time series (Figure 32). Both total abundance and market abundance increased again in 2018 and both remain above their respective target reference points (Figures 32 and 35). Similar to what was observed in other regions, recruitment declined from high levels observed in 2016 and 2017 to relatively low levels like those observed in 2014 and 2015 (Figure 32). In addition, recruitment in 2018 is below the 40th percentile in the MMM region relative to the 1990 to 2018 time series (Table 11). The exploitation rates on the MMM region were 1.2% and 2.7% respectively on all and market sized oysters and both rates declined relative to 2017 (Figure 32).

The SR region also experienced record-low levels of natural mortality (Figure 33). While abundance declined slightly from 2017 to 2018 on the SR region, both market and total abundance remain above their relative targets (Figures 33 and 35) and near the 80th percentiles of the 1990-2018 time series (Table 11). Recruitment, as was the case in most other regions, was low in 2018 on the SR region (Figure 33). Exploitation rate of market sized oysters in the SR region increased slightly from 2017 to a value of 4.0% in 2018, while exploitation rate of all sizes declined from 2017 to a value of 1.4% in 2018 (Figure 33).

Finally, the HM region also experienced low levels of natural mortality relative to recent years, continuing a trend of declining mortality rate since 2009 (Figure 34). Total and market abundance barely changed from 2017 to 2018 (Figure 34). Market abundance continues to remain well above the target, while total abundance remains at or below the threshold (Figures 34 and 35). Interestingly, recruitment increased on the HM region in 2018 relative to 2017 and is near the 50th percentile of the 1990-2018 time series with nearly double the number of spat versus oysters (Figure 34, Table 11). The exploitation rate of all oysters remained almost identical in 2018 (3.24%) as was observed in 2017 (3.30%), but exploitation of markets sized oysters increased from 7.5% in 2017 to 9.6% in 2018 (Figure 34).

IV. SARC EXPLOITATION RATE AND AREA MANAGEMENT RECOMMENDATIONS

Upon review of the status of the stock, the 2019 SARC recommended that the Very Low Mortality region be closed to fishing, that the Low Mortality, Medium Mortality Transplant, Medium Mortality Market, and Shell Rock regions all be allowed to be fished up to the maximum allowable rate, and that on the High Mortality region the maximum allowed exploitation rate be approximately 9% with a transplant and approximately 6.5% without a transplant. A summary of these decisions and their associated quota projections can be found in Table 12.

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 fisheries population modeling 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 2019 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 management strategies; prescribed fishing

exploitation rates implemented since 1996 have had no observed negative impact on production.

VI. SARC SCIENCE ADVICE

Following is a list of science advice recommended by the 2019 SARC (not ordered by priority):

1. Provide some alternative drafts of the "Statement of Sustainability" to the SARC for review in advance of the 2020 SAW.

2. Measure variability in the three tows used to make up the single composite bushel for each surveyed grid.

3. Evaluate how added 50 samples influence survey error and use this information to inform allocation of survey effort.

4. Evaluate the application of other sampling techniques that could be used in tandem with the dredge survey to help determine survey gear efficiency. *Should hear updates on dredge efficiency experiments happening elsewhere at the 2019 SAW

5. Determine if the spat/oyster volume to spat/total volume relationship holds if a subset of data is used to train the model and a separate set of data are used to test it. In addition, plot the recent time series of spatfall by region using both methods and see how they compare.

6. Using growth data, estimate the numbers of oysters that could grow to market size once transplanted and evaluate how adding these to the quota bump on the Direct Market receiver region would affect the total allowable catch there. Include deducting those that could die from natural mortality as well.

7. Evaluate how long dermo mortality has been below long-term levels and how this has affected the population.

8. Evaluate changes in dermo phenology and determine to the extent possible which environmental forces are driving these changes.

9. Evaluate the available data on predator distribution over time given mortality due to disease continues to decline.

10. Recalculate the historical exploitation history using region-specific markets per bushel and evaluate the impact this change could have on exploitation rates and projected quota.

11. Evaluate when it is appropriate to change biological reference points (targets and thresholds).

12. Continue growth experiments and provide an updated analysis of available data in 2019. In addition, add error bars to the figures showing differences in growth from each experiment.

13. Continue to evaluate the success of enhancement programs.

14. Plot trends in stock status metrics by bed (in addition to region).

15. Consider modeling the dynamics of the population to make predictions that can be compared to our annual empirical assessment.

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. 2019. Delaware Bay New Jersey Oyster Seedbed Monitoring Program; 2018 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

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 "Stock Assessment Design" 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. Round Island and Nantuxent were resurveyed in 2018. Cohansey and Bennies Sand are scheduled for resurvey in 2019. 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	2007	2020
	Middle	51	1	2011	2021
	Sea Breeze	48	1	2012	2022
MMM	Cohansey	83	1	2009	**2019**
	Ship John	68	1	2010	2020
SR	Shell Rock	93	3	2016	2026
HM	Bennies Sand	49	1	2009	**2019**
	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. Total number of samples dedicated to each strata given each alternative allocation strategy. Green highlighted strata represent those that would receive more samples and red highlighted strata represent those that would receive less samples relative to the status quo.

Bed, Strata	Status Quo	Bed/Neyman	Bed/Neyman/Min2	Reg/Neyman
Bennies Medium	13	5	4	6
Shell Rock Medium	10	34	19	15
Benny Sand Medium	7	1	2	4
Shell Rock High	7	17	11	8
Ship John Medium	7	6	5	7
Cohansey Medium	6	14	9	13
Ship John High	6	4	4	6
Bennies High	5	2	3	7
Cohansey High	5	10	7	6
NantuxentP Medium	5	1	3	3
New Beds Medium	5	0	2	3
Arnolds Medium	4	16	10	10
Hog Shoal Medium	4	0	2	1
Hope Creek Medium	4	8	6	5
ListonRnge Medium	4	1	3	3
Middle Medium	4	7	6	11
New Beds High	4	0	2	2
RoundIslan Medium	4	1	2	2
Sea Breeze Medium	4	13	9	9
UpperArnol Medium	4	4	4	7
Arnolds High	3	4	4	5
Beadons Medium	3	2	3	1
Benny Sand High	3	1	2	4
FishingCrk Medium	3	0	2	1
Hawk'snest Medium	3	0	2	0
Hope Creek High	3	3	4	3
Middle High	3	4	4	0
NantuxentP High	3	1	3	4
Sea Breeze High	3	4	4	4
Strawberry Medium	3	0	2	0
UpperArnol High	3	3	4	4
UpperMiddl Medium	3	1	2	6
Beadons High	2	1	2	2
FishingCrk High	2	0	2	0
Hawk'snest High	2	0	2	0
Hog Shoal High	2	0	2	3
ListonRnge High	2	1	2	1
RoundIslan High	2	0	2	3
Strawberry High	2	0	2	0
Vexton High	2	0	2	1
Vexton Medium	2	0	2	0
UpperMiddl High	1	1	2	1

Table 7. Direct market and transplant bushel summaries 2009-2018. 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. Note: Sea Breeze was part of the MMM until 2011; it is now MMT. Beds without removals were omitted.

a. Direct Market

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Middle	33	56								
Sea Breeze	627	220		170	5,454	542				
Cohansey	5,909	2,806	19,074	11,288	10,583	8,652	10,669	12,475	20,687	8,709
Ship John	17,989	20,409	19,212	17,755	19,279	24,295	19,837	19,938	16,331	22,021
Shell Rock	22,918	17,493	24,112	22,628	24,280	23,589	29,629	31,794	38,189	31,872
Bennies Sand	13,529	10,147	8,825	5,836	10,841	3,038	6,301		22,339	23,395
Bennies	9,599	5,526	4,997	2,155	870	8,010	10,712	29,293	23,071	21,626
NantuxentP	2,631	6,572	5,467	14,332	10,218	5,154	5,267	2,101	628	11,347
Hog Shoal	3,804	7,281	9,049	1,965	2,385	3,425	103		1,756	283
New Beds	2,778	1,075	1,778	443	226		4,912	4,494	1,143	89
Strawberry	618	25			140					
Hawk's Nest	173	2,693	1,954	1,568		205				
Beadons	82	72								
Vexton			2							
Total	80,690	74,375	94,470	78,140	84,276	76,910	87,430	100,095	124,144	119,342

b. Transplants

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Hope Creek	9,100	1,200	6,150							
Fishing Creek		2,000								
Liston Range		4,750	1,800		550					
Round Island			3,350		2,250					
Upper Arnolds		18,250	2,800		15,550		10,200			
Arnolds	10,400		4,000	7,650	2,700	15,500		4,800		
Upper Middle	2,100			2,100	3,200				3,200	4,750
Middle	12,000		17,750	11,200	5,200	6,600	5,550	8,150	21,350	27,500
Sea Breeze		11,050		8,525	6,200	7,300	10,800	2,400	4,700	7,700
Cohansey		1,500								
Beadons			500							
Total	33,600	38,750	36,350	29,475	35,650	29,400	26,550	15,350	29,250	39,950

Table 8. Council-chosen and fishery-achieved exploitation rates for 2018 for (a) Direct Market regions and (b) Transplant 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.

a. Direct Market

Region	Max SARC Expl. Rate	Chosen Expl. Rate	Achieved Expl. Rate	Chosen Market (bu)	Add'l Transpl Alloc (bu)	Achieved Total (bu)
MMM	3.70%	3.70%	2.74%	35,107	0	30,730
SR	4.88%	4.88%	4.10%	31,507	0	31,872
HM *transpl req'd*	8.99%	8.99%	9.66%	34,118	20,017	56,740
			Total	100,732	20,017	119,342

Total Quota (bu)	Un-harv. Quota (bu)
120,749	1,407

b. Transplant

Region	Max SARC Expl. Rate	Chosen Expl. Rate	Achieved Expl. Rate	Chosen Trans (# oys)	Achieved Trans (# oys)	Under/Over #
VLM	2.32%	NONE	NA	0	NA	NA
LM	2.01%	NONE	NA	0	NA	NA
MMT	2.46%	2.46%	1.76%	15,785,722	12,310,312	-3,475,410

Table 9. Summary of intermediate transplant data. Transplant was conducted in April and May 2018 from the Medium Mortality Transplant region (Upper Middle, Middle, Sea Breeze). Data are derived from daily samples taken from each boat and measured deckloads throughout the transplant.

Donor	Receiver	Bushels Moved	Total # Oysters	Fraction Oysters < 2.5”	Number Oysters ≥ 2.5”	Mkt-Equiv. Bu (>2.5”)	Fraction Cultch
Upper Middle	Bennies	4,750	973,690	0.527	460,846	1,752	0.566
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
MMT	**Totals**	39,950	12,310,312		5,264,582	20,017	

Table 10. 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 11. Color coded summary status of the stock for 2018 using percentiles and targets/thresholds.

<u>2018 Metrics</u>	*Transplant* Very Low <u>Mortality</u>	*Transplant* Low <u>Mortality</u>	*Transplant* Medium <u>Mortality</u>	*Market* Medium <u>Mortality</u>	*Market* Shell <u>Rock</u>	*Market* High <u>Mortality</u>
Total Abundance						
2018 Percentile (1990-2018)	0.727	0.643	0.786	0.75	0.821	0.357
2018 vs. Target-Threshold						
Market Abundance						
2018 Percentile (1990-2018)	0.364	0.571	0.821	0.786	0.786	0.714
2018 vs. Target-Threshold						
Sub-Market Abundance (< 2.5")						
2018 Percentile (1990-2018)	0.818	0.714	0.893	0.786	0.821	0.214
Spatfall						
2018 Percentile (1990-2018)	0.545	0.607	0.321	0.286	0.107	0.464
Mortality						
2018 Percentile (1990-2018)	0.909	0.821	0.036	0.000	0.000	0.036
Dermo WP						
2018 vs. Category	0.00	0.17	1.30	1.40	2.30	1.97

	Green	**Yellow**	**Orange**
2018 Percentile (1990-2018)	Above the 60th	40th - 60th	Below the 40th
2018 vs. Target/Threshold	Above Target	b/w Target and Threshold	Below Threshold
2018 vs. Category	<1.5	1.5-2	>2

Table 12. 2019 SARC recommendations for maximum exploitation rates for each region and the projected quota associated with each decision. *Note that for the High Mortality region 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

Region	Label	Exploitation Rate of All Sizes	Regional Abundance	Removals	Oysters/ Bushel*	App. Deck Bushels	Proportion Of Oysters That Are Markets From Survey	Estimated Potential Quota Bushels**
VLM	-	CLOSED	-	-	-	-	-	-
LM	Max	2.26%	395,636,196	8,941,378	451	19,826	18%	3,569
MMT	Max	2.46%	494,238,761	12,158,274	324	37,526	22%	8,256

Direct Market Regions

Region	Label	Exploitation Rate of Market Sizes	Regional Market Abundance	Removals	Oysters/ Market Bushel*	Quota Bushels	Transplant Required?
MMM	Max	3.70%	250,325,330	9,262,037	263	35,217	No
SR	Max	4.88%	144,078,648	7,031,038	263	26,734	No
HM*		6.50%	98,491,683	6,401,959	263	24,342	No
HM*		8.99%	98,491,683	8,854,402	263	33,667	Yes

Figure 1. The natural oyster beds of Delaware Bay, NJ grouped by regional designations. The six regions are named based on mortality patterns 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.

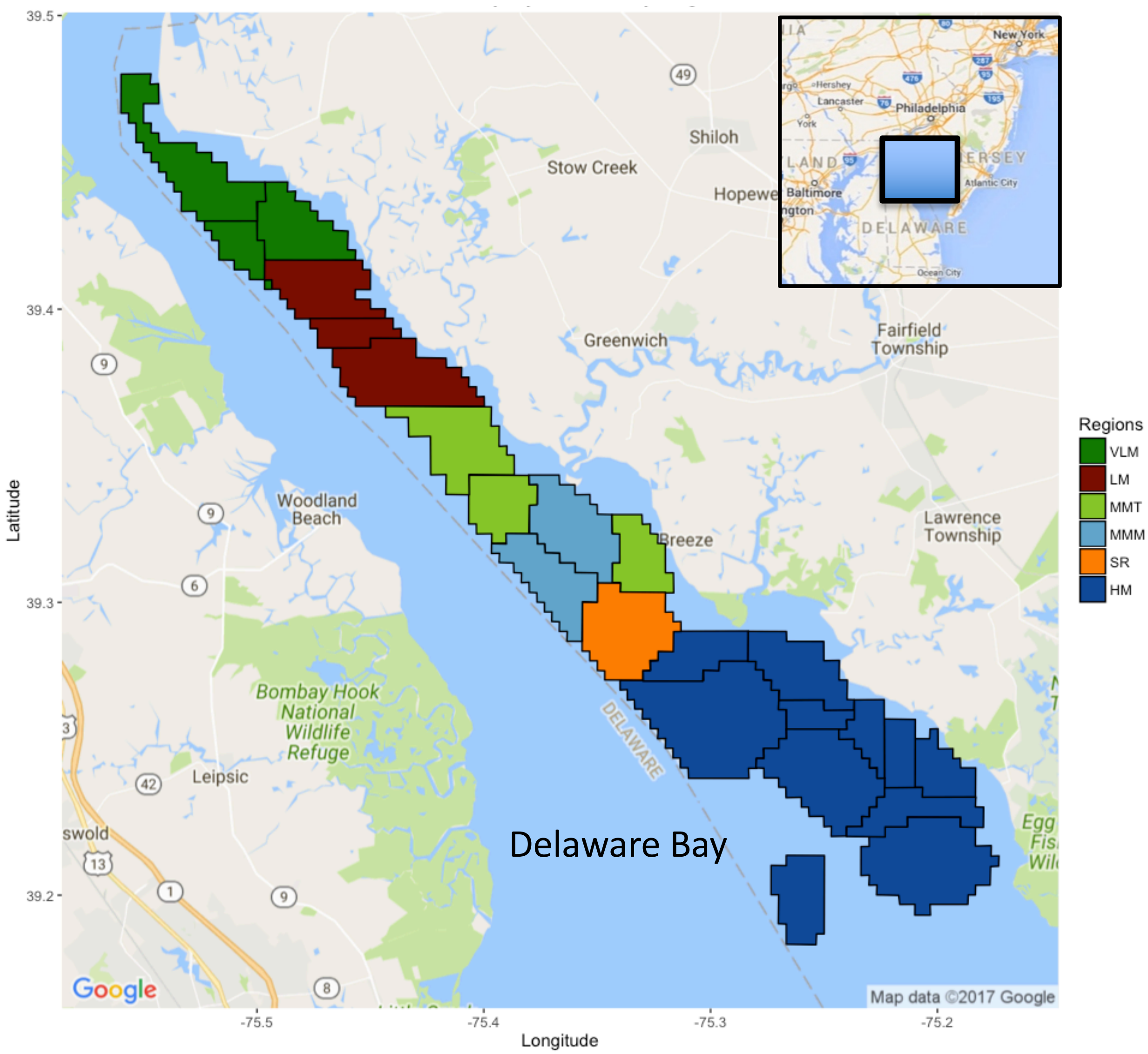


Figure 2. Regional acreage and proportional distribution of the assessed NJ Delaware Bay oyster resource. Regions are organized upbay to downbay clockwise from the VLM. The VLM, LM, and MMT contain three beds each and are termed Transplant regions. The Direct Market regions are the MMM made up of two beds, the SR (one bed), and the HM with eleven beds.

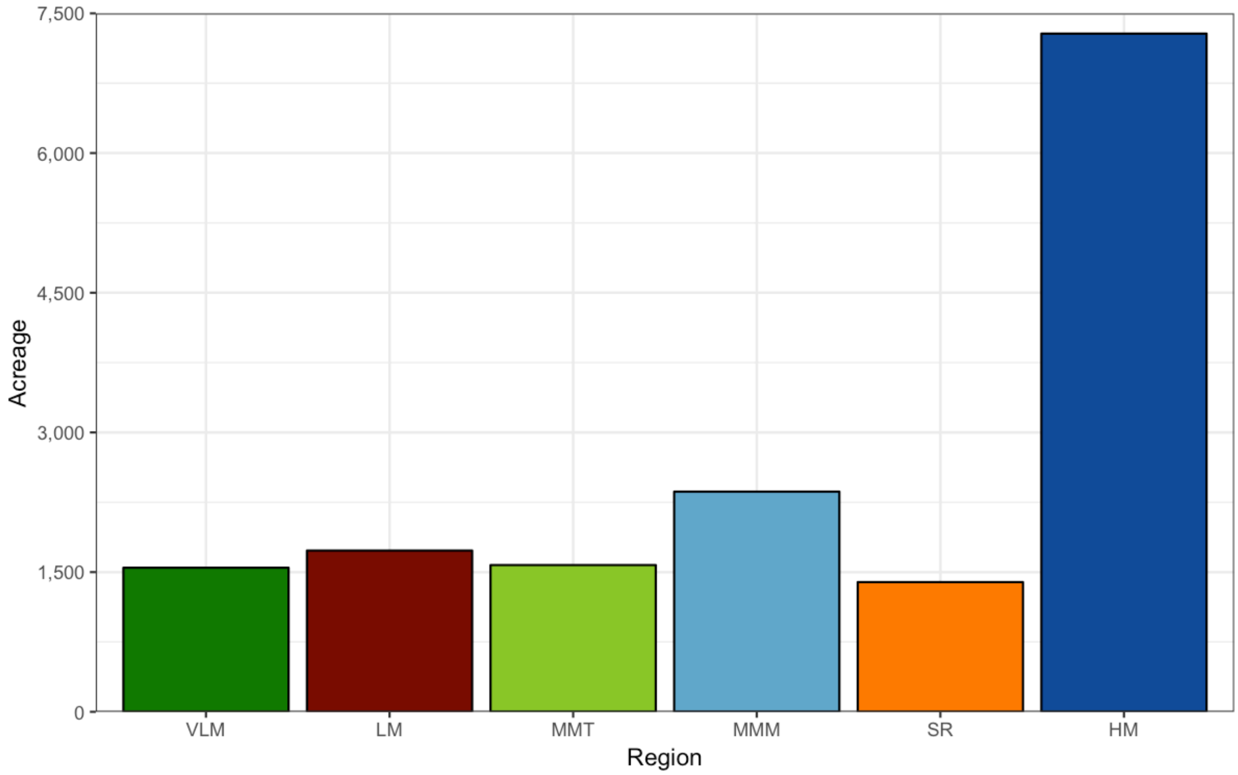
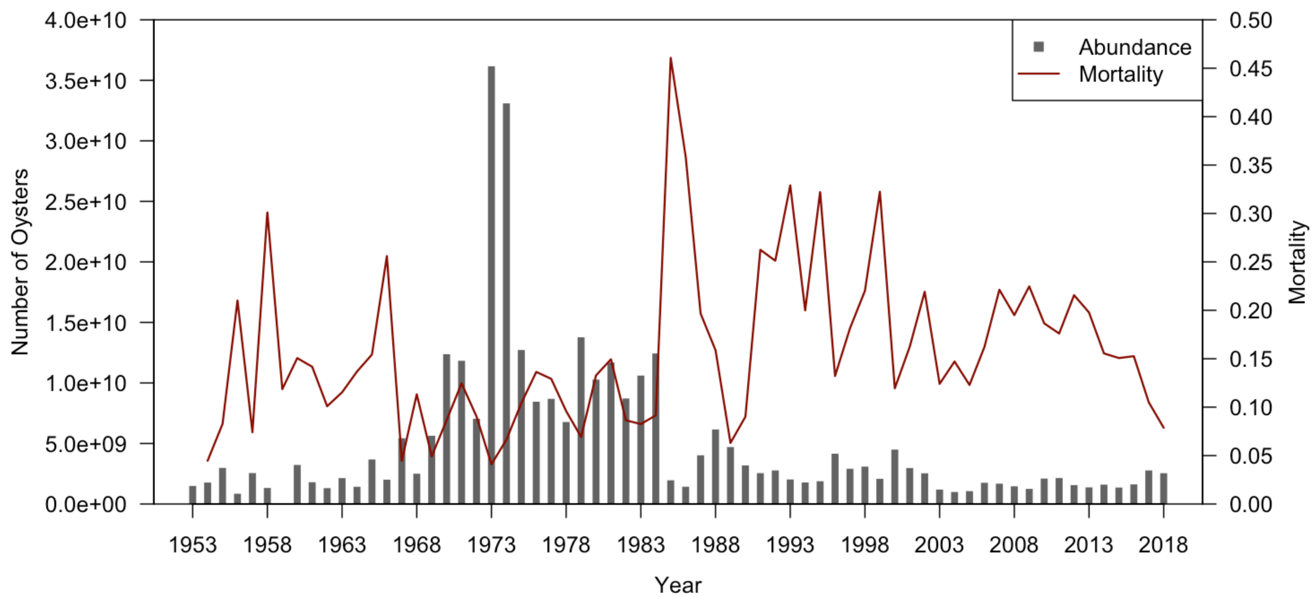


Figure 3. Time series of total oyster abundance (left axes) compared to natural mortality rate (a, right axis) and fishing mortality (b, right axis). Time series of 1953–2018 stock surveys excludes the VLM.

a.



b.

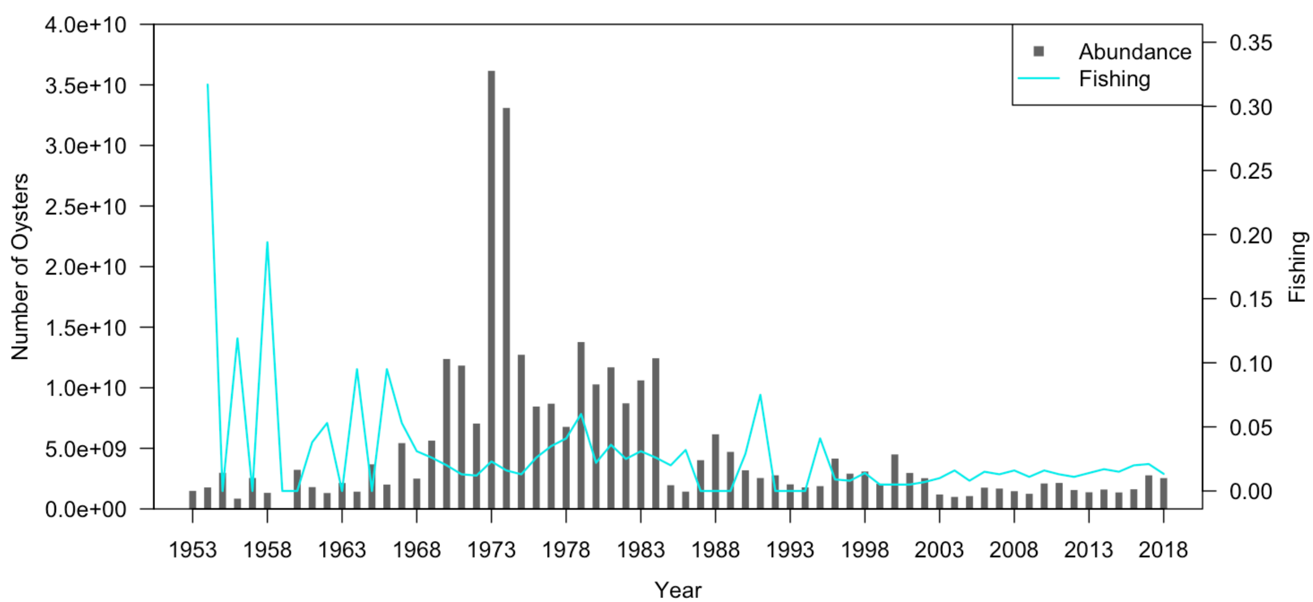
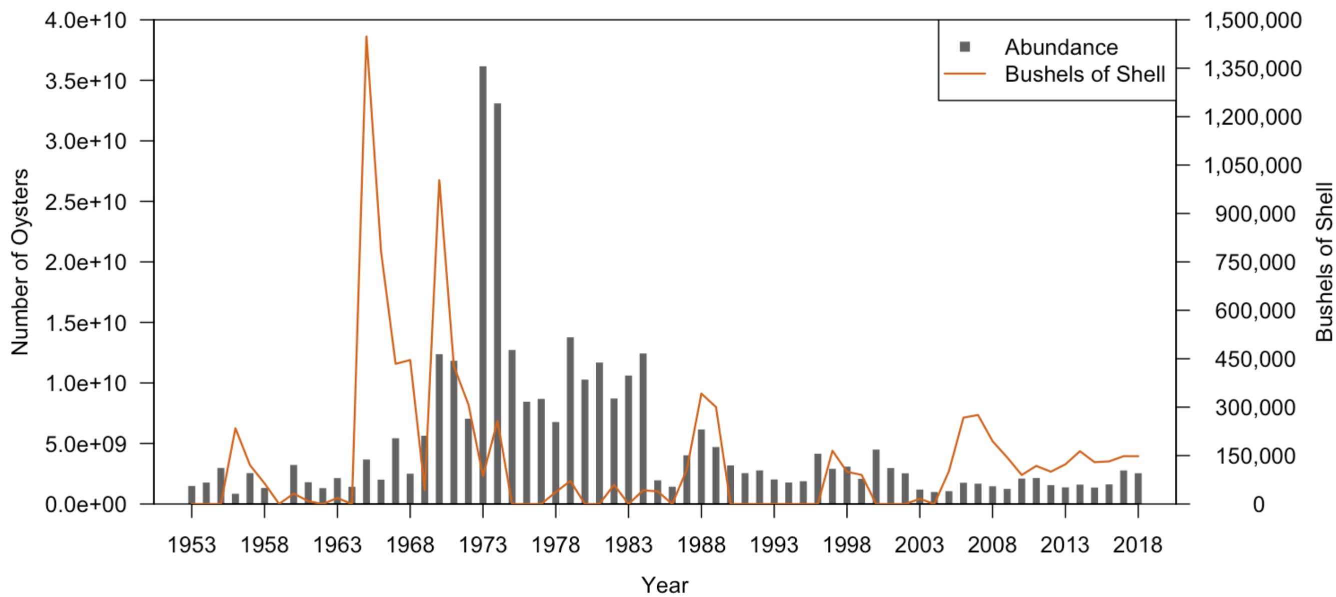


Figure 4. Time series of total oyster abundance (left axes) compared to bushels of shell planted (a, right axis) and total spat abundance from the stock assessment time series (b, right axis). Time series of 1953–2018 stock surveys excludes the VLM.

a.



b.

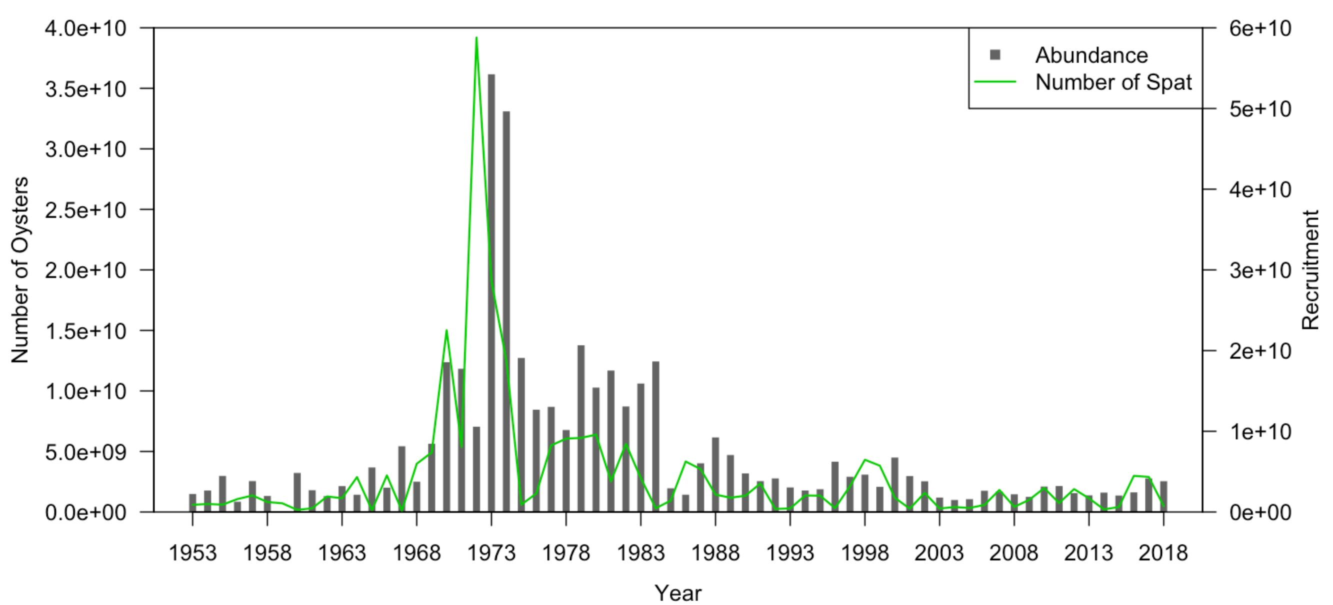


Figure 5. Number of oysters harvested from the natural oyster beds of Delaware Bay, NJ from 1953–2018. Prior to 1996, the bay-season fishery removed oysters from the natural beds and transplanted them downbay to leased grounds. Zeros represent years of fishery closure.

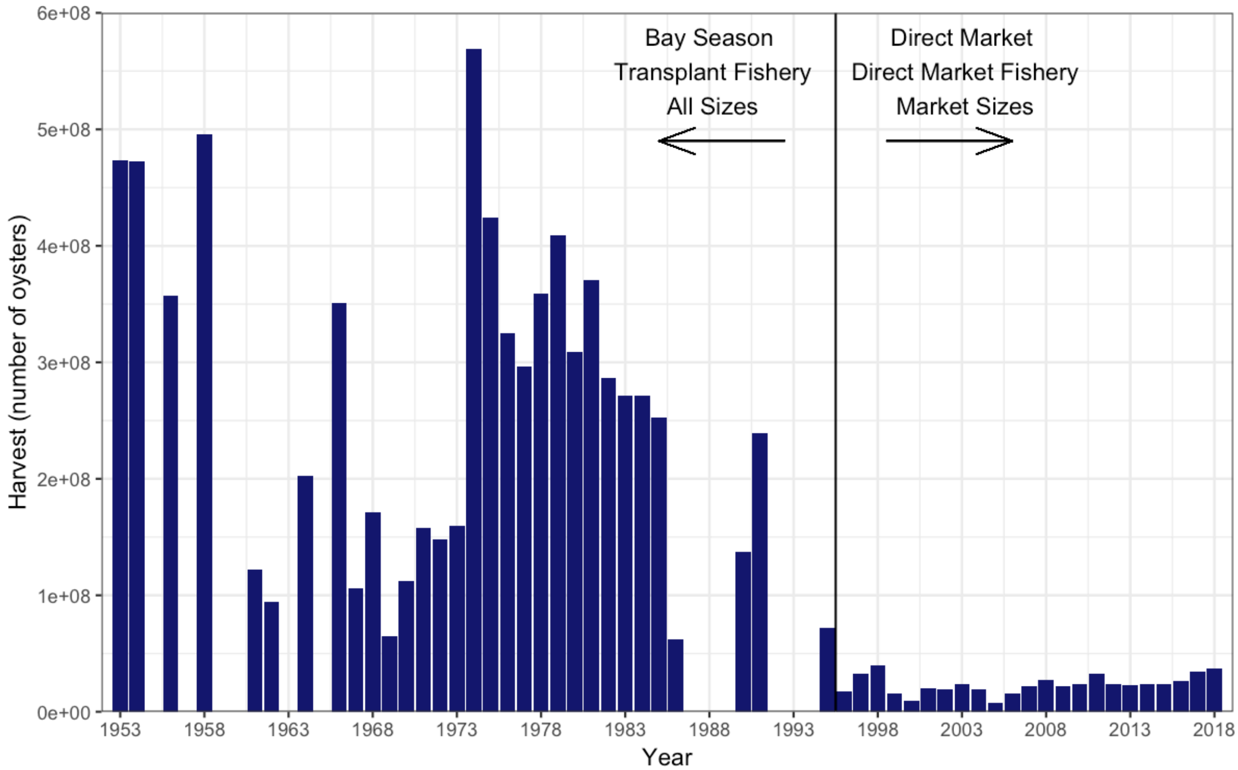


Figure 6. The assessed oyster beds of Delaware Bay, NJ grouped as regions (see Legend) with the 2018 strata designations. White outlines indicate complete boundary of each bed with the high and medium quality strata grids in dark and light colors, respectively. The colors indicate region groupings although strata designations are within-bed not within-region. Clear blue areas in each bed indicate its low quality stratum. 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 (101,175 m² or 10.1 hectares).

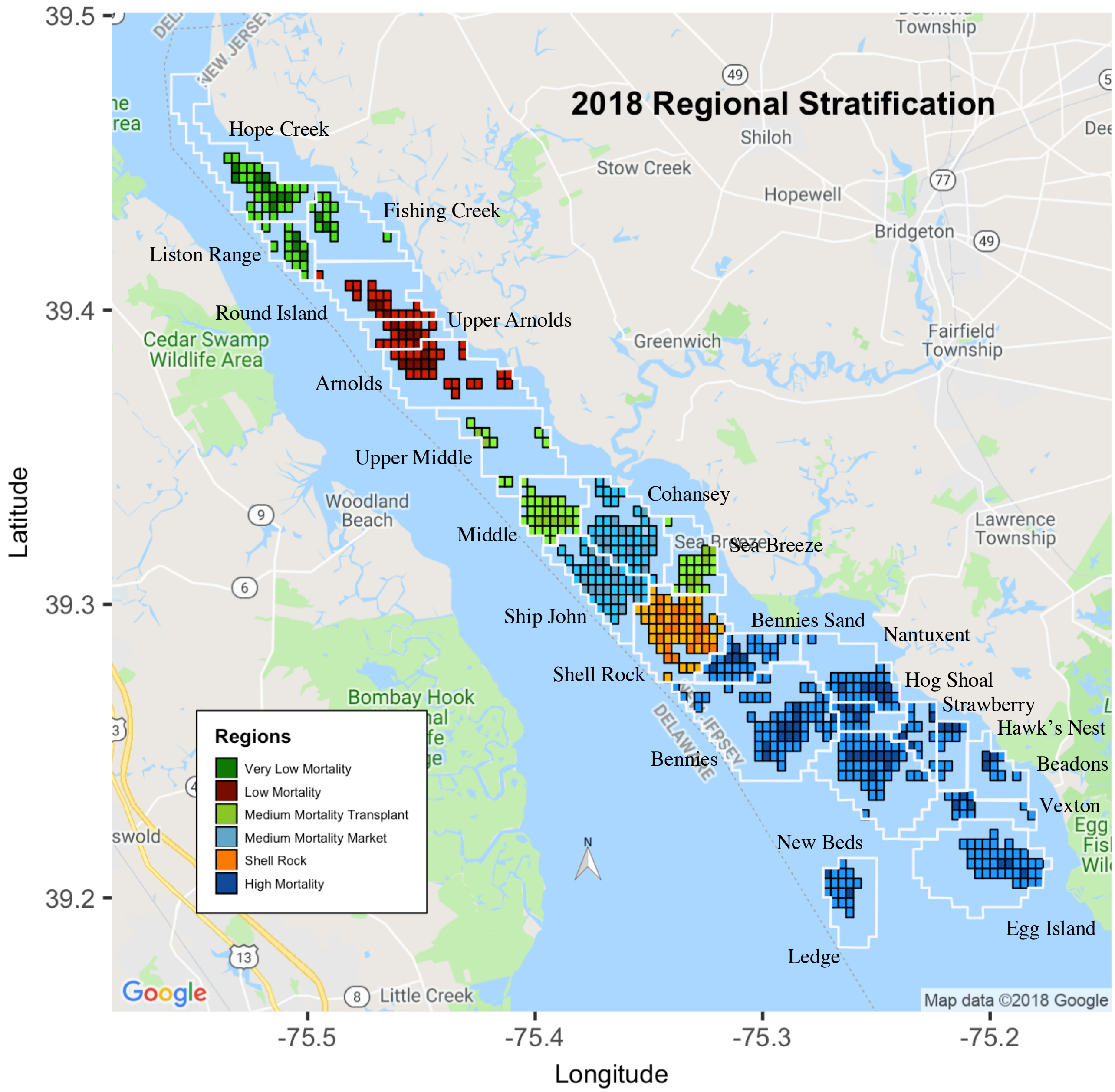


Figure 7. Current restratification density map with survey samples allocated by 1) status quo, 2) Neyman allocation based on bed-level stratification, 3) allocating two samples to each stratum, then allocating the remaining samples based on Neyman allocation, and 4) Neyman allocation applied to grids stratified by region instead of bed.

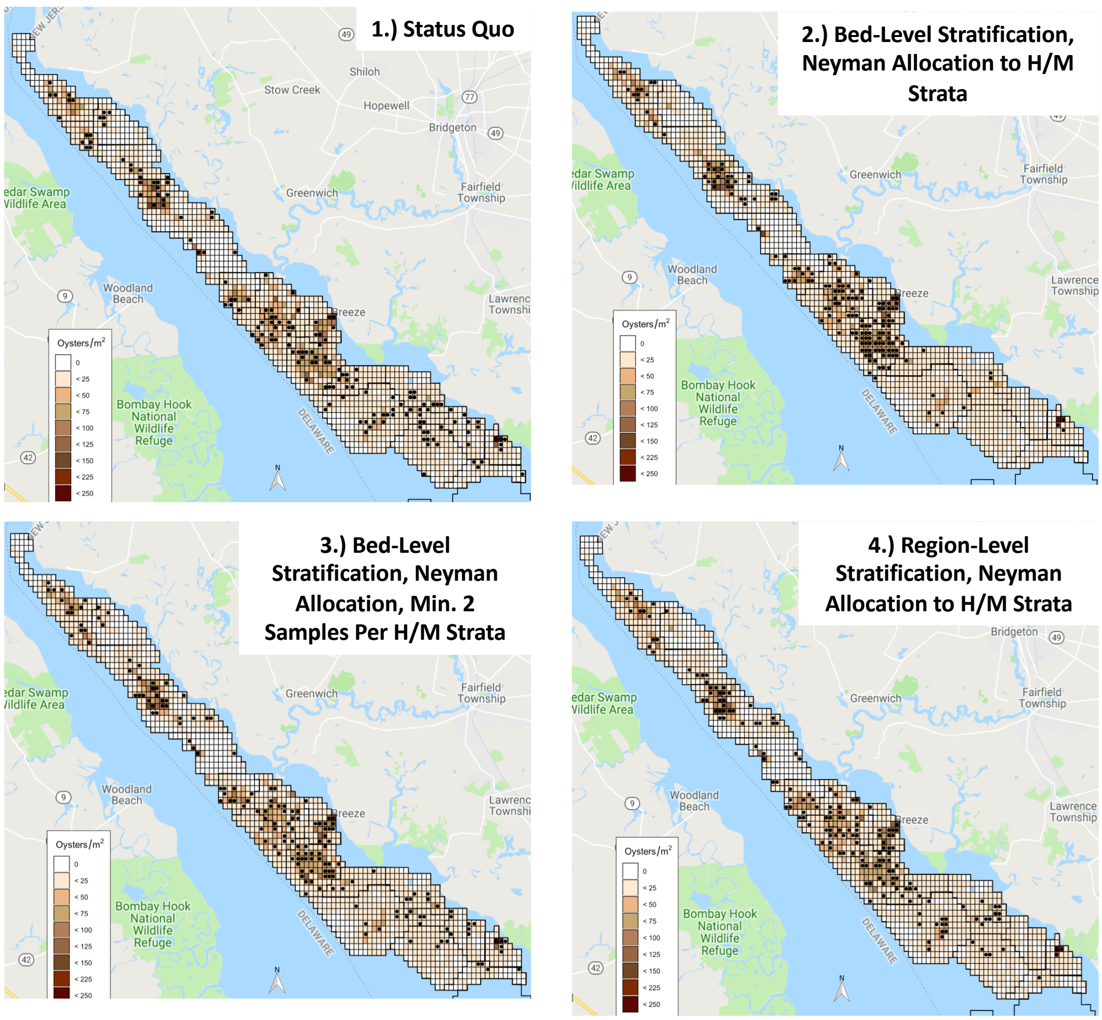


Figure 8. Results of restratifying beds based on market abundance instead of total abundance. Restratification based on market abundance was done for every resurvey event (n=43) in the time series. The number of resurvey events is on the y-axis and the proportion of grids that remained the same is on the x-axis. For example, 12 resurvey events had 85-90% of the grids remain the same after restratifying by market abundance.

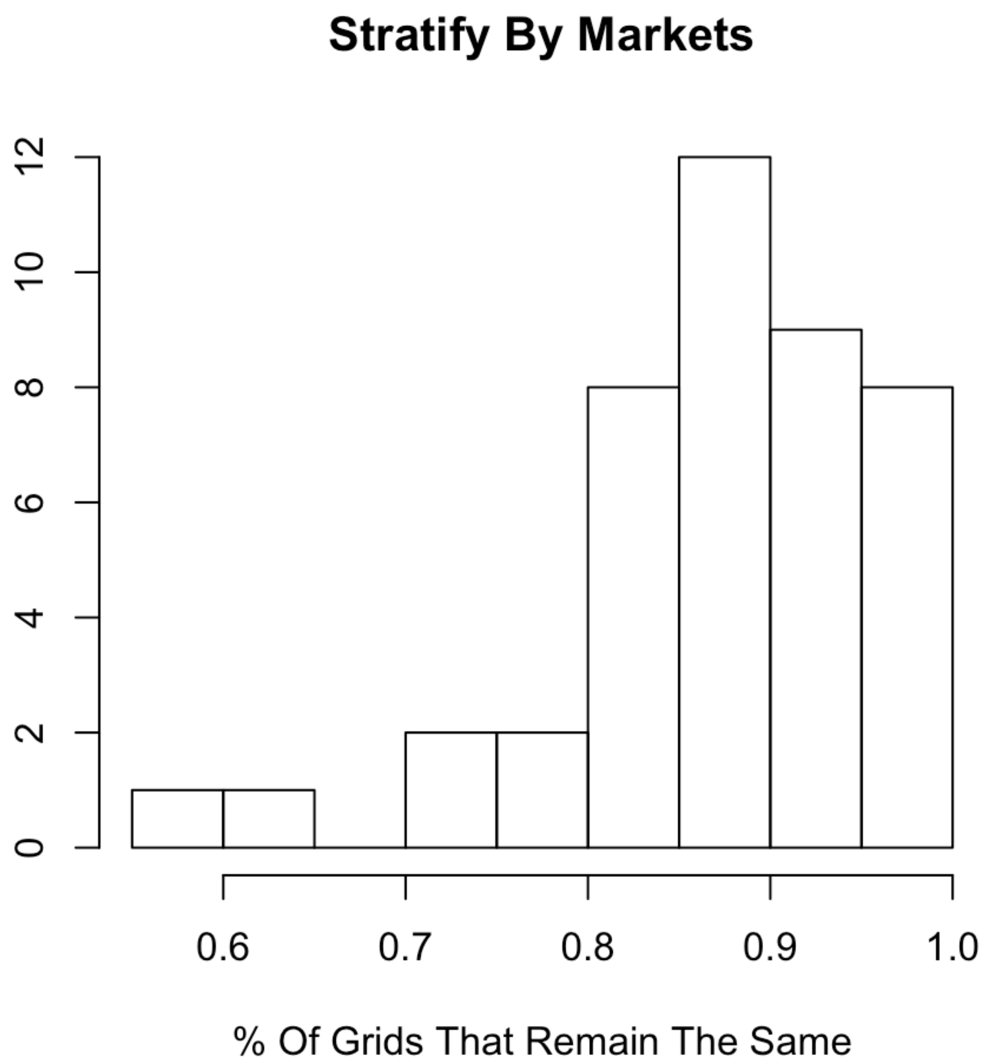


Figure 9. Mean squared error as a function of the total oysters measured for medium (~200 oysters), large (~300 oysters), and very large (~400 oysters) samples. Red lines represent the best fit exponential decay model. Black lines indicate 10% and 5% of the slope at its origin.

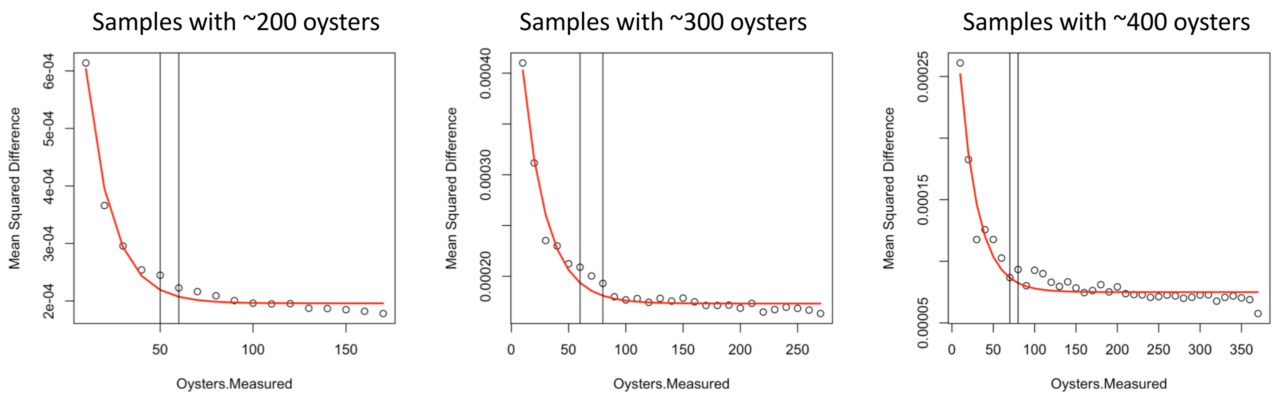


Figure 10. Cumulative size frequency of oysters when a random subsample of 100 are measured (sub) and when the entire sample is measured (full). Note some beds did not have over 100 oysters in the sample so there is no "full" (ex. Bennies, Hog Shoal, Beadons).

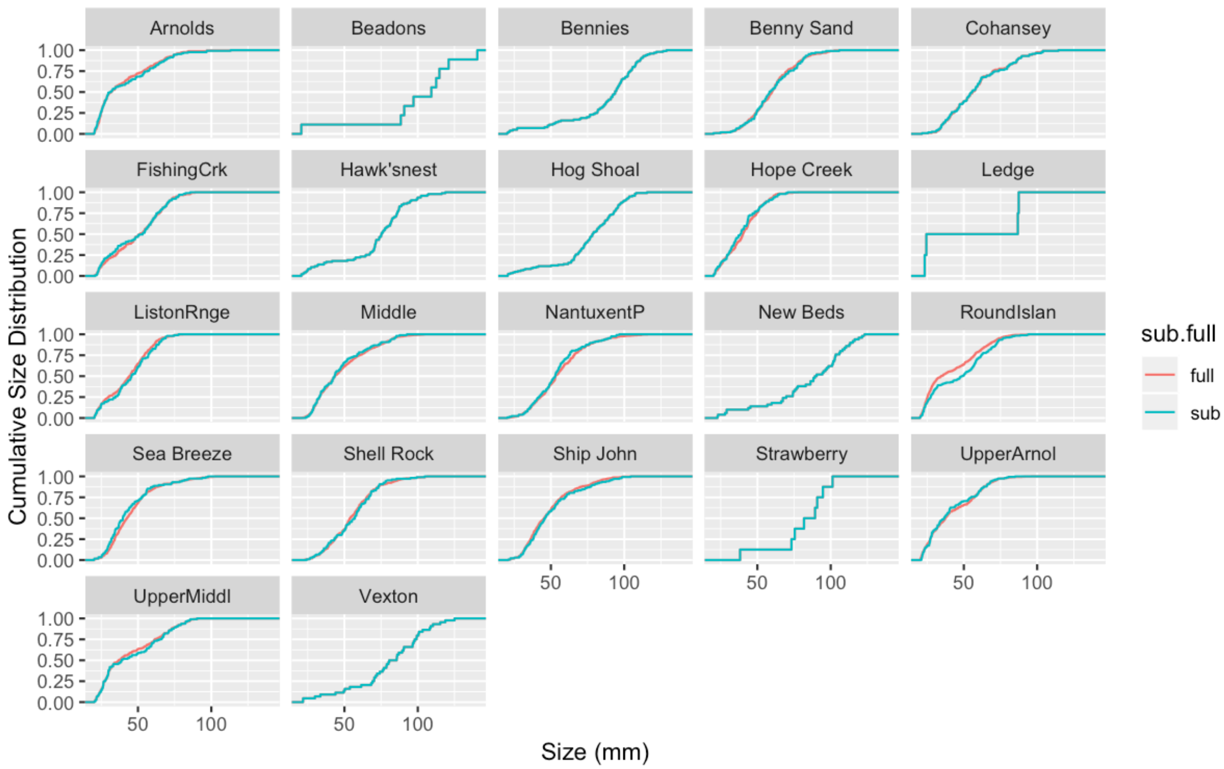


Figure 11. "Spat/Sample Volume" as a function of "Spat/Oyster Volume" for all samples collected from 2007-2017. The line is for the best fit linear model through the data.

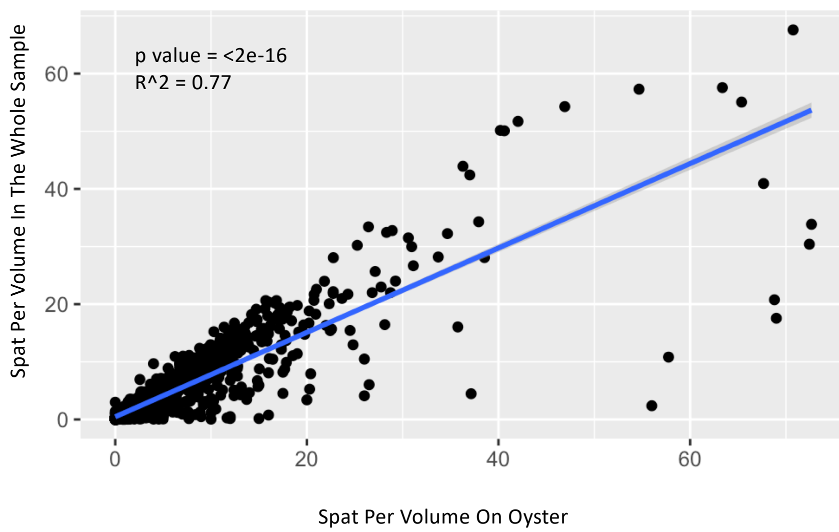


Figure 12. Pairwise comparison of total spatfall for each region over the last four years (2014-2017) using two methods ("Count Spat On Everything" and "Count Spat On Oyster And Scale It To Spat On Everything"). The linear model in Figure 11 was used to generate spat/volume for each individual sample. The diagonal line represents the 1:1 line.

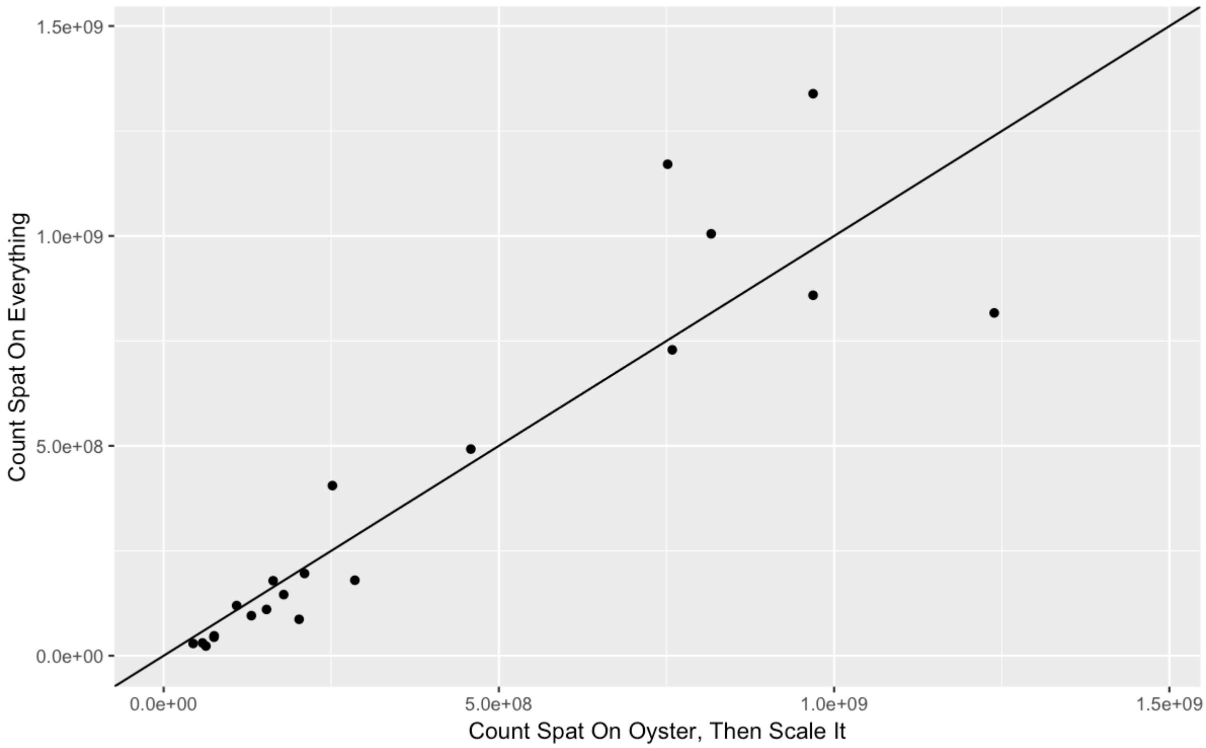


Figure 13. Box and whiskers plot of mean capture efficiency of the survey dredge at different oyster reef locations. Bold horizontal lines represent the mean, boxes encompass the interquartile range, black whiskers extend to the 5th and 95th percentiles, and dots are outliers. Reef locations are organized on the x-axis from lower bay (left side) to upper bay (right side). Empty black boxes around the reef names represent the regional groupings of bed-specific catchability coefficients applied in the 2015 Delaware Bay oyster stock assessment based on data collected from the 2003 experiments (Powell et al. 2007). Shaded, offset boxes represent the regional groupings of bed-specific catchability coefficients identified as statistically appropriate from the 2013 experiments (Morson et al. 2018) and applied in the assessment from 2016 to present. Horizontal boxes at the bottom represent the different management regions. *Adapted from Morson et al. (2018)*

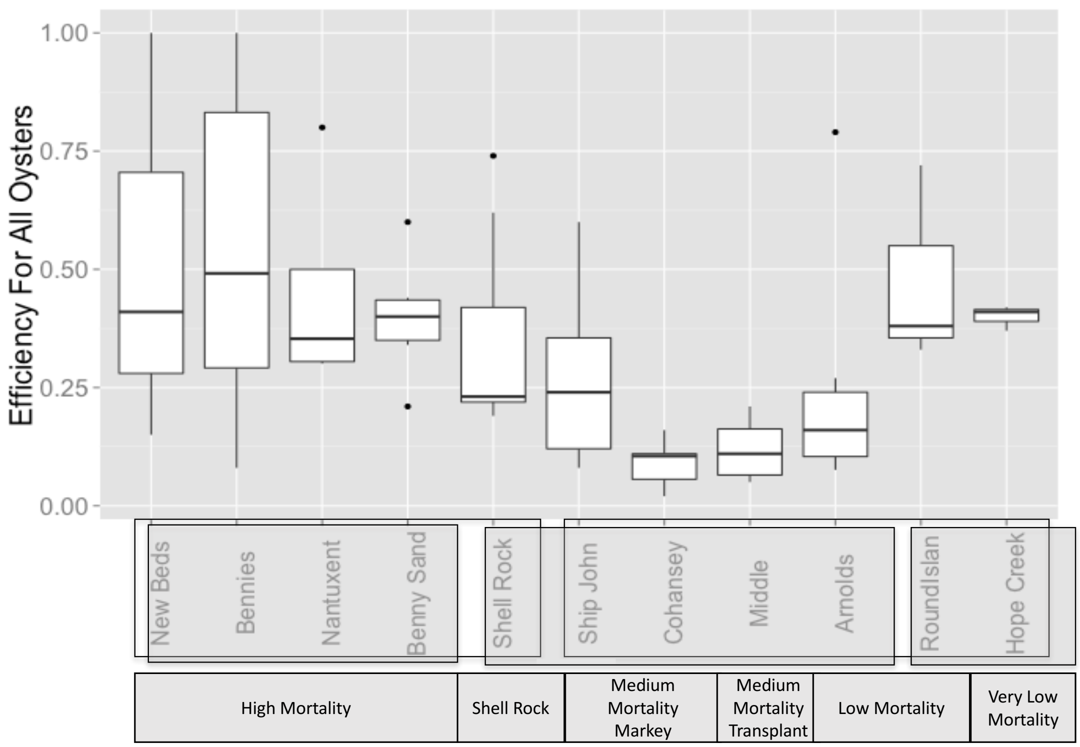


Figure 14. Survey gear capture efficiency as a function of true oyster density. Error bars represent the standard deviation from 1,000 boostrap simulations. Line indicates the best fit power model estimated by weighted nonlinear least squares. *Adapted from Morson et al. (2018)*

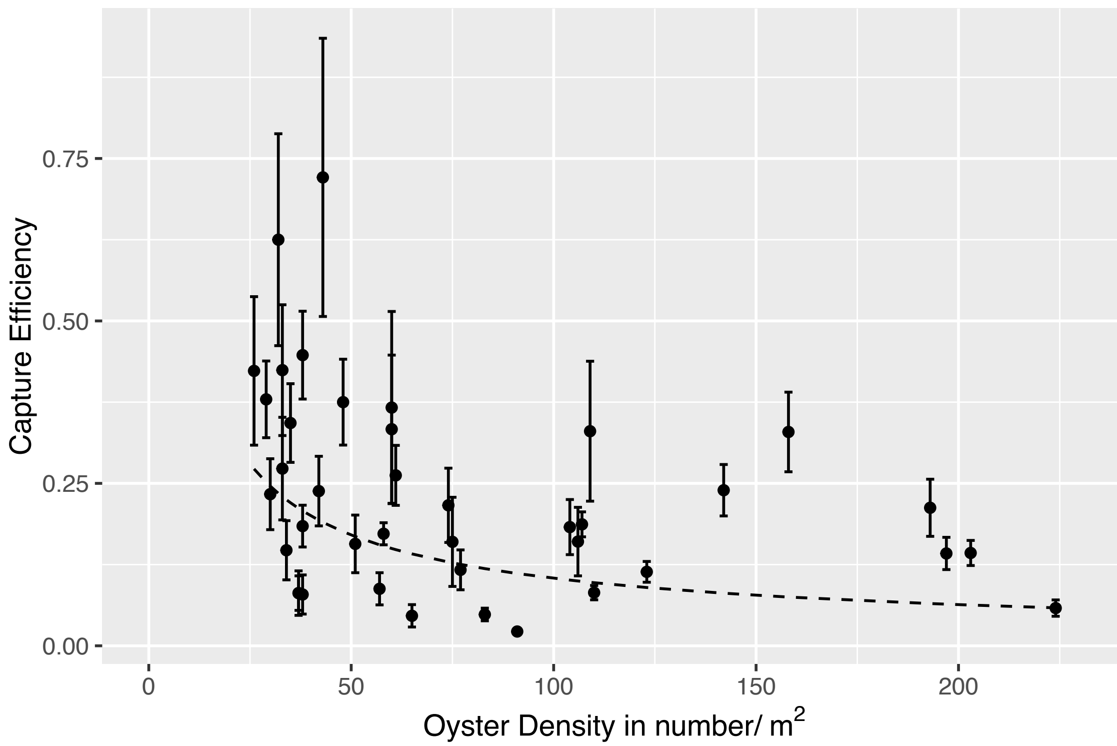


Figure 15. Boxplot of capture efficiency (OysE) as a function of regional group (see Figure 13 and Table 2 for definitions of regional groups) and year group. The "far upbay" group only includes data from 2013 for the "2003/2013" year group. The numbers overlaid on the boxplots represent the mean true density of oysters for each experimental regional/year group.

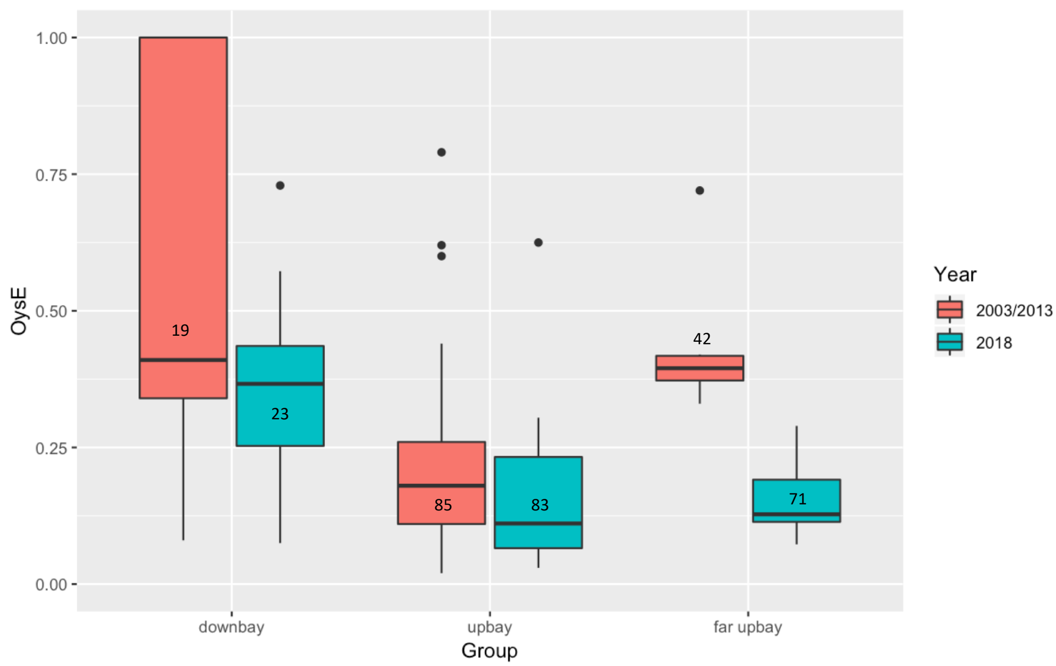


Figure 16a. Realized exploitation fractions of the >2.5” oyster stock on the Direct Market regions in Delaware Bay NJ for two time periods: 1996-2006 and 2007-2015. The 2007-2015 median (dotted line) is based on the realized exploitation values with shading indicating the range. Negative values reflect oysters added through intermediate transplanting.

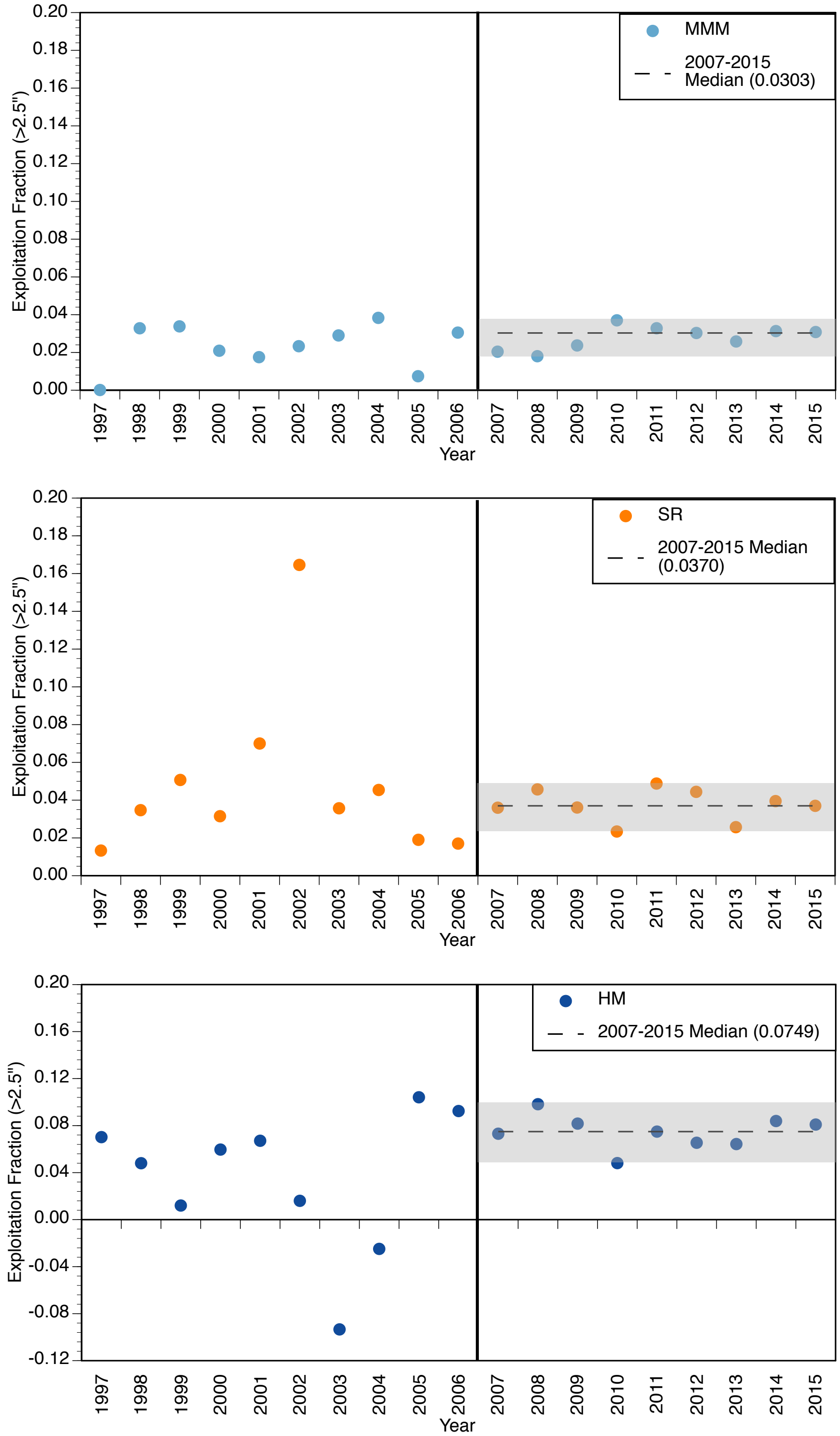


Figure 16b. Realized exploitation fractions of the whole oyster stock, excluding spat, on the Transplant regions in Delaware Bay NJ for two time periods: 1996-2006 and 2007-2015. The 2007-2015 median (dotted line) is based on the realized exploitation for each region with shading indicating the range. 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.

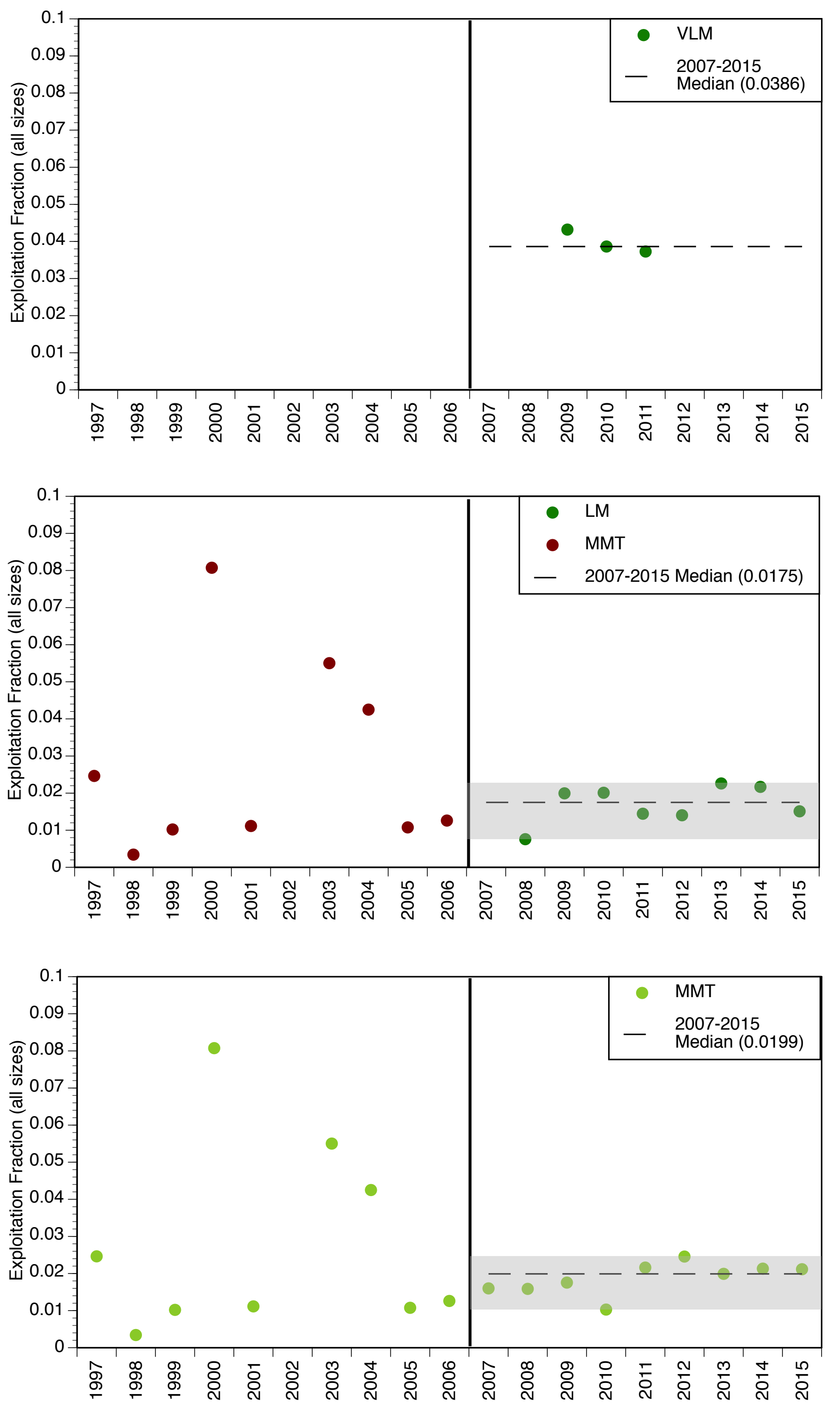


Figure 17. Landed oysters per bushel in three groups: market-size (>2.5”), smaller attached oysters, and smaller unattached oysters. The number of market-size oysters per landed bushel in 2018 averaged 228, while the total oysters per landed bushel averaged 306. The long-term mean of all oysters and market oysters per landed bushel (263) is shown as an orange line.

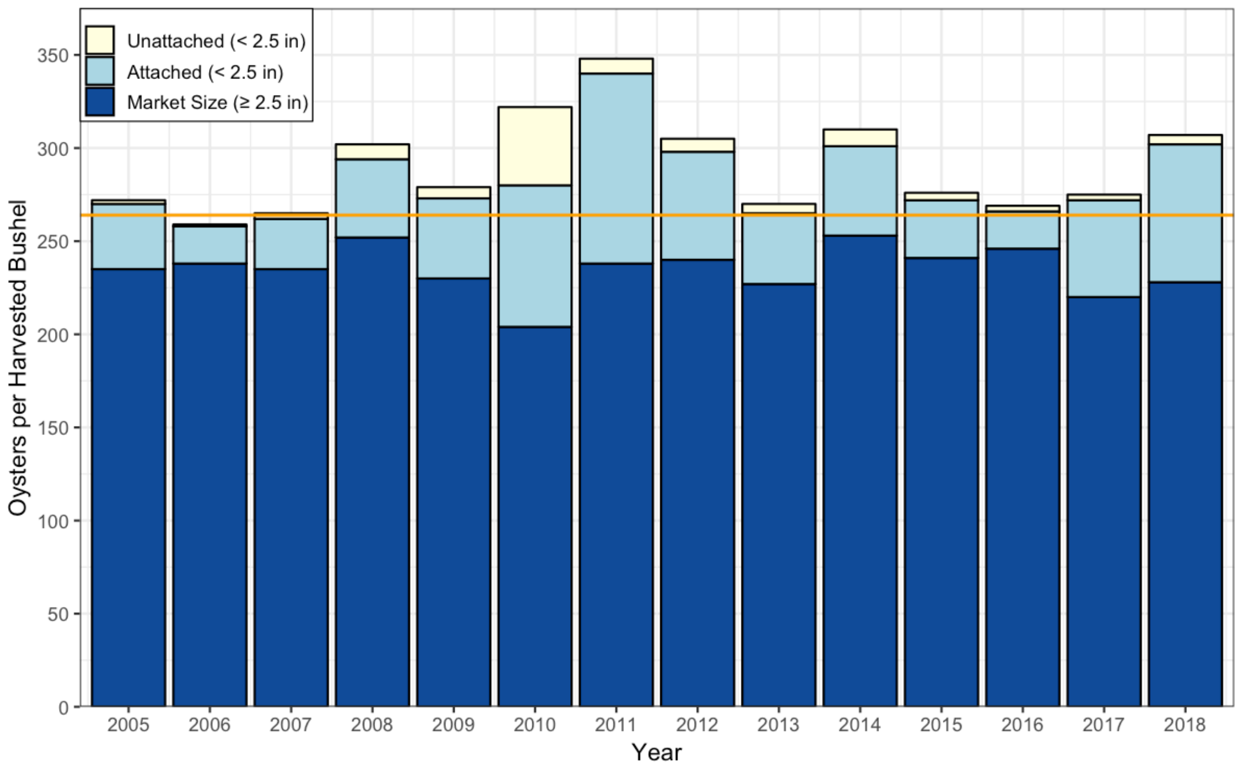


Figure 18. Numbers of single and dual dredge boats (stacked bars) participating in the NJ Delaware Bay oyster harvest overlaid with LPUE (bushels landed per hour) for each dredge type.

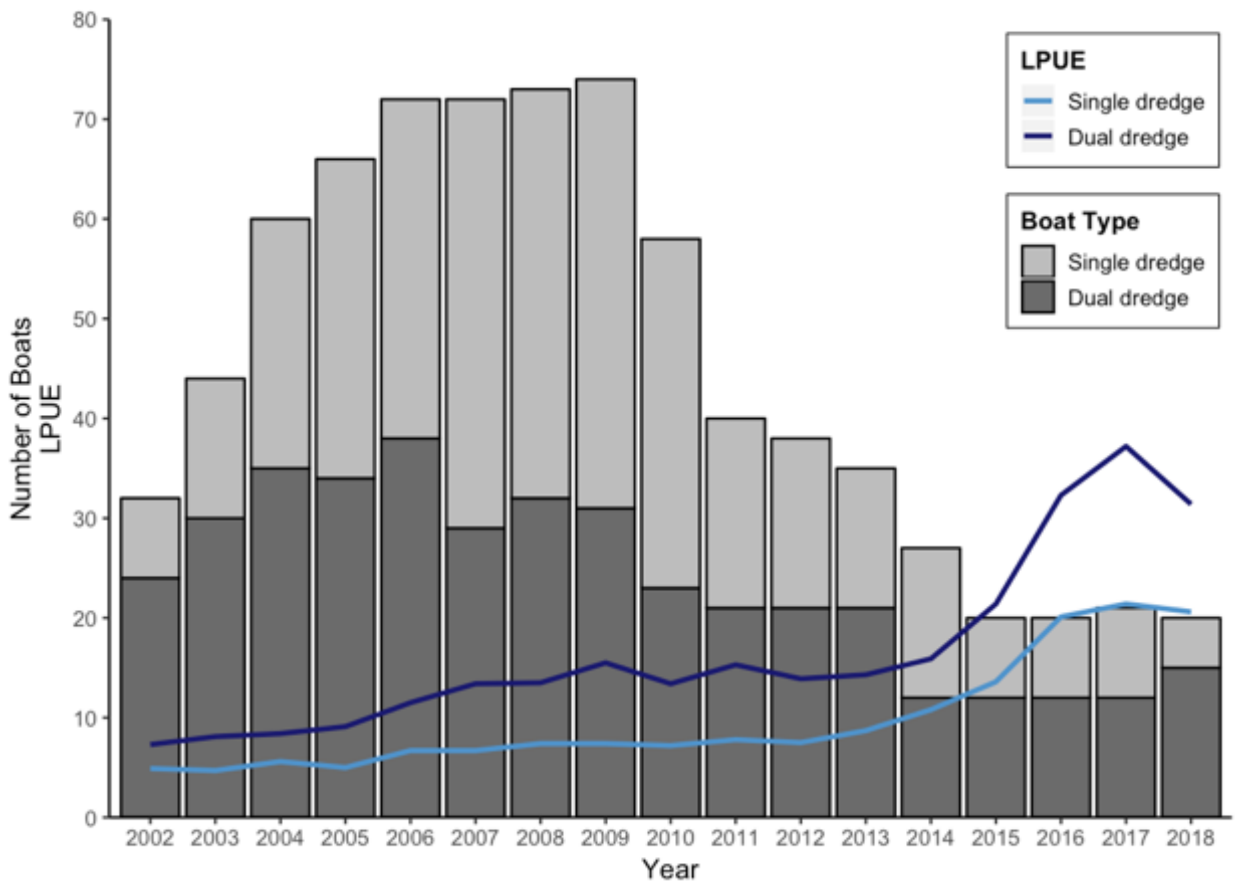


Figure 19. Size frequency of oysters landed by the fishery in direct market regions (top panel) and within the surveyed population (bottom panel). Vertical line indicates the market-size cutoff (≥ 2.5 inches).

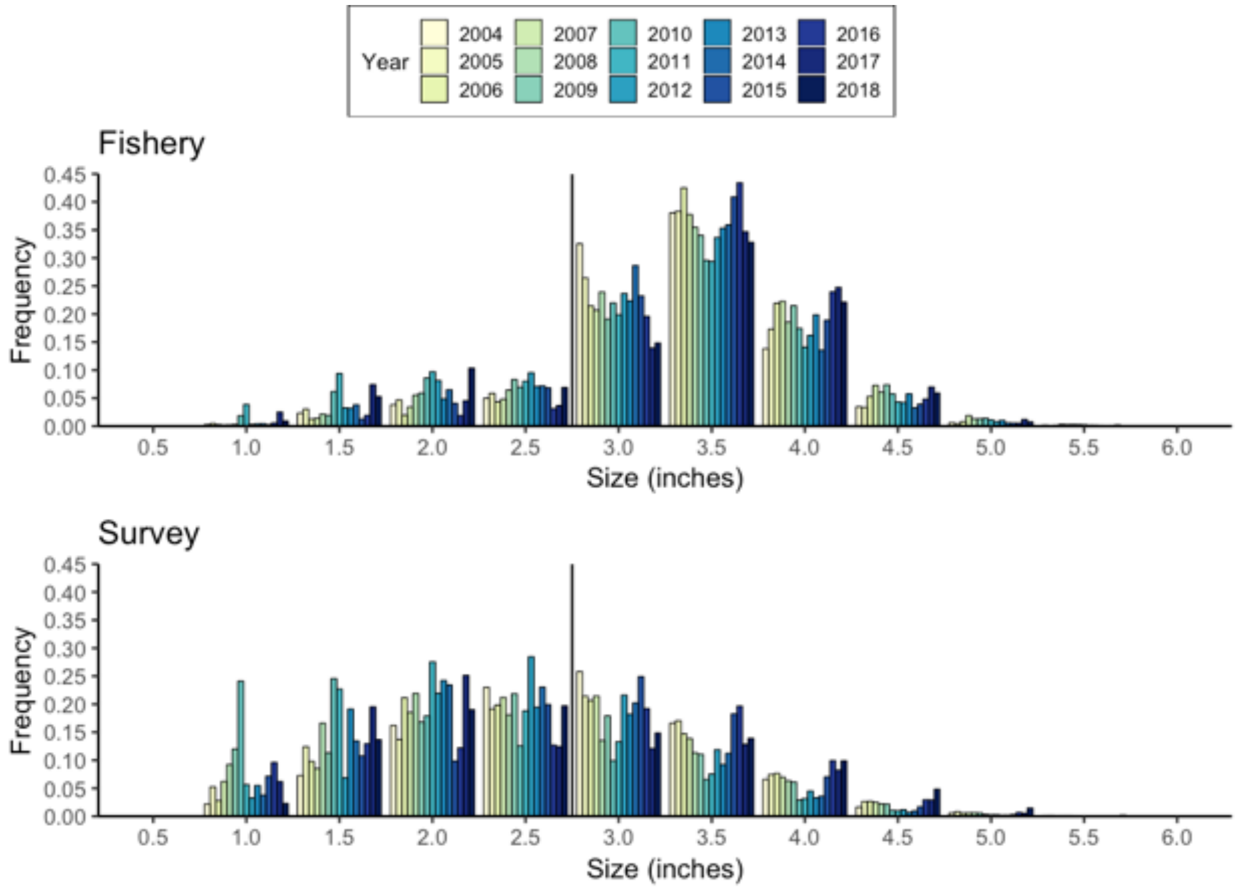


Figure 20. Frequencies of large and small market-size (≥ 2.5 inches) oysters landed by the fishery in direct market regions (top panel) and within the surveyed population (bottom panel).

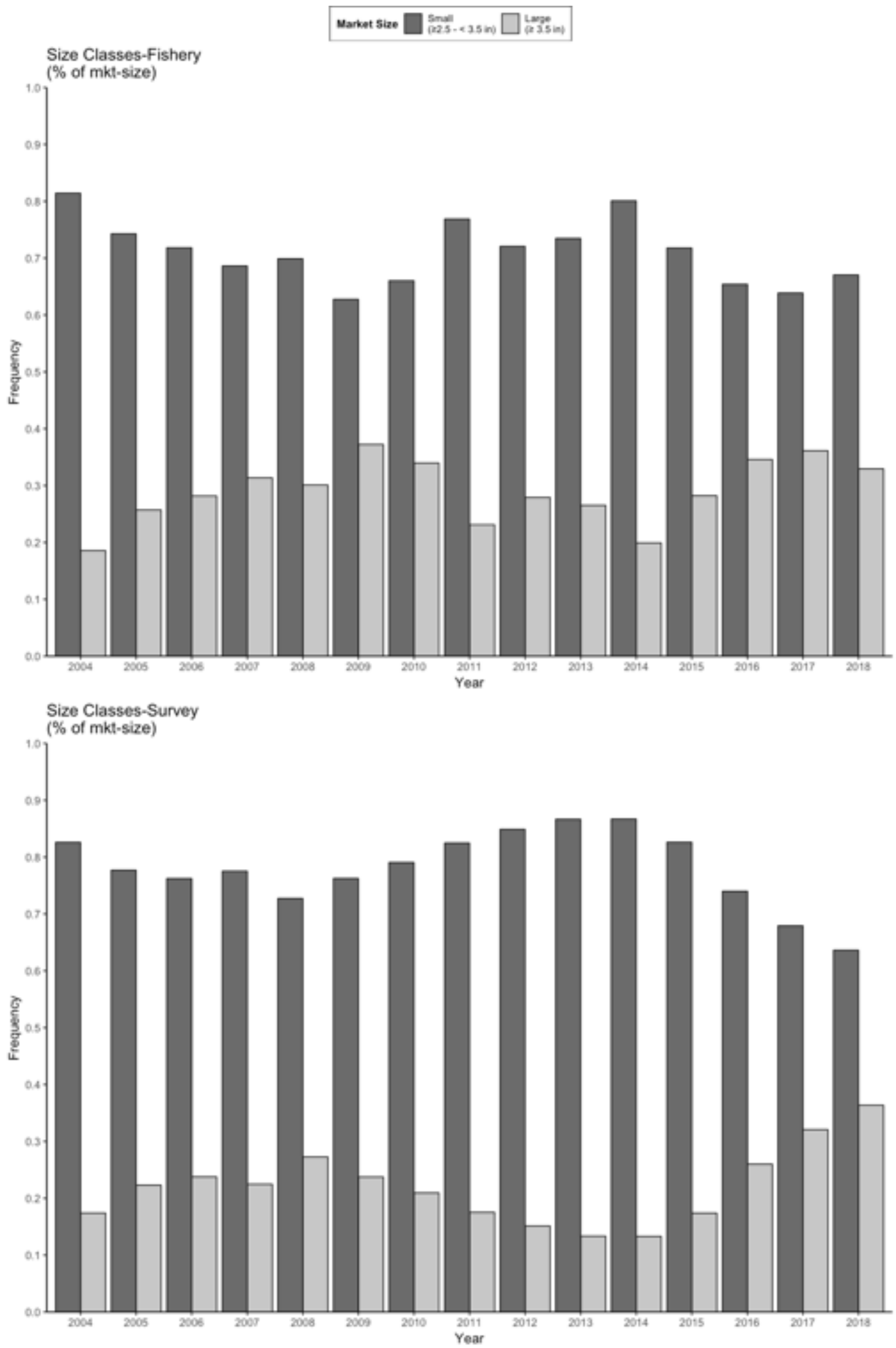


Figure 21. Mean cumulative growth increment for different sized oysters measured during experiments conducted in 2018 and in 2001 (Kraeuter 2001).

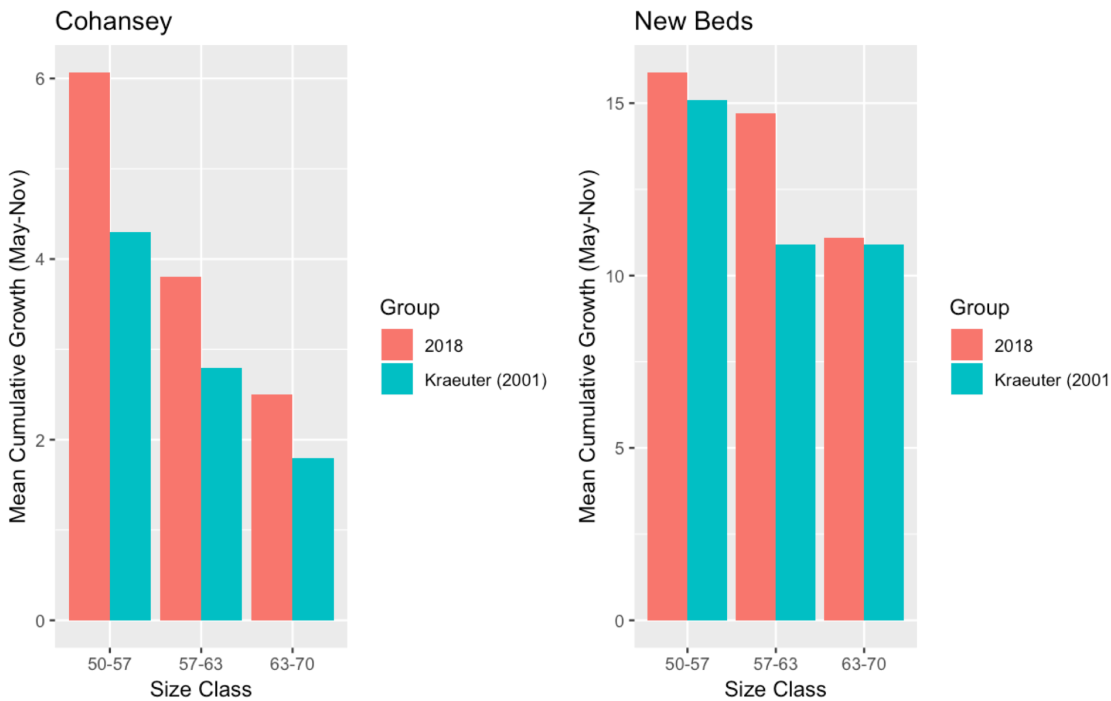


Figure 22. Population fecundity on the Direct Market regions from 2000 to 2018. Fecundity at size was estimated using a power model described in Mann et al. (2014).

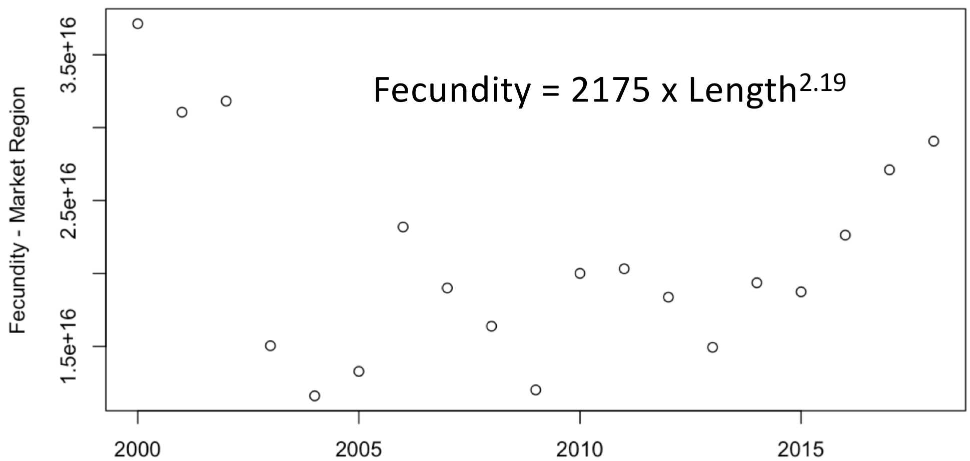


Figure 23. Number of bushels harvested from the natural oyster beds of Delaware Bay since the inception of the direct-market program in 1996. The 23-yr average harvest is 81,175 bushels. The 2006-2007 line shows the beginning of the current exploitation and management strategy.

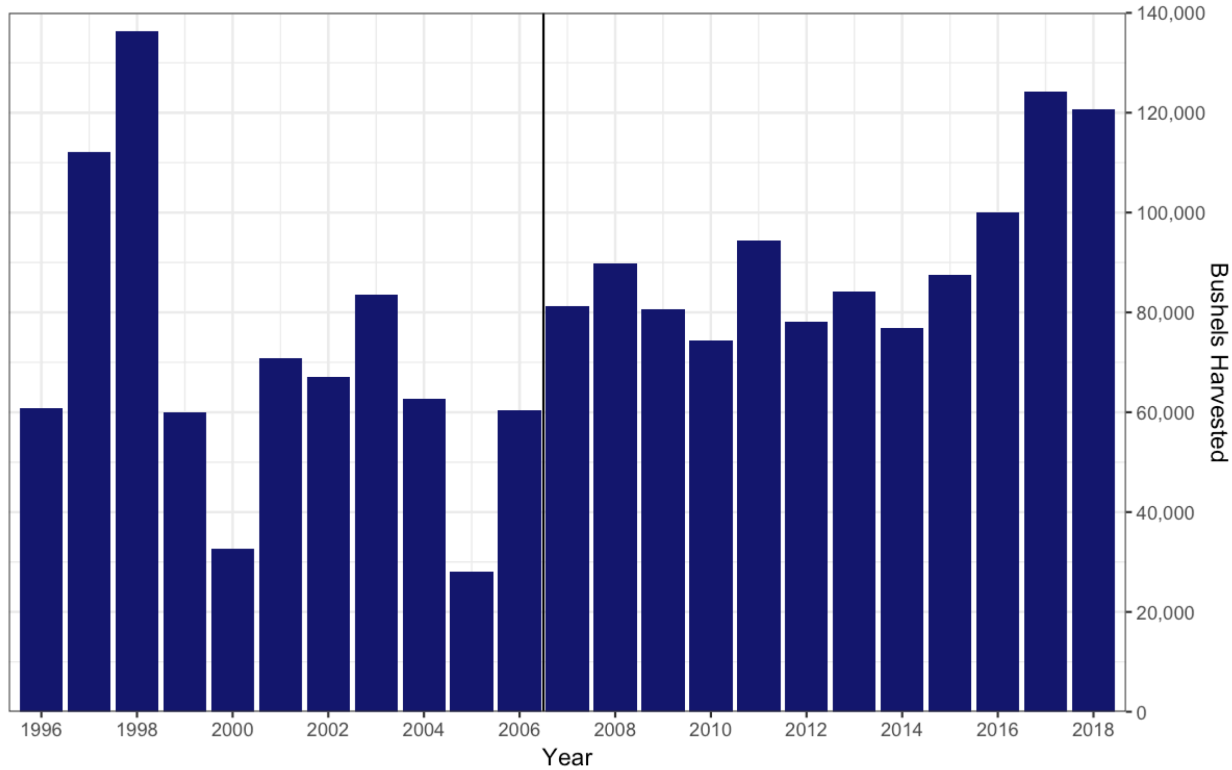
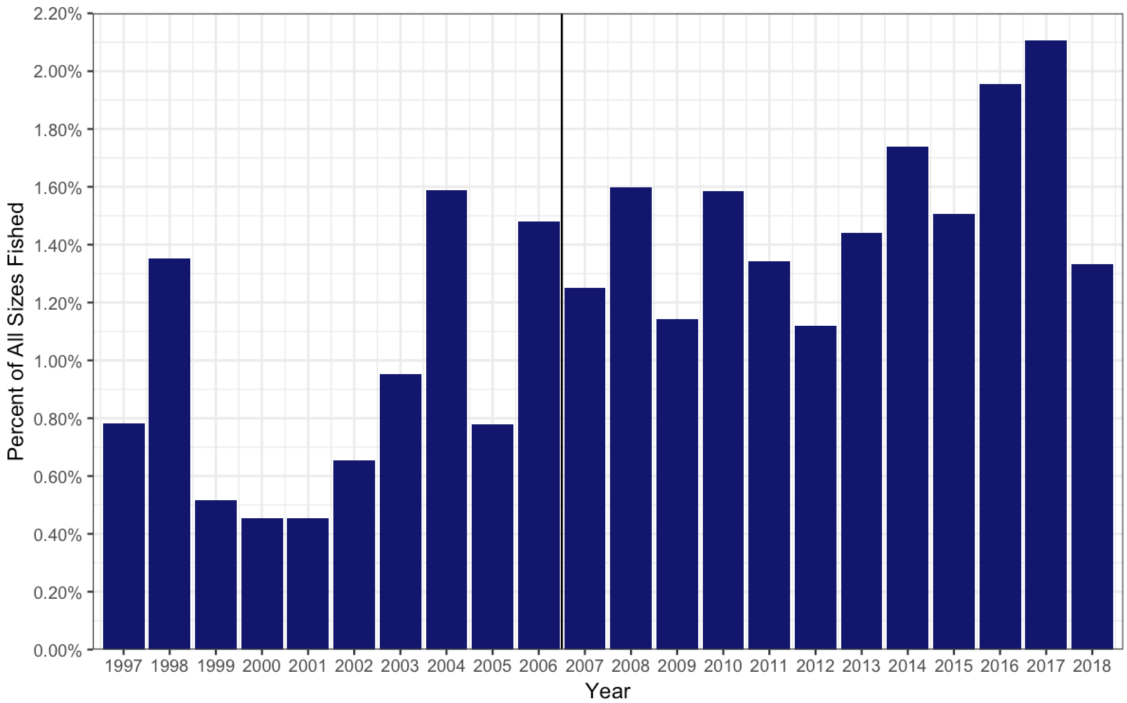


Figure 24. Fishing mortality as a percentage of (a) total oyster abundance and (b) the market-sized oyster abundance (≥ 2.5”) over all regions excluding the VLM. Regional abundance-based quotas began in 2007 (vertical line).

a.



b.

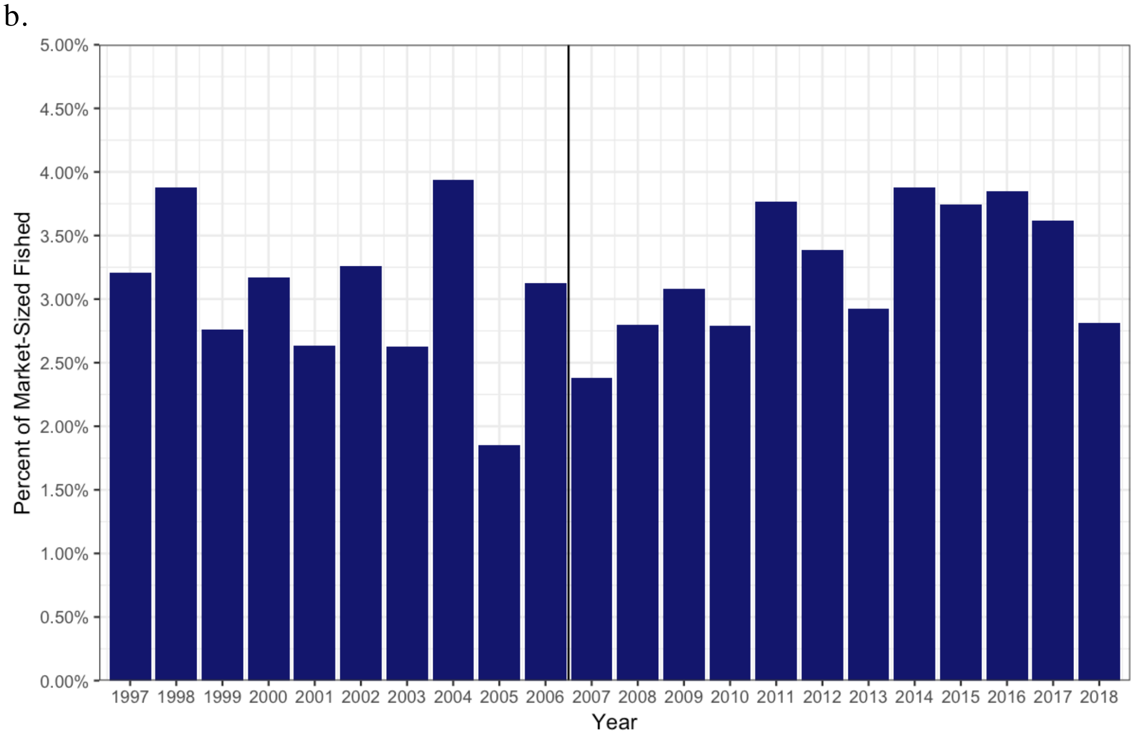


Figure 25. Change in oyster density on grids on Shell Rock that either received enhancement or did not receive enhancement.

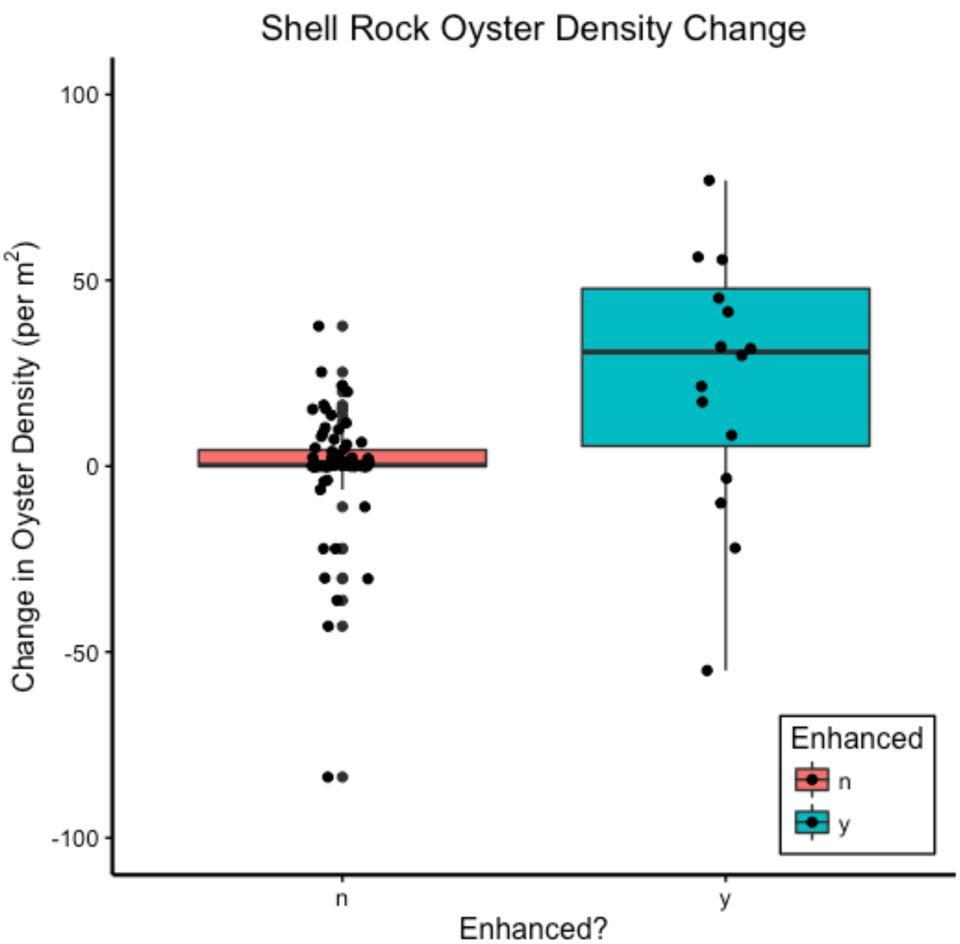


Figure 26. Map of the 2018 oyster stock assessment sample sites. Black dots are sites from the high quality stratum on each bed and white dots are sites from the medium quality stratum on each bed. Red dots indicate transplant enhancement sites and green dots indicate shellplant enhancement sites.

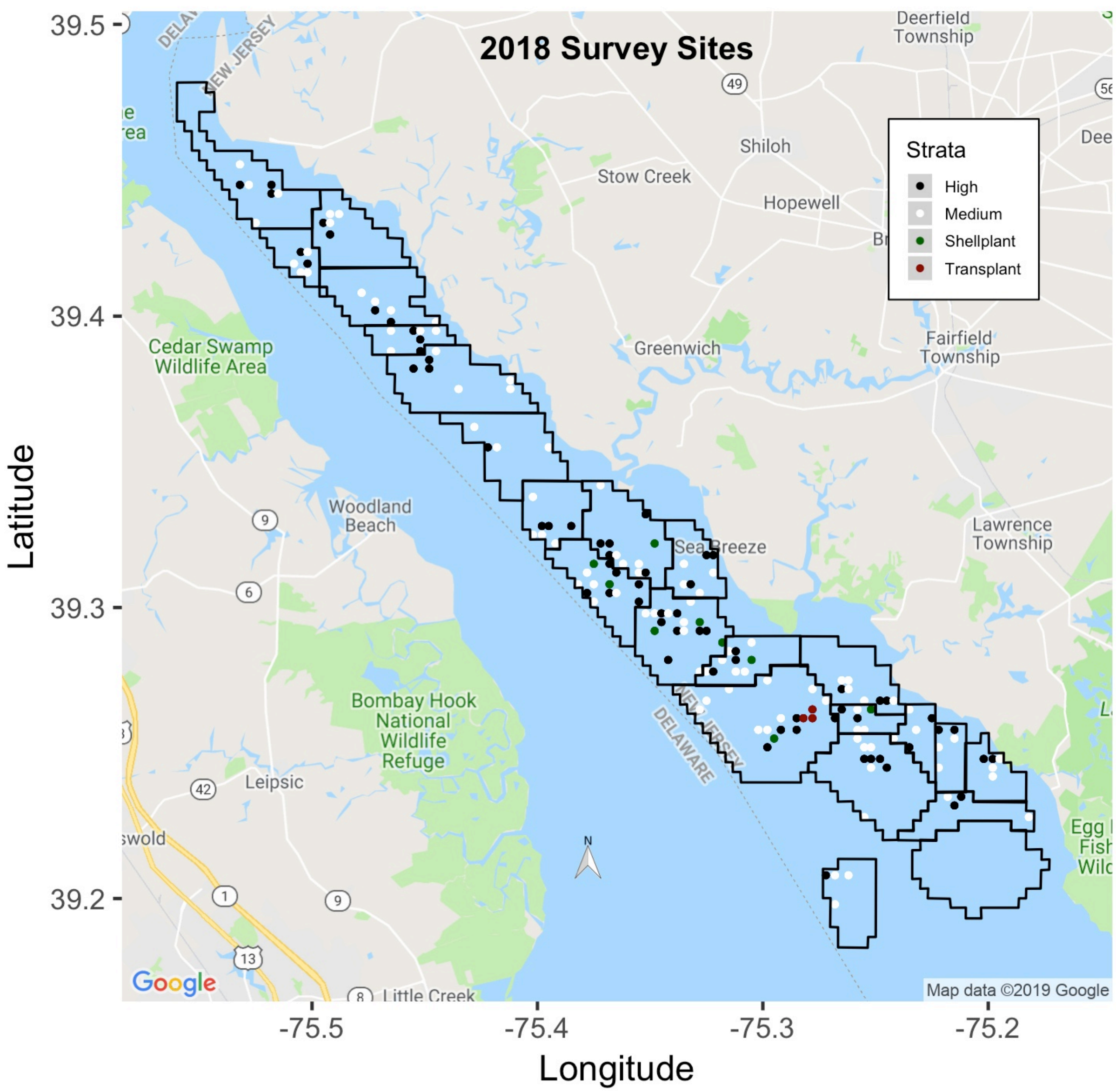


Figure 27. Ten-year time series summary for the population. Left panels: total abundance (≥ 20 mm) and mortality rate. Right panels: size class abundances (≥ 20 mm) and spat abundance (< 20 mm). Dashed horizontal lines represent the threshold and solid horizontal lines represent the target for abundance in panel A and for market abundance in panel B.

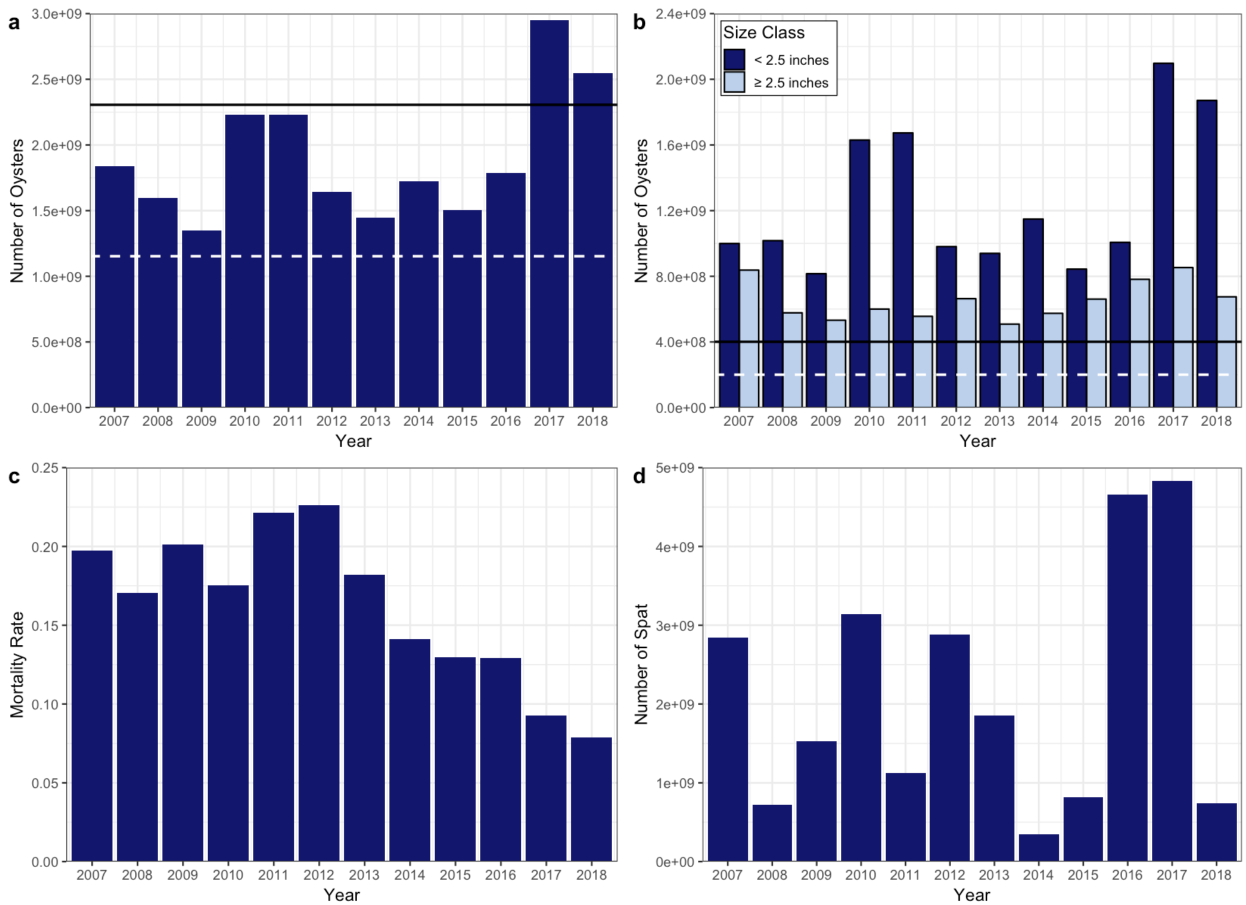


Figure 28. Position of the oyster stock 2014–2018 with respect to abundance and market abundance (≥ 2.5") targets and thresholds. Targets and thresholds are defined in Table 10. Error bars on the 2018 values are the 10th and 90th percentiles of 1,000 simulations of estimates incorporating both survey error and gear efficiency error.

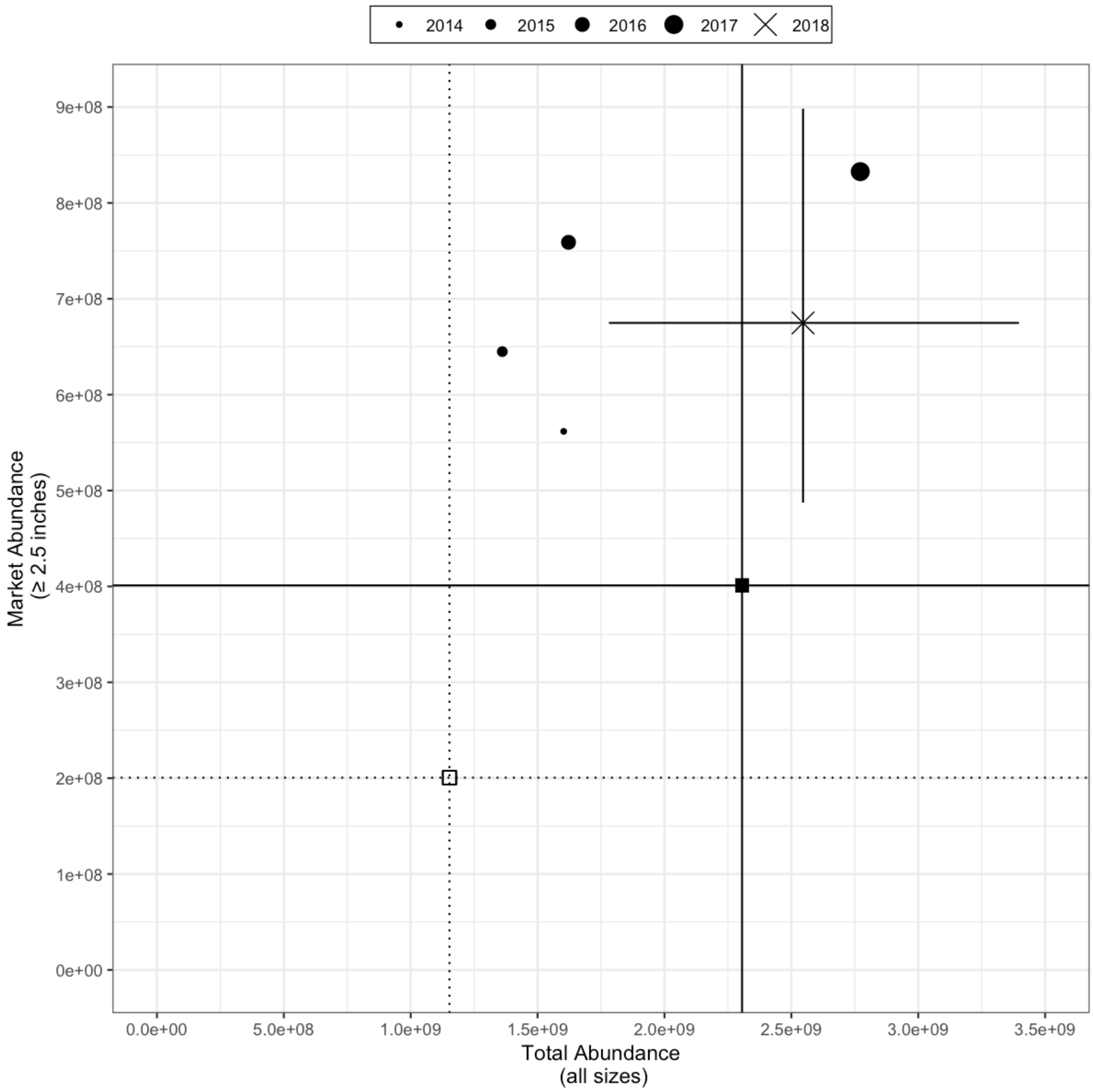


Figure 29. Ten-year time series summary for the VLM. Left panel: total abundance (≥ 20 mm), size class abundances (≥ 20 mm), and spat abundance (< 20 mm). Right panel: Dermo levels, box-count mortality rate and fishing mortality rate relative to both total (≥ 20 mm) and market-size (≥2.5") abundance. Dashed horizontal lines represent the threshold and solid horizontal lines represent the target for abundance and market abundance.

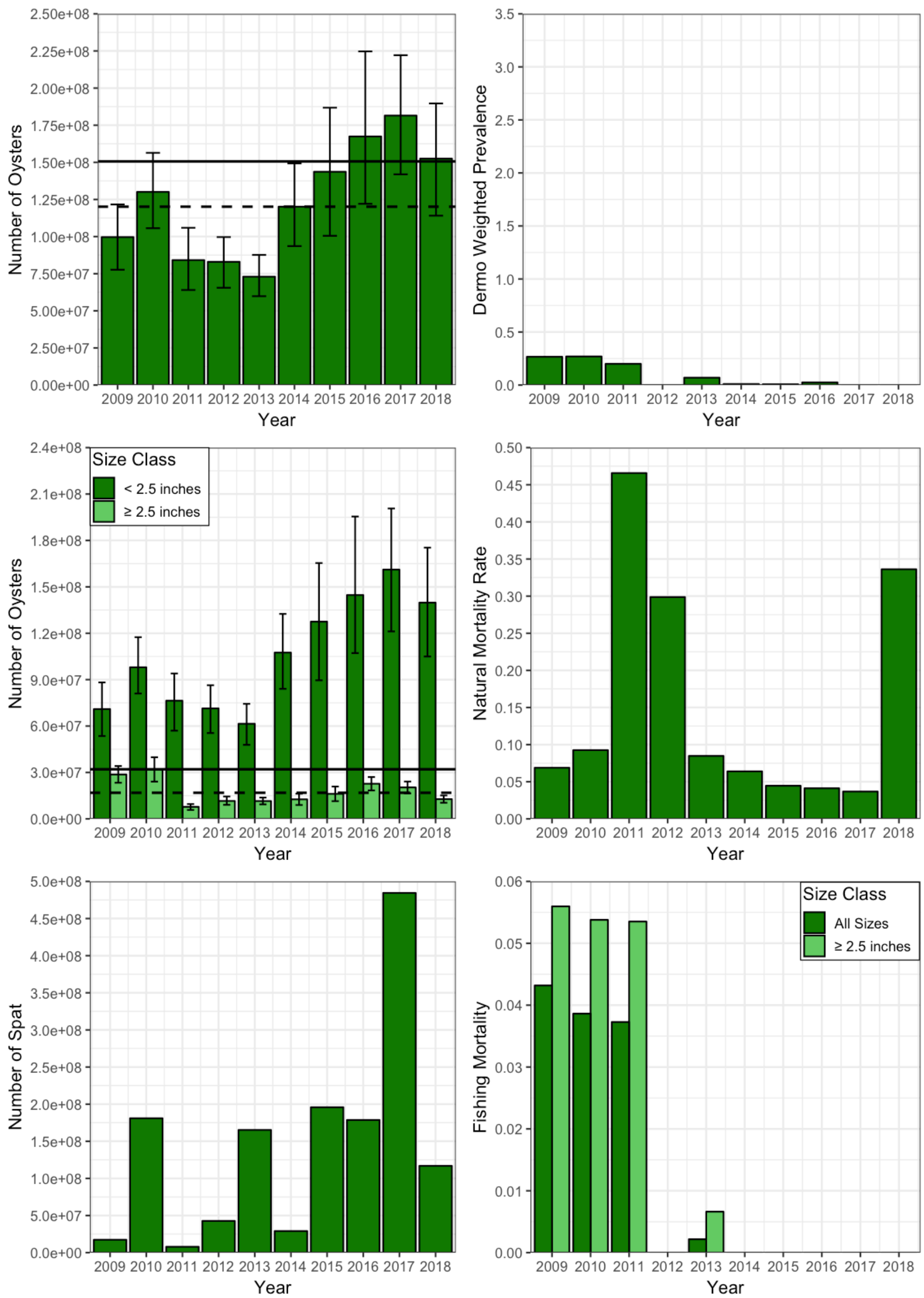


Figure 30. Ten-year time series summary for the LM. Left panel: total abundance (≥ 20 mm), size class abundances (≥ 20 mm), and spat abundance (< 20 mm). Right panel: Dermo levels, box-count mortality rate and fishing mortality rate relative to both total (≥ 20 mm) and market-size (≥2.5") abundance. Dashed horizontal lines represent the threshold and solid horizontal lines represent the target for abundance and market abundance.

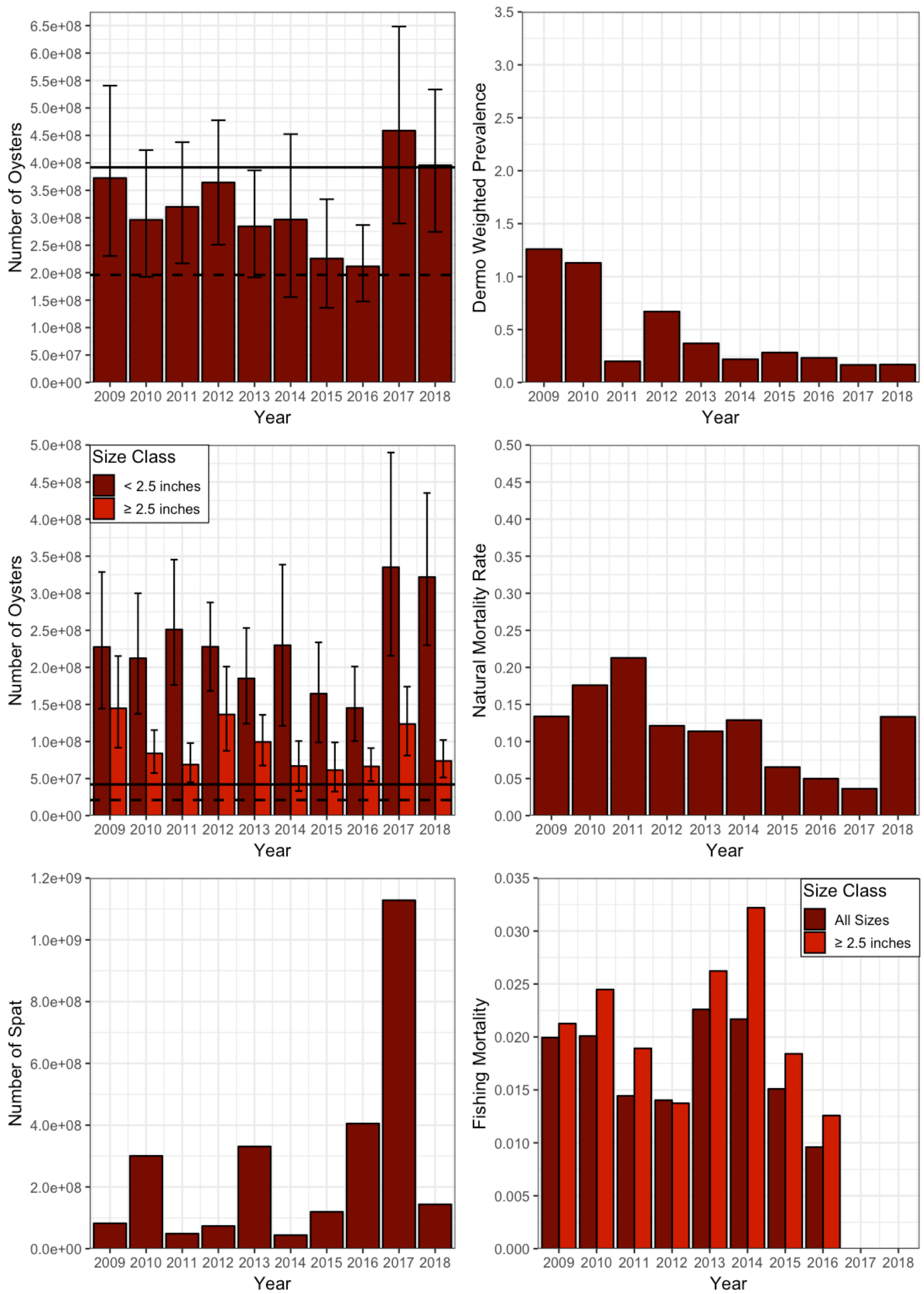


Figure 31. Ten-year time series summary for the MMT. Left panel: total abundance (≥ 20 mm), size class abundances (≥ 20 mm), and spat abundance (< 20 mm). Right panel: Dermo levels, box-count mortality rate and fishing mortality rate relative to both total (≥ 20 mm) and market-size (≥2.5”) abundance. Dashed horizontal lines represent the threshold and solid horizontal lines represent the target for abundance and market abundance.

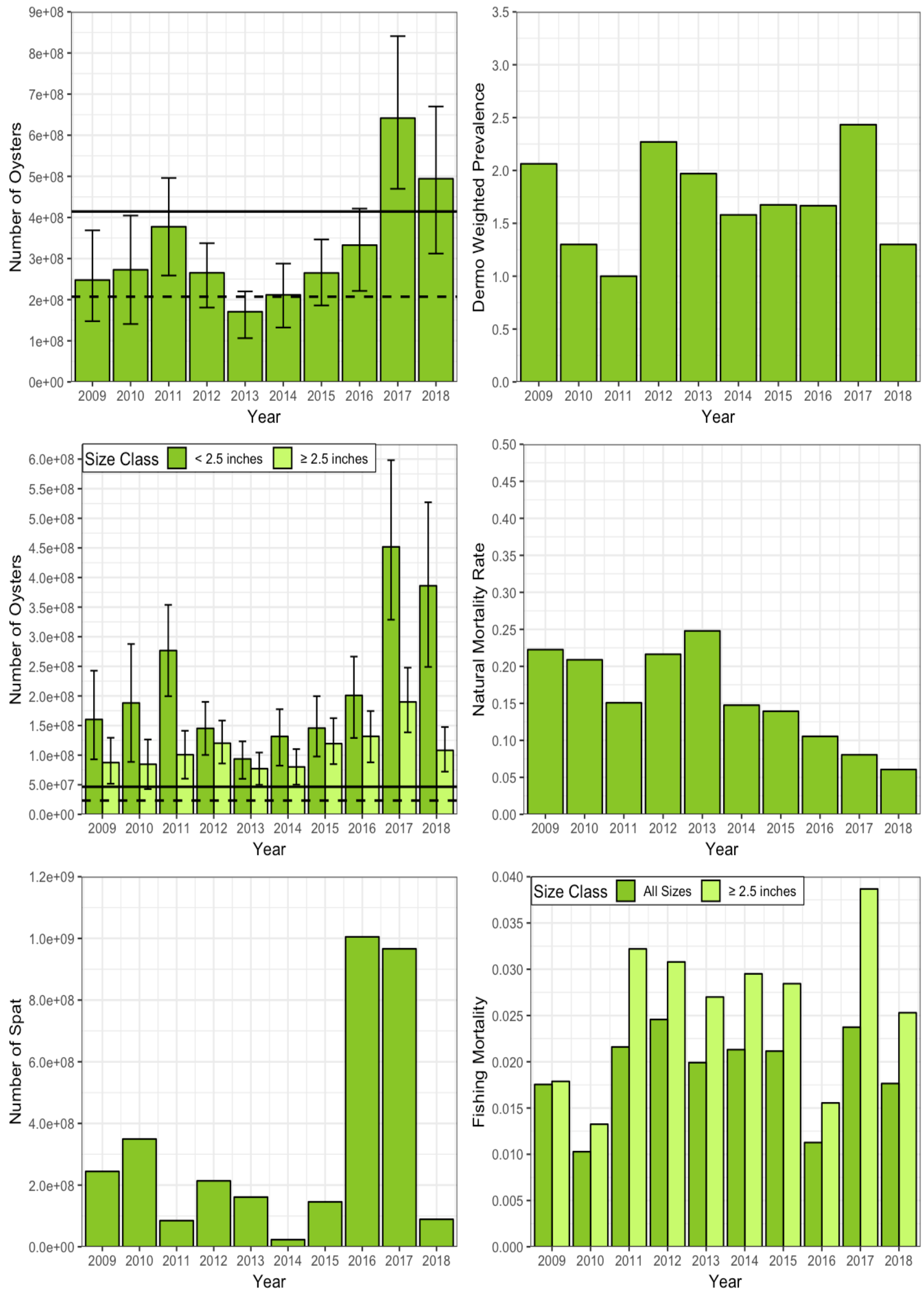


Figure 32. Ten-year time series summary for the MMM. Left panel: total abundance (≥ 20 mm), size class abundances (≥ 20 mm), and spat abundance (< 20 mm). Right panel: Dermo levels, box-count mortality rate and fishing mortality rate relative to both total (≥ 20 mm) and market-size (≥2.5") abundance. Dashed horizontal lines represent the threshold and solid horizontal lines represent the target for abundance and market abundance.

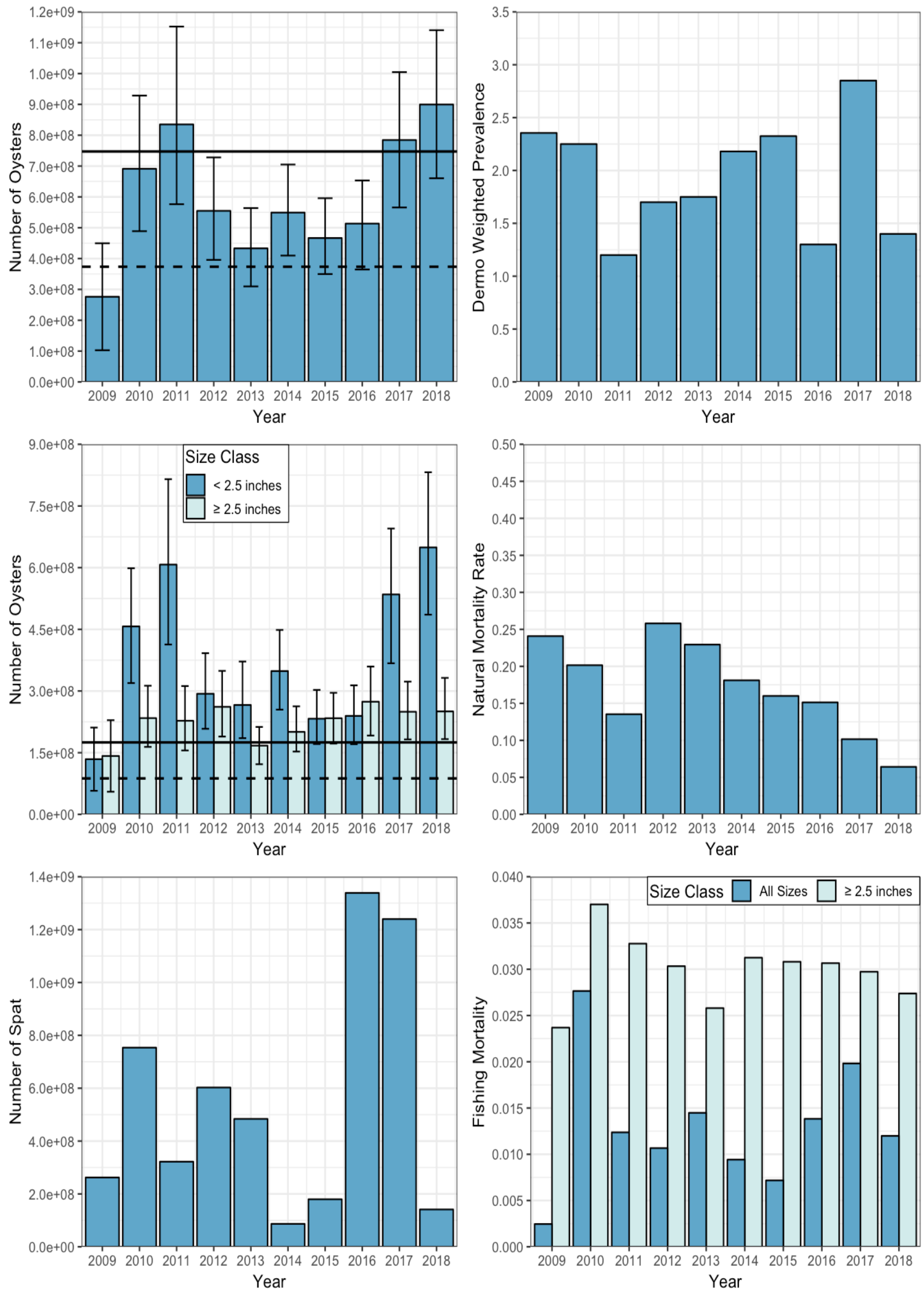


Figure 33. Ten-year time series summary for the SR. Left panel: total abundance (≥ 20 mm), size class abundances (≥ 20 mm), and spat abundance (< 20 mm). Right panel: Dermo levels, box-count mortality rate and fishing mortality rate relative to both total (≥ 20 mm) and market-size (≥2.5”) abundance. Dashed horizontal lines represent the threshold and solid horizontal lines represent the target for abundance and market abundance.

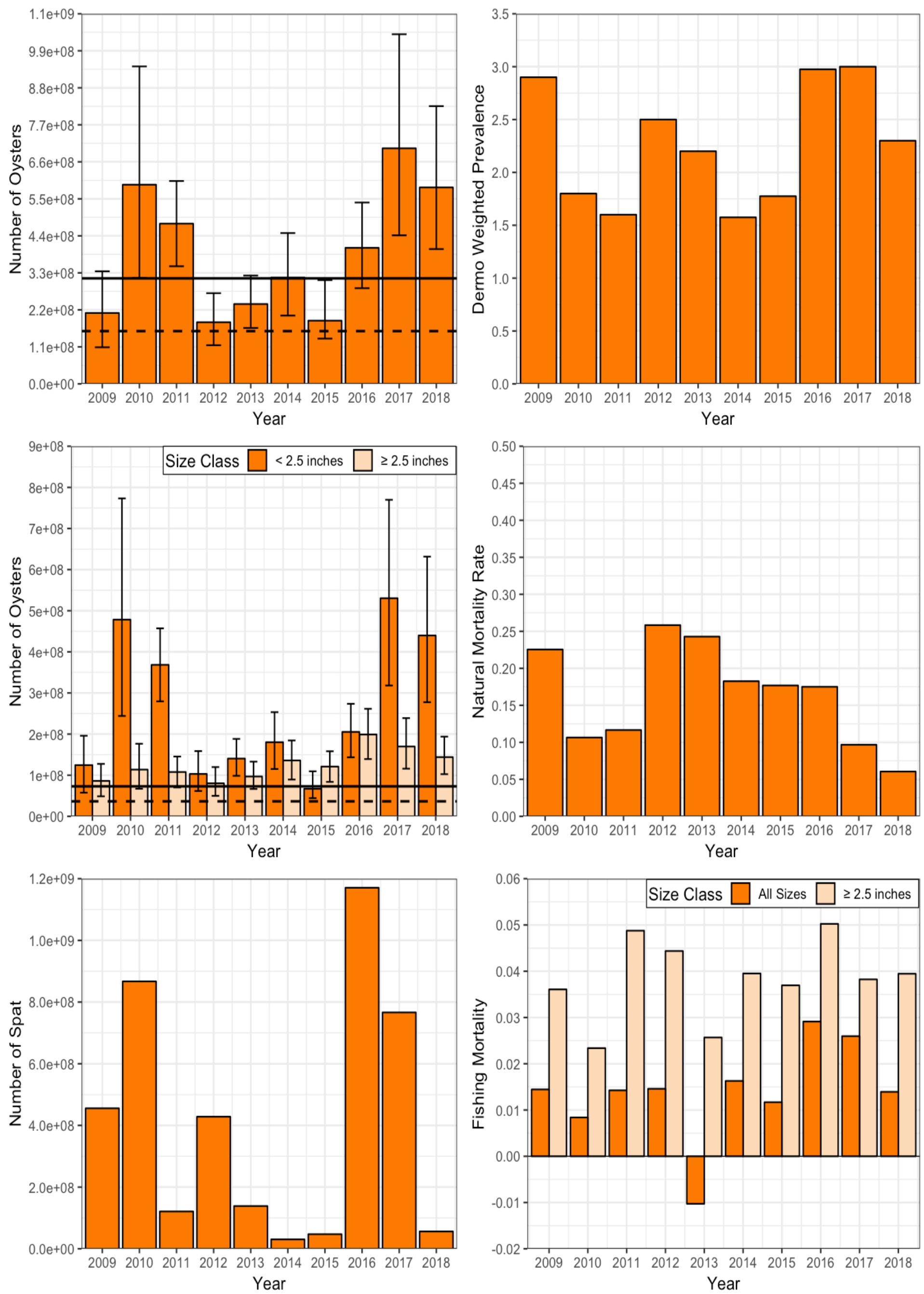


Figure 34. Ten-year time series summary for the HM. Left panel: total abundance (≥ 20 mm), size class abundances (≥ 20 mm), and spat abundance (< 20 mm). Right panel: Dermo levels, box-count mortality rate and fishing mortality rate relative to both total (≥ 20 mm) and market-size (≥2.5") abundance. Dashed horizontal lines represent the threshold and solid horizontal lines represent the target for abundance and market abundance.

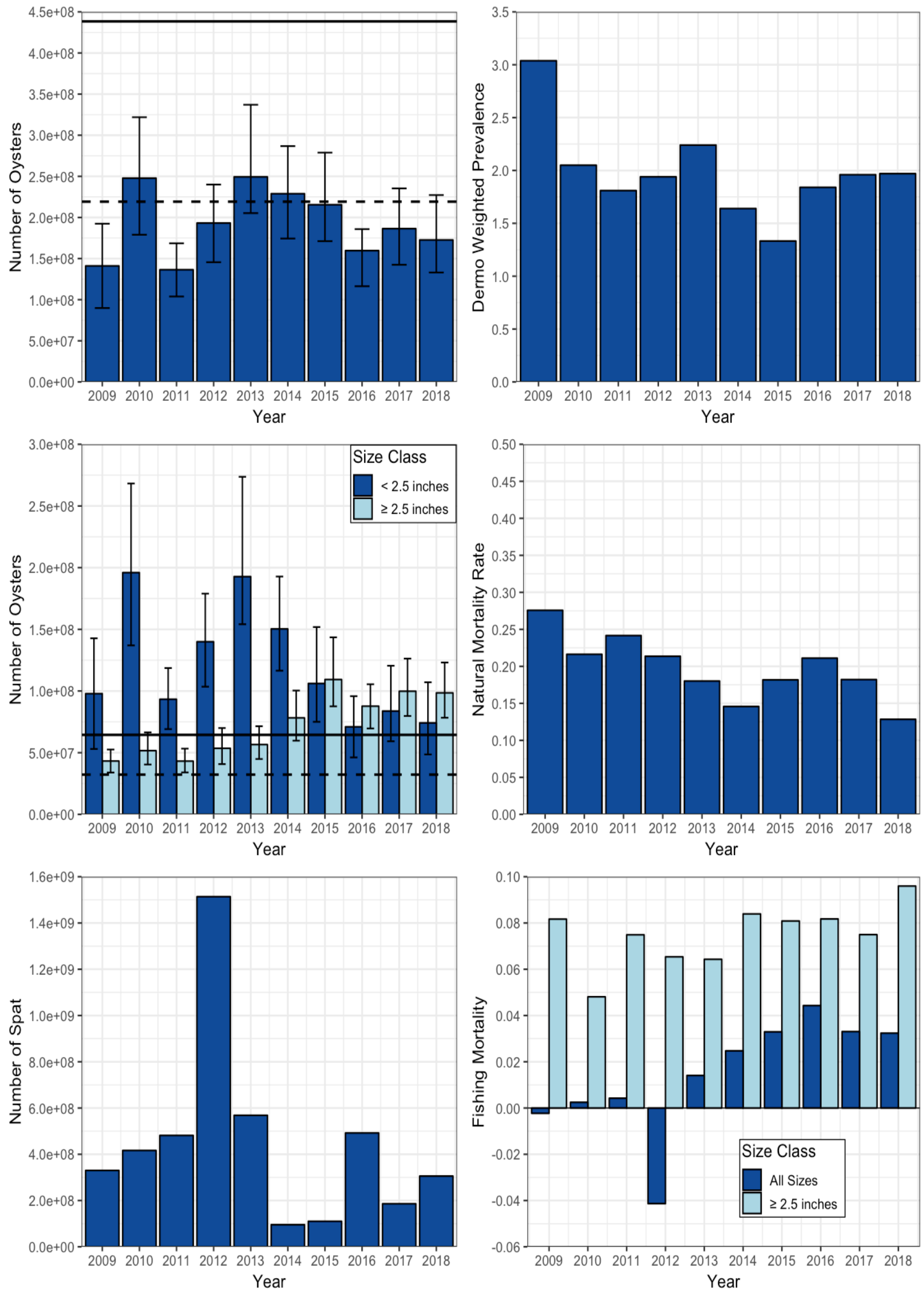
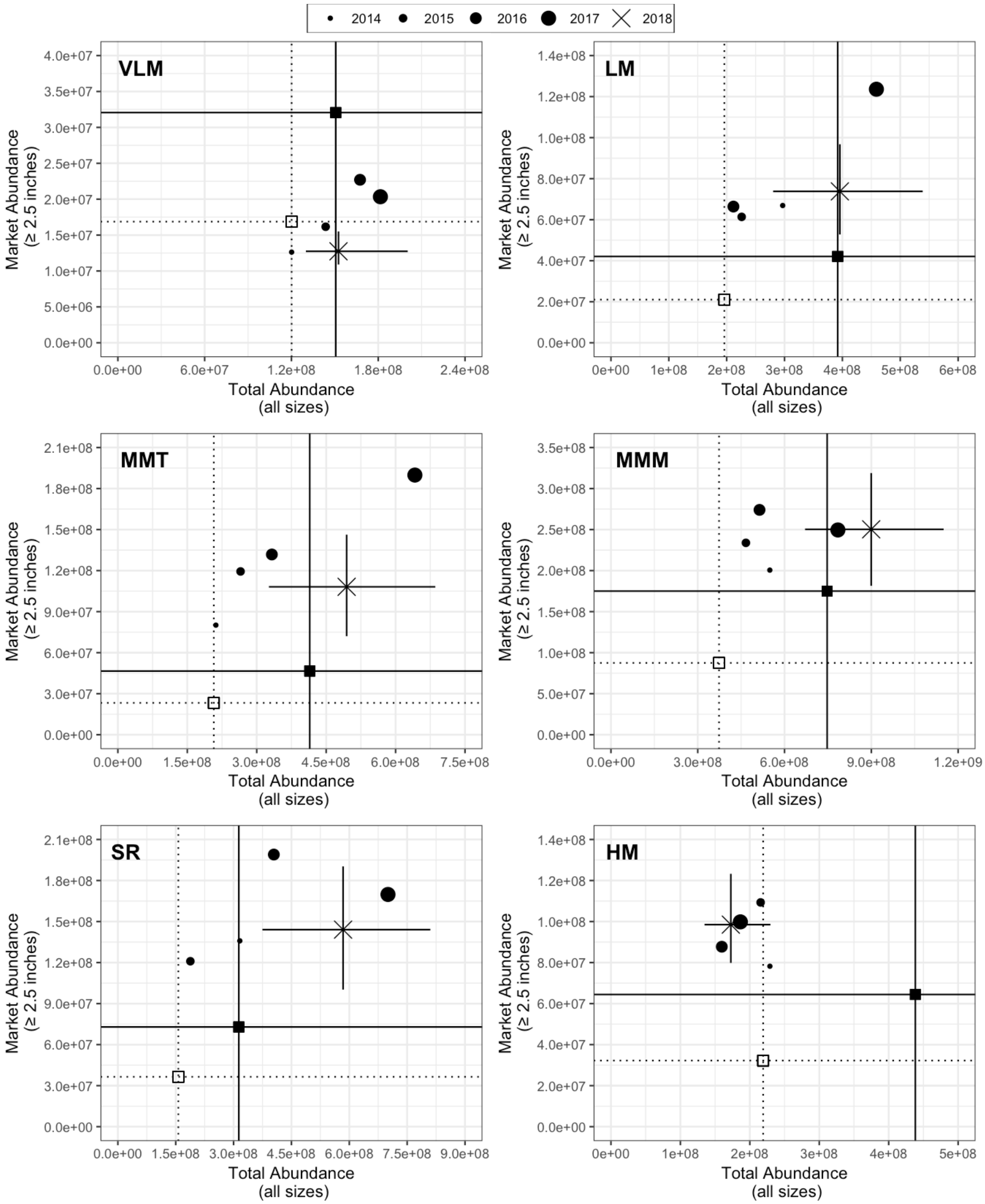


Figure 35. Position of the oyster stock 2014–2018 with respect to abundance and market abundance (≥ 2.5”) targets and thresholds for each region. Targets and thresholds are defined in text. Error bars on the 2018 values are the 10th and 90th percentiles of 1,000 simulations of estimates incorporating both survey error and gear efficiency error.



Appendix A. History of partial (P) and full (F) resurveys for all beds, grouped by region. The entire resource was gridded and stratifiedbetween 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
VLM	Hope Creek	97			P	P									F	
VLM	Fishing Creek	67			P	P										
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											
MMT	Middle	51	P						F							
MMT	Sea Breeze	48	P							F						
MMM	Cohansey	83	P				F									
MMM	Ship John	68	P					F								
SR	Shell Rock	93	P			F				F				F		
HM	Bennies Sand	49	P	P			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							
HM	Vexton	47		F					F							
HM	Egg Island	125														
HM	Ledge	53														

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