STATISTICAL COMPARISON OF MORTALITY, SPAT, AND BIOMASS OF SANCTUARY AND PSFA OYSTER BARS IN CHESAPEAKE BAY

by

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Abstract

The eastern oyster (*Crassostrea virginica)* is a keystone species in Chesapeake Bay, providing nutrient and sediment filtration and crucial habitat. While the eastern oyster was once abundant in Chesapeake Bay, over-harvesting, pollution, and disease have led to massive declines in their populations, with some estimates as less than one percent of historical levels. Dredge harvesting has flattened many of the three-dimensional reef structures, leading to a major decline in important habitat. To aid in oyster reef restoration, the State of Maryland implemented sanctuaries – areas where commercial harvest is entirely banned – and separated them from Public Shellfish Fishery Areas (PSFAs), where harvest is permitted. These sanctuaries have been politically controversial with watermen disputing the effectiveness of sanctuaries and lobbying to have them opened for harvest.

This research utilized data gathered in annual dredge surveys conducted by the Maryland Department of Natural Resources to test the hypothesis that there were statistically significant differences in mortality, number of spat, and biomass in oyster bars in sanctuaries to bars in PSFAs from 2010 to 2019. Utilizing RStudio, it was found that there were only statistically significant differences in mortality across all bars and in a single geographical code, and in the number of spat per bushel across all bars and in low salinity bars. Most comparisons were not statistically significant, likely due in part to the high level of variability in the data and small sample sizes. Comparison of the means in every individual year from 2010 to 2019 showed broadly similar trends in sanctuary and PSFA bars while showing a greater mean biomass after 2013 for sanctuary bars compared to PSFA bars. Further research on the statistical differences in sanctuary and PSFA bars should focus on a narrower region with similar environmental factors.

Acknowledgements

I would like to thank Dan Boward for serving as my mentor and providing his wealth of knowledge and experience from his career at the Maryland Department of Natural Resources. He supported this research every step of the way, from when it was just a vague notion of analyzing data from the sanctuaries, all the way to the final project.

Special thanks to Jodi Baxter from the Maryland Department of Natural Resources for providing me the information from the Fall Surveys and lending her expertise to help me better understand the underlying data. This project would not have been possible without her assistance.

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1. Introduction

Chesapeake Bay is the largest estuary in the United States and provides productive habitat for a diverse array of plant and animal species. The Bay's watershed covers 64,000 square miles and six states and supports more than 3,600 species (Chesapeake Bay Program [CBP], n.d.-a). However, over time the watershed has changed significantly, and the health and water quality of the Bay has suffered due to numerous anthropogenic causes. A significant factor in the decline of the Bay's health is tied to the Eastern Oyster (*Crassostrea virginica).* The Eastern Oyster holds several important ecosystem functions by filtering excess nutrients and sediment as well as providing habitat and food for other species (Baggett et al., 2014). However, the oyster population is at a fraction of the population prior to the arrival of European colonists, with one study comparing data from the current levels calculated that the current population of oysters is only 0.3% of the numbers in the 1800s (Wilberg et al., 2011).

The critically low numbers of oysters in Chesapeake Bay and the resulting reduction in filtration and habitat is a significant factor in the poor health of the Bay. As such, restoring oyster populations in the Bay is a critical component in improving the ecological health of the Bay as a whole. A cornerstone in oyster restoration efforts in the State of Maryland has been the establishment of sanctuaries – areas of oyster bar in which commercial harvest is banned entirely (Maryland Department of Natural Resources [MDNR], n.d.-b). However, this strategy has faced political pushback from watermen and some Maryland lawmakers, who have lobbied for opening sanctuaries for harvest as well as resisting the establishment of new sanctuaries (Miller 2019).

Since opposition to sanctuaries is likely to continue, monitoring and measuring the progress of sanctuary bars can provide useful data for both scientists and policymakers supporting the establishment of sanctuaries. The Maryland Department of Natural Resources (MDNR) (n.d.-a) conducts an annual fall survey of important oyster bars across Chesapeake Bay, both in sanctuaries and in Public Shellfish Fishery Areas (PSFAs), areas where harvest is permitted.

Using these data, comparisons can be made between oyster populations in sanctuaries and PSFAs to determine if the establishment of sanctuaries has yielded a measurable positive effect on oyster recovery. Since many sanctuaries were established in 2010, the decade of 2010-2020 provided a logical data analysis timeframe to test the hypothesis that sanctuary bars will have statistically significant greater values of change in number of spat and biomass, as well as statistically significant lower values of change in mortality, than PSFA bars. If this hypothesis can be validated, it will indicate that designating an area with oyster bars as a sanctuary will have positive and measurable effects on the oyster populations in these areas.

2. Background

2.1 Eastern Oyster Ecology

The Eastern Oyster (*Crassostrea virginica)* serves as an ecosystem engineer and as a keystone species providing numerous ecosystem services (Grabowski & Peterson, 2007). As filter-feeders, oysters trap excess nutrients, sediments, and contaminants (Grabowski & Peterson, 2007). With a single oyster capable of filtering more than fifty gallons of water per day, oyster populations play a critical role in improving water quality and clarity, which in turn benefits numerous other species (CBP n.d.-b). The water clarity improvements are particularly important for submerged aquatic vegetation, which itself provides food and habitat for other species (CBP, 2015).

Oyster reefs provide important habitat in Chesapeake Bay, as they provide hard surface habitat unlike the typical soft-sediment bottom (Grabowski & Peterson, 2007). This hard surface habitat can house other filter feeders such as mussels and tunicates, which in turn increases the total filtration of oyster reefs. Modelling rates of the filtration rates in Harris Creek found that tunicates and mussels together filtered an average of 3.3% of the volume of the system daily, compared to oysters which filtered an average of 4.0% (Kellogg, 2018). Oyster reefs also provide important habitat for non-sessile species as well, including crustaceans and fish, with Chesapeake Bay reefs showing significantly higher abundance and diversity than areas outside of reefs (Bruce et al., 2021). As well as providing food for these species, the structure of reefs provide shelter for juveniles of several species, including the blue crab (*Callinectes sapidus*) – one study found that survival of juvenile crabs in oyster reefs was over three times higher than those in bare sand areas (Bruce et al., 2021).

The Eastern Oyster is found throughout Chesapeake Bay, but salinity heavily influences oyster populations, as it impacts reproduction, growth, and mortality (MDNR, 2016). Salinity limits the range of oysters in Chesapeake Bay, as they do not occur at areas with very low average salinity and so they are not found at the northernmost reaches of Chesapeake (MDNR, 2016). Oysters in low salinity zones are also particularly susceptible to mortality from freshets, the influx of fresh water from high precipitation (MDNR, 2016). Land use within a tributary's watershed can also influence salinity, since a high percentage of impervious surface will lead to more fresh water from rainfall entering the tributary and further lowering salinity.

Salinity is also a significant factor in the prevalence of two diseases amongst oysters in Chesapeake Bay – Dermo and MSX. Dermo is the common name for the parasite *Perkinsus marinus* and was first seen in Chesapeake Bay in 1949. Dermo has had a greater impact on oyster populations since the mid-1980s (Virginia Institute of Marine Sciences [VIMS], n.d.). Dermo prevalence is influenced by both temperature and salinity. It intensifies above 20°C and rapidly spreads and kills above 25°C, but declines below 15-20°C, so Dermo infections follow a seasonable pattern (VIMS, n.d.). The highest intensities are found above salinities of 12-15 ppt, and infection is low at salinities consistently below 9 ppt, although the parasite can persist in low salinity areas for years once it is established (VIMS, n.d.).

MSX is the common name for the parasite *Haplosporidium nelson* and was first found in Chesapeake Bay in 1959 (VIMS, n.d.). MSX, as with Dermo, is highly influenced by temperature and salinity. Initial infections occur above 20°C, but after infection, it proliferates amongst the population from 5-20°C and kills susceptible oysters above 20°C (VIMS, n.d.). Infection only occurs at salinities of at least 15 ppt, and high mortality occurs at 20 ppt or above, while the parasite is expulsed at salinities below 10 ppt (VIMS, n.d.).

Due to these factors, oyster bars at low salinities are more susceptible from mortality from freshets, while oyster bars at higher salinities are more susceptible from mortality from MSX and Dermo. All oyster bars in Maryland are in the mesohaline salinity zone of 5 to 18 ppt, but this can vary seasonally so MSX and Dermo infections can still be a significant cause of mortality on oyster bars in the lower salinity zones, particularly in dry years (MDNR, 2016).

2.2 Establishment of Sanctuaries

Due to the importance of oysters in improving water quality and providing habitat, restoring oyster populations has become a major goal in efforts to restore Chesapeake Bay as a whole. In support of Executive Order 13508 on Chesapeake Bay Protection and Restoration, issued in 2009, a goal was set by the Federal Leadership Committee for the Chesapeake Bay

(2010) to restore native oyster populations in 20 candidate tributaries by 2025. To meet these goals, the MDNR established sanctuaries – areas of oyster bar where commercial harvest is banned. While sanctuaries existed prior to 2009, only 1,475 acres were covered; in 2009, three new sanctuaries were established bringing the total protected area to 2,581 acres of oyster habitat – approximately 9% of total oyster habitat in the Maryland portions of the Bay (MDNR, n.d.-b). The most significant effort to expand sanctuaries in Maryland came in September 2010, when the amount of bar protected as sanctuaries was expanded from 9% to 25% (MDNR, 2010). This marks the point where utilizing no-harvest sanctuaries became a key part of Maryland's plan to restore oyster habitat. A map of the sanctuaries and PSFAs found in Maryland waters can be found in Image 1.

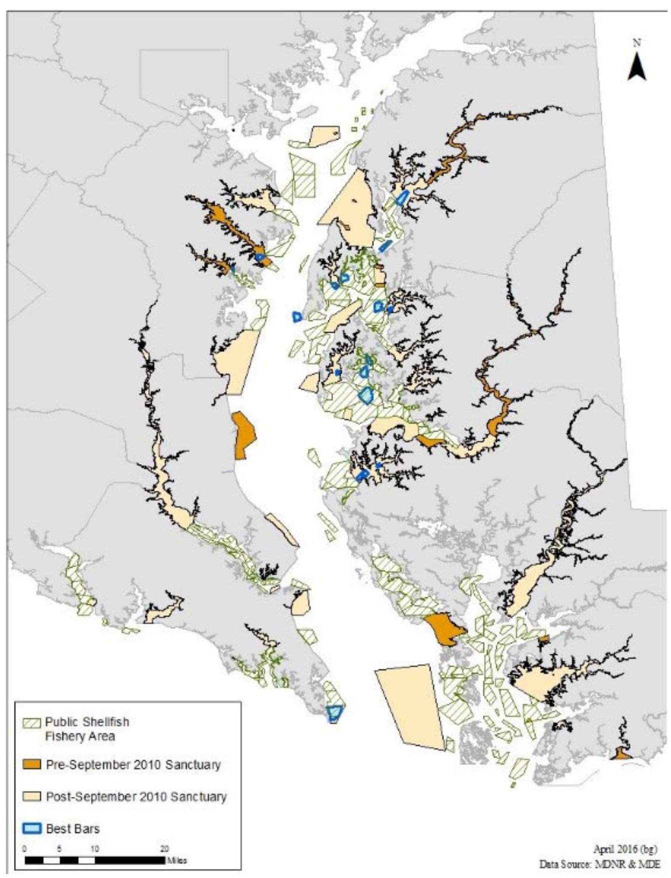

Image 1: Map of Sanctuaries and PSFAs in Maryland portions of Chesapeake Bay (MDNR, 2016)

The elimination of harvest, particularly dredge harvest, should be beneficial for oyster populations. Dredge harvesting has been shown to reduce the height of oyster reefs, increasing sedimentation, and impacting recruitment, growth, and mortality (Mercaldo-Allen and Goldberg, 2011). However, watermen and politicians representing them have pushed back against the establishment of sanctuaries as well as lobbying for existing sanctuaries to be opened to harvest. In addition to arguing for the economic benefit of harvest, opponents of sanctuaries also claim that occasionally dredging for harvest clears sediment and promotes growth on the reefs, though scientific studies do not support this claim (Miller, 2019) and in fact studies show that dredging increases sedimentation rates (Mercaldo-Allen and Goldberg, 2011). Despite the lack of support for the claim that harvest is beneficial for oyster bars, political pressure to open sanctuaries to harvest is unlikely to disappear.

2.3 Monitoring of Sanctuaries and PSFAs

Monitoring the progress of oyster bars has been ongoing for decades through the Annual Fall Surveys. Every year, MDNR conducts a dredge-based survey of oyster bars within Chesapeake Bay and its tributaries. Fifty-three sites were chosen in 1975 as 'Key Bars', selected for "adequate geographic coverage and continuity of data going back to 1939" and a forty-three-bar subset of 'Disease Bars' were added for surveying data on "parasite prevalence and intensity" (MDNR, n.d.-a). There is significant overlap between the Key Bar and Disease Bar subsets, with thirty-one of the Disease Bars also found in the Key Bar subset (MDNR, n.d.-a). MDNR releases a report on the annual surveys every year, with methodology and analysis of that year's findings. The reports also include limited analysis on the progress of sanctuary bars, but it is noted in the reports that an in-depth analysis of the performance of the sanctuary system is outside to their scope (Tarnowski, 2020).

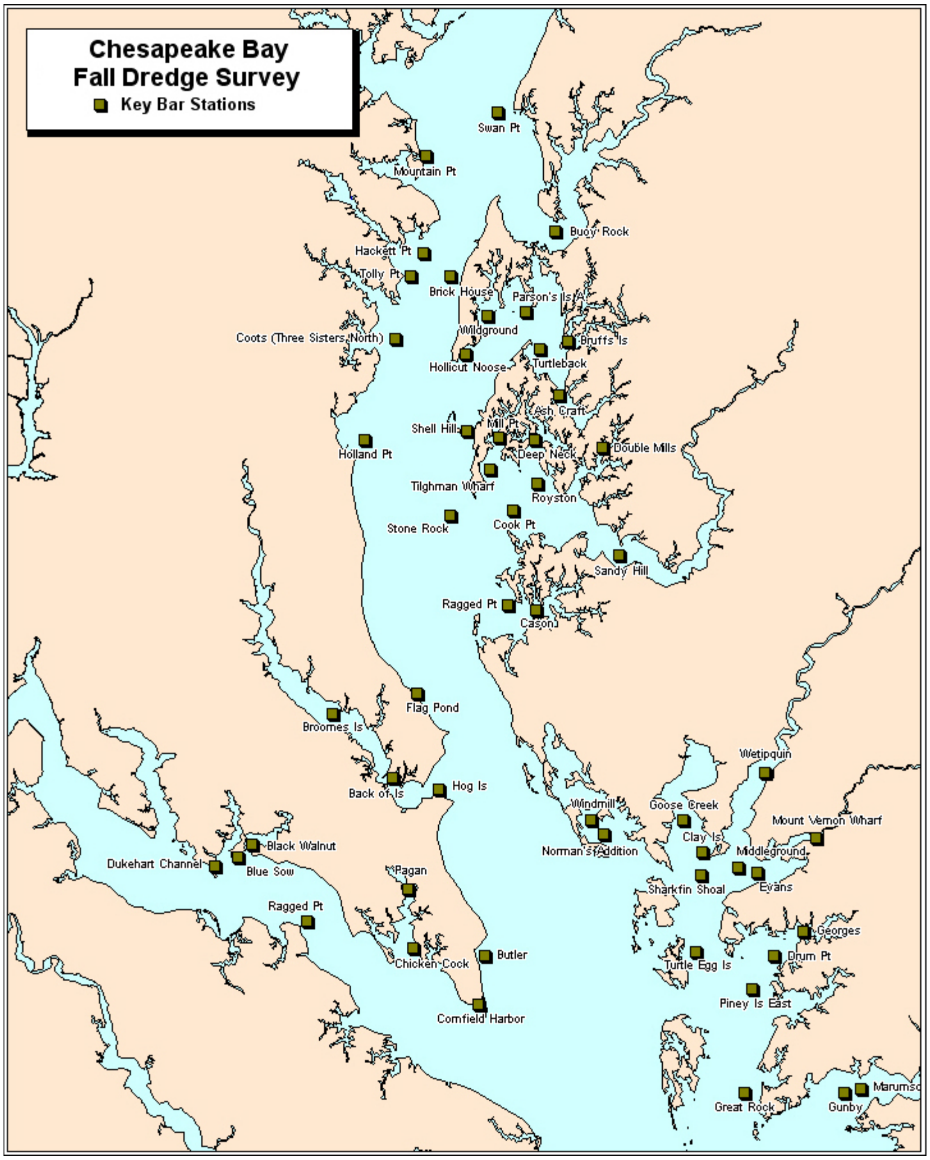

Image 2: Key Bars Utilized in MDNR Fall Dredge Surveys (MDNR, n.d.-a)

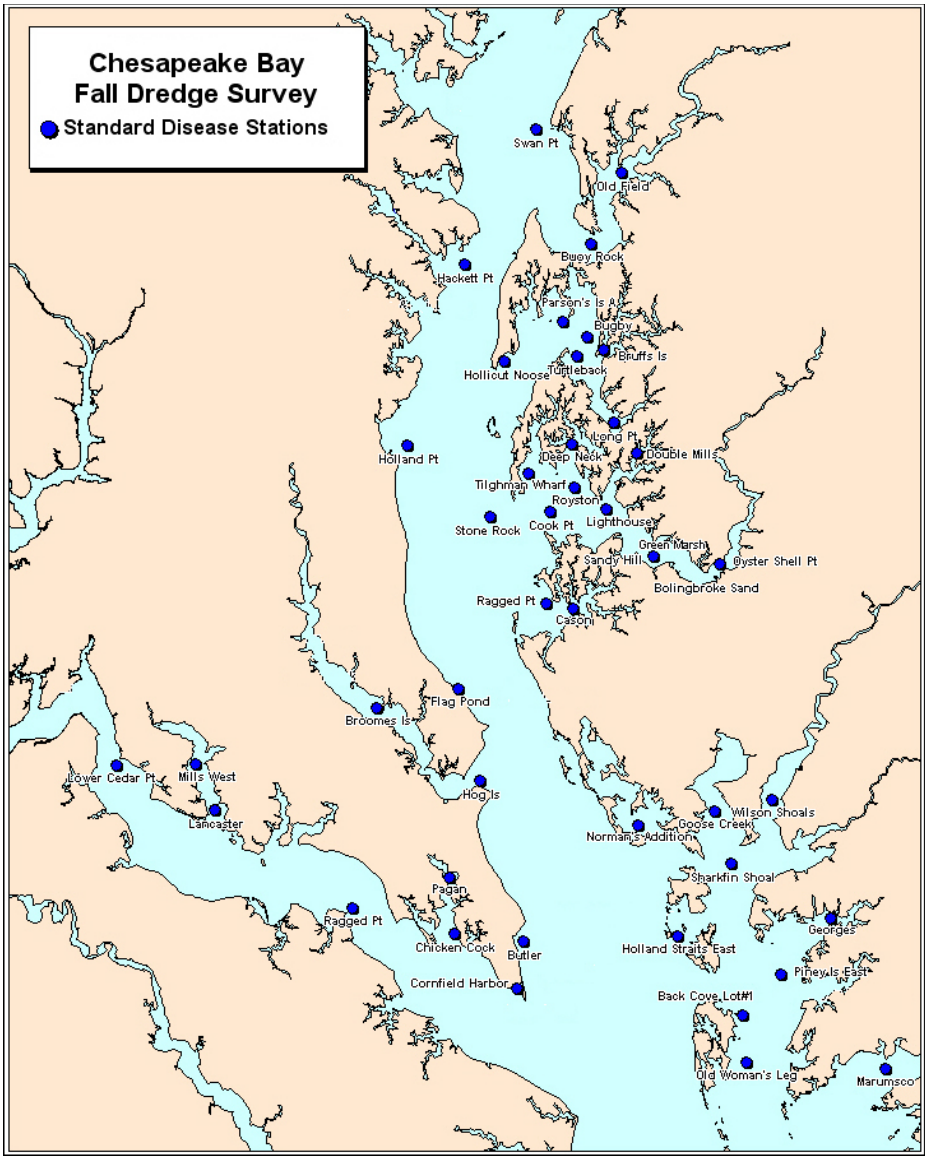

Image 3: Disease Bars used in MDNR Fall Dredge Surveys (MDNR, n.d.-a)

The most comprehensive analysis of the sanctuary system to date is MDNR's 2010-2015 Oyster Management Review, intended to review the effectiveness of sanctuaries, PSFAs, and aquaculture areas within the Maryland portions of Chesapeake Bay. These reports were intended to be released every five years after 2010, but at the time of this writing, the 2020 review was not available. This review conducted extensive analysis of data collected from the Annual Fall

Surveys in both sanctuary and PSFA bars, comparing their performance against two separate sets of objectives (MDNR, 2016). Notably, the review does not conduct any large-scale analysis comparing sanctuary metrics to PSFA metrics, but rather focused on comparing each separately against its own set of objectives.

2.4 Existing Research on Sanctuaries vs. PSFAs

A notable study comparing sanctuaries and PSFAs in a geographical area larger than a single tributary was on the Choptank River complex, an area encompassing the Choptank River, Little Choptank River, the Tred Avon River, Harris Creek, and Broad Creek (Damiano & Wilberg, 2019). This area is particularly important because it houses Maryland's three largest sanctuaries as well as providing 28% of Maryland's total annual oyster fishery yield as of 2016 (Damiano & Wilberg, 2019). The combination of sanctuaries and PSFAs in a single geographic area provided an ideal site for comparing the effectiveness of these two bar types. The results of this comparison were mixed. Natural mortality was found to be lower overall in sanctuaries than PSFAs, but abundance and recruitment of spat was down in the area in both sanctuaries and PSFAs without a clear difference in performance in the two types of bars (Urick, 2019). The comparison of the two categories in this area is also complicated by the fact that only 23% of 'best bar' – defined by MDNR as the most productive bars – was closed to harvest, so the proportion of the most productive oyster populations is heavily weighted towards PSFAs (Urick, 2019).

Most other existing research comparing sanctuaries and PSFAs focus either on a specific area or on modelling, and while it has provided some evidence of the effectiveness of sanctuaries using population metrics, it has only done so on a smaller scale – often within a single tributary.

Directly comparing trends in population metrics in sanctuaries and those in PSFAs across the Maryland portion of Chesapeake Bay does not appear to be available in the literature (Urick, 2019).

3. Methodology

3.1 Data Sources

The data for this analysis were provided by the Maryland Department of Natural Resources from their Annual Fall Surveys from 2010 to 2019. The samples for these surveys were collected using 32-inch-wide dredges, with two 0.5-bushel subsamples taken from Key and Disease Bar sites, five 0.2-bushel subsamples from seed production areas, and a single 0.5-bushel sample taken from all other sites (Tarnowski, 2020).

The data for the Fall Surveys were provided by MDNR in two distinct datasets. The first of these provided the numbers of spat-sized, small, and market-sized oysters as well as the number of spat. It also included the mortality of the sample amongst small (less than 3 inches long) and market-sized oysters (3 or more inches long). Mortality was calculated from these samples as the number of dead oysters divided by the total of live and dead oysters of small or market size (Tarnowski, 2020). Each sample was separated by the sample year, the report region, bar name, and sub-area, as well as the latitude and longitude of the sample. The samples were also given the sanctuary name if appropriate, and the year(s) of any plantings that had occurred on the sampled oyster bar. This dataset included samples from 2010 to 2019, as the 2020 information was not available at the time of this writing.

The second dataset included length and biomass samples. The biomass was measured as the gram per dry weight per bushel of material by removing, oven-drying, and weighing the meat of the oysters in the sample (Tarnowski, 2020). The biomass samples only included the sample year, report region, bar name, and sub-area, so the supporting information was not as extensive as the main dataset.

The time period of 2010 to present was chosen as many sanctuaries were established in September 2010, expanding the sanctuary program from protecting 9% to 25% of oyster bars (MDNR, 2010). The time period from 2010 to the most recent available surveys provided a logical timeframe to conduct analysis on comparing the effect of establishing sanctuaries on oyster populations due to this expansion of the sanctuary system.

3.2 Grouping Samples by Bar

The main survey dataset was organized by the bar name, subarea, sample year, and specific latitude and longitude of the sample. Two primary measurements in this dataset were utilized in this analysis – the number of spat collected in the sample and the percentage of mortality amongst small and market-sized oysters. The size of the various samples differed, so the number of spat was normalized by the size of the sample to calculate the number of spat per bushel. Any bar with a planting between 2010 to 2020 was removed from the dataset, because plantings could significantly skew the population characteristics of these bars within the given time frame. Once these bars were removed, the data were split into two bins – sanctuary bars and non-sanctuary bars.

The biomass dataset was organized by bar name, subarea, and sample year. It did not include NOAA Codes, but the NOAA Codes were derived by matching the region, bar name, and subarea with the appropriate NOAA Code in the first dataset. The sanctuary status was also not recorded in this dataset. To classify samples as sanctuaries, the dataset was matched by bar name with the first dataset. A small number of bar names were found both as sanctuaries and PSFAs in the first dataset. Since there was no way in the biomass dataset to identify where the sample was taken within the bar, these samples had to be discarded. Most bar names, however, matched up only to either a sanctuary or PSFA, and this dataset was also separated into two bins for sanctuary and non-sanctuary bars. Plantings were not recorded in this dataset, so no bars were removed due to plantings within this time frame.

3.3 Calculating Changes

Utilizing R Studio Version 1.4.1103, the change over time in the number of spat per bushel, mortality, and biomass were calculated for each bar. In the main dataset, for each unique combination of bar name and coordinates of the sample, the number of spat per bushel and mortality of the earliest sample was subtracted from the same characteristics of the most recent sample to get the value of the change in spat and mortality over the time period for these sample areas. If the earliest and most recent sample for a specific sample location were less than eight years apart, the calculation was left out of the dataset, as fewer than eight years was judged not to be enough time to calculate the changes over the last decade. The percentage of change rather than the raw change in number of spat per bushel was considered but was deemed inappropriate because some of the samples had zero spat per bushel.

For the biomass dataset, the relative change over time in biomass was calculated by taking the biomass of the most recent sample for each bar and dividing it by the biomass of the earliest sample and multiplied by 100 to get the relative proportion of the most recent sample compared to the earliest. Any bar that did not have at least eight years between the earliest and most recent sample were also not included.

3.4 Binning the Data

To reduce variability due to geographic environmental characteristics, bars were then binned into three separate sub-categories – NOAA Code, salinity level, and MDNR tier level (Table 1). This allowed the hypothesis to be tested within these sub-categories as well as across all bars, to reduce the influence of other environmental factors on mortality, number of spat, and biomass, which would help provide better confidence that the differences in these metrics was due primarily to the variable of whether a bar was in a sanctuary or PSFA.

The NOAA Code is a unique code given to a specific geographical area of Chesapeake Bay and its tributaries for reporting harvest (MDNR, 2016). Tier designations were given in the MDNR 2010-2015 Oyster Management Review, with a value between one and three to represent the relative productivity of oysters within that NOAA Code and provide a way to compare sanctuary and PSFA bars of similar productivity (MDNR, 2016). Salinity level influences the growth, mortality, and reproduction of oysters, so comparing bars within similar salinity levels would minimize variability in population metrics due to salinity (Baggett et al., 2014). A map of the NOAA Codes in the Maryland portions Chesapeake Bay is found in Image 4.

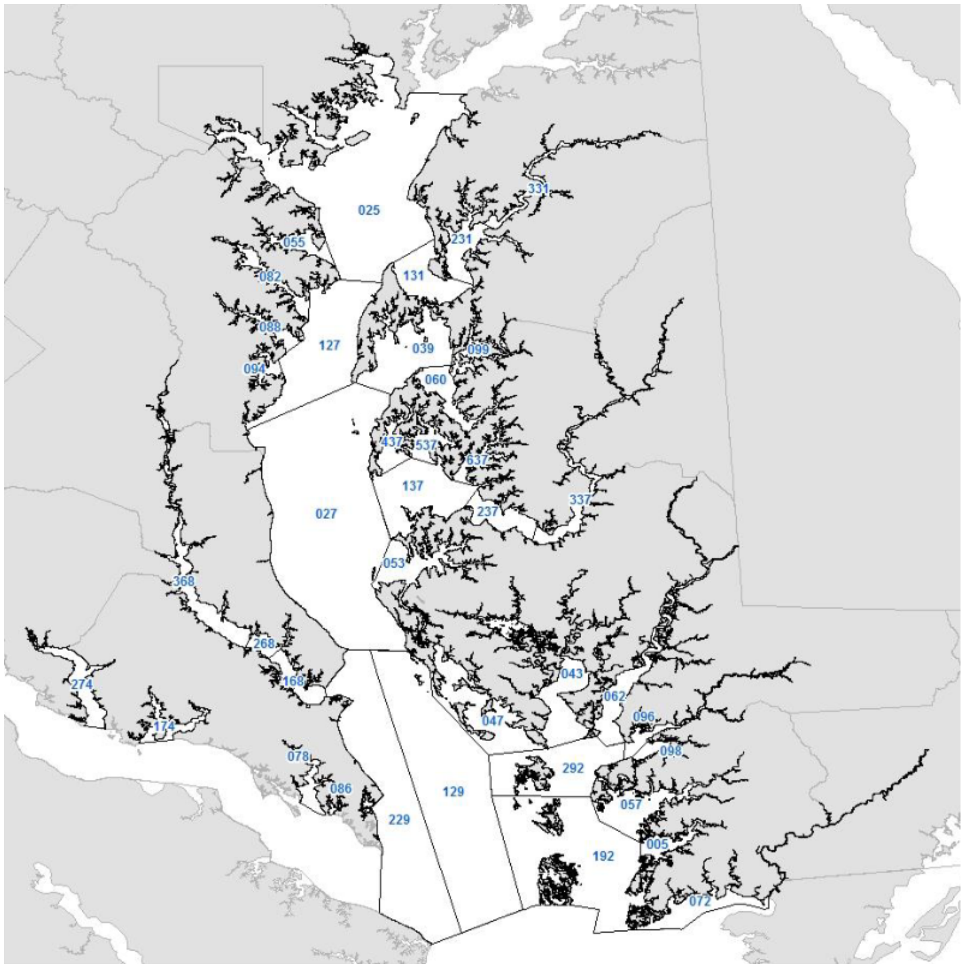

Image 4: Map of NOAA Codes in Maryland portions of Chesapeake Bay (MDNR, 2016)

The salinity level and tier designations were determined using the NOAA Code of each bar and assigning it a salinity level of low, medium, or high and a tier designation of 1, 2, or 3 based on MDNR's 2010-2015 Oyster Management Review. For the purpose of these classifications, low salinity zones are those with average salinities from 5 to 11 ppt, medium salinity zones have average salinities from 12 to 14 ppt, and high salinity zones have average salinities above 14 ppt (MDNR, 2016). The salinity zones of sanctuaries can be found in Image 5, and the classifications by bar are listed in Table 1 in Appendix A. Every bar was matched with the appropriate salinity level and tier designation by matching its NOAA Code with the corresponding salinity and tier for that code.

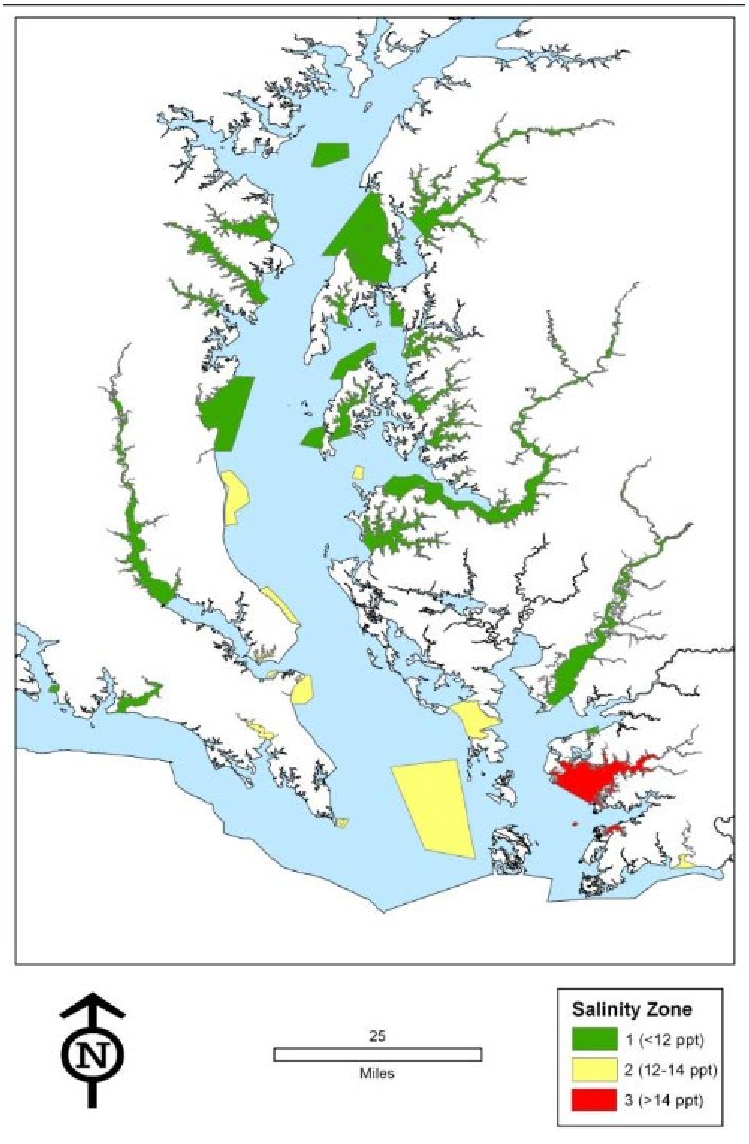

Image 5: Three Salinity Zones by Sanctuary in Maryland waters of Chesapeake Bay (MDNR, 2016)

3.5 Analysis Methods

The change in mortality, number of spat per bushel, and biomass were compared between sanctuary and PSFA bars, both overall and within each of the three bins described above. R Studio was used to create boxplots of these comparisons using the boxplot function to generate box and whisker plots showing the median and lower and upper quartiles. The outliers were hidden in the box and whisker plots for readability. Additionally, the mean, median, min, and max functions were leveraged to provide descriptive statistics within each of the bins.

Due to the high amount of variability in the samples, a non-parametric test was utilized to compare the sanctuary and PSFA datasets – an approach also used by the Maryland Department of Natural Resources in the past by using the Friedman's Two-Way Rank Sum Test (Tarnowski, 2018). The Mann-Whitney U Test was selected for this report, since this test was more appropriate than the Friedman's Two-Way Rank Sum Test for the comparison of the two independent samples of sanctuaries and PSFA averages. The test was conducted in R using the wilcox.test function to compare the changes in mortality, spat per bushel, and biomass between sanctuary and PSFA samples both overall and within each bin. The p-values of these tests were compared to an alpha value of 0.05; if the p-value of the test is above 0.05, the null hypothesis will be accepted that there is no statistically significant difference between the two datasets.

4. Results

4.1 Mortality

When comparing the change in mortality across all bars in all Maryland bars, sanctuary bars had a mean increase in mortality of 0.55% while PSFA bars had a mean decrease in mortality of 4.25% (Table 2). The Mann-Whitney U Test comparing the two datasets generated a p-value of .02251, representing a statistically significant difference (Table 2). This disproved the hypothesis, as sanctuary bars had greater values of change in mortality than PSFA bars.

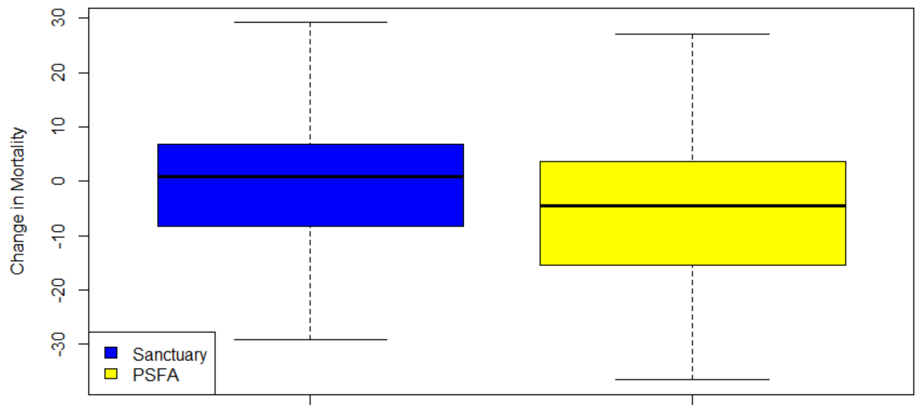

Figure 1: Box and Whisker Plot of Change in Mortality of Sanctuary and PSFA Bars from 2010-2019

In low salinity bars, sanctuary bars had a mean increase in mortality of 3.2% and PSFA bars had a mean increase of 2.45% (Table 3). In medium salinity bars, sanctuary bars had a mean decrease in mortality of 5.08% and PSFA bars had a mean decrease of 8.63% (Table 3). In high salinity bars, sanctuary bars had a mean decrease in mortality of 4.78% and PSFA bars had a mean decrease of 11.99% (Table 3). None of these were found to be a statistically significant difference, disproving the hypothesis that sanctuary bars would have lower values of change in mortality than PSFA bars in all salinity zones.

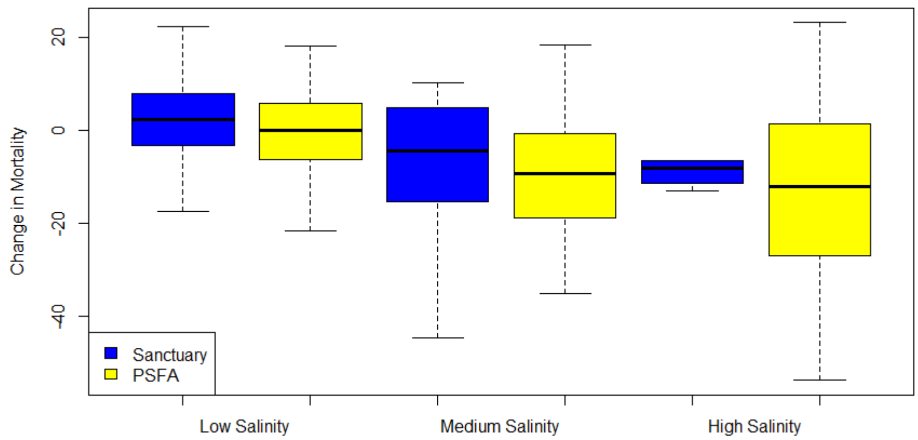

Figure 2: Box and Whisker Plot of Change in Mortality of Sanctuary and PSFA Bars by Salinity Level from 2010-2019

In tier 1 bars, sanctuary bars had a mean decrease in mortality of 4.2% while PSFA bars had a mean decrease of 8.92% (Table 4). In tier 2 bars, sanctuary bars had a mean decrease in mortality of 0.03% while PSFA bars had a mean decrease of 0.69% (Table 4). Neither of these differences were statistically significant, disproving the hypothesis that sanctuary bars would have lower values for change in mortality for tier 1 and tier 2 bars. There were no tier 3 PSFA bars that had sufficient time between samples to compare mortality in these bars, so calculation could be made for tier 3.

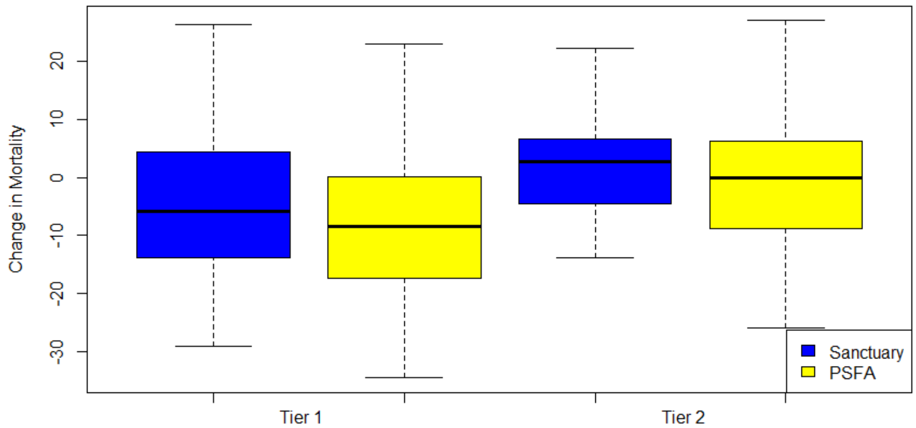

Figure 3: Box and Whisker Plot of Change in Mortality of Sanctuary and PSFA Bars by MDNR Tier from 2010-2019

There were sufficient samples in NOAA Codes 192, 027, 078, and 053 to compare sanctuary and PSFA bars. However, only the difference in Code 192 was statistically significant, with sanctuary bars having a mean increase in mortality of 8.59% and PSFA bars had a mean decrease of 17.74% (Table 5). The hypothesis was disproven as sanctuary bars had greater values in change in mortality compared to PSFA bars in NOAA Code 192, and there was no statistically significant difference between sanctuary and PSFA bars in NOAA Codes 027, 078, and 053.

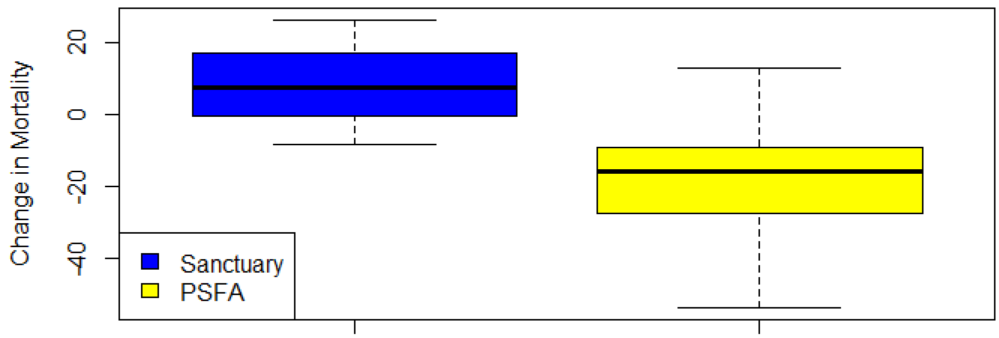

Figure 4: Box and Whisker Plot of Change in Mortality of Sanctuary and PSFA Bar in NOAA Code 192 from 2010-2019

4.2 Spat Per Bushel

When comparing the change in spat per bushel across all bars in the system, sanctuary bars had a mean decrease of 15.17 spat per bushel and PSFA bars had a mean decrease of 24.29 spat per bushel (Table 6). The Mann-Whitney U Test comparing the two datasets generated a p-value of 0.01253, representing a statistically significant difference (Table 6). As such, this validated the hypothesis as sanctuaries had greater values of change in spat per bushel than PSFA bars.

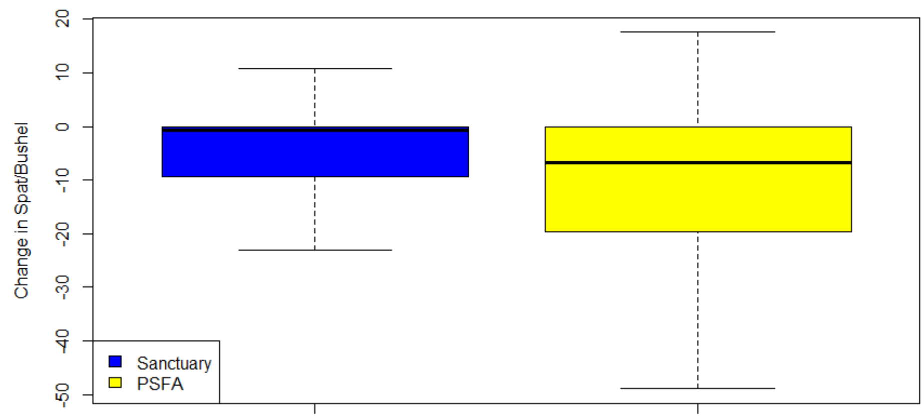

Figure 5: Box and Whisker Plot of Change in Spat per Bushel of Sanctuary and PSFA Bars from 2010-2019

Within low salinity zones, sanctuary bars had a mean increase of 0.43 spat per bushel, while PSFA bars had a mean decrease of 7.42 spat per bushel (Table 7). This was calculated to be a statistically significant difference, with a p-value of 0.003164 (Table 7). This validated the hypothesis that sanctuaries would have greater values of change in spat per bushel for low salinity zones.

In medium salinity zones, sanctuary bars had a mean decrease of 4.56 spat per bushel and PSFA bars had a mean decrease of 17.87 spat per bushel (Table 7). In high salinity zones, sanctuary bars had a mean decrease of 114.87 spat per bushel and PSFA bars had a mean decrease of 79.61 spat per bushel (Table 7). The differences in medium and high salinity bars were not statistically significant, disproving the hypothesis that sanctuary bars would have greater values of change in spat per bushel for medium and high salinity zones.

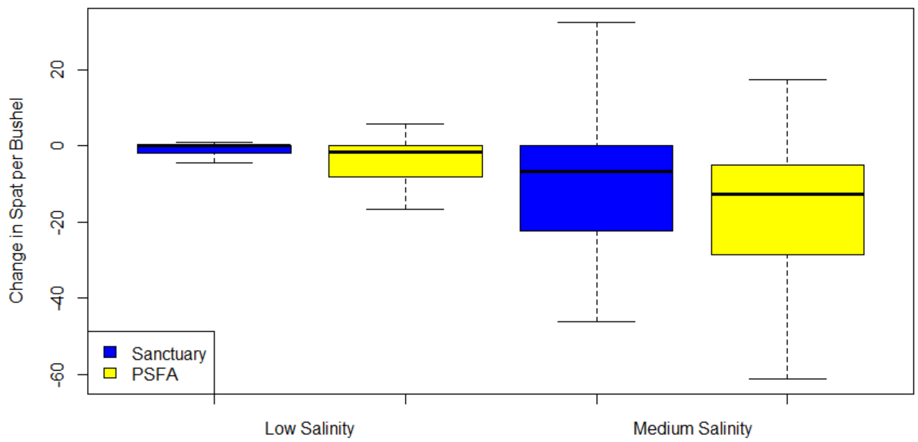

Figure 6: Box and Whisker Plot of Change in Spat per Bushel of Sanctuary and PSFA Bars in Low and Medium Salinity from 2010-2019

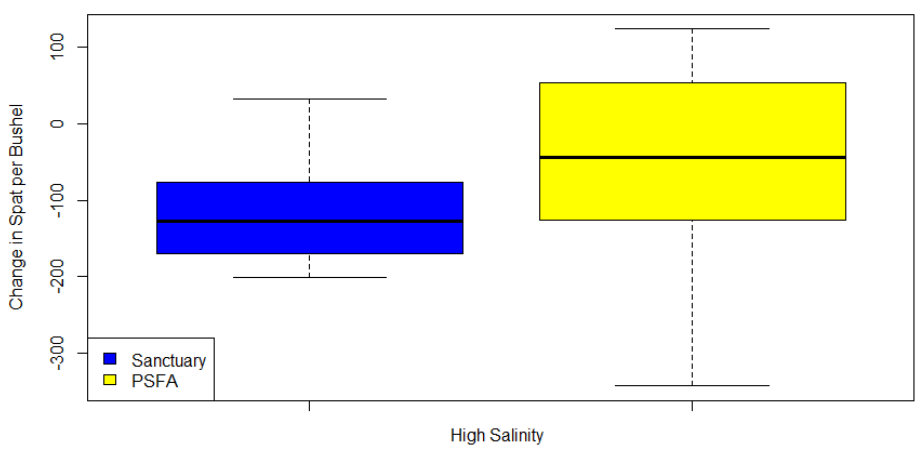

Figure 7: Box and Whisker Plot of Change in Spat per Bushel of Sanctuary and PSFA Bars in High Salinity from 2010-2019

In tier 1 bars, sanctuary bars had a mean decrease of 18.94 spat per bushel and PSFA bars had a mean decrease of 40.40 spat per bushel (Table 8). In tier 2 bars, sanctuary bars had a mean decrease of 2.86 spat per bushel and PSFA bars had a mean decrease of 7.28 spat per bushel (Table 8). Neither of these were statistically significant differences, disproving the hypothesis that sanctuary bars would have greater values for change in spat per bushel than PSFA bars in all tiers. As with mortality, there were no tier 3 PSFA bars that had sufficient time between samples to compare spat in tier 3 bars.

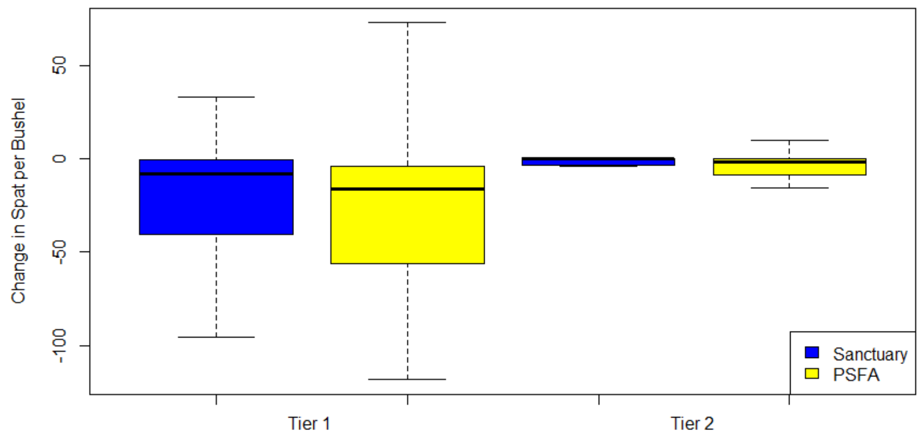

Figure 8: Box and Whisker Plot of Change in Spat per Bushel of Sanctuary and PSFA Bars by MDNR Tier from 2010-2019

There were sufficient samples in NOAA Codes 192, 027, 078, and 053 to compare sanctuary and PSFA bars, but none of the differences in spat per bushel were statistically significant (Table 9). This disproved the hypothesis that sanctuary bars would have greater values for change in spat per bushel than PSFA bars in all NOAA codes.

4.3 Biomass

Within all bars, sanctuary bars had a mean increase of 147.66% in biomass and PSFA bars had a mean increase in biomass of 186.22% (Table 10). The medians were significantly lower, however – with a median increase in biomass of 40.94% for sanctuaries and 19.66% for PSFA bars (Table 10). The difference between sanctuary and PSFA bars was not found to be statistically significant, disproving the hypothesis that sanctuary bars would have greater values change in biomass across all bars.

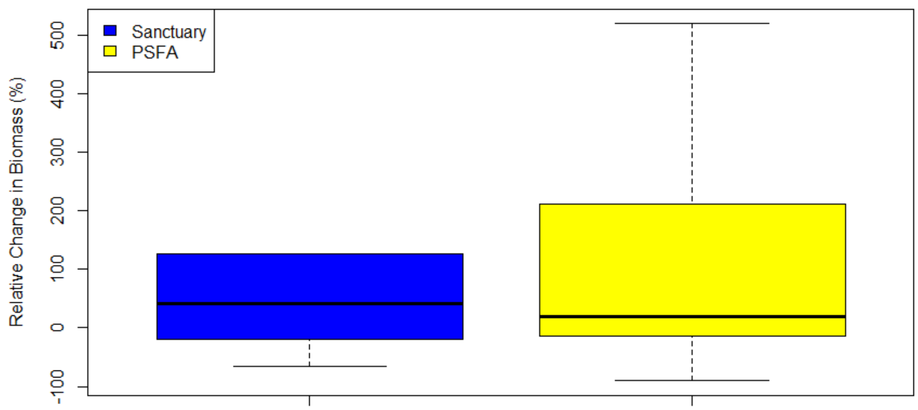

Figure 9: Box and Whisker Plot of Relative Change in Biomass of Sanctuary and PSFA Bars from 2010-2020

In low salinity zones, sanctuary bars had a mean increase in biomass of 176.84% and PSFA bars had a mean increase of 314.31% (Table 11). The medians for low salinity bars were significantly lower, with a median increase in biomass of 74.10% for sanctuary bars and a median increase in biomass of 60.57% for PSFA bars (Table 11). The difference between the two sets was not statistically significant, disproving the hypothesis that sanctuary bars would have higher values of change in biomass than PSFA bars in low salinity zones. The sample sizes for medium and high salinity bars were too low to make an effective comparison, as there was only a single sanctuary bar that had samples with enough time between them in medium and high salinity zones.

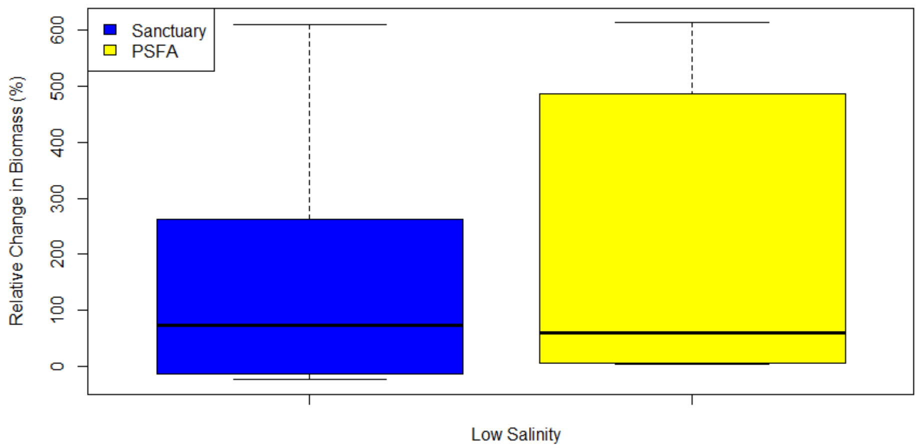

Figure 10: Box and Whisker Plot of Relative Change in Biomass of Sanctuary and PSFA Bars in Low Salinity from 2010-2020

Within tier 1 bars, sanctuary bars had a mean biomass increase of 265.32% and PSFA bars had a mean increase of 127.18% (Table 12). The median for the PSFA bars, however, was a decrease in biomass, with a median decrease of 4.56% (Table 12). Within tier 2 bars, sanctuary bars had a mean increase in biomass of 150.63% and a median increase of 95.48%, and PSFA bars had a mean increase in biomass of 266.81% and a median increase of 56.26% (Table 12). The differences in change in biomass in tier 1 and tier 2 bars were not statistically significant, disproving the hypothesis that sanctuary bars would have greater values for change in biomass than PSFA bars. There were no tier 3 bars PSFA that met the minimum amount of time between samples to compare biomass in tier 3 bars.

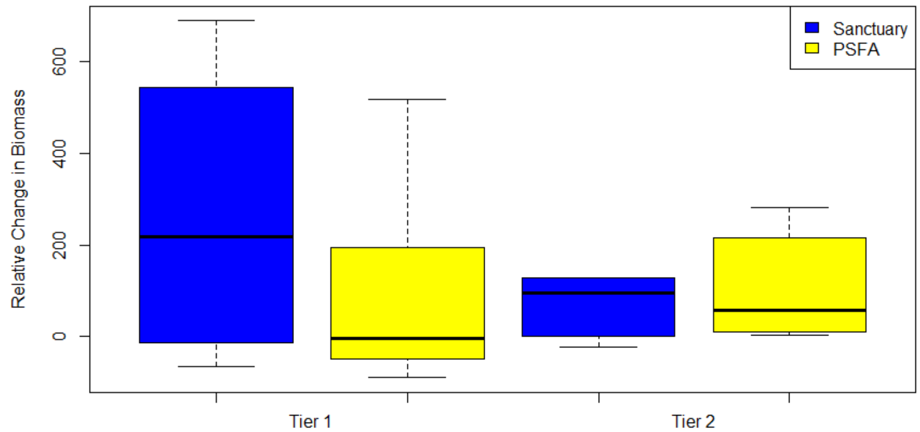

Figure 11: Box and Whisker Plot of Relative Change in Biomass of Sanctuary and PSFA Bars by MDNR Tier from 2010-2020

5. Discussion

There were few statistically significant differences between sanctuary and PSFA bars, as only four of the p-values calculated from the Mann-Whitney U Tests were less than 0.05, and thus most differences between changes in sanctuary and PSFA bars were not statistically significant. The only metrics that had statistically significant differences were the change in mortality across all bars, the change in mortality in NOAA Code 192, the change in spat per bushel across all bars, and the change in spat per bushel in low salinity bars. The change in mortality across all bars and in NOAA code 192 was lower for PSFA bars than sanctuary bars, which was the opposite of the hypothesis that sanctuary bars would have lower changes in mortality than PSFA bars. As such, the hypothesis was only validated in the change in biomass across all bars and the change in biomass in low salinity bars.

In many of the comparisons within salinity levels, tiers, and NOAA codes, the number of bars with sufficient samples to calculate a change of eight or more years was too small for effective statistical comparisons. Limiting a bar within a specific NOAA code led to particularly small sample sizes, and for tier 3 bars, there were no PSFA bars at all that met the requirement for samples eight or more years apart. This meant that effective statistical comparison was not feasible in these sub-categories.

The hypothesis was disproven in most of the sub-categories due to the lack of a statistical difference between sanctuary bars and PSFA bars. As such, this does not indicate that sanctuaries performed poorly compared to PSFAs, but rather that the difference between these metrics in sanctuary and PSFA bars was statistically negligible. As such, any positive impact of sanctuaries may not be measurable on a large scale within the timeframe. The high amount of variability in the data, particularly for biomass, also indicates that there may be too many environmental variables influencing the population metrics to perform an effective comparison based solely on whether a bar was in a sanctuary or PSFA.

5.1 Mortality Analysis

When considering the change in mortality, PSFA bars had greater mean decreases in mortality than sanctuaries. An important caveat in this comparison is that the mortality calculated from the Fall Surveys is natural mortality, i.e., it does not include harvest mortality. The Fall Surveys can only measure the mortality of the collected sample and does not account for any oysters removed by commercial harvest, and in practice there is some degree of overlap between the surveys and the fishing season, which could add some bias to the observed mortality if fishing removes more live oysters than dead shell (Doering et al., 2021). While a sanctuary area may have a small amount of harvest mortality due to poaching, they should have much lower rates of harvest mortality than PSFAs since harvest is banned in sanctuaries, and so the combination of natural and harvest mortality is likely to be higher in PSFAs than sanctuaries.

Additionally, when looking at the mean annual mortality from 2010 to 2019, there is not a clear trend favoring either sanctuary or PSFA bars (Figure 12). In 2010, the mortality of PSFA bars was higher than sanctuary bars, while in 2019, mean mortality was below that of sanctuary bars, which likely accounts for the statistically significant difference in the change of mortality over this time period. When considering the mean mortality for all samples from sanctuary and PSFA bars without plantings in the entire 2010-2019 range, sanctuary bars have a slightly lower mean mortality overall – at 14.2% compared to 14.87% for PSFA bars – but the difference is not statistically significant. Notably, these means are significantly below the 35-year average of 22.2% mortality, a decrease attributed to lower disease pressure, so natural mortality is less of a problem for either sanctuaries or PSFAs compared to the past (Tarnowski, 2020).

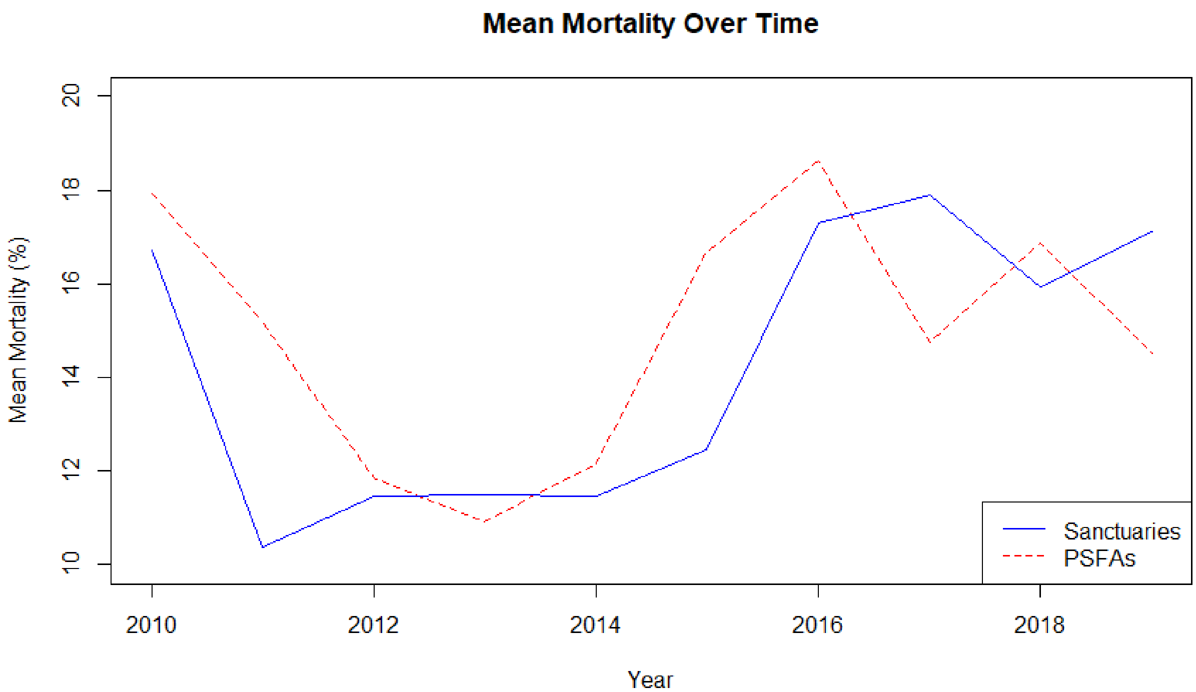

Figure 12: Annual Mean Mortality in Sanctuary and PSFA Bars from 2010-2019

The annual changes for mortality in both sanctuary and PSFA bars over the 2010-2019 follow a similar path, with the lowest mortalities in the 2012-2014 period before increasing from 2014 to 2016. This significant increase in both cases is likely due to increased disease mortality, as MSX prevalence in oysters was particularly high in 2015 and 2016 (Tarnowski, 2020). A comparison of low salinity bars to medium and high salinity bars further supports this, as bars in medium and high salinity bars have high mortality in these years, before dropping again after 2016 (Figure 14). Mortality in low salinity bars, on the other hand, continue to increase after 2016 (Figure 13). This suggests that mortality in low salinity bars is less driven by disease mortality – which follows as MSX is prevalent in higher salinities, and thus a greater factor in mortality in drier seasons when there are less severe freshwater inputs to lower salinity

(Tarnowski, 2020). Conversely, wetter seasons drive higher mortality in low salinity bars, since low salinity areas are more susceptible to freshwater inputs pushing salinity to levels too low for oysters to survive (Tarnowski, 2020).

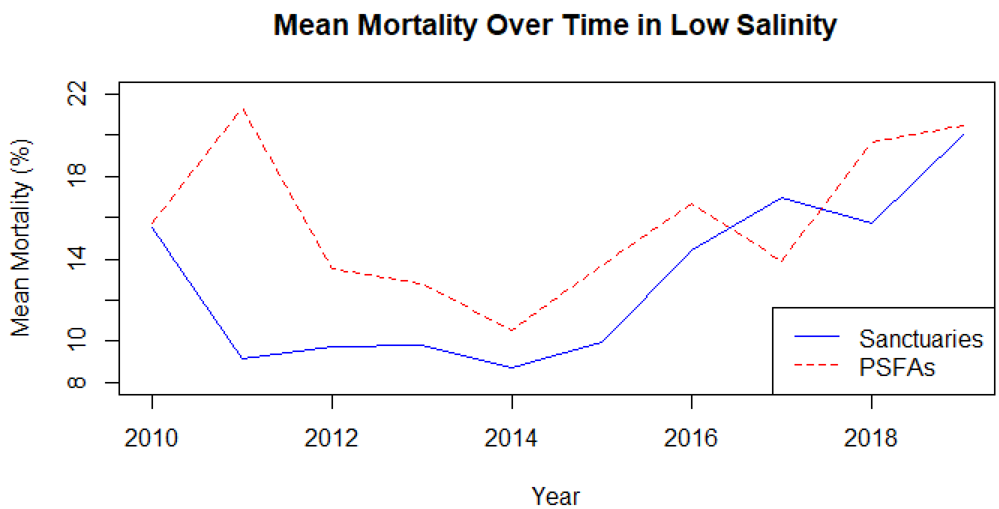

Figure 13: Annual Mean Mortality in Sanctuary and PSFA Bars in Low Salinity from 2010-2019

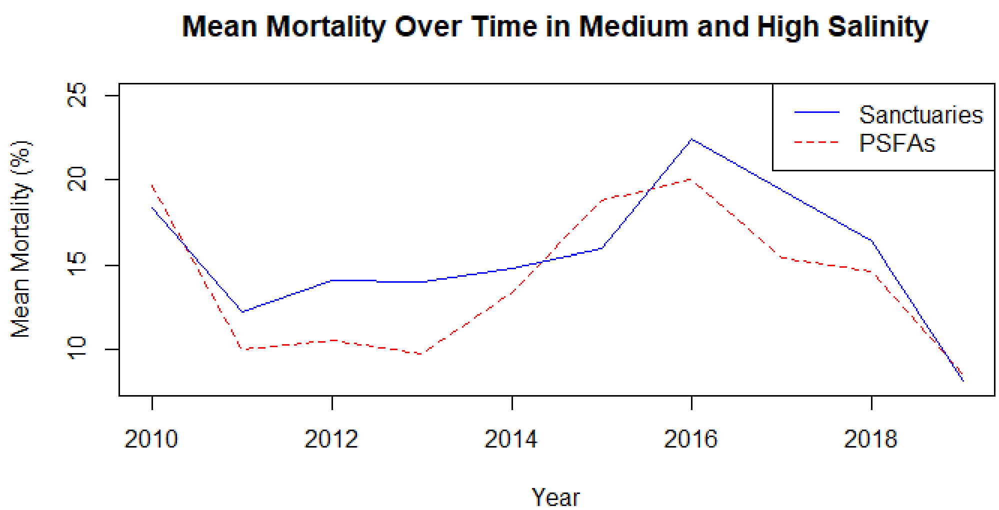

Figure 14: Annual Mean Mortality in Sanctuary and PSFA Bars in Medium and High Salinity from 2010-2019

While these broad trends apply in both sanctuary and PSFA bars, mean mortality for sanctuaries is lower than PSFA bars in low salinity zones, while the mean mortality for sanctuaries is higher than PSFA bars in medium and low salinity zones. The reason behind this is unclear and may be due to factors other than the harvest status of the bar. In theory, protecting larger individuals that have survived disease from harvest could help increase disease resistance in the greater oyster population, but this does not seem to be reflected in the comparison of mortality of sanctuary and PSFA bars in medium and high salinity areas (MDNR, 2016). However, such resistance would take time to develop, and the time frame of this analysis may simply be too short to see any benefit of sanctuary bars for disease resistance reflected in the data, so no conclusions can be made from this comparison.

Finally, there is a single NOAA code in which there was a statistically significant difference in the change in mortality, 192. However, a closer examination of the individual samples in these bars shows that this difference may be misleading. The sanctuary dataset only has three sample sites from a single oyster bar –Piney Island East Add 1. The three samples in this bar had a mean increase in mortality of 8.59% and a median increase of 7.64%. When comparing them to all PSFA bars in NOAA code 192, this is a significant increase. However, this bar is an addition on an existing bar – the Piney Island East bar, which is a PSFA bar. The Piney Island East bar has a single sample site with an increase in mortality of 7.14%. This is much closer to the mean and median change in mortality for the Piney Island East Add 1 bar, so when comparing the PSFA and sanctuary parts of this bar only, the difference in the change in mortality is insignificant. This suggests the increase in mortality compared to the rest of the bars in 192 are due to other factors than the sanctuary or PSFA status.

Overall, natural mortality in PSFAs and sanctuaries seem to follow broadly similar trends and the presence or absence of harvest does not appear to have a consistent influence on the natural mortality of a bar. Other factors, particularly salinity, seem to be much more significant factors in determining natural mortality of a bar. A potential factor that could be accounted for in future studies would be land use within the individual watersheds since high amounts of impervious surfaces could lead to greater amounts of fresh water and sediment from precipitation entering the tributary and impacting salinity.

5.2 Spat Analysis

In comparing the changes in spat per bushel, the trend favors sanctuary bars, although both sanctuaries and PSFAs indicated a mean decrease in the number of spat per bushel within the time frame. The only category that saw a mean increase in the number of spat per bushel was in sanctuary bars in low salinity areas, and even this increase was very small, with a mean increase of only 0.42 spat per bushel. Otherwise, sanctuary bars tended to have lower decreases in spat per bushel than PSFA bars, and this difference was statistically significant in both the overall system and in low salinity areas. The better performance over time of sanctuary bars may be due to more reproductive-age adults compared to PSFAs, where many adults of reproduction age could be harvested. Another potential explanation is that sanctuary bars have more hard-surface area than PSFA bars, since dredge harvesting tends to reduce the size of oyster reefs and remove settlement area for spat (Mercaldo-Allen and Goldberg, 2011). Even if there is sufficient reproduction, hard-surface area is necessary for spat to settle and grow into adult oysters – without sufficient settlement area, a reef will not be able to recruit new spat.

The annual means for spat per bushel does not show a clear difference between sanctuaries and PSFAs (Figure 15). Both follow similar annual trends with similar values, except for 2012 when PSFA bars had a significantly higher mean. This trend indicates that there does not appear to be a significant difference in the annual means between sanctuaries and PSFAs.

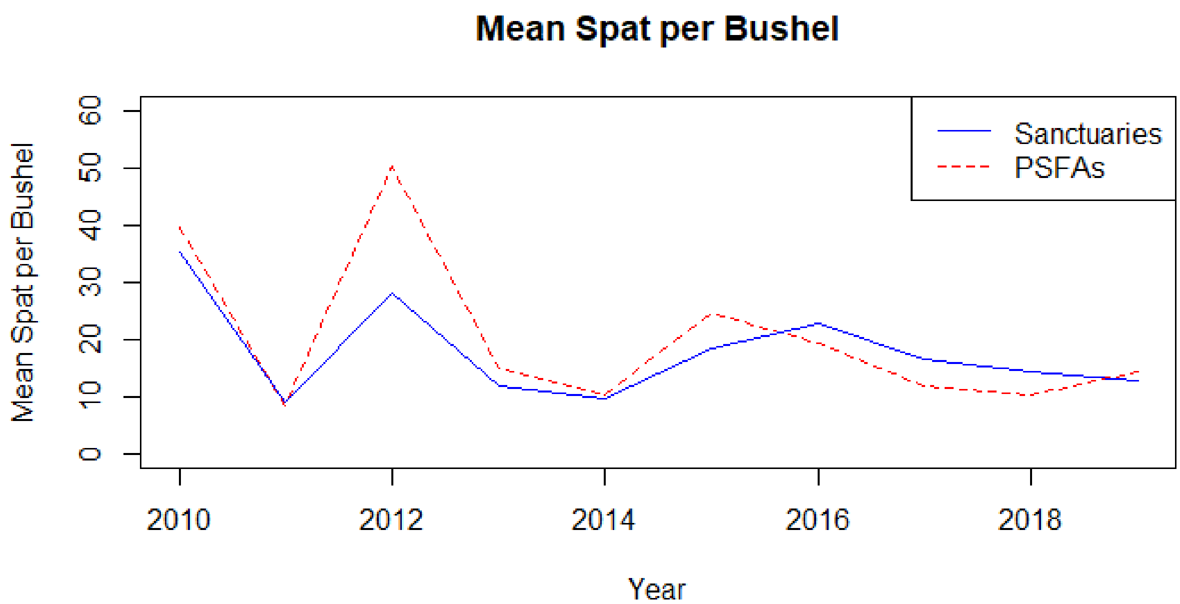

Figure 15: Annual Mean Spat per Bushel in Sanctuary and PSFA Bars from 2010-2019

A study of recruitment in the Great Wicomico River in Virginia provided evidence that sanctuary areas can serve as a reproductive reserve for nearby reefs, including those that allow harvest (Schulte & Burke, 2014). Oyster larva are planktonic and so do not necessarily settle in the reef that spawned them, so high reproductive rates in one reef could benefit other reefs that may have lower reproductive rates. If Maryland sanctuaries are acting as this sort of reproductive reserve, however, that does not appear to be reflected in the annual changes in spat per bushel. The sample size and the variability of the data may be too large to see any effect, and a study into the effect of sanctuaries as reproductive reserves would likely need to be conducted on a smaller scale with both sanctuary and PSFA reefs in very similar environmental conditions.

5.3 Biomass Analysis

Of the population metrics analyzed, biomass had the greatest amount of variability. The most extreme example of this is the overall PSFA biomass data, which ranged from a decrease of over 90% to an increase of near 1,700%. This made comparisons of the means of biomass changes in sanctuary and PSFA bars misleading, as demonstrated by the major discrepancy between the mean and medians of these datasets. The mean of the change in biomass for PSFA bars was greater than the mean for sanctuary bars, but the median for PSFA bars was less than the median for sanctuary bars. This made a comparison in the relative change in biomass between these two bar types unclear.

Looking at the mean annual biomass from 2010 to 2019, however, showed a clear trend that sanctuaries had higher mean biomass than PSFAs, particularly after 2013 (Figure 16). The 2013-2014 year sees sanctuary bars having a high increase in the mean biomass, while PSFA bars show a small decrease. When considering the time between 2013 and 2014 in mean mortality and spat per bushel, there are no major changes in either mortality or spat that would explain the major increase in sanctuary biomass, so this increase must be due to other factors. On the other hand, when considering the decrease in biomass for both types of bars from 2014 to 2016, mortality could be a factor since both sanctuary and PSFA bars indicated a significant increase in mortality in this same time period. Despite the decrease in sanctuary biomass from 2014 to 2016, mean biomass in sanctuary areas remained significantly above those in PSFA areas.

The trend in higher biomass in sanctuary areas, particularly after 2013, could be explained by the lack of harvest pressure in sanctuary areas. Biomass is sensitive to the number of large individuals in an oyster population, so the higher biomass in sanctuaries indicates that they tend to have larger and older individuals than PSFA bars (MDNR, 2016). This is likely a direct result of the lack of harvest in sanctuary bars, since commercial harvest will prize the largest and oldest individuals for selling to consumers.

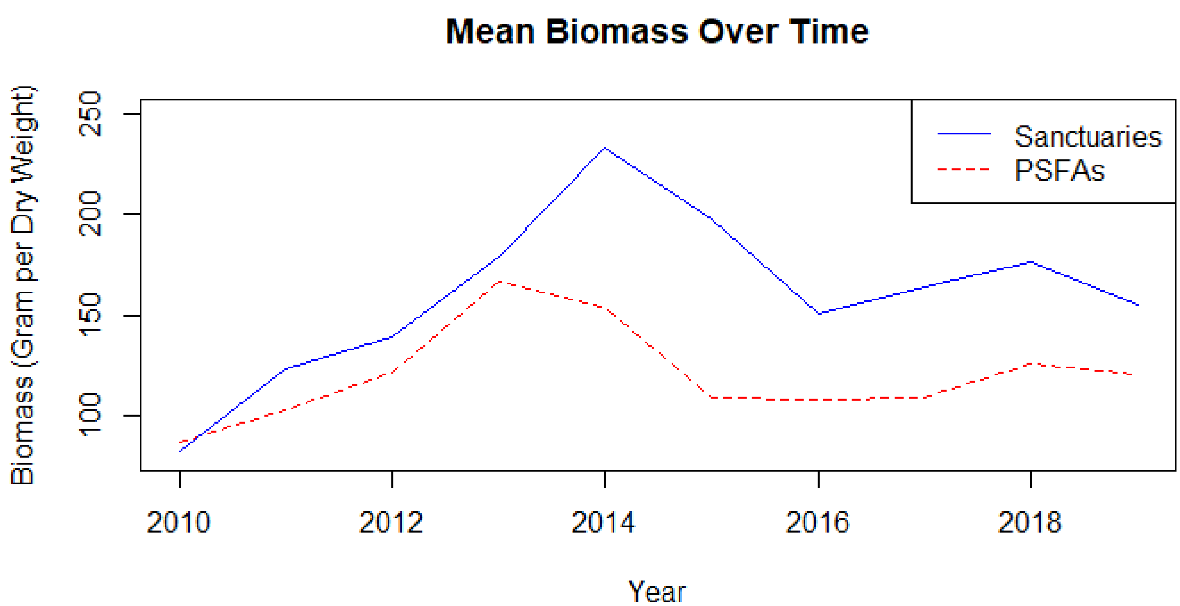

Figure 16: Annual Mean Biomass in Sanctuary and PSFA Bars from 2010-2019

Biomass is an important attribute for oyster's ecosystem services, as larger individuals have greater filtration capacity than smaller individuals (Ehrich & Harris, 2015). Larger individuals also provide more area for spat to settle and be added to the reef, even after the individual dies. While mortality and spat recruitment are relevant metrics for oyster populations, neither of them are considered one of the four universal metrics for oyster restoration within the

Oyster Habitat Restoration Monitoring and Assessment Handbook, a joint public-private guideline for assessing the success of oyster restoration (Baggett et al., 2014). While biomass itself is not considered a universal metric, size-frequency distribution is one of these metrics, and biomass is largely a factor of the size of the individuals in the population (Baggett et al., 2014). Given this, biomass could be considered the most important of the three metrics analyzed here. The fact that the annual means in sanctuaries are significantly above those of PSFA areas is a promising sign for the positive effect of banning harvest.

The comparison of annual means of biomass seems a more effective comparison for biomass than looking at the relative change from 2010 to 2019. The relative change in biomass, expressed as a percentage increase or decreases, had too much variability to effectively compare. While the mean percentage increase in PSFA bars was higher than sanctuary bars, the median increase for sanctuary bars was higher than for the PSFA bars, as there are several extreme outliers. But the raw annual means showed a much clearer trend towards higher biomass in sanctuaries. Future analysis could be conducted on year-by-year changes in biomass and may provide a better statistical comparison between sanctuary and PSFA bars.

5.4 Future Analysis

Given the lack of statistically significant differences between sanctuary bars and PSFA bars in the separate salinity zones, tiers, and NOAA codes, future research should consider different methodology to produce more distinct comparisons. Analyzing the annual means appears to provide a more accurate comparison between the two types of bars, particularly for biomass. Calculating the change between two individual years that were at least eight years apart did not consider the yearly fluctuations in mortality, spat, and biomass, which in retrospect are important factors in comparing these population metrics between sanctuary and PSFA bars. While some analysis was conducted on the trends in the annual means, a more in-depth statistical analysis of the annual means could provide clearer comparisons.

Additionally, future studies comparing sanctuary and PSFA bars would likely be more effective conducted at a smaller scale, eliminating as many variables as possible by choosing bars with similar environmental conditions. Even on this scale, the timeframe of ten years since the establishment of most sanctuaries may be too short to see the benefits. The restoration of oyster populations in Chesapeake Bay will be a long process, and the effectiveness of sanctuaries in the strategy to restore populations may not be fully measurable until many years later.

6. Conclusion

The lack of statistically significant results when comparing sanctuary and PSFA bars in the 2010–2019 timeframe suggests that statistical comparisons of the means of change in population metrics between sanctuary and PSFA bars may not have been feasible in the first place, particularly within the sub-categories of salinity zones, MDNR tiers, and NOAA codes. There are too many potential factors that influence mortality, spatfall, and biomass to isolate the differences in sanctuary and PSFA bars, particularly within a nine-year time frame. The detriments of dredge harvesting on oyster populations have been well-established, so the philosophy behind sanctuaries is sound, but these effects are difficult to separate from the many other variables on oyster population metrics, such as temperature, salinity, disease, predation, and sedimentation.

An analysis of the means in mortality and spat per bushel for each individual year from 2010 to 2019 showed similar annual means between sanctuary bars and PSFA bars, but an examination of the mean biomass for each year from 2010 to 2019 showed a noticeably higher mean biomass for sanctuaries compared to PSFAs from 2013 onwards, suggesting that the establishment of sanctuaries has had a positive effect on biomass compared to PSFA oyster bars.

Because of the high amount of variability found in the data for this study, future studies into the effect of banning harvest on oyster populations should consider limiting the study area to a smaller geographical area to limit the influence of environmental factors such as salinity, temperature, and land use. If a study were limited to a small number of bars, it would be necessary to collect more regular samples to provide a larger sample set for effective statistical comparisons.

There is also potential for a mesocosm study on the effect of sanctuaries on population metrics and could help reduce the influence of different environmental factors by establishing study areas in very similar environmental conditions, with one experiencing harvest and the other free of harvest. A mesocosm study on the effect of alternative reef substrates on the Eastern Oyster measured mortality, recruitment, and biomass in the study populations (Theuerkauf et al., 2015). Similar methodology in setting up the study populations and measuring the population metrics could be utilized in a study on the effect of banning harvest. The challenge with such a mesocosm study would be accurately simulating dredge harvest both in the individuals it removes from the population and how it alters the reef structure. If an effective methodology for simulating dredge harvest could be developed, a mesocosm study has potential to compare the population dynamics of oyster populations between those experiencing regular harvest and those free from harvest while minimizing the impact of environmental variables.

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Appendix A: Supporting Tables

Table 1: Chesapeake Bay geographical area with corresponding NOAA Code, Salinity Level, and Tier assigned by MDNR for relative productivity of oyster bars

NOAA Code	Area Name	Salinity	Tier
005	Big Annemessex River	High	3
025	Chesapeake Bay Upper	Low	2
027	Chesapeake Bay Lower Middle	Medium	1
039	Eastern Bay	Low	2
043	Fishing Bay	Low	1
047	Honga River	Medium	1
053	Little Choptank River	Medium	1
055	Magothy River	Low	3
057	Manokin River	High	3
060	Miles River	Low	2
062	Nanticoke River	Low	3
072	Pocomoke Sound	High	1
078	St Mary's River	Medium	1
082	Severn River	Low	3
086	Smith Creek	Medium	1
088	South River	Low	2
094	West River and Rhode River	Low	3
096	Wicomico River East	Medium	2
098	Monie Bay	Medium	3
099	Wye River	Low	3
127	Upper Middle Chesapeake	Low	2
129	Lower East Chesapeake Bay	Medium	3
131	Chester River Lower	Low	2
137	Choptank River Lower	Medium	1
168	Patuxent River Lower	Medium	2
174	St. Clements and Breton Bay	Low	2
192	Tangier Sound South	High	1
229	Lower West Chesapeake Bay	Medium	1
231	Chester River Middle	Low	2
237	Choptank River Middle	Low	2
268	Patuxent River Middle	Medium	3
274	Wiconomic River West	Low	2
292	Tangier Sound South	Medium	2
331	Chester River Upper	Low	3
337	Choptank River Upper	Low	3
368	Patuxent River Upper	Low	1

437	Harris Creek	Low	1
537	Broad Creek	Medium	1
637	Tred Avon River	Low	2

Table 2: Descriptive Statistics and P-value of Mann-Whitney U Test for Change in Morality in Sanctuary and PSFA Bars from 2010-2019

Bar Type	Mean	Median	Minimum	Maximum	P-Value
Sanctuary	0.5544843	0.7532957	-44.49602	48.14815	0.02251
PSFA	-4.247033	-4.603175	-54.7619	90.90909	

Table 3: Descriptive Statistics and P-value of Mann-Whitney U Test for Change in Morality in Sanctuary and PSFA Bars by Salinity Level from 2010-2019

Salinity Level	Bar Type	Mean	Median	Minimum	Maximum	P-Value
Low	**Sanctuary**	3.197757	2.369008	-33.33333	48.14815	0.332
	PSFA	2.445643	0.01249465	-54.7619	90.90909	
Medium	**Sanctuary**	-5.078741	-4.555249	-44.49602	42.30769	0.4049
	PSFA	-8.633786	-9.423077	-47.89941	52.12121	
High	**Sanctuary**	-4.780177	-8.188657	-22.46503	26.42857	0.3171
	PSFA	-11.98588	-12.10683	-53.72549	23.0303	

Table 4: Descriptive Statistics and P-value of Mann-Whitney U Test for Change in Morality in Sanctuary and PSFA Bars by MDNR Tier from 2010-2019

Tier	Bar Type	Mean	Median	Minimum	Maximum	P-Value
1	**Sanctuary**	-4.322076	-5.789791	-44.49602	42.30769	0.3215
	PSFA	-8.920781	-8.409091	-53.72549	52.12121	
2	**Sanctuary**	-0.02912586	2.70751	-33.33333	22.22222	0.4044
	PSFA	0.6863672	0	-54.7619	90.90909	

Table 5: Descriptive Statistics and P-value of Mann-Whitney U Test for Change in Morality in Sanctuary and PSFA Bars by NOAA Code from 2010-2019

Code	Bar Type	Mean	Median	Minimum	Maximum	P-Value
192	Sanctuary	8.593142	7.639979	-8.289125	26.42857	0.03235
	PSFA	-17.7415	-15.91795	-53.72549	12.99376	
027	Sanctuary	12.87798	12.87798	-16.55172	42.30769	1
	PSFA	5.229673	2.827767	-3.070175	18.33333	
078	Sanctuary	-7.42652	-7.426522	-9.063253	-5.78979	0.2667
	PSFA	-22.913	-18.53758	-47.89941	-6.67727	
053	Sanctuary	-12.2748	-3.320707	-44.49602	10.07646	0.6905
	PSFA	-10.2745	-9.713869	-14.04942	-7.19306	
237	Sanctuary	1.816877	1.170569	0.625	3.655063	0.2
	PSFA	-0.41958	-0.419584	-0.6875	-0.15167	

Table 6: Descriptive Statistics and P-value of Mann-Whitney U Test for Change in Spat/Bushel in Sanctuary and PSFA Bars from 2010-2019

Bar Type	Mean	Median	Minimum	Maximum	P-Value
Sanctuary	-15.17012	-0.6285714	-201.5385	101.3333	0.01253
PSFA	-24.28597	-6.84058	-688.1061	128.4615	

Table 7: Descriptive Statistics and P-value of Mann-Whitney U Test for Change in Spat/Bushel in Sanctuary and PSFA Bars by Salinity Level from 2010-2019

Salinity Level	Bar Type	Mean	Median	Minimum	Maximum	P-Value
Low	Sanctuary	0.429991 5	0	-41.11111	101.3333	0.00316 4
	PSFA	-7.415604	-1.516544	-91.35065	5.882353	
Medium	Sanctuary	-4.564923	-6.620837	-95.83333	76.1039	0.1528
	PSFA	-17.87261	-12.7193	-151.4545	128.4615	
High	Sanctuary	-114.8677	- 126.7368	-201.5385	32.98246	0.09468
	PSFA	-79.60929	-43.23341	-688.1061	124	

Table 8: Descriptive Statistics and P-value of Mann-Whitney U Test for Change in Spat/Bushel in Sanctuary and PSFA Bars by MDNR Tier from 2010-2019

Tier	Bar Type	Mean	Median	Minimum	Maximum	P-Value
1	Sanctuary	-18.94418	-7.948718	-95.83333	32.98246	0.3383
	PSFA	-40.39715	-16	-688.1061	128.4615	
2	Sanctuary	-2.863513	0	-23.07692	0.4878049	0.09825
	PSFA	-7.279732	-1.614583	-56	10.03008	

Table 9: Descriptive Statistics and P-value of Mann-Whitney U Test for Change in Spat/Bushel in Sanctuary and PSFA Bars by NOAA Code from 2010-2019

Code	Bar Type	Mean	Median	Minimum	Maximum	P-Value
192	**Sanctuary**	-39.1597	-74.1539	-76.3077	32.98246	0.5912
	PSFA	-83.1554	-19.3047	-688.106	124	
27	**Sanctuary**	-2.41667	-2.41667	-4.16667	-0.66667	0.1333
	PSFA	-26.4553	-20.8421	-57.1429	-6.9943	
78	**Sanctuary**	-68.1132	-68.1132	-95.8333	-40.393	0.5333
	PSFA	-29.876	-27.7564	-61.2987	-2.69231	
53	**Sanctuary**	-10.1356	-9.65217	-22.3077	0	1
	PSFA	-8.74502	-10.5714	-12.735	-2.61539	
237	**Sanctuary**	-8.04253	-1.53846	-23.0769	0.487805	0.8
	PSFA	-5.15385	-5.15385	-8	-2.30769	

Table 10: Descriptive Statistics and P-value of Mann-Whitney U Test for Change in Biomass in Sanctuary and PSFA Bars from 2010-2019

Bar Type	Mean	Median	Minimum	Maximum	P-Value
Sanctuary	147.675	40.93645	-66.44813	690.0558	0.9414
PSFA	186.2522	19.66432	-90.29378	1681.449	

Table 11: Descriptive Statistics and P-value of Mann-Whitney U Test for Change in Biomass in Sanctuary and PSFA Bars by Salinity Level from 2010-2019

Salinity Level	Bar Type	Mean	Median	Minimum	Maximum	P-Value
Low	**Sanctuary**	176.8442	74.10105	-23.73964	690.0558	0.3494
	PSFA	314.3092	60.57458	3.749963	1681.449	
Medium	**Sanctuary**	40.93645	40.93645	40.93645	40.93645	0.7273
	PSFA	198.9313	107.6547	-76.71799	817.5223	
High	**Sanctuary**	-66.44813	-66.44813	-66.44813	-66.44813	1
	PSFA	-48.30786	-48.30786	-48.30786	-48.30786	

Table 12: Descriptive Statistics and P-value of Mann-Whitney U Test for Change in Biomass in Sanctuary and PSFA Bars by MDNR Tier from 2010-2019

Tier	Bar Type	Mean	Median	Minimum	Maximum	P-Value
1	**Sanctuary**	265.3222	218.8405	-66.44813	690.0558	0.4107
	PSFA	127.1783	-4.562485	-90.29378	817.5223	
2	**Sanctuary**	150.632	95.48677	-23.73964	610.0083	0.7325
	PSFA	266.8075	56.26437	3.749963	1681.449	