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A Stock Assessment of the Eastern Oyster, *Crassostrea virginica*, in the Maryland waters of Chesapeake Bay

DRAFT REPORT FOR PEER REVIEW

14 March 2025

Maryland Department of Natural Resources Fishing and Boating Services

in consultation with

The University of Maryland Center for Environmental Science

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1 Background and Introduction

1.1 Distribution and Biology

The Eastern oyster, *Crassostrea virginica*, is native to coastal waters from the Gulf of St. Lawrence in Canada to the Atlantic coast of Argentina (Carriker and Gaffney, 1996). It is common in estuaries and coastal areas of reduced salinity and can occur as extensive reefs or 'bars' on hard to firm bottoms in both the intertidal and subtidal zones (Carriker and Gaffney, 1996). As is typical of animals that have evolved to inhabit the environmentally variable estuarine environment, *C. virginica* can tolerate a broad range of both temperatures and salinities (Shumway, 1996). In Maryland, sub-freezing temperatures and ice scouring restrict oyster bars primarily to the subtidal zone (Galtsoff, 1964).

In the Maryland portion of Chesapeake Bay variable salinity and temperature regimes are primary environmental determinants of oyster population dynamics, given their influence on reproduction, growth, and mortality (Shumway, 1996). Mortality rates, in particular, are interrelated with temperature and salinity because of the presence of two oyster protozoan parasites, *Perkinsis marinus* (dermo disease) and *Haplosporidium nelsoni* (MSX disease), although the relationship between the environment and disease mortality may have changed over time (Doering 2019). Dermo disease was identified in Chesapeake Bay oysters in 1949 but did not become a major problem until the mid-1980s (Ford and Tripp, 1996). MSX disease appeared in the Bay in 1959 and by the 1970s had dramatically reduced oyster densities in Virginia's high salinity oyster grounds (National Research Council, 2004). The MSX pathogen can tolerate salinities down to 10-12 parts per thousand (ppt) and become lethal at about 15 ppt and higher; they are active at temperatures above 10°C (Ford, 1985; Sprague at al., 1969; Ford and Tripp, 1996). The highly lethal dermo disease proliferates most rapidly at temperatures between 25° and 30°C and salinities greater than 15 ppt but survives at much lower temperatures and salinities (Ford and Tripp, 1996). During the latter part of the 1900s to the early 2000s, these diseases had a devastating impact on oyster populations in Chesapeake Bay, although they acted on a population that was already compromised by poor water quality, fishing and habitat loss (National Research Council, 2004). In any case, the presence of these two pathogens adds complexity to oyster population dynamics in Chesapeake Bay because mortality rates may vary substantially among years and also spatially within the same year depending on where the oysters are located within the Bay.

All oyster bars in Maryland are in mesohaline salinities (5-18 ppt). Within this salinity range, Maryland oyster bars are further classified into three zones for disease monitoring whose boundaries, especially in the mid ranges, shift with varying climatic conditions. Zone 1 has an average salinity between 5 and < 12 ppt, Zone 2 has an average salinity between 12 and 14 ppt and Zone 3 salinities are greater than 14 ppt (Maryland Department of Natural Resources, 2004). In general, disease pressure intensifies during dry years because of the northward intrusion of the salt wedge and the resulting elevated salinities (Tarnowski, 2024). In these years, Zone 1 can serve as a refuge from disease so that oysters in these areas may have lower mortality rates relative to the other zones. However, oysters in these less saline areas have low reproductive capability so that the influx of oyster larvae is intermittent, and settlement rates are low. Oysters in Zone 1 can also be subject to episodic freshets that result in substantial mortality (Maryland Department of Natural Resources, 2004). Zone 2 represents a transition area and oysters in these areas may have fluctuating rates of reproduction, growth and mortality based on the salinity variation between wet and dry years (Maryland Department of Natural Resources, 2004). In the Maryland portion of Chesapeake Bay, Zone 3 salinities are equal to or above 14 ppt and generally fall within what is thought to be the optimal salinity range (14 - 28 ppt) for C. virginica (Shumway, 1996). Although disease pressure can be persistent and mortality rates high in Zone 3, reproductive capability is maximized so that there is likely to be consistent recruitment of new oysters.

Gametogenesis and spawning in oysters are directly related to water temperature (Shumway, 1996). In the Chesapeake, oysters begin gametogenesis in the spring and spawning can occur from late May to late September and generally peaks in late June/early July (Shumway, 1996; Thompson et al., 1996). The larval stage lasts for about two to three weeks, depending on food availability and temperature. Larval growth rates increase rapidly with increasing temperature; the fastest rates occur near 30°C (Shumway, 1996). Larvae appear to migrate vertically, particularly at later stages, tending to concentrate near the bottom during the outgoing tide and rising in the water column during the incoming tide, thus increasing their chance of being retained in the estuary (Kennedy, 1996; Shumway, 1996).

C. virginica are either male or female (the reported incidence of hermaphroditism is less than 0.5%) but may change sex over the winter when they are reproductively inactive (Thompson et al., 1996). Generally, the animals function as males when they first mature which can happen as early as 6 weeks post settlement. As individuals grow, the proportion of functional females in each size class increases, with an excess of females occurring among larger (and presumably older) animals (Galtsoff, 1964).

The assessment team could not find any definitive study of the longevity of *C. virginica*. Several ages have been proposed, the most common being 20 years (Sieling ca. 1972; Buroker, 1983; Mann et al., 2009; NOAA-CBO, 2018), but the statements are either unsupported or make questionable inferences from other sources. Sieling (ca. 1972) comments “Oysters may live as long as 20 years, at least if undisturbed, as records of oysters kept in laboratories for that long are well known”, but with no supporting references. Powell and Cummins (1985) are cited in two papers for *C. virginica* lifespans of 10 to 15 years and 10 to 20 years, even though this species is never mentioned by them. Likewise, Lavoie and Bryan (1981) are cited for a longevity estimate of at least 15 years, although the only suggestion of longevity in their paper is a von Bertalanffy curve that extends to 14 years but with observed data only up to age 8. The highest estimate, 30 years, was made by Lockwood (1882). He based it on very old-appearing oysters that were supposedly planted 30 years earlier. He supported this assertion by counting 30 bands in the hinge area of both the upper and lower valves of a single oyster, a technique that subsequently has not gained widespread acceptance. Oysters in Maryland appear to survive at least 10 years based on plantings at restoration sites which are not thought to have received natural spat sets (Paynter et al. 2010). It is likely that the maximum longevity is substantially longer than 10 years.

1.2 The Importance of Substrate

Larvae of *C. virginica* require a firm, sediment-free surface upon which to settle and metamorphose (Kennedy, 1996), and this substrate is typically provided by oyster shell. The larvae's gregarious settlement response produces dense aggregations of oysters coexisting in communities, often called bars, reefs, or rocks (Smith et al., 2005). Oysters are somewhat unique in that they create the hard bottom habitat they require for population growth. In the absence of fishing, the rate of shell accretion through recruitment, growth and mortality must exceed the rate of shell loss at some densities for oysters to persist (Mann and Powell, 2007). Fishing not only removes adult animals but also potentially decreases productivity of the population by altering and diminishing necessary habitat (DeAlteris, 1988; Lenihan and Peterson, 1998). Reefs with higher profiles above the seafloor appear to promote enhanced oyster productivity. Low-profile reefs are subject to sediment deposition on the reef surface (DeAlteris, 1988; Seliger and Boggs, 1988). Increased sedimentation reduces the nutritional value of material that oysters ingest, leading to reduced growth and reproduction and heightened physiological stress from clogging of the oyster's filtering mechanism (MacKenzie, 1983). Siltation on reefs also impairs habitat quantity and quality for settling larvae and attached juveniles (Bahr, 1976). Smith et al. (2005) concluded that, regardless of the cause, high rates of oyster mortality in the Maryland portion of Chesapeake Bay have reduced the ability of natural oyster bottom to accrete more shell, thereby rendering the remaining shell more susceptible to being covered by sediment. An evaluation of the effects of harvest practices on oyster bottom is provided in Appendix A.

1.3 Description and History of Fisheries

At the peak of its production in the late 1800s, Chesapeake Bay was the greatest oyster-producing region of the world, with an oyster harvest twice that of the rest of the (non-US) world (Kennedy and Breisch, 1983). However, commercial landings in Maryland plummeted in the last part of the 19th century, with annual harvests decreasing by more than half between the late 1800s and the 1930s (Table 1; Figure 1). Over the following 50 years, harvests remained relatively stable, fluctuating around 2 million bushels annually until another decline occurred in the late 1980s primarily due to the oyster diseases MSX and Dermo (Maryland Department of Natural Resources, 1987). Since that time, commercial yields mostly remained at less than 400,000 bushels with a low of 26,000 bushels occurring in the 2003-2004 oyster season due to drought conditions and resulting elevated disease-related mortality (Maryland Department of Natural Resources, 2016). There has been an increase in the most recent years, when commercial yield was above 700,000 bushels and 500,000 bushels in the 2021-2022 season and 2022-2023 season, respectively; however, in the most recent year, commercial yield was slightly more than 400,000 bushels. Part of the reason for the decline was market driven. Demand was very low this season compared to the peak season of 700,000 bushels with many oystermen not working a number of days per week.

Maryland's commercial oyster fishery remains an important cultural and economic driver within Bay-side communities. Since the 2005-2006 harvest season, the average annual ex-vessel value of the Maryland oyster fishery is estimated to be $10.5 million (with a range of $2.6 million to $31.2 million).

Oyster bars throughout the Maryland portion of Chesapeake Bay vary widely in their habitat quality and level of productivity. The patchiness of oyster habitat combined with the regional management of the harvest gears and the department's planting activities with the County Oyster Committees (Section 1.4.1) results in an oyster population and fishery that is spatially complex. During the time series covered by this assessment (2005-2006 to 2023-2024), the bulk of the harvest (~70 percent) is generated by a small percentage of harvest reporting regions, called NOAA codes, and the fishery is mostly consolidated in the mid and lower Eastern Shore areas of the Maryland portion of the Chesapeake, particularly Tangier Sound and Choptank River. Although the department has harvest records back to the latter part of the 19th century, this stock assessment is conducted based on a 19-year time series beginning with the 2005-2006 harvest season through the 2023-2024 season. This represents the period when survey tow distances were recorded in the Fall Dredge Survey.

1.4 Management

1.4.1 Public Fisheries

The Maryland oyster fishery is currently managed using a variety of laws and regulations that are mainly targeted at controlling effort including a cap on the number of licenses, spatial gear restrictions, daily effort restrictions, and daily harvest limits.

Licensing and limited entry: Maryland has a cap of 2,091 commercial fishing licenses which is an "umbrella" license that enables the harvester to participate in a wide variety of fisheries including oysters. For those who don't need the all-encompassing license, there is also a separate Oyster Harvester License available, which allows up to 737 individuals to commercially harvest oysters. As such, there are 2,828 individuals who have the potential to harvest oysters in any given year (Code of Maryland Regulations [COMAR] 08.02.01.05, Natural Resources Article §4-10). Any license holder who wants to oyster must also pay the annual surcharge of $300 (USD), which allows the department to identify which subset of these licensees are active in an oyster season. Since the 2005-2006 oyster season, an average of 892 individuals paid the annual surcharge for oyster harvest. However, this number can fluctuate dramatically with changes in oyster abundance and market factors such as demand and price. For example, the number of surcharges has ranged from 469 in the 2006-2007 season to 1,354 in the 2022-2023 season.

Gear: There are a variety of permissible gears for the commercial harvest of oysters that are restricted both in terms of when and where they can be used as well as in their dimensions (Code of Maryland Regulations [COMAR] 08.02.04, Natural Resources Article §4-10). The primary gears are hand tongs, patent tongs, diver, power dredge, and sail dredge. Hand tongs are typically constructed of two wooden shafts ranging from 16 to 30 feet long that are attached at a pivot point with a pin, like scissors. At the end of each shaft is a metal rake to gather oysters as the tongs are manually opened and closed. Patent tongs also have rakes that gather oysters, but they are much larger and heavier than hand tongs and are attached to a rope (not shafts). Patent tongs are opened and closed with hydraulic power. Divers use a surface-supply air hose or, in some cases, SCUBA to collect oysters, cull them, and then send them to the surface. A power dredge is a chain-mesh bag attached to a frame that is lowered to the bottom using a winch. The dredge is pulled along the bottom using a motorized vessel to collect oysters and then retrieved. A sail dredge, operated from a sailboat or skipjack, is typically a chain-mesh bag attached to a frame and pulled across the bottom using a boat under sail power. Sail dredges are allowed to use an auxiliary yawl boat to push the skipjack two days per week, which renders them similar to power dredges.

Season and time limits: The harvest of wild oysters in Maryland is restricted to the months of October through March (power dredging and sail dredging are conducted November-March). The department has the authority to extend the season into April in the event of significant icing that impedes harvest during the normal season. Harvesting is allowed Monday through Friday (except for a restriction on harvesting on Wednesday during 2018-2020) from sunrise to 3 p.m., and the hours are extended to sunset in November and December. Because oyster harvest seasons straddle two calendar years, this report refers to 'seasons' rather than years. In cases where a year is used, it refers to the beginning year of the season.

Bushel limits: Currently, the daily catch limit for hand tong, dive, and patent tong is 12 bushels/license/day, not to exceed 24 bushels/vessel. Power dredges are allowed 10 bushels/license/day, not to exceed 20 bushels/vessel. Sail dredges are allowed 100 bushels/vessel/day. The current bushel limits went into effect during the 2019-2020 season. Prior to that, daily catch limits remained basically unchanged since the 1980s, with all gear types except power and sail dredge were allowed 15 bushels/license/day, not to exceed 30 bushels/vessel. Power dredges were allowed 12 bushels/license/day, not to exceed 24 bushels/vessel. Sail dredges were allowed 150 bushels/vessel/day.

The dimensions of the official MD bushel are defined in regulation as a specific number of cubic inches, which equates to approximately 46 L per MD bushel. Historically this official MD bushel container was heavy gage metal and was used dockside to offload the catch, however very few of these containers still exist. Since 2011, commercial harvesters have been allowed to use readily available plastic baskets which are now commonly used in the fishery. The more recent plastic baskets, referred to as the “orange basket”, are also 46 L, although harvest practices typically result in a smaller volume of oysters being harvested per container. The volume of oysters calculated from commercial bushels sampled by DNR after landing were an average of 36 L (Maryland Department of Natural Resources 2018).

Size limits: In 1927 the minimum size limit for oysters harvested from public grounds was increased from 2.5 to 3 inches, and this size limit remains in place to the present day (Kennedy and Breisch, 1983). Harvest of undersized oysters is legal, with up to 5% undersized oysters per bushel (by volume) being permitted.

In addition to the traditional use of effort and size limit controls described above, the Maryland wild oyster fishery has been historically managed on a fine spatial scale (bar level) in cooperation with the oystermen of the State. In 1947, legislation created county oyster committees whose charge is to interact with management and to advise on closing and opening bars; and on shell and seed planting activities (Kennedy and Breisch, 1983). The county oyster committees remain in place to the present day and are closely involved in the management of harvest bars (Natural Resources Article §4-1106). Funding for county efforts to improve certain bars through the planting of shell, hatchery spat on shell, or wild seed oysters is generated from the $300 license surcharge paid by each oysterman, by a $2 tax levied on each bushel of oysters harvested, a $1 per bushel oyster export tax on oysters shipped out of State, (Natural Resources Article §4-1020, §4-701), and, from 1996-2024 by a grant from the Maryland department of Transportation, Port Authority.

Active management of the wild oyster fishery has historically focused on bolstering the productivity of regions and individual bars to maintain and enhance harvest, rather than on population level parameters related to overall stock sustainability.

In 2010 the Maryland Department of Natural Resources amended its Oyster Management Plan (OMP) to include a 10-point plan for the restoration of the oyster population and fishery in the Maryland portion of Chesapeake Bay (Maryland Department of Natural Resources, 2010). To implement the amended plan, the Maryland Department of Natural Resources overhauled its regulations for managing oysters; expanding the scale of oyster sanctuaries, creating new opportunities for oyster aquaculture, and designating areas to be maintained for the public fishery. Several objectives were laid out within the preamble to the regulations including to "Implement a more targeted and scientifically managed wild oyster fishery" (Maryland Register, 2010). The OMP was revised again in 2019, replacing the 2010 version. Then in 2023, an amendment to the 2019 OMP was added that embodied consensus recommendations developed by the Oyster Advisory Commission; addressing topics such as shell, the Fall Survey, the oyster stock assessment, and implementing DNR's Eastern Bay Project. The commitment to the three priorities of sanctuaries, aquaculture, and the public fishery remained firm, as did the objective to have a more targeted and scientifically managed fishery.

1.4.2 Sanctuaries

Oyster sanctuaries are areas where harvesting of oysters is prohibited; however, these areas are open to crabbing, fishing, and in some cases, clamming. During 1961-2009 Maryland created 29 oyster sanctuaries and the majority of these were small, i.e., < 500 acres (Maryland Department of Natural Resources, 2016). The first sanctuary was established in the Tred Avon River in 1961 to support research at the Cooperative Oxford Laboratory. Subsequent sanctuaries were established during this time to support additional research, education, or restoration goals. In 2010, Maryland DNR expanded the sanctuary program to increase the oyster population and ecological benefits from oysters. After 2010, there were a total of 51 sanctuaries, which included some of the pre-2010 sanctuaries and represented about 24% of the oyster habitat in Maryland. Also, since 2010 there have been significant investments to restore oyster populations in five Maryland sanctuary tributaries where bottom habitat has been restored using a variety of materials and hatchery spat on shell have been planted on the restored reefs and unrestored bottom (Maryland and Virginia Oyster Restoration Interagency Workgroups of the Chesapeake Bay Program's Sustainable Fisheries Goal Implementation Team, 2024). Figure 2 shows the extent of the current oyster sanctuaries in Maryland.

1.5 Terms of Reference

The terms of reference for this stock assessment were developed by the stock assessment team:

1) Complete a thorough data review: survey data, reported harvest and effort data, studies and data related to population rates (growth, mortality and recruitment), available substrate, shell budgets, and sources of mortality.
    a) List, review, and evaluate the strengths and weaknesses of all available data sources for completeness and utility for stock assessment analysis, including current and historical fishery-dependent and fishery-independent data.
    b) Identify the relevant spatial and temporal application of data sources.
    c) Document changes in data collection protocols and data quality over time.
    d) Justify inclusion or elimination of each data source.
2) Develop a stock assessment model (or models) that estimates status of the stock relative to biological reference points. To the extent possible, quantify sources of uncertainty within model.
3) Compare estimates of stock status generated by the previous assessment model with the new model. Justify selected approach.
4) Provide research recommendations for improving the stock assessment.

2 Description of Data Sources

2.1 Fishery Dependent Data

2.1.1 Harvest Data

Two sources of commercial harvest and effort data are collected by the Maryland Department of Natural Resources: seafood dealer buy tickets and individual harvester reports (harvest reports). Every dealer licensed to buy oysters in Maryland completes a buy ticket report for every purchase made from a licensed commercial harvester. These reports are then submitted to the department. Because oysters are harvested and sold to seafood dealers on the same day, buy tickets represent a record of daily oyster harvest. Individual harvester reports are required from all commercial license holders who paid the annual surcharge to harvest oysters, even if no oysters were harvested. Harvest reports are submitted to the department monthly and describe daily harvest, effort, and other information for that month.

Buy tickets and harvest reports both include useful information for estimating effort and harvest as they include trip-level data on total bushels harvested, gear used, location of harvest, and hours spent harvesting. The primary difference between the two data sources is that buy tickets indicate whether there were one or two licensees aboard the same vessel whereas harvester reports are submitted for each individual, and it cannot be determined if two harvesters were working from the same boat. Therefore, buy tickets have important additional information because two licensees aboard a vessel each may harvest a full bushel limit so that vessels with 2 licensees have effectively twice the bushel limit of a vessel with only one licensed harvester aboard. The other major difference between the two data sources is the length of time for which the data are available.

Buy tickets have been collected by the department since the 1970s and are available in an electronic database since 1988. The department did not require harvest reports until the 2009-2010 season, and these data are available through 2024. This assessment is based on a 19 year period (2005-06 through 2023-24 seasons) using harvest reported via buy ticket data. Typically, the oyster season starts on October 1 and ends on March 31, hence the denotation of the harvest season being two years.

The spatial scale of this assessment is by NOAA code (Figure 3). Harvest location is reported by the name of the oyster bar and by NOAA code (Maryland Department of Natural Resources, 2016). Individual oyster bars were delineated in surveys conducted between 1906 and 1912 (Yates, 1913) and these delineations were amended until the 1980s. There are currently 1,105 Yates bars and amendments with areas ranging from 1.2 to 4,988 acres with a mean size of 299 acres. NOAA codes are statistical reporting areas that were created for the purpose of reporting fishery harvest. There are currently 47 NOAA codes used by the department for shellfish harvest reporting but only 39 were considered for use in this stock assessment. The NOAA codes range in size from 846-185,468 acres with a mean size of 32,078 acres. A single NOAA code may contain multiple oyster bars. For convenience of presentation, individual NOAA codes are grouped into nine geographical regions: Tangier Sound, Choptank River, Eastern Bay, Chester River, North Mainstem, South Mainstem, Patuxent River, Potomac River, and the Western Shore. Table 2 presents summary details for each NOAA code.

Trip-level NOAA code information is included in buy ticket data for the entire time series. Twelve of the 47 NOAA codes were excluded from this analysis either because they were outside of the department's management jurisdiction (i.e., Potomac River NOAA codes 177, 277, and 377) or because the area is outside Chesapeake Bay (Maryland coastal bays NOAA codes 12, 212, 312, and 412) or because no oyster bars are located in the NOAA code based on historic surveys (NOAA code 14) or because they were data poor (NOAA Code 5, 55, 94, 98). Specifically, data poor areas were either not consistently surveyed during the fall dredge survey or adult oysters were not consistently observed in the fall dredge survey.

2.1.2 Description of Harvest and Effort

Harvest, effort and the annual number of participants showed very similar patterns over the time series (Figure 4). The number of participants varied over time and is equal to the number of oyster license surcharges purchased each year. Effort is likely a primary determinant of harvest. Under current management, the fishery appears to be self-regulating in that effort diminishes when oyster density drops to a point where it is no longer commercially profitable to fish resulting in a boom and bust dynamic (Mace et al. 2024).

Over the 19-year period (2005-06 through 2023-24), a total of 5.2 million bushels was reported harvested. Harvest was low and stable during the period of 2005-06 to 2011-2012 with an average of about 122,000 bushels per year. The reported harvest rose sharply in the 2012-2013 season to 348,000 bushels, following the strong spat sets of 2010 and 2012, and continued at this higher level through the 2015-2016 harvest season (Figure 5). Harvest decreased during the 2017-18 and 2018-19 seasons. After the 2019-20 season, harvest increased sharply to a high of 722,000 bushels. Effort also increased with more license holders purchasing surcharges and participating in the fishery.

2.1.3 Patterns of Harvest by NOAA Code

No particular gear is used exclusively in any NOAA code but the harvest from most NOAA codes is dominated by a single gear (Figure 6). Eight NOAA Codes had 75 percent of the reported harvest (3.9 million bushels) during 2005-2023, all located in southern or eastern regions of the Maryland portion of Chesapeake Bay (Figure 7). All other NOAA codes together contributed <25% to the overall harvest.

During the 19-year time series, the top 8 NOAA codes with the highest harvest are (in order from highest to lowest): Tangier Sound North (292), Broad Creek (537), Tangier Sound South (192), Fishing Bay (043), Patuxent River Lower (168), Honga River (47), Eastern Bay (39), and Choptank River Lower (137). Harvest was reported from all of these NOAA codes for at least 18 seasons of the time series, however, they were not consistently the highest harvest NOAA Codes throughout the time series (Table 3). NOAA Codes 292 and 537 were the top two highest reported harvest NOAA Codes for 13 and 12 seasons, respectively. In comparison, NOAA Code

39 was only in the top two highest reported harvest NOAA Codes for 2 seasons (2005-06 and 2006-07) and in the top 75% for 8 seasons.

Several NOAA codes were inconsistently harvested, resulting in zero-harvest for many seasons (Table 4). Between one to nine NOAA Codes did not have reported harvest annually. The NOAA Codes that most consistently had zero reported harvest include: the Severn River (82), the Wye River (99), St. Clements and Breton Bay (174), and the Upper Chester River (331). Apart from St. Clements and Breton Bay, the other three NOAA Codes are primarily non-harvest, sanctuary areas.

2.1.4 Patterns of Harvest by Gear

Over the 19-year time series, 71% of the total harvest was from power dredge and patent tong (46% and 24%, respectively). Hand tonging provided another 15% of the harvest, followed by diver and sail dredge at 7% each (Table 5; Figure 8). There was likely sail dredge harvest occurring in 2005-06 to 2009-10 season, however, the data at that time were combined with power dredging. Harvest by gear has shifted through the times series (Figure 10). Diver harvest was highest in the earlier part of the time series. Hand tonging was also highest in the earlier part of the time series, then decreased during 2009-10 to 2011-12, increased and remained stable between 2012-13 to 2020-21, and then decreased afterwards. Power dredging produced the highest amount of harvest during 2008-09 to 2013-14. Sail dredge and patent tong harvest has remained stable throughout the period (Table 5).

The gears used among the NOAA codes with the most harvest varied (Table 6; Figure 6). Tangier Sound North (292) and lower Patuxent River (168) were predominately patent tong harvest. Broad Creek (537) has separate hand tong and power dredge areas, and reported hand tong harvest is higher than power dredging. Power dredge harvest was highest in Tangier Sound South (192), Fishing Bay (043), Honga River (047), and the lower Choptank River (137).

2.1.5 Harvest Data Assumptions

Reported harvest, whether from buy tickets or harvester reports, is not expected to be a completely accurate accounting of harvest as under-reporting and reporting errors are known to occur. An additional means to estimate harvest is through a tax that is collected by the department from dealers for every bushel purchased from harvesters. Until the 2023-24 season, this tax was set at $1 USD per bushel purchased. In 2023-24, the tax was increased to $2 USD per bushel at the request of the harvesters. These and other funds are used to maintain and enhance oyster bars through the additions of oyster shell, wild seed (naturally set, transplanted oysters), and hatchery-reared spat. The pattern of harvest was similar among buy tickets, harvester reports, and bushel taxes (Figure 10).

The three harvest reporting methods provide the opportunity to estimate an under reporting rate which can be applied to the time series of harvest used in the assessment model. Harvester reports were required for the first time in the 2009-2010 oyster season. During the first two years these were required, catch reported by individual harvesters was greater than that reported via buy tickets. In these first two years, harvester reporting was not enforced and it is assumed that this catch represents 'true fishing behavior' of the harvesters and therefore is a reasonable estimate of a scaling factor to apply to buy ticket data to correct for under reporting. The average difference between the two harvest estimates for these two years is about 10 % (90 % of the harvest reported on harvester reports was reported on buy tickets). As such, 10% was applied as a scalar to adjust the annual harvest from buy tickets used in the assessment upward. However, after the 2013-14 season, the reporting rate for harvesters has decreased. In the most recent season, only about 60% of the harvesters submitted the required information to the department. Harvest as reported by the seafood dealers on buy tickets is required for the assessment due to low harvester reporting compliance.

The buy ticket records within the assessment period are not all complete, and there is no means to independently verify the reported catch. Some records do not have gear type or NOAA code recorded. Gear codes are used on the form to facilitate data entry but caused confusion among some dealers, especially during the period covered by this assessment. This is likely due to the co-occurrence of power dredging and traditional skipjack dredging, also known as “dredge boat” or “sail dredge.” For example, there was apparently no reported sail dredge harvest from 2005-2006 to 2009-2010 through buy tickets although it is known that skipjacks were harvesting during this period. While sail dredge harvest was not used in these analyses as its own category, it is likely that this harvest was erroneously coded as power dredge. Some of the smaller NOAA codes may have also had a disproportionate amount of error due to the difficulty for harvesters and dealers to ascertain the proper boundaries on the maps provided to them or typos or other errors in entering data.

Due to the issues described above, some decisions had to be made when calculating total catch within each NOAA code for each year. Harvest that did not have a NOAA code recorded or a NOAA code that was not an official NOAA code was assigned to other NOAA codes based on the proportion of harvest for records where the NOAA code was recorded. Records with a gear from a NOAA code where that gear is not allowed were treated similarly to records with no NOAA code. If a NOAA code was not modeled, harvest was reported outside of the season, or the record was missing the number of bushels harvested, then the records were excluded

For use in the population dynamics model, harvest was converted from bushels to number of individual oysters using a conversion factor of 228 individuals per bushel based on limited port sampling data (Maryland Department of Natural Resources 2018). We also assumed 8% of the harvested oysters were small (<76 mm). Limited port sampling has been conducted with samples from 18 oyster bushels from seven NOAA codes (Eastern Bay - NOAA code 39; Fishing Bay - NOAA code 43; Miles River - NOAA code 60; Lower Patuxent River – NOAA code 168; Middle Choptank River – NOAA code 237; Upper Tangier Sound – NOAA code 292; Broad Creek – NOAA code 537) representing all gear types except for sail dredge. For each bushel, the total number of oysters were counted and every fifth oyster was measured to determine the proportion of small oysters per bushel. A detailed description of the sampling and results are in

Appendix III in Maryland Department of Natural Resources (2018). Observed catch was adjusted using an assumed underreporting rate of 10%.

In most NOAA codes, some harvest occurs before the Fall Dredge Survey, which will bias estimates of density from the beginning of the season. To account for harvest that occurred before the Fall Dredge Survey sampled in a NOAA code (see Section 3.1.1), we also summarized harvest by pre- and post-Fall Survey sampling in each NOAA code in each year. The first date of sampling for the Fall Survey in a NOAA code was used as a cutoff to determine the pre- and post-Fall Dredge Survey harvest.

2.1.6 Exploitation Fraction and Fishing Mortality Rate

In the previous Maryland Oyster Stock Assessment, fishing mortality rate was calculated using catch-per-unit-effort data from the buy tickets in a depletion analysis (Maryland Department of Natural Resources, 2018; Mace and Wilberg, 2020), which was then used as an index of fishing mortality in stock assessment model. In some of the NOAA codes with high harvest, e.g., Upper and Lower Tangier Sound – 292 and 192, there has been no observed decrease in fishery CPUE across the fishing season in recent years, which caused issues when fitting the depletion models because these models rely on a decrease in CPUE to estimate fishing mortality. Several attempts were made to fit the depletion models by considering alternative CPUE metrics and excluding the first few weeks of harvesting when power dredging is not allowed, but issues with estimation remained. Therefore, these depletion analyses were not included in this assessment.

2.2 Fishery Independent Data

2.2.1 Fall Dredge Survey

Since 1939, the Maryland Department of Natural Resources and its predecessor agencies have conducted dredge surveys to monitor the oyster population in the Maryland portion of Chesapeake Bay. Samples are collected on natural oyster bars, seed and shell plantings and in sanctuaries from mid-October through late November (Tarnowski, 2024). This is an index-based approach designed to look at long-term trends in aspects of the oyster population (spat density, disease, biomass and mortality) rather than absolute abundance. The raw data prior to the late 1970s are missing, and only a partial summary is available (Meritt 1977). Since 1975, 53 sites have been designated as "key bars" and are used to provide an annual index of spat settlement intensity at fixed locations. Since 1990, a subset of 43 bars, 31 of which are also key bars, are used to collect information on oyster parasite prevalence and intensity. From 2005 to 2023, the number of dredge tows taken during the survey ranged from 311 to 385 (mean = 342) and the number of oyster bars sampled ranged from 247 to 265 (mean = 255).

The survey uses a 32-inch-wide (.81 m) oyster dredge to obtain samples. Beginning in 2005, the distance for each tow has been recorded using a hand-held GPS unit. The total volume of dredged material is recorded prior to a sample being removed. A full dredge is 2.1 Maryland bushels (Maryland bushel = 2008.9 cubic inches or 45 liters). On key bar and disease bar sites, two one-half bushels samples are collected from replicate dredge tows, while at most other stations, a single half-bushel sample is taken. Water quality data (salinity and temperature) are collected on each bar. For each sample, live oysters are sorted into spat (recently settled oysters), smalls (<76 mm), and markets (≥ 76 mm). Small and market boxes (dead oysters with hinges articulated) are also counted, and the relative age of the boxes is assessed based on the amount of fouling. For disease bars, key bars, and selected other samples, all live oysters and boxes are measured to the nearest millimeter. For the remainder, a range of oyster shell heights and an estimate of the mean are taken. Samples of live oysters are retained for disease testing at the 43 disease sites and selected other locations in the Bay.

The oyster stock assessment used data from the fall dredge survey for 2005-2023 for all NOAA codes except for the Potomac River, West and Rhode rivers, and Monie Bay. Potomac River samples are excluded because bars in that area are managed by the Potomac River Fisheries Commission. The other NOAA codes have no fall dredge survey samples for the time series. Figure 11 shows the sample sites for the 2023 fall dredge survey, excluding the Potomac River.

In the stock assessment, relative counts of live and dead oysters (boxes) per area swept were used to fit the oyster population model to estimate abundance and natural mortality (see Sections 2.3.1 and 3.1 for a complete description of the model and standardization procedure).

2.2.2 Bottom Habitat Surveys

Several attempts have been made to assess the area of oyster habitat in Maryland's portion of the Chesapeake Bay. The first comprehensive survey was the Yates survey during 1906-1912. The purpose of this survey was to identify the boundaries of "Natural Oyster Bars" within Maryland's portion of the Bay, so that areas outside of oyster bars could be used for oyster aquaculture leases. The original Yates survey and subsequent surveys identified approximately 1,100 oyster bars and over 300,000 acres of oyster habitat (Table 2). Later studies have estimated that only 36,000 acres is viable oyster habitat currently (U.S. Army Corps of Engineers, 2009).

The Maryland Bay Bottom Survey (MBBS) was conducted during 1975-1983 to generate maps that updated the Yates bars (Table 2). This survey used a dragged acoustical device (hydrophone), patent tongs, and sonar to produce bottom classifications that included sand, mud, cultch (shells of live and dead oysters) and hard bottom. Cultch and mixed-cultch categories are substrate types that provide habitat for oyster spat. These surveys (and other, more recent, side-scan sonar surveys conducted in sanctuaries and other areas) can be used to estimate the amount of habitat available for oysters. The original MBBS maps for Eastern Bay (NOAA code 39), Wye River (NOAA code 99), and Miles River (NOAA code 60) were lost so there is no MBBS habitat estimates for these NOAA codes. For Eastern Bay (NOAA code 39) and Wye River (NOAA code 99), more recent sonar survey data was used as the basis for the habitat estimate. For the Miles River (NOAA code 060), recent sonar surveying did not cover the entire NOAA code. Therefore, habitat was estimated by multiplying the habitat area of the historic Yates bars by the overall average percent difference between historic Yates bar area and habitat area from the MBBS for the other NOAA codes in the assessment. The average estimated amount of habitat per NOAA code relative to the historic bar area is 46.84%, which when multiplied by the historic bar area (3,481.7 acres) resulted in an estimated habitat area of 1,630.9 acres for Miles River (Table 2).

2.2.3 Replenishment and Restoration Efforts

Almost every oyster bar in Maryland has been manipulated over time through replenishment and restoration efforts to improve oyster bar productivity. Most replenishment efforts were intended to enhance the public fishery and occurred prior to the establishment of sanctuaries. Restoration efforts were those activities occurring after the establishment of a sanctuary with the objective to restore oyster populations for ecosystem and ecological benefits. The types of enhancements employed include planting fresh and dredged oyster shell, quarried fossil oyster shell, reclaimed oyster shell from previous plantings, clam and whelk shell, and non-shell substrates such as stone and crushed concrete, as well as transplanting natural, wild seed, and planting hatchery-reared spat-on-shell. Records of these activities date back to 1960, but shell and seed plantings only since 2005 will be presented. All replenishment and restoration planting data are stored in an ArcGIS geodatabase. Information recorded includes planting year, planting type, planting location, and planting amount. Both the planting center point latitude and longitude are recorded along with the corner coordinates.

Since 2010 planting data have been recorded using GPS trackers, and vessel tracklines were provided to the department. Prior to 2010 there are issues within the data concerning both precision and completeness of records, and care must be used when trying to infer total planting volume within a given area. The area of the Bay bottom treated by the planted materials (Table 2) was calculated with ArcPro using the dissolve tool on the polygon layer within the DNR oyster plantings geodatabse for materials planted during the years 2005-2023. Due to the spatial overlap of plantings in multiple years this method allows for the estimation of the “footprint” of the area treated whereas simply summing the area planted in each year would result in an overestimate and not be directly comparable to the other areas used in the assessment (e.g., habitat area, historic bar area).

Wild seed plantings were recorded in bushels, and to account for these plantings in the population dynamics model, bushels were converted to individuals by assuming 1,267 individuals per bushel (MARYLAND DEPARTMENT OF NATURAL RESOURCES, unpublished data).

2.2.4 Patent Tong Surveys

The Maryland Department of Natural Resources regularly conducts patent (hydraulic) tong surveys for a variety of purposes: 1) to evaluate the effects of power dredging, 2) to assess the effects of waterway dredging or construction on oyster populations and 3) to assess potential aquaculture lease sites. When Maryland expanded the oyster sanctuary program in 2010, the department began a study to evaluate oyster populations within sanctuaries. Most sanctuaries have been sampled at least once (Maryland Department of Natural Resources, 2016).

These surveys use a stratified random sampling design, with the strata based on substrate type. The number of sampling points varies based on the estimated amount of potential oyster habitat within the sanctuary but ranges generally from 50 to 300. The patent tongs used in these surveys sample an area of 1 square meter. Any oysters in the sample are sorted into spat (newly settled oysters), small (< 76 mm), market (≥ 76 mm) and boxes (dead oysters with hinges articulated). Live oysters and boxes are counted and measured. The amount of total material in a sample is measured to the nearest 0.5 liter and the amount of surface material is estimated. Depth and bottom type are also recorded.

Because patent tongs sample a fixed area of the bottom, oyster density can be calculated. The average density of oysters based on all samples collected within a sanctuary is used to derive the overall density of oysters within the sanctuary. The relative proportion of surface material (especially oyster shell) to buried shell in the samples can also be used to estimate the amount of oyster habitat, since exposed shell is the preferred material for larval oyster settlement. A greater proportion of surface shell indicates greater potential for spat settlement. The relatively large number of samples taken during these surveys can be used to examine the spatial distribution of oysters within the area sampled.

Patent tong data were not used in the current assessment because of the potential lack of representativeness due to most surveys being conducted in oyster sanctuaries. Therefore, they may not represent oyster density across an entire NOAA code. In addition, the catchability of patent tongs was assumed to be 100% in the previous Maryland Oyster Stock Assessment (Maryland Department of Natural Resources, 2018), but catchability of patent tongs has been shown to be less than 100% in Harris Creek (437) (Wilberg et al. 2022). It is unknown how catchability may vary across NOAA codes due to different bottom types, oyster density, etc., so patent tong data could not be adjusted for catchability. For these reasons the patent tong survey data were not included in this assessment.

2.3 Fishery Independent Data - Calculations for Model Inputs

2.3.1 Density - Standardization of Fall Dredge Survey Indices

A mixed-effects generalized linear model (GLM) was used to obtain standardized estimates of the number of oysters per m^2 from the fall dredge survey data. The standardization was done to account for unbalanced sampling over time.

The mixed effects GLM was applied to each stage of oyster as classified in the fall dredge survey: spat, small, small box, market and market box. Spat boxes are rarely encountered, so they were not considered further. The model included a fixed effect for year, a random effect for bar, a random effect for the interaction of bar and year, and an offset term for the distance of the dredge tow in meters,

$$ln(y_{i,j,k}) = \beta_0 + \beta_i x_i + a_j + b_{i,j} + ln(d_{i,j,k}),$$

where $y_{i,j,k}$ is the number of oysters in a particular stage (e.g., live markets) observed in dredge tow k on bar j in year i, β_0 is the overall intercept, β_i is the coefficient associated with year x_i, a_j is a random effect for bar, $b_{i,j}$ is a random effect for the interaction of bar and year, and $ln(d_{i,j,k})$ is an offset term to account for the length of the dredge tow. All models used a negative binomial distribution and a log link function. The indices were standardized separately for each NOAA code and for each oyster stage. The models were implemented in R using the INLA package (Lindgren and Rue, 2015). To get estimates for the index in each year, an additional data set was appended to the original data set when fitting the model. This additional data set had the NOAA code, years, and 1 m for dredge tow length specified, but did not specify a bar or interaction for bar and year. With this additional data set, when fitting the model, INLA provided estimates of the indices (i.e., relative counts) for each NOAA code in each year for a 1 m dredge tow. After standardization, all indices were multiplied by 0.813, the width of the dredge in meters, to get indices in units of relative count m^{-2}.

Some years and bars were excluded from the standardization analyses. Years with no observations or with all zeros for a stage were removed prior to the analysis because they are not estimable (i.e., the MLE of the year effect is undefined as the logarithm of zero). The resulting standardized indices were used to fit the population dynamics model.

Only bars with at least 10 years of data were included because those with fewer than five years probably would not be informative for estimating trends over the entire 19-year time series. Few bars (9/279) were sampled for only 5-10 years.

There were four NOAA codes where only one bar that met the above criteria and therefore precluded the use of the standardization model that was applied on all other NOAA codes. For these four NOAA codes (Severn River - 82; Lower Bay East - 129; St. Clements and Breton Bay - 174; Middle Potomac River -268) the nominal indices were used as input to the population dynamics model.

3 Methods

3.1 Assessment Model

A statistical, spatial, stage-structured model for oysters was constructed for 35 regions located in the Maryland portion of Chesapeake Bay. The model was fitted to standardized indices of density from the Maryland Department of Natural Resources fall dredge survey during 2005-2023 (Section 2.3.1) using a penalized maximum likelihood approach. The processes in the model included recruitment (natural and plantings), growth, natural mortality (including disease-related mortality), fishing mortality, and the disarticulation of small and market boxes. The model was built in R Template Model Builder (Kristensen 2023; Kristensen et al., 2016).

3.1.1 Population model

The model was stage-based using the five stages described in the fall dredge survey: spat (recently settled oysters, < 1 year old), small (> 1 year old and <76mm), market (≥ 76mm), small box, and market box. The model year began October 1, which is the beginning of the oyster season for all gears except power dredge which begins November 1. The model year coincides with the timing of the fall dredge survey. Each year was divided into two six-month periods: (1) the oyster fishing season, which occurs during October through March the following year, and (2) the portion of the year when oyster harvest was not allowed but growth and natural mortality occur (April-September). In Maryland, oyster growth during winter is low, and recruitment and natural morality are thought to mostly occur during summer and fall (Mace et al., 2021). The primary sources of natural mortality are thought to be diseases and predators and most mortality from these two sources occurs during April-October. For example, Ford and Tripp (1996) showed that monthly prevalence of disease-causing parasites is highly correlated with observed mortality rates, and almost all observed mortality occurred during April-October. Many of the predators of eastern oysters are less active during winter, and predation rates decline at low water temperatures (Pearse and Wharton, 1938; Carriker, 1955; Landers and Rhodes, 1970; Gunter, 1979; Garton and Stickle, 1980) such as those that occur in Chesapeake Bay during the commercial fishing season from October through March. Therefore, the only process affecting abundance of oysters during the fishing season was fishing mortality (i.e., no growth, recruitment, or natural mortality occurs), while recruitment, growth, and natural mortality were modeled to occur outside of the fishing season. No effect of harvest beyond removal of harvested individuals could be detected (See Section 7.1) and so the population model did not include any additional effects of harvest on habitat. Model variables and parameters are described Table 7.

Fishing Season (October-March)

Harvest was the only process that affected population dynamics in the first six-month period of each year. Abundance in spring of a given year was the difference between abundance and estimated catch (i.e., estimated number of individuals removed by fishing) during the fall,

$$N_{y,t=2,\mathrm{r},s} = N_{y,t=1,r,s} - \hat{C}_{y,r,s},$$

where estimated catch was calculated as the product of abundance and the exploitation rate,

$$\hat{C}_{y,r,s} = u_{y,r,s} N_{y,t=1,r,s}.$$

The exploitation rate was calculated to ensure it was between zero and one,

$$u_{y,r,s} = 1 - \frac{f\left(N_{y,t=1,r,s} - C_{y,r,s}\right)}{N_{y,t=1,r,s}},$$

where $f(x) = \frac{x}{(1+e^{-25x})} + c$.

This approach to accounting for catch was taken to avoid calculations resulting in negative abundance.

The abundance of recruits (i.e., spat) on October 1 was the sum of the number of spat planted (adjusted for mortality from the time of planting to October 1) and the estimated number of natural recruits

$$N_{y,t=1,r,s=sp} = P_{y,r} S_P + R_{y,r}.$$

The log-scale mean recruitment and year specific log-scale deviations were estimated parameters. We assumed that 15% of planted spat survived from planting to October 1 based on densities of spat one to two months after planting relative to the initial planting density (K. Paynter, UMCES, unpublished data; Damiano and Wilberg, 2019). In the model, spat did not experience fishing mortality such that the abundance of spat on April 1 was equal to the abundance on October 1.

Outside of Fishing Season (April-September)

Growth and natural mortality occurred during the second six-month period, April-September. The abundance of small oysters in October on each bar was calculated as the sum of spat that survived, small oysters from the previous season that survived and remained small, and planted wild seed oysters,

$$N_{y+1,t=1,r,s=sm} = S_{sp} N_{y,t=2,r,s=sp} + N_{y,t=2,s=sm}(1 - G_r)e^{-M_{y,r}} + S_W W_{y,r} e^{-M_{y,r}}.$$

Survival of planted wild seed from planting until October 1 (S_w) was assumed to known and constant at an instantaneous natural mortality rate of 0.1 (approximately 90% survival). The natural mortality of spat was assumed to be known and constant at an instantaneous rate of 0.5 per year (approximately 60% percent survival) based on estimates of density of age-0 and age-1 oysters in the Great Wicomico River, VA (Southworth et al., 2010). The probability of growth (G_r) from the small to the market stage and the natural mortality rates for smalls and markets each year were estimated parameters.

The abundance of market oysters in fall was calculated as the sum of small oysters that survived and grew to become market-sized and market-sized oysters that survived natural mortality,

$$N_{y,t=2,r,s=mk} = N_{y,t=1,r,s=sm} G_r e^{-M_{y,r}} + N_{y,t=1,r,s=mk} e^{-M_{y,r}}.$$

The model also tracked the number of boxes in the small and market stages to assist in estimating natural mortality rates. The number of small boxes each year was calculated as the sum of the number of small boxes from previous years that did not disarticulate, and the number of small oysters did not grow to markets and that experienced natural mortality,

$$B_{y+1,r,s=sm} = N_{y,t=1,r,s=sm}(1 - e^{-M_{y,r}})(1 - \delta)(1 - G_r) + B_{y,r,s=sm} e^{-\beta}.$$

Note that this equation implies that growth occurs before natural mortality. The number of market boxes each year was calculated as the sum of the number of market boxes from previous years that did not disarticulate, the number of small oysters that grew to markets and experienced natural mortality, and the number of market oysters that experienced natural mortality,

$$\begin{aligned} B_{y+1,r,s=mk} = {} & (1 - \delta)(N_{y,t=1,r,s=sm}(G_r)(1 - e^{-M_{y,r}}) + N_{y,t=1,r,s=mk}(1 - e^{-M_{y,r}})) \\ & + B_{y,r,s=mk} e^{-b} \end{aligned}$$

We assumed that all smalls and markets that died from natural mortality became boxes and that a proportion (δ) of small and market boxes disarticulated before the fall survey and, therefore, were not available to be sampled. The proportion (δ) of small and market boxes that disarticulated before the fall survey and instantaneous box disarticulation rate (b) was the same for small and market boxes and was constant over all regions and years based on Doering et al. (2021). The abundances of small and market boxes in the first year were estimated parameters.

3.1.2 Observation Model

The model predicted indices of density for the fall dredge survey that were calculated as the product of catchability, abundance at October 1, and proportion of live oysters harvested before the fall dredge survey,

$$\hat{I}_{N_{y,r,s}} = \frac{N_{y,\mathrm{t=2,r,}s} u_{bd,y,r,s}}{A_r} q_{N_r},$$

where the proportion of live oysters harvested before the fall survey occurs was calculated to avoid abundance becoming negative,

$$u_{bd,y,r,s} = \frac{f(N_{y,t=2,r,s} - C_{bd,y,r,s})}{N_{y,t=2,r,s}}$$

where $C_{bd,y,r,s}$ is the catch of a stage in a region before the fall survey occurred in that region and $f(x) = \frac{x}{(1+e^{-25x})} + c$. The predicted indices for small and market boxes was calculated as the product of catchability and the density of boxes on October 1,

$$\hat{I}_{B_{y,r,s}} = \frac{B_{y,\mathrm{r},s}}{A_r} q_{B_r}.$$

Catchability (q) was assumed to vary among regions and to be the same for the live small and market stages ($q_{N_{s\,=\,sm}} = q_{N_{s\,=\,mk}}$) and for the small and market box stages ($q_{B_{s\,=\,sm}} = q_{B_{s\,=\,mk}}$) within a region based on Powell et al. (2007) and Marenghi et al. (2017).

3.1.3 Model Fitting

Model parameters were estimated by minimizing the objective functions, which was the sum of the negative log likelihood functions for each data source and penalties,

$$-LL = L_{N_{s=sp}} + L_{N_{s=sm}} + L_{N_{s=mk}} + L_{B_{s=sm}} + L_{B_{s=mk}} + q_{P,N} + q_{P,ratio,s} + G_p + b_p + M_P + R_{dev_P} + C_{P,s} + N_{P,s} + B_{P,s}.$$

A lognormal negative log-likelihood function was used for all fall dredge survey indices in the model,

$$L_X = \frac{n}{2}\ln(2\pi) + \frac{n}{2}\ln(\sigma_X^2) + \frac{1}{2\sigma_X^2}\sum_y \sum_r (\ln(X_{y,r}) - \ln(\hat{X}_{y,r}))^2$$

where X refers to a particular index (e.g., live markets) and n was the sample size of an index (i.e., number of years with data). The log-scale standard deviations σ_X for each of the time series were the average of standard errors (SEs) over time from the index standardization model. For regions where the nominal index was used, the maximum estimated SE for a given stage across regions was used for the log-scale standard deviation.

Penalties were incorporated on some of the parameters to stabilize the estimates and to include outside information in the parameter estimation (Maunder, 2003). The standard deviations σ_X for each penalty were assumed to be known. In the following penalty equations, n refers the number of parameters (e.g., $n = 35$ for G_P because there was one G parameter for each region). The catchability of live adult oysters (smalls and markets) was penalized using a normal distribution (i.e., prior),

$$q_{P,N} = \frac{n}{2} ln(2\pi) + \frac{n}{2} ln\left(\sigma^2_{q_{P,N}}\right) + \frac{1}{2\sigma^2_{q_{P,N}}} \sum_r (q_{N,r} - \bar{q}_N)^2.$$

where the mean, $\bar{q}_N$, was 0.24 and the standard deviation $\sigma_{q_{P,N}}$ was 0.02. The values for $\bar{q}_N$ and $\sigma_{q_{P,N}}$ were calculated from catchability estimates of oysters in Delaware Bay (Powell et al., 2007; Marenghi et al. 2017). A lognormal penalty for the ratio of live adults (i.e., smalls and markets) to spat and boxes was included to stabilize their estimates,

$$q_{P,ratio,s} = \frac{n}{2} \ln(2\pi) + \frac{n}{2} \ln\left(\sigma^2_{q_{P,ratio,s}}\right) + \frac{1}{2\sigma^2_{q_{P,ratio,s}}} \sum_r (ln(q_{ratio,s,r}) - ln(\bar{q}_{ratio,s}))^2$$

where the mean $ln(\bar{q}_{ratio,N,s=sp})$ for spat was -0.24 (approximately 76% of live adult catchability) and the log-scale standard deviation $\sigma_{q_{P,ratio,N,s=sp}}$ was 0.10 while the mean $\ln(\bar{q}_{ratio,B,s\neq sp})$ for small and market boxes was -0.56 (approximately 57% of live adult catchability) and the log-scale standard deviation $\sigma_{q_{P,ratio,B,s\neq sp}}$ was 0.12. These numbers were calculated from estimates of the relative catchability of adult (small + market) oysters and spat and boxes in Delaware Bay (Powell et al. 2007; Marenghi et al. 2017).

The transition probability from the small to market stage was penalized using a normal distribution,

$$G_P = \frac{n}{2} \ln(2\pi) + \frac{n}{2} \ln(\sigma^2_G) + \frac{1}{2\sigma^2_G} \sum_r (G_r - \bar{G})^2$$

where the mean ($\bar{G}$) was 0.35 and the standard deviation (σ_G) was 0.075. These values were calculated based on the fraction of oysters expected to grow from small to market size using a von Bertalanffy growth model fitted to size-at-age data from known age oysters in Maryland oyster sanctuaries (Paynter et al., 2010). Normal penalties were also applied to the instantaneous rate of box disarticulation based on field-based estimates from Maryland and Delaware Bay (Christmas et al., 1997; Ford et al., 2006),

$$b_P = \frac{1}{2} \ln(2\pi) + \frac{1}{2} \ln(\sigma^2_b) + \frac{(b - \bar{b})^2}{2\sigma^2_b}$$

where the mean $\bar{b}$ was 1.11 (i.e., approximately 67% of boxes disarticulate each year) and the standard deviation σ_b was 0.02. These values were based on the posterior distribution of box decay rates in Doering et al. (2021).

A lognormal penalty was applied to the year- and region-specific deviations in recruitment

$$R_{dev_P} = \frac{n}{2}\ln(2\pi) + \frac{n}{2}\ln(\sigma_R^2) + \frac{1}{2\sigma_R^2}\sum_y \sum_r (ln(R_{dev_{y,r}}))^2$$

where the log-scale standard deviation σ_R was 2.0.

A normal penalty was applied to constrain the variability in natural mortality rates over time within each region,

$$M_P = \frac{n}{2}\ln(2\pi) + \frac{n}{2}\ln(\sigma_M^2) + \frac{1}{2\sigma_M^2}\sum_y \sum_r (\ln(M_{y,r}) - \ln(\widehat{M}_r))^2$$

where $\widehat{M}_r$ is the geometric mean of the estimated natural mortality rates within region r over all years and the log-scale standard deviation σ_M was assumed to be 0.5.

To ensure that catch did not exceed estimated abundance, we applied a normal penalty to the difference between the observed and estimated catch of small and market oysters,

$$C_{P,s} = \frac{n}{2}\ln(2\pi) + \frac{n}{2}\ln\left(\sigma_{C,s}^2\right) + \frac{1}{2\sigma_{C,s}^2}\sum_y \sum_r (C_{y,r} - \hat{C}_{y,r})^2$$

where the standard deviation $\sigma_{C,s}$ was 1 and 1,000 for small and market oysters, respectively. For the base model, this penalty was zero for the final estimates, but it was included to ensure that the likelihood remained defined (i.e., abundance was greater than zero).

A normal penalty was applied to estimates of the number of live oysters and boxes for the small and market stages in the initial year for differences from equilibrium stage structure,

$$N_{P,s} = \frac{n}{2}\ln(2\pi) + \frac{n}{2}\ln\left(\sigma_{N_{P,s}}^2\right) + \frac{1}{2\sigma_{N_{P,s}}^2}\sum_r (N_{y=0,t=2,r,s} - N_{eq,s})^2,$$
$$B_{P,s} = \frac{n}{2}\ln(2\pi) + \frac{n}{2}\ln\left(\sigma_{B_{P,s}}^2\right) + \frac{1}{2\sigma_{B_{P,s}}^2}\textstyle\sum_r (B_{y=0,t=2,r,s} - B_{eq,s})^2,$$

where the $N_{eq,s}$ and $B_{eq,s}$ were the equilibrium abundances for live and boxes, respectively, and the standard deviation for live oysters $\sigma_{N_{P,s}}$ and boxes $\sigma_{B_{P,s}}$ was 0.2.

3.2 Biological Reference Points

For comparison of model estimates with both the density and exploitation rate reference points, we calculated the mean adult density or mean market exploitation rate in the three most recent years to compare to the reference points in each NOAA code. We used the mean of the three most recent years instead of the value in 2023 to consider the interannual variability.

3.2.1 Density Reference Points

Our goal was to estimate a long-term target density (number per m^2) of adult oysters that was common across all NOAA codes to represent a desired level of the oyster population. The goals for this target were that there would be enough oysters to avoid larval limitation and to provide ecosystem services like reef building, filtration, nitrogen removal, and harvest. Metrics depicting "healthy" densities of oysters are not available for subtidal oyster bars in the Maryland portion of the Chesapeake Bay. Another desired aspect of the target is that it should be empirically achievable in that target oyster densities have been observed over large areas in Maryland. Therefore, we chose to calculate a target oyster density based on the densities achieved on restored oyster bars in Maryland.

Marine protected areas (or "sanctuaries" for oysters) can provide estimates of carrying capacity (Field et al., 2006). The large-scale oyster restoration efforts that began in 2012 in Harris Creek, the Little Choptank River, and the Tred Avon River provide information on the density of oysters that can persist on subtidal Maryland oyster bars. These oyster bars represent achievable, unharvested densities. Similar to many other fisheries, a fraction of the unharvested density (i.e., abundance if habitat is considered constant) can serve as a target reference point for population size. One half of unfished abundance is a common reference point for a population that follows a logistic growth model (Hilborn and Walters, 1992; Quinn and Deriso, 1999), whereas 40% of unfished biomass is a common reference point for long-lived fishes (Clark, 2002). Oysters are reef-building organisms that create their own habitat, such that ½ of carrying capacity is likely a minimum estimate of the abundance that would support maximum sustainable yield and other ecosystem services (Wilberg et al., 2013). Additionally, oysters have been previously described as extremely depleted (>1% of pre commercial harvest abundance; Newell, 1988; Wilberg et al., 2011), such that an increase to ½ of unfished abundance would represent a substantial improvement in the resource. Therefore, we selected ½ of an estimate of the density on restored 3-dimensional oyster reefs as a target. Lastly, ½ of the density in the large-scale restoration areas is a substantially higher density than that used for evaluating success of the large-scale restoration areas (target: 50 oysters m^{-2} over 30% of the reef = 15 oysters m^{-2}; lower limit: 15 oysters m^{-2} over 30% of the reef = 4.5 oysters m^{-2}). A higher density target than was used for the restoration areas is appropriate because we now have more information on the potential of subtidal habitats in Maryland to support high densities of oysters.

We used data from the monitoring of restored oyster bars that was conducted six years after initial restoration. Data from six-year monitoring of the restoration efforts in Harris Creek, the Little Choptank River, and the Tred Avon River were available. We calculated the restored density estimated using data collected during the 2020 – 2022 Oyster Recovery Partnership (ORP) 6-year monitoring diver surveys. Divers used a 0.5 m^2 quadrat for every sample event and all oysters were counted with a subsample being measured. We developed a target for adult (small and market combined) oyster density, which encompassed oysters with shell heights greater than 45 mm. We used only density from reefs sampled by divers because 1) we are confident that the efficiency of diver sampling is close to 1.0 (Wilberg et al., 2022), and 2) most of the reefs sampled by divers had been built up with stone or other substrate before being planted with spat on shell. Oyster densities are higher on three-dimensional reefs (Schulte et al., 2009). Based on historical accounts (Brooks, 1905; Kennedy and Breisch, 1983), oyster reefs in Maryland were likely three dimensional and more similar to these restored reefs.

The average adult density of the 6-year diver monitoring sites was 188 oysters m^{-2}, and the long-term target was estimated to be 1/2 of that density, which resulted in 94 oysters m^{-2}. A target adult oyster abundance for each NOAA code can be obtained as the product of oyster bottom habitat area and the target density. This value represents a long-term target because achieving high densities of oysters will likely require rebuilding of habitat, which is expected to take decades to centuries (Wilberg et al., 2013).

We developed a lower limit density reference point and a "cautionary level" reference point to describe low densities that management would like to avoid because of likely impairment of ecosystem services. The lower limit reference point is based on the minimum threshold from the large-scale oyster restoration of 4.5 adult oysters m^{-2} (15 oysters m^{-2} over 30% of an oyster bar). The cautionary limit is set at twice the threshold (9.0 adult oysters m^{-2}) so that management can be alerted to low density before it crosses the threshold.

3.2.2 Limit and target exploitation rate reference points

We developed a limit exploitation rate reference point based on the exploitation rate that was expected to achieve no net loss of oyster shell habitat over time. Because oysters create their own habitat for recruitment (i.e., settlement), maintaining habitat is essential for population persistence. We estimated the exploitation rate that achieved no net habitat loss by conducting a linear regression of year-over-year changes in cultch per m^2 from the Fall Dredge Survey against estimated exploitation rate from the assessment model. The target reference point was selected as 75% of the upper limit based on Restrepo et al. (1998).

Adjusted Exploitation Rate - accounting for plantings of live oysters

Planting oysters, shell, and artificial substrate continue to be important management strategies to supplement the fishery and to attempt to restore oyster populations. Therefore, we calculated an exploitation rate that accounts for an equivalence between planted oysters that were expected to reach market size and harvested oysters. Specifically, the calculation of the adjusted exploitation rate assumes that planted oysters are harvested before wild oysters,

$$u_{comp} = \frac{c_{y,mk} - n^*_{y,mk}}{c_{y,mk} - n^*_{y,mk}},$$

where u_{comp} was the exploitation rate adjusted for planting live oysters, $C_{y,mk}$ was the harvest of market oysters (in numbers), $N_{y,mk}$ was the estimated abundance of market oysters, and

$n^*_{y,\mathrm{mk}}$ was the number of planted market oysters that remain in the population at the beginning of the year assuming that planted oysters are harvested before wild oysters and have the same natural mortality rates as wild oysters,

$$n^*_{y,mk} = (n^*_{y-1,mk} - C_{y-1,mk})e^{-M_{y-1}} + (n^*_{y-1,sm} - C_{y-1,sm})Ge^{-M_{y-1}}$$

where $n^*_{y-1,sm}$ is the number of small, planted oysters that remain in the population at the beginning of the year. The number of planted market oysters remaining in the population after harvest was set to zero if $C_{y-1,mk} > n^*_{y-1,mk}$. The number of planted small oysters that remain in the population at the beginning of the year was calculated as

$$n^*_{y,sm} = (n^*_{y-1,sm} - C_{y-1,sm})(1-G)e^{-M_{y-1}} + S_W W_{y-1} + P_{y-1}S_P$$

where W_{y-1} is the number of wild seed planted, S_W is the survival of wild seed from planting to October 1, P_{y-1} is the number of hatchery spat planted, and S_P is the survival of hatchery spat from planting until October 1.

This formulation of the reference point assumes that oysters are planted with the goal of growing them out for harvest. In cases where plantings are for restoration efforts instead of supplementing the fishery, the exploitation rate calculated from the total *N* should be used.

3.3 Sensitivity Analyses

We tested the sensitivity of the model to changes in assumed values and plausible alternative model structures using a total of 27 sensitivity analyses (Table 8). For each sensitivity analysis, only the specified change was made before rerunning the model (e.g., only the mean prior for catchability was changed and all other assumptions were the same as the base model). All changes below are with respect to the base model.

The values assumed for penalties on recruitment deviations, adult catchability, initial abundance of live oysters and boxes, variation in natural mortality among regions, transition probability, and the box decay rate were all doubled. The mean value used for the prior on adult catchability was doubled and also decreased by 50%. The value for spat natural mortality was increased and decreased by 20%. The proportion of boxes not available to the Fall Dredge Survey was decreased to 10% and increased to 30%. The reporting rate was increased to 100% (i.e., all harvest was reported) and decreased to 80% (i.e., only 80% of harvest was reported). The area of habitat was decreased by 90%, 80%, 70%, 60%, 50%, and 37%. A value of 37% decrease in habitat was used because this is the decline calculated by Smith et al. 2005.

Plausible alternative model structures were also considered. An alternative for catchability assumed that there was only one catchability parameter for adult live, spat, and boxes across all NOAA codes. The number of oysters per bushel in the harvest and percentage of small oysters in the harvest were modified by using a higher number of oysters per bushel together with a higher percentage of small oysters per bushel and a lower number of oysters per bushel and lower percentage of small oysters per bushel in the harvest. Instead of accounting for harvest before the Fall Dredge Survey, no harvest was assumed to occur before the Fall Dredge Survey in any NOAA code. All full dredge tows were removed from the Fall Survey data before calculating indices of abundance.

Sensitivity analyses were also conducted to examine how the exploitation rate reference point may change when excluding some years or NOAA codes from the calculation. Specifically, this reference point was calculated only including all NOAA codes with average exploitation rates > 0.01 yr^{-1} and with average exploitation rates > 0.02 yr^{-1}. Also, the exploitation rate reference point was calculated using subsets of years: 2005-2021, 2005-2020, 2005-2019, 2005-2018, and 2005-2017.

3.4 Continuity Run

We ran the 2018 Maryland oyster stock assessment model with updated data through the 2023-2024 season and calculated stock status relative to the reference points. We did this to determine how model estimates and stock status from the previous model compared with stock status calculated with the new model described in this document.

The previous Maryland oyster stock assessment model is a stage-based model with the same stages as in the new model. The primary differences between the old and new models were how the indices of abundance are calculated and how habitat is modeled. In the old model, we used data from the Fall Survey starting in 1999. Therefore, indices used in the old model were using counts per bushel of cultch instead of counts per area swept as we did in the new model. In the old model we also modeled the change in habitat over time as a declining exponential function with the only increases due to substrate plantings. In the new model, habitat area is assumed to be constant over time. For a detailed description of the previous model see MD DNR (2018) and Mace et al. (2021).

4 Results

4.1 Assessment Model Results

4.1.1 Model Fit and Diagnostics

The model fit the Fall Dredge Survey indices for all NOAA codes across all oyster stages relatively well. Estimated survey indices usually fell within the 95% confidence intervals for the observed indices. There was relatively little consistent patterning in the residuals among NOAA codes (Figure 12-Figure 46). The most notable residual pattern was that a few NOAA Codes located in the Tangier Sound region (Fishing Bay - 43, Honga River - 47, North and South Tangier Sound - 192 and 292, and Pocomoke Sound - 72) had a pattern in the residuals where the model overestimated the number of small and market boxes compared to the fall survey indices, primarily during 2012-2017. Model parameters were reasonably precisely estimated with a coefficient of variation less than 20% (Table 9).

4.1.2 Estimated parameters

Transition probability

The estimated transition probabilities averaged about 0.31 yr^{-1}, but there was substantial variability among NOAA codes, with estimates ranging from 0.11 yr^{-1} to 0.65 yr^{-1} (Figure 47). The NOAA codes with the lowest transition probabilities were the St. Mary's River (78) and Broad Creek (537), and the highest transition probability was in the Wye River (99). The coefficient of variation of the estimates varied among NOAA codes from 6% to 25% and estimates from most NOAA codes did not include the mean of the prior within their 95% confidence intervals. Generally, NOAA codes with the highest catches had the highest precision for the transition probability.

Catchability

Estimated adult catchability averaged about 0.23 and there was relatively little variability in the estimates (Figure 48), which was likely due to the tight penalty on these values. The lowest adult catchability was estimated for the North Mid-Bay (127), and the highest was estimated for Fishing Bay (43), although the difference between the highest and lowest estimates was only about 29%. The 95% confidence intervals of adult catchability for all NOAA codes included the mean of the prior, and most estimates were within 10% of the prior mean.

Estimated spat catchability was more variable than adult catchability (Figure 49), which was expected because the penalty was looser for spat catchability than for adults. Spat catchability averaged about 0.17 across NOAA codes. The highest spat catchability was in Lower Tangier Sound (192), and the lowest spat catchability was in the Tred Avon River (637). The difference between the highest and lowest spat catchability was 61%. The spat catchability estimates were reasonably precise with the coefficient of variation ranging from 11% to 14%.

Estimated catchability of boxes averaged about 0.13 across NOAA codes (Figure 50), with an average coefficient of variation of 12%. The NOAA code with the lowest box catchability was the North Mid-Bay (127), and the highest estimate as in the Lower Patuxent River (168). Most NOAA codes included the prior mean within their 95% confidence intervals, and the among NOAA code variability in box catchability estimates was between adult catchability and spat catchability.

Natural mortality

Estimated natural mortality rates varied over time and among NOAA codes with differing trends among NOAA codes (Figure 51). On average, NOAA codes in the Tangier Sound region had the highest estimated natural mortality rates, and the lowest estimated natural mortality rates were in the Choptank region. Natural mortality rate estimates had an average coefficient of variation of 41%. In most years and NOAA codes the coefficient of variation was less than 60%, but some years and NOAA codes had substantially higher uncertainty (e.g., the Miles River – 60, the Wicomico River (East) 96, North Mid-Bay – 127, Breton and St. Clements Bays – 174, and the Upper Chester River - 331).

Estimated natural mortality rates within each NOAA code usually had a similar trend over time as the box count natural mortality rate estimates, although the model estimates were sometimes slightly higher than the box count estimates (Figure 51). In the NOAA codes that showed residual patterns in small and market boxes, the model estimates of natural mortality were high relative to the box count estimates during 2010-2020.

Estimated Abundance, Exploitation Rates, and Natural Mortality

Bay-Wide Estimated Abundance

Estimated adult abundance (small + market) increased from 2.4 billion in 2005 to 5.6 billion in 2011 before decreasing to 3.5 billion in 2016. After 2016, there was an increase to a maximum of 8.6 billion in 2022 with a slight decrease to 7.6 billion in 2023 (Figure 52). Adult abundance was highest in the Tangier Sound, Choptank River, and Patuxent River regions, while the Chester River and Western Shore regions had the lowest adult abundance. There was an increasing trend from the early 2000s to 2023 for the Choptank River, Tangier Sound, Patuxent River, and Potomac River region such that estimated adult abundance was higher in 2023 than in 2005. There was a decreasing trend in the Chester River such that estimated adult abundance was higher in 2005 than in 2023. Estimated adult abundance varied with no strong trend over time in the remaining regions, but estimated adult abundance was higher in 2023 than in 2005, except for in the North Mainstem region.

Estimated market abundance increased from about 1.4 billion individuals in 2005 to approximately 3.2 billion individuals in 2023 (Figure 53). Estimated market abundance reached a minimum of approximately 1 billion individuals in 2007, then increased to 2.3 billion in 2014, before decreasing until 2017 and finally reaching a maximum of 3.2 billion in 2023. In 2005, estimated market abundance was highest in the North Mainstem, Choptank River, and Eastern Bay regions. After 2010, estimated market abundance was highest in the Choptank River, Tangier Sound, and Patuxent River regions. Similar to adult abundance, there was an increasing trend in estimated market abundance in the Choptank River, Tangier Sound, Patuxent River, and Potomac River regions and a decreasing trend in the Chester River region. Estimated market abundance varied with no strong trend over time in the remaining regions, but most had a higher estimated adult abundance in 2023 than in 2005, except for the North Mainstem region.

Estimated small abundance increased from 975 million individuals in 2005 to 4.1 billion individuals in 2011 before declining to 1.7 billion individuals in 2016 (Figure 54). After 2016, the abundance increased to a maximum of 5.6 billion individuals in 2022 before declining slightly to 4.3 billion individuals in 2023. Estimated small abundance was highest in the Choptank River and Tangier Sound regions and was lowest in the Chester River and Western Shore Regions. Similar to adult abundance, there was an increasing trend in estimated market abundance in the Choptank River, Tangier Sound, Patuxent River, and Potomac River regions and a decreasing trend in the Chester River region. Estimated small abundance varied with no strong trend over time in the remaining regions, but most had a higher estimated adult abundance in 2023 than in 2005, except for the North Mainstem region.

Estimated spat abundance was more variable than small and market abundance with peaks of greater than 4 billion individuals in 2006, 2010, 2020, and 2023 (Figure 55). The average spat abundance during 2005-2023 was 266 million individuals. Estimated spat abundance varied over time in all regions but generally was highest in the Choptank River and Tangier Sound regions and lowest in the North Mainstem, Chester River, and Western Shore regions.

The results for each region are presented below, followed by the details for each NOAA code within a region. The regions are presented in order of importance by harvest. The percentage after the name and number of each NOAA code is the percentage of harvest from the NOAA code out of all NOAA codes during 2005-2023.

Tangier Sound Region

In the Tangier Sound Region, estimated adult abundance increased from 363 million individuals in 2005 to 2.4 billion in 2011 before decreasing to 922 million individuals in 2016 (Figure 56). After 2016, adult abundance increased to 3 billion in 2021 before decreasing to 2.2 billion individuals in 2023. Overall, estimated adult abundance increased by approximately 600% during 2005-2023. Estimated adult abundance was highest in Tangier Sound South (192) in most years; however, during some years estimated adult abundance was highest in Honga River (47), Manokin River (57), and North Tangier Sound (292). Trends in estimated adult abundance over time differed among NOAA codes but was lowest at the beginning of the time series in most NOAA Codes and highest near the end of the time series.

In the northern Tangier Sound region, estimated abundance of market oysters fluctuated between 92 and 857 million individuals during 2005-2023 (Figure 57). Estimated market abundance had an increasing trend during 2005-2013, decreased to 295 million individuals in 2017, and then increased to 712 million individuals in 2023. Overall, estimated market abundance increased by approximately 500% during 2005-2023. Estimated market abundance was highest in Tangier Sound South (192) in most years; however, during some years, estimated abundance was highest in upper Tangier Sound (292) or the Manokin River (57). Trends in abundance over time differed among NOAA codes but estimated market abundance was lowest at the beginning of the time series in most NOAA Codes and highest at the end of the time series.

Estimated spat and small abundance varied over time more than market abundance, with peaks greater than two billion individuals in 2006, 2010, 2020, and 2023 for spat and greater than 1.75 billion individuals in 2007, 2011, 2021, and 2022 for small oysters (Figure 58, Figure 59). The overall average abundance of spat was 142 million and 153 million for small oysters. Estimated spat and small abundance was highest in Tangier Sound South (192) in most years; however, during some years it highest in Fishing Bay (43), Honga River (47), Manokin River (57), North Tangier Sound (292).

Fishing Bay (43) (7.9%)

Estimated abundance of market oysters in Fishing Bay (43) was relatively low compared to other NOAA codes in the Tangier Sound Region except during 2010-2015 and 2021-2023 when estimated abundance approached 76 million and 99 million individuals, respectively (Figure 60). The estimated abundance of spat, small, and market oysters remained low until the 2010 when a large recruitment event occurred resulting in an increase in small and market abundance until 2013. Small and market abundance decreased in 2014 when the abundance of all three stages decreased to below 100 million individuals. There was a very large recruitment event in 2020 that resulted in an increase in estimated market and small abundance in the most recent years. The estimated market exploitation rate was less than 5% yr^{-1} until the 2008-2009 season, after which it increased until reaching approximately 25% yr^{-1} in the 2015-2016 season (Figure 61). The market exploitation rate decreased to approximately 5% yr^{-1} in the in the 2018-2019 season, which was followed by an increase. The market exploitation rate was approximately 10% yr^{-1} in the most recent season. The estimated small exploitation rate followed a similar trend over time as for markets but never exceeded 1.5% yr^{-1}. Trends in exploitation rates over time generally followed patterns in the catch density. The adjusted market exploitation rate was very similar to the non-adjusted market exploitation in all years due to only a few years with spat or wild seed plantings (Figure 61, Figure 62). Estimated natural mortality rates were below 35% yr^{-1} in most years except for an increase to approximately 75% yr^{-1} in 2015, and there has been an increasing trend in recent years with an estimate of approximately 45% in the most recent year.

Honga River (47) (5.1%)

Estimated abundance of market oysters was low at the beginning of the time series and increased to approximately 92 million individuals in 2012 before decreasing to approximately 19 million in 2017 (Figure 63). Estimated market abundance increased since 2017 to the highest estimate of the time series of 105 million individuals in 2023. There were four relatively large recruitment events in the first half of the time series that resulted in a relatively high abundance of small and market oysters during that time. Spat and small estimated abundance was low during 2015-2019, until a large recruitment event in 2020 and 2023, which resulted in increased small and market estimated abundance in recent years. The estimated market exploitation rate was less than 5% yr^{-1} until the 2007-2008 season, after which it fluctuated without a trend until the 2023-2024 season (Figure 64). The market exploitation rate was estimated to be about 5% yr^{-1} in 2023-2024. The estimated small exploitation rate followed a similar trend as for markets overtime but did not exceed 1% yr^{-1}. Small and market exploitation rates had similar trends over time as the catch density. The adjusted market exploitation rate was very similar to the non-adjusted market exploitation in all years due to only one year with spat plantings (Figure 64, Figure 65). The estimated natural mortality rate varied over 2006-2015 with no obvious trend and had a mean of 36%. There was an increase to about 73% in 2016 followed by a decrease to less than 20% except for an increase to 37% in 2023.

Manokin River (57) (0.3%)

Estimated market abundance was low until 2010 when there was an increase to about 137 million by 2015. Market abundance has remained high since 2014 with an estimate of 101 million individuals in 2023 (Figure 66). Spat and small estimated abundance was low until a large recruitment event in 2010 that resulted in a large increase in small and market abundance, but spat and small estimated abundance has decreased since 2011. The estimated market exploitation rate was low in all years and did not exceed 2% yr^{-1} (Figure 67). The estimated small exploitation rate followed a similar trend over time but was never above 1% yr^{-1}. Most of the Manokin River is currently a sanctuary (Table 2). The adjusted market exploitation rate was very similar to the non-adjusted market exploitation in all years due to no wild seed plantings and spat plantings in only the most recent years (Figure 67, Figure 68). The estimated natural mortality rate varied over time with, perhaps, a slight declining trend. In most years the estimated natural mortality was less than 40% yr^{-1}, and the mean natural mortality rate was 30% yr^{-1}.

Nanticoke River (62) (2.2%)

Estimated abundance of market oysters increased over time from approximately 7 million oysters in 2005 to about 111 million in 2023, which is the second highest 2023 market abundance in the Tangier Sound region (Figure 69). Estimated abundance of spat and smalls also increased over time, with spat increasing from very low levels to more than 50 million in recent years, and small oysters increasing to nearly 75 million in recent years. The estimated market exploitation rate was <2% yr^{-1} until the 2008-2009 season and fluctuated about a mean of 4% yr^{-1} until 2021-2022 (Figure 70). The estimated market exploitation rate decreased to approximately 1% in 2023-2024. The estimated small exploitation rate followed a similar trend over time as for markets but did not exceed 1% yr^{-1}. Most of the Nanticoke River is currently a sanctuary (Table 2). The adjusted market exploitation rate was lower than the non-adjusted market exploitation rate due to spat and wild seed plantings (Figure 70, Figure 71). Estimated natural mortality varied over time with an average of 13% yr^{-1}, but was <25% yr^{-1} in all years.

Pocomoke Sound (72) (2.8%)

Estimated market abundance was low at the beginning of the time series and increased to 59 million individuals in 2012 before decreasing to 13 million individuals in 2017 (Figure 72). Since 2017, there has been an increasing trend with an estimate of 30 million oysters in 2023. Estimated abundance of spat and small oysters was relatively stable except for a large recruitment event in 2010 that resulted in a large increase in small oysters in 2011. Estimated market exploitation was < 5% yr^{-1} until the 2012-2013 season when it increased to 14% (Figure 73). After the 2012-2013 season, estimated market exploitation rate decreased to about 4% yr^{-1} in 2023-2024. The estimated small exploitation rate followed a similar trend over time but was never above 0.5% yr^{-1} in any year. The adjusted market exploitation rate was the same as the non-adjusted market exploitation in all years because there were no spat or wild seed plantings (Figure 73, Figure 74). Estimated natural mortality increased during 2006 to 2017 to about 60% yr^{-1} and decreased to 12% yr^{-1} in 2019. There has been an increasing trend since 2019 with an estimated natural mortality rate of 47% yr^{-1} in the most recent year.

Wicomico River East (96) (0.7%)

Estimated market abundance increased over time with an estimate of 0.5 million individuals in 2005 to 15.9 individuals in 2023. Estimated spat and small abundance increased during 2005 to 2012, decreased and stayed relatively low during 2012-2018, and increased in recent years. This NOAA code had the lowest average market abundance in the Tangier Sound region (Figure 75). Estimated market exploitation rates were less than 10% yr^{-1} except for the 2015-2016 and 2016-2017 seasons when it was above 20% yr^{-1} (Figure 76). The estimated small exploitation rate followed a similar trend over time as market exploitation rates and was never greater than 0.5% yr^{-1} except in the 2015-2016 and 2016-2017 seasons when it was 5% and 4% yr^{-1}, respectively. The adjusted market exploitation rate was less than the non-adjusted market exploitation rate after 2010 due to spat plantings in many years (Figure 76, Figure 77). The estimated natural mortality rate averaged 15% yr^{-1} and was less than 20% yr^{-1} in most years.

Tangier Sound South (192) (13.8%)

Estimated market abundance in Tangier Sound South was consistently among the highest compared to other NOAA codes in the Tangier Sound region (Figure 78). The estimated abundance of market oysters increased during 2005-2008, decreased and reached a minimum during 2009-2018, and has since increased to about 200 million during 2021-2023. Spat and small abundance showed similar trends over time as market abundance, but their timing was lagged one to two years earlier. The estimated market exploitation rate increased over time from about 1% yr^{-1} in 2005-2006 to about 13% yr^{-1} in 2023-2024 (Figure 79). The estimated small exploitation rate followed a similar trend over time and never exceeded 1% yr^{-1}. The adjusted market exploitation rate was slightly lower than the non-adjusted market exploitation before 2018 due to the planting of spat and wild seed (Figure 79, Figure 80). The estimated natural mortality rate was greater than 40% yr^{-1} in most years during the first half of the time series with a mean of 37%. After 2016, the estimated natural mortality decreased to less than 20% yr^{-1} in 2019-2021 but increased in the most recent years.

Tangier Sound North (292) (20.6%)

Estimated market abundance was high compared to other NOAA codes in the Tangier Sound region in most years (Figure 81). Estimated market abundance increased from 16 million individuals in 2005 to 86 million individuals in 2023 with peaks related to strong recruitment in 2012 and 2020. Spat abundance varied over time with large recruitment events in 2006, 2010, and 2016 that caused peaks in small abundance in 2011 and 2017. Estimated small abundance decreased somewhat in recent years to approximately 125 million individuals in 2023 (Figure 82). The estimated market exploitation rate increased over time and was 14% yr^{-1} in the most 2023, with several years exceeding 20% yr^{-1} since 2014. The estimated small exploitation rate had a similar trend over time as markets and reached maximum of approximately 2% yr^{-1} in 2015-2016 and 2021-2022. The adjusted market exploitation rate was slightly lower than the non-adjusted market exploitation rate in some years due to the planting of spat and wild seed (Figure 82, Figure 83). The estimated natural mortality rate varied over time between about 10%-50% yr^{-1} and was 36% yr^{-1} in 2023-2024.

Choptank Region

Maryland-wide, the Choptank Region had the highest estimated abundance of adult and market oysters during most years (Figure 84, Figure 85). Estimated adult abundance increased approximately 800% to 3.1 billion individuals during 2005-2024 while market oysters increased approximately 600% to 1.5 billion individuals during the same period. The Little Choptank River (53) had the highest estimated adult and market abundance in every year, except for in 2005, 2006, and 2023 when adult abundance was highest in Broad Creek (537).

Estimated small abundance increased 1100% to 1.6 billion individuals in 2023 (Figure 86). Estimated small abundance was highest in the Little Choptank River (53) in most years but was also highest in Broad Creek (537) in a few years. Estimated spat abundance varied over time more than small and markets oysters, with peaks above one billion individuals in 2010, 2020, and 2023 (Figure 87). Estimated spat abundance was also highest in the Little Choptank River (53) in most years, however, it was also highest in at least one year in every other NOAA code in the Choptank River region during 2005-2023.

Little Choptank River (53) (1.4%)

Estimated market abundance increased from 56 million oysters in 2005 to 370 million in 2014 and then declined to 160 million in 2017 (Figure 88). Since 2017 market abundance increased to 482 million individuals in 2023. Spat abundance varied over time with relatively large recruitment events every two to five years. Estimated small abundance was low at the beginning of the time series but increased to approximately 600 million individuals in 2011 and has remained relatively high since then. The estimated market exploitation rate was less than 2% yr^{-1} in all years (Figure 89). Much of this area is a sanctuary (Table 2). The estimated small exploitation rate followed a similar trend over time but was never above 0.5% yr^{-1}. The adjusted market exploitation rate was similar to the non-adjusted market exploitation rate during the first half of the time series, but the adjusted rate was zero after 2016 due to the large amount of spat that were planted (Figure 89, Figure 90). The estimated natural mortality rate was <30% yr^{-1} in most years and the mean 20% yr^{-1}.

Lower Choptank River (137) (3.6%)

Estimated market abundance increased from 30 million individuals in 2005 to 151 million individuals in 2023 (Figure 91). Estimated spat abundance varied but was relatively low until large recruitment events in 2020 and 2023. Estimated small abundance increased to approximately 150 million individuals in 2011, then decreased to approximately 50 million individuals in 2020, before increasing to about 225 million individuals in 2023. The estimated market exploitation rate was <3% yr^{-1} until the 2012-2013 season, increased to 7% yr^{-1} in 2014, and then declined and has been below 3% yr^{-1} since 2016 (Figure 92). The estimated small exploitation rate followed a similar trend over time but was never above 1% yr^{-1} in any year. The peak in market and small exploitation rates matched a peak in the catch during 2014-2015. The adjusted market exploitation rate was slightly lower than the non-adjusted market exploitation rate in a few years due to spat and wild seed plantings (Figure 92, Figure 93). The estimated natural mortality rate was less than 20% yr^{-1} in all years with a mean of 9% yr^{-1}.

Mid Choptank River (237) (1.2%)

Estimated market abundance increased from 37 million individuals in 2005 to 229 million individuals in 2023 (Figure 94). Estimated spat abundance varied but was relatively low until higher average recruitment since 2020. Estimated small abundance was relatively low until 2021 when it increased to approximately 150 million individuals and has remained high since. The estimated market exploitation rate was less than 2% yr^{-1} except for the 2015-2016 season when it was slightly above 2% yr^{-1} (Figure 95). The estimated small exploitation rate followed a similar trend as market exploitation rates over time and was <1% yr^{-1} in almost all years. After 2007, market and small exploitation rates generally tracked the catch. The adjusted market exploitation rate was similar to the non-adjusted market exploitation rate in the first few years, but the adjusted market exploitation rate was zero after the 2009 due to consistent spat plantings (Figure 95, Figure 96). The estimated natural mortality rate was always <20% yr^{-1} with an overall mean of 9% yr^{-1}.

Upper Choptank River (337) (<0.1%)

Estimated market abundance had an increasing trend from 16 million individuals in 2005 to 102 million individuals in 2015. Afterwards, estimated market abundance decreased to 65 million individuals in 2023 (Figure 97). Estimated abundance of spat was relatively low except for two large recruitment events in 2011 and 2022. Estimated small abundance was low until an increase to approximately 100 million individuals in 2012 before declining to <50 million during 2016-2021. Estimated small abundance increased in the most recent years to approximately 100 million in 2023. The estimated market exploitation rate was never higher than 1% yr^{-1} (Figure 98). This area is currently a sanctuary (Table 2). The estimated small exploitation rate was similar to the market trend and never exceeded 0.5% yr^{-1}. The adjusted market exploitation rate was zero for most years except at the beginning of the time series due to spat and wild seed plantings and zero at in the last several years due to no harvest (Figure 98, Figure 99). Estimated natural mortality rates were <10% yr^{-1} in most years and had an overall mean of 9% yr^{-1}.

Harris Creek (437) (2.2%)

Estimated market abundance increased over time from less than 50 million individuals in 2005 to 197 million oysters in 2023 (Figure 100). Estimated spat abundance varied over time with the highest peaks in 2010 and 2020. Estimated small abundance was below 50 million individuals until 2010, after which it increased to approximately 175 million individuals and has remained at about that level. Estimated market exploitation was <4% yr^{-1} (Figure 101). The estimated small exploitation rate was similar to that for markets and did not exceed 1% yr^{-1}. Much of this area is a sanctuary (Table 2). The adjusted market exploitation rate was 0% yr^{-1} for almost years except at the beginning of the time series primarily due to the large spat plantings during 2010-2020 (Figure 101, Figure 102). Estimated natural mortality varied over time with no strong trend and was <20% yr^{-1} in all years except 2016-2017 with an overall mean of 13% yr^{-1}.

Broad Creek (537) (13.9%)

Estimated market abundance increased from <75 million oysters in 2005-2016 to 196 million individuals in 2023 (Figure 103). Estimated spat abundance was relatively low most years except for a very large recruitment event in 2020. Estimated small abundance increased to about 200 million oysters in 2020 and had a large increase in 2021 to approximately 750 million individuals. The estimated market exploitation rate had a spike in 2006-2007 to 28% yr^{-1} and then decreased to <5% yr^{-1} during the 2007-2008 to 2010-2011 seasons (Figure 104). After the 2010-2011 season, the estimated market exploitation rate increased again to a mean of 26% yr^{-1} during the 2012-2016 seasons. After the 2015-2016 season it decreased to approximately 8% yr^{-1} in 2023. The estimated small exploitation rate followed a similar trend over time and was <1% in all but one season, when it increased to approximately 2% yr^{-1}. The adjusted market exploitation rate was lower than the non-adjusted market exploitation rate in several years due to spat and wild seed plantings (Figure 104, Figure 105). The estimated natural mortality rate varied over time with no strong trends and was always <15% yr^{-1} with an average of 8% yr^{-1}.

Tred Avon River (637) (0.6%)

Estimated market abundance was <50 million individuals until 2010, after which it increased to 186 million individuals in 2023 (Figure 106). Estimated spat abundance was relatively low except for large recruitment events in 2009, 2020, and 2023. Estimated small abundance had spikes the year after strong recruitment events with lower abundance in the intervening years. Estimated small abundance in 2023 was approximately 90 million individuals. Estimated market exploitation rates varied over time but were <1% yr^{-1} in all years (Figure 107). The estimated small exploitation rate followed a similar trend over time and was <0. 5% yr^{-1}. The estimated exploitation rates had similar trends over time as the harvest. Much of this area is a sanctuary (Table 2). The adjusted market exploitation rate was similar to the non-adjusted market exploitation rate except in the most recent years when it was zero primarily due to the large amount of spat plantings since 2016 (Figure 107, Figure 108). The estimated natural mortality rate varied over time with no strong trends and was <20% yr^{-1} in all years with an overall mean of 12% yr^{-1}.

Patuxent River Region

Estimated adult and market abundance increased over time, with a 270% increase for adults to 640 million individuals in 2023 for adults and a 220% increase to 342 million individuals for markets (Figure 109, Figure 110). The Upper Patuxent River (368) had the highest estimated adult and market abundance in almost every year except a few years when estimated abundance was highest in the Mid Patuxent River (268). Estimated spat and small abundance varied over time more than adult and market abundance, with peaks in spat abundance in 2007, 2009, 2016, 2021, and 2023, usually followed the next year by a peak in estimated small abundance (Figure 111, Figure 112). In most years, estimated small abundance was highest in the Upper Patuxent River (368), but estimated spat abundance was highest in the Mid Patuxent River (268) in most years.

Lower Patuxent River (168) (6.5%)

Estimated market abundance approximately doubled between 2006-2017 and 2020-2023 to an estimated 34 million individuals in 2023 (Figure 113). Estimated spat abundance varied over time with relatively large recruitment events in 2010, 2016, 2019, and 2023. Estimated small abundance increased from 30 million individuals in 2005 to 103 million individuals in 2021 and then decreased to 48 million individuals in 2023. Estimated market exploitation rates were <10% yr^{-1} until 2012, after which it reached 37% yr^{-1} in 2015 (Figure 114). After 2015, market exploitation rates decreased to 9%yr^{-1} in 2018, increased to 34% yr^{-1} in 2022, and decreased to 12% yr^{-1} in 2023. Estimated small exploitation rates were <2% yr^{-1} in most years with peaks in the same years as market exploitation rates. The adjusted market exploitation rate was slightly less than the non-adjusted market exploitation rate in many years due to spat and wild seed plantings (Figure 114, Figure 115). The estimated natural mortality rate was highest in 2006 at 48% yr^{-1} and then decreased and remained less than 30% yr^{-1} in most years with an overall mean of 18% yr^{-1}.

Mid Patuxent River (268) (0.6%)

Estimated market abundance increased from 33 million individuals in 2005 to 108 million individuals in 2011 and remained lower than 100 million individuals after 2011 (Figure 116). Estimated spat and small abundance had several peaks from recruitment events in 2007, 2016, 2021, and in 2023, but the estimates were highly uncertain. Estimated market exploitation rates were low in most years and have been <2% yr^{-1} since 2006 (Figure 117). Estimated small exploitation rates were <0.5% yr^{-1} except in the first year. The adjusted market exploitation rate was similar to the non-adjusted market exploitation rate in most years due to few spat or wild seed plantings (Figure 117, Figure 118). The estimated natural mortality rate was relatively stable over time about a mean of 23% yr^{-1}.

Upper Patuxent River (368) (0.5%)

Estimated market abundance had an increasing trend over time from 85 million individuals in 2005 to 215 million individuals in 2023 (Figure 119). Estimated spat and small abundance varied over time with relatively large recruitment events in 2009, 2016, and 2021, and peaks in small abundance one year later. The estimated market exploitation rate was <1% yr^{-1} and the estimated small exploitation rate was <0.5% yr^{-1} in all years (Figure 120). Most of this area is a sanctuary (Table 2). The adjusted market exploitation rate was less than the non-adjusted market exploitation rate in most years due to spat and wild seed plantings (Figure 120, Figure 121). The estimated natural mortality rate decreased over time and remained <25% yr^{-1} in all years with a mean of 13% yr^{-1}.

Eastern Bay Region

The Eastern Bay Region had a relatively high estimated abundance (> 250 million) of adult and market oysters at the beginning of the time series (Figure 122, Figure 123). However, both estimated adult and market abundance declined quickly and stayed below 150 million individuals for most years. In 2023, there was an increase to 398 million individuals for adult abundance and 192 million individuals for market abundance, which is near the abundance in 2005. Estimated adult and market abundance was always highest in Eastern Bay (39). Estimated spat and small abundance varied over time with no strong trend from 2005-2020 and was less than 75 million individuals in most years (Figure 124, Figure 125). There was a large recruitment event in 2021 that resulted in a large increase in spat and small oysters in subsequent years. In almost all years, estimated spat and small abundance was highest in Eastern Bay (39).

Eastern Bay (39) (4.3%)

Estimated market abundance was high at the beginning of the time series at 167 million individuals in 2005 but declined quickly and remained below 80 million individuals before increasing in 2023 to 146 million individuals (Figure 126). Estimated spat and small abundance were relatively low until the most recent years when there was a large recruitment event in

2021. The estimated market exploitation rate was highest in 2006-2007 at 9% yr^{-1} and then decreased to <5% yr^{-1} in almost all years since 2006-2007 (Figure 127). The estimated small exploitation rate followed a similar trend over time as for markets and never exceeded 2% yr^{-1}. The adjusted market exploitation rate was similar to the non-adjusted market exploitation rate in the first few years but has been zero for most of the time series due to spat and wild seed plantings (Figure 127, Figure 128). Estimated natural mortality was high at the beginning of the time series (53% yr^{-1} in 2007 but decreased and has been <20% yr^{-1} in most years.

Miles River (60) (0.3%)

Estimated market abundance was 62 million in 2005 but declined and stayed below 20 million until 2022 before increasing to 33 million individuals (Figure 129). Estimated spat and small abundance were relatively low (<25 million individuals) until large recruitment events in 2018, 2021, and 2023. Estimated market exploitation rate was <2% yr^{-1} until reaching a maximum of 5% yr^{-1} in the 2015-2016 season and has been near zero in recent seasons (Figure 130). The estimated small exploitation rate followed a similar trend over time as market exploitation and was never >3% yr^{-1}. The adjusted market exploitation rate was less than the non-adjusted market exploitation rate in many years due to spat and wild seed plantings (Figure 130, Figure 131). The estimated natural mortality rate was 58% yr^{-1} in 2007 but has been <20% yr^{-1} in most years since 2007.

Wye River (99) (<0.1%)

Estimated market abundance was relatively low compared to the other NOAA codes in the Eastern Bay region (Figure 132). Estimated market abundance varied with no strong trend and was <10 million except for in 2023 when it was 13 million individuals. Estimated spat and small abundances were <10 million individuals in most years except for a large recruitment event in 2021. The estimated market exploitation was <0.5% yr^{-1} most years except for 2009-2010 when it was approximately 1.5% (Figure 133). The estimated small exploitation rate followed a similar trend over time as market exploitation and never exceeded 2% yr^{-1}. The adjusted market exploitation rate was the same as the non-adjusted market exploitation rate due to no spat or wild seed plantings except in 2023 (Figure 133, Figure 134). The estimated natural mortality rate reached a maximum of 28% yr^{-1} in 2010 and has been <20% yr^{-1} since 2010.

Potomac River Region

In the Potomac River region, estimated adult and market abundance increased over time with a 380% for adults to 509 million individuals in 2023 and a 166% increase to 122 million individuals in 2023 for market oysters (Figure 135, Figure 136). The Wicomico River (West) (274) and the St. Mary’s River (78) had the highest estimated adult and market abundance among NOAA codes in the Potomac River region. Breton and St. Clements Bay (174) and Smith Creek (86) had low estimated adult and market abundance compared to the NOAA codes in all other regions.

Estimated spat abundance varied over time with no strong trend from 2005-2020 and was less than 150 million individuals in most years (Figure 137, Figure 138). Over the same period, abundance of small oyster approximately doubled from about 60 million in 2005 to 120 million in 2020. Since 2020, estimated spat abundance has increased, which also resulted in an increasing trend for estimated small abundance with both reaching a maximum in 2023. The Wicomico River (274) and the St. Mary's River (78) had the highest estimated spat and small abundance among NOAA codes in the Potomac River region.

St. Mary's River (78) (2.9%)

Estimated market abundance was 7.4 million individuals in 2005, increased to 14 million individuals by 2012, and has been relatively stable since 2012 about a mean of 15 million individuals (Figure 139). Above average recruitment has been common with spat abundance up to about 100 million oysters in 2023. Estimated small abundance was relatively stable during 2007-2021 about a mean of 56 million individuals, with an increase to 113 million individuals in 2023. Estimated market exploitation rates increased over time from about 5% yr^{-1} in 2005 to 32% yr^{-1} in 2023 (Figure 140). The estimated small exploitation rate followed a similar increasing trend over time and was <1% yr^{-1} in all years. The adjusted market exploitation rate was about the same as the non-adjusted market exploitation rate (Figure 140, Figure 141). A large fraction of this area is a sanctuary (Table 2). The estimated natural mortality rate had a declining trend over time and was <40% yr^{-1} in all years with an overall mean of 22% yr^{-1}.

Smith Creek (86) (0.2%)

Estimated market abundance was relatively stable over time with a mean of 1.7 million individuals during 2005-2022 with an increase to 2.7 million individuals in 2023 (Figure 142). Estimated spat and small abundance was <5 million individuals in most years except for after 2020 when spat and small abundance increased. The estimated market exploitation rate was <5% yr^{-1} until increasing to 15% yr^{-1} in 2014. It stayed above 10% yr^{-1} until 2019 when it decreased to about 5% yr^{-1} where it has remained (Figure 143). Estimated small exploitation rates had a similar trend as market exploitation rates and were <2% yr^{-1} in all years. The adjusted market exploitation rate was the same as the non-adjusted market exploitation rate in all years because no spat or wild seed were planted (Figure 143, Figure 144). The estimated natural mortality rate varied over time with no strong trend a mean of 21% yr^{-1}.

Breton & St. Clements Bays (174) (<0.1%)

Estimated market abundance in Breton & St. Clements Bays was the lowest among all NOAA codes. Estimated market abundance declined from 1.2 million individuals in 2005 to 0.3 million individuals by 2022 with an increase to 0.7 million individuals in 2023 (Figure 145). Estimated spat and small abundance was relatively low and highly uncertain. The estimated market exploitation rate varied over time but was <4% yr^{-1} (Figure 146). The estimated small exploitation rate was <1% yr^{-1} in all years. The adjusted market exploitation rate was nearly identical to the non-adjusted market exploitation rate due a lack of spat or wild seed plantings except in the most recent years (Figure 146, Figure 147). The estimated natural mortality rate was stable over time with a mean of 25% yr^{-1}.

Wicomico River (West) (274) (0.7%)

Estimated market abundance declined during 2005-2014 and increased thereafter to 102 million individuals in 2023 (Figure 148). Estimated spat and small abundance also showed increasing trends over time with the largest recruitment events in recent years. Estimated market exploitation rates were <3% yr^{-1} in all years, reaching a maximum of 3% yr^{-1} in the 2014-2015 season (Figure 149). The estimated small exploitation rate was <0.5% yr^{-1} in all years. The adjusted market exploitation rate was zero for most of the time series due to spat and wild seed plantings (Figure 149, Figure 150). The estimated natural mortality rate reached a maximum of 41% yr^{-1} in 2007, then declined and remained <20% yr^{-1} in most years with an overall mean of 14% yr^{-1}.

North Mainstem Region

Estimated adult and market abundance in the North Mainstem Region were relatively high in 2005 but declined by >50% during 2010-2011 (Figure 151, Figure 152). Since 2012, estimated adult and market abundance increased slightly over time and were approximately 300 and 200 million individuals, respectively, in 2023. Both estimated adult and market abundance was highest in the Upper Bay (25) in all years.

Estimated small abundance also was relatively high in 2005 before decreasing by >50% by 2011 (Figure 153). Since 2011, estimated small abundance increased by about 50% over time and was approximately 125 million individuals in 2023. Spat abundance varied over time more than small and market oysters, with peaks greater than 100 million individuals in 2016 and 2020 (Figure 154). Estimated spat and small abundance was highest in the Upper Bay (25) in most years.

Upper Bay (25) (1.6%)

Estimated market abundance was about 250 million individuals until 2011 when there was a substantial decrease to 88 million individuals (Figure 155). Since 2011, there has been a slight increasing trend with an estimate of 132 million individuals in 2023. Estimated spat abundance has been relatively low except for larger recruitment events in 2005, 2016, and 2021. Estimated small abundance decreased from approximately 200 million individuals in 2008 to about 50 million in 2012. Since 2011, estimated small abundance has remained <100 million in most years. Estimated market exploitation rates varied over time but were less than 2% yr^{-1} in all years (Figure 156). The estimated small exploitation rate followed a similar trend over time as market exploitation rates and was <0.5% yr^{-1} in all years. The adjusted market exploitation rate was zero after 2006-2007 due to spat and wild seed plantings (Figure 156, Figure 157). The estimated natural mortality rate was <20% yr^{-1} in almost all years, except for a large increase to 69% yr^{-1} in 2011, and the overall mean was 14% yr^{-1}. The spike in natural mortality in 2011 coincided with large freshwater runoff from the Susquehanna River associated with Hurricane Irene and Tropical Storm Lee (Tarnowski 2012).

South Mid-Bay (27) (1.6%)

Estimated market abundance was relatively stable over time and had an overall mean of 27 million individuals (Figure 158). Estimated spat abundance was relatively low except for 2010, 2012, 2020, and 2023 when spat abundance was ≥25 million. Estimated small abundance was relatively stable over time with an overall mean of 17 million individuals. Estimated market exploitation rates were near 10% yr^{-1} in the 2005-2006, 2006-2007, and 2015-2016 seasons but were <5% yr^{-1} in all other years (Figure 159). The estimated small exploitation rate followed a similar trend as the market exploitation rate over time and was ≤2% yr^{-1} in all years. The adjusted market exploitation rate was lower than the non-adjusted market exploitation rate in most years due to spat and wild seed plantings (Figure 159, Figure 160). The estimated natural mortality rate was relatively consistent over time with a mean of 13% yr^{-1}.

North Mid-Bay (127) (0.5%)

Estimated abundance of market oysters was approximately 60 million individuals in 2005 but declined and remained at about 25 million individuals during 2009-2021 (Figure 161). In 2022 and 2023, there was an increase to 35 million individuals. Estimated spat abundance was relatively low except for a large recruitment event 2020. Estimated small abundance had a decreasing trend until 2015 followed by an increasing trend to approximately 35 million individuals in 2023. Estimated market exploitation rates varied over time but were <3% yr^{-1} in all seasons except for 2016-2017 (Figure 162). Estimated small exploitation rates followed a similar trend as market exploitation rates and were <0.5% in all years. The adjusted market exploitation rate was zero for most of the time series due to spat and wild seed plantings (Figure 162, Figure 163). The estimated natural mortality rate reached a maximum of 54% in 2009 and then decreased to vary about a mean of 16% yr^{-1}.

South Mainstem Region

In the South Mainstem region, estimated adult and market abundance was relatively stable over time with the highest abundances in the most recent years and an overall average of 241 million individuals and 60 million individuals, respectively (Figure 164, Figure 165). The Lower Bay East (129) had higher estimated adult and market abundance than the Lower Bay West (229).

Estimated spat and small abundance also varied over time with no strong trend with maximum values occurring in 2020 and 2022, respectively (Figure 166, Figure 167). The overall average for estimated small abundance was 181 million individuals and was 175 million individuals for spat. The Lower Bay East (129) had higher estimated spat and small abundance than the Lower Bay West (229).

Lower Bay East (129) (1.9%)

Estimated market abundance was 62 million oysters in 2005 and then declined and varied between 20 to 50 million individuals before increasing in 2022 and 2023 to 70 million individuals (Figure 168). Estimated spat abundance had peaks in 2006, 2007, 2020, and 2021 around 300 million oysters, and small oysters had peaks that were lagged from spat by about a year. Estimated market exploitation rates varied over time, but they were <5% yr^{-1} in most years and were <2% yr^{-1} in the 2022-2023 and 2023-2024 seasons (Figure 169). The estimated small exploitation rate was similar to the market exploitation rate and was <0.2% yr^{-1} in all years. The exploitation rates followed the same patterns over time as the catch. The adjusted market exploitation rate was the same as the non-adjusted market exploitation rate in all years because no spat or wild seed were planted (Figure 169, Figure 170). The estimated natural mortality rate was relatively high and had a slight decreasing trend with an overall mean of 47% yr^{-1}.

Lower Bay West (229) (2.0%)

Estimated market abundance decreased until 2011 and reached a maximum of 34 million individuals in 2022 (Figure 171). There was a slight decrease to 25 million individuals in 2023. Estimated spat abundance varied over time with the largest recruitment events in 2016, 2019, and 2023 between 30 and 45 million individuals. The estimated small abundance increased during 2005-2020 but decreased somewhat thereafter. Estimated market exploitation rates were less than 5% yr^{-1} until the 2012-2013 season and reached a maximum of 18% yr^{-1} in 2022 (Figure 172). The estimated market exploitation rate in 2023 was 9% yr^{-1}. Estimated small exploitation rates had a similar trend as market exploitation rates and were <2% yr^{-1} in all years. The adjusted market exploitation rate was less than the non-adjusted market exploitation rate during 2014-2021 due to spat and wild seed plantings (Figure 172, Figure 173). The estimated natural mortality rate had a decreasing trend over the assessment period until 2022. The estimated natural mortality rate remained <30% yr^{-1} in all years with an overall mean of 17% yr^{-1}.

Chester River Region

The Chester River region had a declining trend for estimated adult and market abundance during 2005-2023 (Figure 174, Figure 175). Estimated adult abundance was highest in 2006 at 138 million individuals but declined by approximately 75% to 37 million individuals in 2023. Similarly, estimated market abundance was highest at nearly 100 million oysters in 2005, but it declined by nearly 70% to about 30 million oysters in 2023. The Mid Chester River (231) was the NOAA code with the highest adult and market abundance in the Chester River region in all years. Estimated adult and market abundance declined in all NOAA codes in this region during 2005-2023.

Estimated spat and small abundance also had a declining trend from 2005 to 2023 (Figure 176, Figure 177). Estimated small abundance declined approximately 80% from 36 million individuals in 2005 to 6 million individuals in 2023. Estimated spat abundance declined by approximately

90% from 50 million individuals in 2005 to 6 million individuals in 2023. The Mid Chester River (231) was the NOAA code with the highest spat and small abundance in the Chester River region in most years. Estimated spat and small abundance declined in all NOAA codes in this region during 2005-2023.

Lower Chester River (131) (0.3%)

Estimated market abundance was less than 15 million individuals in 2005 and increased to about 17 million oysters in 2013 (Figure 178). After 2014, estimated market abundance declined to 5 million individuals in 2023. Estimated spat and small abundance was above 10 million oysters in several years at the beginning of the time series but decreased by 80-90% after 2014. Estimated market exploitation rates were around 5% yr^{-1} during the 2006-2009 and 2017-2018 seasons, and it has been <2% since 2018 (Figure 179). The estimated small exploitation rate was <2% in all years except the 2017-2018 season when it increased to approximately 3.5%. Patterns in exploitation rates closely matched patterns in the harvest. The adjusted market exploitation rate was only similar to the non-adjusted market exploitation rate in the first two seasons and then was zero for the rest of the time series due to spat and wild seed plantings (Figure 179, Figure 180). The estimated natural mortality rate was consistently low over time and with an overall mean of 20% yr^{-1}.

Mid Chester River (231) (0.4%)

Estimated market abundance declined from 43 million individuals in 2005 to 24 million individuals in 2023 (Figure 181). Estimated spat and small abundance also declined by about 75% during the assessment period with some variability. Estimated market exploitation rates varied over time but were <2% yr^{-1} in all years (Figure 182). Estimated small exploitation rates were <1% yr^{-1} in all years. Much of this area is a sanctuary (Table 2). The adjusted market exploitation rate was similar to the non-adjusted market exploitation rate only in the first two years and was zero for the rest of the time series due to spat and wild seed plantings (Figure 182, Figure 183). The estimated natural mortality rate declined from about 20% yr^{-1} in 2005 to about 10% yr^{-1} in 2023 with a mean of 14% yr^{-1}.

Upper Chester River (331) (<0.1%)

Estimated market abundance declined by nearly 90% from 19 million individuals in 2005 to 2 million individuals in 2023 (Figure 184). Estimated spat and small abundances also decreased over time. Estimated market and small exploitation rates were zero or near zero in most years except for the 2010-2011 and 2017-2018 seasons (Figure 185). All of this area is currently a sanctuary (Table 2).The adjusted market exploitation rate was nearly zero in all years due to some spat plantings before 2010 (Figure 185, Figure 186). The estimated natural mortality rate increased over time and remained <30% yr^{-1} in most years with an overall mean of 23% yr^{-1}.

Western Shore Region

The Western Shore Region consistently had the lowest estimated abundance of adult and market oysters among all regions (Figure 187, Figure 188), which was not surprising because it is the smallest region. Estimated adult and market abundance increased from 2005 to a maximum in 2008 and 2022, respectively, before declining afterwards until 2020. After 2020, there was a slight increase in estimated adult and market abundance. The Severn River (82) had higher estimated adult and market abundance than the South River (88).

Estimated spat and small abundance varied over time with no strong trend expect for a large peak of estimated spat abundance in 2007 that led to a large peak in estimated small abundance in 2008 (Figure 189, Figure 190). In most years, estimated spat and small abundance was higher in the Severn River (82) than in the South River (88).

Severn River (82) (<0.1%)

Estimated market abundance was 11 million individuals in 2005, then increased to 44 million individuals in 2011 before decreasing to 15 million individuals in 2023 (Figure 191). Estimated spat and small abundance was relatively low except for a relatively large recruitment event in 2007 followed by an increase in smalls in 2008. The estimated market and small exploitation rates varied over time but were <0.1% yr^{-1} in all years (Figure 192). Most of this area is a sanctuary (Table 2).The adjusted market exploitation rate was also extremely low (Figure 192, Figure 193). The estimated natural mortality rate was consistently low with a mean of 16% yr^{-1}.

South River (88) (0.4%)

Estimated market abundance was relatively stable over time about a mean of 6 million individuals (Figure 194). Estimated spat and small abundance was relatively low except for peaks in recruitment in 2011, 2020, and 2023. The estimated market exploitation rate varied over time about a mean of 4% yr^{-1} but was <10% yr^{-1} in all years (Figure 195). The estimated small exploitation rate was <3% yr^{-1} in all years. Most of this area is a sanctuary (Table 2). The adjusted market exploitation rate was similar to the non-adjusted market exploitation rate only in the first three years and was then zero for the rest of the time series due to spat and wild seed plantings (Figure 195, Figure 196). The estimated natural mortality rate during 2006-2024 averaged 21% yr^{-1} with higher rates during 2007-2009.

4.2 Biological Reference Points

Only one NOAA code, Broad Creek (537), was above the long-term adult density target (Table 12). Most NOAA codes (24/35) had a mean adult density in the three most recent years that was between the cautionary level and the long-term target; NOAA codes that were mostly sanctuary or had large-scale restoration were closest (>60%) to the long-term target (Little Choptank River - 53, Manokin River - 57, Nanticoke River - 62, Harris Creek - 437, and the Tred Avon River - 637). Three NOAA codes (Miles River - 60, Severn River - 82, and Lower Bay West - 229) were between the lower threshold and the cautionary level and seven were below the lower threshold. Six of the NOAA codes below the lower density threshold were either in the Chester River or the North Mainstem Regions.

The estimated exploitation rate that resulted in no year-over-year change in cultch was 0.126 yr^{-1} (Figure 197) The upper threshold exploitation rate reference point was, therefore, 0.126 yr^{-1}, and the target exploitation rate reference point was 0.095 yr^{-1}.

Most NOAA codes (29/35) had a mean adjusted market exploitation rate that was below the target exploitation rate reference point. Two NOAA codes were between the target and limit (Fishing Bay - 43 and Lower Bay West - 229), and four NOAA codes (St. Mary's River - 78, Lower Patuxent River - 168, Tangier Sound South - 192, and Tangier Sound North - 292) were above the limit exploitation rate reference point (Table 13).

4.3 Sensitivity Analyses

Sensitivity analyses indicated that model estimates of abundance, exploitation rates, transition probabilities, and natural mortality were not particularly sensitive to plausible alternative assumptions (Figure 198-Figure 205), and stock status from the sensitivity analyses were almost identical to the base model (Table 10, Table 11). The most impactful assumptions were ones about the area of oyster habitat or catchability of adults in the Fall Dredge Survey. For these models, the change in estimated abundance was approximately proportional to changes in habitat area and inversely proportional to changes in Fall Dredge Survey catchability. Estimated exploitation rates showed the opposite patterns compared to estimated abundance. However, estimated stock status was nearly identical across these models because the estimated exploitation rate reference points scaled with estimated exploitation rates. Other assumptions about number of oysters per bushel, proportion of small oysters in the harvest, box decay rates, fraction of boxes that disarticulated before the Fall Dredge Survey, harvest reporting rate, the value for means or standard deviations on penalties, harvest before the Fall Dredge Survey, spat natural mortality rate, and one catchability parameter per category (adult, spat, and boxes) across all NOAA codes had relatively minor effects on estimates of abundance and exploitation rates, but they did affect estimates of natural mortality and transition probabilities. The sensitivity analysis that evaluated the effect of removing full tows in the Fall Dredge Survey from the indices of abundance indicated slightly higher abundance and slightly lower exploitation rates, on average, than the base model.

We conducted sensitivity analyses of the approach for calculating the exploitation rate reference points. Removing the NOAA codes with very low harvest (exploitation rates <0.01 or < 0.02) had a small effect on the estimated exploitation rate reference points (Figure 206). However, the effect of modifying the years included in the calculation was more substantial (Figure 207-Figure 211). When the most recent years were removed from the analysis, the estimated exploitation rate reference points were lower. This effect is likely because there were high recruitment events at the end of the time series. The stock assessment committee agreed that using all years in the exploitation rate reference point estimation was the most appropriate approach because the recruitment events observed after 2020 are expected to occur with similar frequency in future years (i.e., approximately once every 10-20 years).

4.4 Continuity Run

Estimated abundance was generally higher in the new model but estimated stock status was similar between the two models. In all NOAA codes, except for Breton & St. Clements Bays (174), the estimated abundance market oysters was higher in the new model compared to the old model (Figure 212). Most (33/35) NOAA codes had the same status relative to the limit abundance reference points the old and new model. Most of the NOAA codes (28/33) were above the limit abundance reference point in both the new and old model while five NOAA codes were below the abundance limit reference point in both the new and old model (Table 12). Two NOAA codes (Upper Bay - 25 and South Mid-Bay - 27) switched from being above the abundance limit reference point in the old model to below the limit in the new model.

There were 28 NOAA codes that had the same status relative to the exploitation rate reference point in both the old and the new model (Table 13). Most of these NOAA codes (23/28) were below the target exploitation reference point and one NOAA code was between the target and the limit reference point. Four NOAA codes, St. Mary's River (78), the lower Patuxent River (168), Tangier Sound South (192), and Tangier Sound North (292), were above the exploitation limit rate reference point in both the old and new model. Seven NOAA codes changed status relative to the exploitation rate reference point in the new model compared to the old model (Table 13). Five NOAA codes went from being above the limit exploitation rate reference point in the old model to below the target exploitation rate reference point in the new model. One NOAA code (Smith Creek - 86) went from being between the target and limit reference point in the old model to below the target reference point in the new model. One NOAA code (Lower Bay West - 229) went from being above the exploitation rate reference point in the old model to being between the target and limit reference point in the new model.

The results from the new assessment model are likely more reliable than the old model because the old model only allowed habitat to decrease over time (in the absence of planting), and there is evidence from the Fall Dredge Survey and recent high spat sets that oyster cultch habitat has been stable or increasing over much of the Maryland portion of the Chesapeake Bay.

5 Research Recommendations

The following research recommendations were developed by the stock assessment team (Maryland Department of Natural Resources and University of Maryland Center for Environmental Science) in the process of completing this stock assessment. They are not arranged in order of priority.

- Conduct fishery-dependent sampling of oyster size distribution to better quantify the number of oysters per bushel and the number of under-sized oysters per bushel among NOAA codes.
- Incorporate a shell budget into stage structured assessment to allow internal estimation of biological reference points.
- Examine updated habitat estimates as they become available from the recent Bay Bottom Survey for inclusion in the assessment model.
- Conduct research to better quantify growth rates that can be incorporated into stock assessment models.
- Measure shell volume (separate from volume of live oysters) in Fall Dredge survey samples to potentially help with modeling changes in habitat volume over time.
- Examine potential for survey samples taken after fishing season to inform estimates of fishing mortality in the assessment model.
- Revisit spatial aspects of the Fall Dredge Survey to determine the area that is represented by samples, especially with respect to the new habitat data from the Bay Bottom Survey that is currently being conducted. Consider including a subset of random sites in the Fall Dredge Survey.
- Conduct experiments to estimate catchability of the Fall Dredge Survey.

Progress was made on many of the following research recommendations identified during the last benchmark stock assessment.

Data

- Develop mechanisms to improve accuracy and resolution of reported harvest data including bar level data, the number of licensed individuals on a vessel, and the hours spent harvesting.

  <u>Progress</u>: Not achieved

- Conduct fishery dependent sampling of oyster size distribution to better quantify the number of oysters per bushel and the number of under-sized oysters per bushel.

  <u>Progress</u>: Not achieved

- Conduct research to better quantify growth rates that can be incorporated into stock assessment models.

Progress: Not achieved

- Conduct research to better quantify natural mortality of wild and hatchery -planted spat.

  Progress: Not achieved

- Develop a means to mark hatchery-reared planted spat so that the proportion of planted wild spat can be determined in subsequent surveys.

  Progress: Preliminary work on marking hatchery-reared oysters with Calciene has been done (Spires and North, 2022). Additionally, this approach has been approved by the FDA. However, this practice has not been adopted on a large scale by hatcheries. Additionally, genotyping of the hatchery brood stock has recently been started for a trial in the Manokin River.

Natural Mortality

- Studies to improve estimates of box decay rate. Because box abundance is a critical element in the estimation of annual mortality, understanding how long boxes persist under varying conditions will improve estimates of natural mortality.

  Progress: Not achieved

- Explore the effects of timing of the harvest relative to when fall survey is occurring to see if explains some of the difference between model-based and box count estimates of natural mortality.

  Progress: This recommendation was incorporated into the current stock assessment model.

- Research to better define longevity and identify primary sources of natural mortality of oysters.

  Progress: Not achieved

- Examine resiliency of oyster populations to event of high M.

  Progress: Not achieved, but natural mortality rates have been relatively low throughout most of Maryland since 2005.

Exploitation Rates

- A survey conducted just prior to and directly following the fishery would provide a direct means to estimate exploitation within a given year and could provide a snap shot of conditions relative to selected reference points.

  Progress: A trial version of this approach was attempted for the 2023-2024 harvest season. However, there were issues with determining which sites to sample given a reduced amount of survey effort could be used in the spring relative to the fall.

Habitat

- Conduct ground-truthing surveys on unverified current SONAR data so that existing sonar data can be accurately utilized in determining oyster habitat.

  Progress: A new survey of oyster bottom throughout the Maryland portion of the Chesapeake Bay is currently underway. This new survey is collecting extensive data to validate sonar-based habitat classification algorithms.

- Develop comprehensive maps of current oyster habitat within the Maryland portion of Chesapeake Bay.

  Progress: See above.

- Studies designed to quantify the rate of habitat decay would better inform the assessment and reference point models; and would contribute to development of a shell budget.

  Progress: We attempted to develop a dynamic shell budget model as part of this assessment. However, there were issues that could not be resolved within the time frame of the assessment.

- Develop a mechanism to better understand how shell plantings contribute to habitat and how habitat is quantified.

  Progress: Not achieved.

- Conduct research examining how harvest gears impact oyster habitat.

  Progress: We conducted several analyses to quantify the effects of oyster harvest on oyster habitat. See Appendix A (Section 7.1).

Sanctuaries and Spatial Scale

- The contribution of sanctuaries to oyster population and fishery dynamics within a NOAA code is an important question for management and will require finer scale spatial survey data within and outside of sanctuaries as well as more accurate bar-level harvest data than is currently available.

Progress: A previous effort (Mace et al., 2024) developed a model that forecasted the effects of multiple types of management actions including sanctuaries. The model included larval transport among bars.

- Conduct research to help elucidate how individual NOAA codes (as well as sanctuaries and fished areas) contribute to one another's oyster populations. This would allow for a more complete stock assessment model that incorporates feedback among areas rather than the current assessment which treats each NOAA code as though it is an isolated population.

  Progress: See Mace et al. (2024).

Assessment Model

- Incorporate a shell budget into stage structured assessment in order to allow internal estimation of biological reference points.

  Progress: We attempted to develop a dynamic shell budget model as part of this assessment. However, there were issues that could not be resolved within the time frame of the assessment. The new approach for estimating reference points does not rely on a different population dynamics model.

- Continue to improve the stock assessment model based on lessons learned from this assessment and as new information becomes available.

  Progress: The current assessment includes a variety of improvements over the 2018 benchmark assessment.

- Examine alternative spatial structure for stock assessment.

  Progress: We considered an alternative spatial structure for the stock assessment, but the NOAA code spatial structure was considered to best match the understanding of the population dynamics and the information desired for fishery management.

Biological Reference Points

- Fishing reference points for oysters should account for the accretion and loss of shell since oysters produce their own habitat that is required for population growth. Developing a spawner recruit type analysis that instead of egg production represents shell per recruit. Research is needed to determine the ratio of shell per recruit that is suitable for target and threshold reference points.

Progress: We developed a shell per recruit model but thought that the harvest rate reference points developed in the assessment were more defensible. The shell per recruit model indicated higher target rates of fishing mortality under cases of higher natural mortality, which is likely opposite of the appropriate management response. Also, we were unable to develop a relatively objective cutoff for an appropriate shell per recruit reference point within the time frame of this assessment.

- Research on target levels of abundance including biological limits of abundance (e.g. necessary conditions for successful fertilization).

  Progress: We developed target and limit levels of oyster abundance based on the abundance observed in the large-scale restoration areas and the targets used for evaluating success of the large-scale restoration areas.

Aquaculture

Developing an aquaculture database that tracks plantings of diploid and triploid oysters at the NOAA code spatial scale would be improve the model's ability to quantify the contribution of aquaculture plantings to the population dynamics within the NOAA code.

Progress: Not achieved.

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Table 1. Oyster harvest from the Maryland portion of Chesapeake Bay beginning with the 1889-1890 season through the 2023-2024 season.

Harvest Year	Oyster Landings (Bushels)	Harvest Year	Oyster Landings (Bushels)	Harvest Year	Oyster Landings (Bushels)	Harvest Year	Oyster Landings (Bushels)
1870-71	8,947,803	1934-35	2,100,233	1965-66	1,645,144	1996-97	171,630
1875-76	14,000,000	1935-36	2,407,693	1966-67	3,014,670	1997-98	278,292
1879-80	10,600,000	1936-37	3,081,063	1967-68	3,000,272	1998-99	413,010
1884-85	15,000,000	1937-38	3,245,816	1968-69	2,509,701	1999-00	370,784
1889-90	10,450,087	1938-39	3,403,549	1969-70	2,533,275	2000-01	342,879
1890-91	9,945,058	1939-40	3,129,403	1970-71	2,395,528	2001-02	150,594
1891-92	11,632,730	1940-41	3,430,269	1971-72	2,900,547	2002-03	55,828
1892-93	10,142,500	1941-42	2,792,069	1972-73	2,925,236	2003-04	25,843
1897-98	7,254,934	1942-43	2,328,541	1973-74	2,845,924	2004-05	72,357
1900-01	5,685,561	1943-44	2,413,349	1974-75	2,559,112	2005-06	153,693
1904-05	4,500,000	1944-45	2,436,133	1975-76	2,449,440	2006-07	165,280
1906-07	6,232,000	1945-46	2,322,185	1976-77	1,891,614	2007-08	75,606
1910-11	3,500,000	1946-47	2,157,838	1977-78	2,311,434	2008-09	100,683
1916-17	4,120,819	1947-48	2,027,381	1978-79	2,197,457	2009-10	134,100
1917-18	2,461,603	1948-49	2,702,814	1979-80	2,111,080	2010-11	108,424
1918-19	3,743,638	1949-50	2,495,787	1980-81	2,532,321	2011-12	118,594
1919-20	4,592,001	1950-51	2,170,556	1981-82	2,308,619	2012-13	348,422
1920-21	4,959,962	1951-52	2,339,976	1982-83	1,481,942	2013-14	432,920
1921-22	4,435,186	1952-53	2,642,147	1983-84	1,076,884	2014-15	403,185
1922-23	3,687,489	1953-54	2,129,115	1984-85	1,142,493	2015-16	390,702
1923-24	3,440,810	1954-55	2,878,755	1985-86	1,557,091	2016-17	225,752
1924-25	2,787,047	1955-56	2,799,788	1986-87	976,162	2017-18	183,224
1925-26	2,367,122	1956-57	2,259,882	1987-88	363,259	2018-19	145,859
1926-27	2,571,540	1957-58	2,190,074	1988-89	397,180	2019-20	274,305
1927-28	2,260,898	1958-59	1,968,894	1989-90	413,113	2020-21	346,549
1928-29	1,993,591	1959-60	2,114,899	1990-91	416,720	2021-22	550,236
1929-30	1,839,772	1960-61	1,635,123	1991-92	318,128	2022-23	722,924
1930-31	1,775,738	1961-62	1,495,235	1992-93	59,605	2023-24	438,072
1931-32	2,041,043	1962-63	1,243,498	1993-94	78,817		
1932-33	1,626,214	1963-64	1,383,617	1994-95	164,673		
1933-34	1,835,364	1964-65	1,340,177	1995-96	193,629		

Table 2. Surface area (acres) and historic oyster bar area (acres) for each NOAA Code in the Maryland Chesapeake Bay. Historic oyster bar area is defined as oyster bottom area charted in the Yates Oyster Survey from 1906 to 1912 plus its amendments. Summary of oyster seed and shell planting data for each NOAA Code in the Maryland Chesapeake Bay during 1999-2017. Habitat is the amount (acres) of material, primarily fresh or dredged oyster shell, planted on the bottom. Hatchery and Wild refer to the number (millions of individuals) of hatchery reared or transplanted wild seed placed on the bottom.

Region	NOAA code	NOAA code name	NOAA code Acres	Percent of NOAA code in Sanctuary	Historic Bar Acres	Habitat Acres In 2024 Assessment (from BBS)*	Habitat Acres Planted (Total Acres All Plantings 05-23)	Habitat as Percent of Historic Bar	Hatchery Seed Acres (05 to 23)	Fresh Shell Acres (05 to 23)	Wild Seed Acres (05 to 23)	Alt Sub Acres (05 to 23)
Choptank River	53	Little Choptank River	19,456	48%	4,182	3,346	430	80.0%	363	23	0	100
	137	Choptank River Lower	34,736	14%	20,216	6,279	215	31.1%	62	51	3	5
	237	Choptank River Middle	11,952	52%	7,370	2,977	136	40.4%	135	0	6	0
	337	Choptank River Upper	13,313	100%	1,542	1,392	233	90.3%	222	0	11	0
	437	Harris Creek	7,179	65%	3,468	1,496	430	43.1%	403	15	6	162
	537	Broad Creek	7,751	0%	2,745	999	325	36.4%	10	242	29	0
	637	Tred Avon River	6,500	64%	2,401	1,127	171	46.9%	159	1	11	63
Eastern Bay	39	Eastern Bay	33,032	25%	15,381	6,445	272	41.9%	149	35	40	4
	60	Miles River	12,667	27%	3,476	1,631	19	46.8%	19	0	0	0
	99	Wye River	6,414	100%	1,099	308	8	28.1%	8	0	0	0

Table 2. (cont.)

Region	NOAA code	NOAA code name	NOAA code Acres	Percent of NOAA code in Sanctuary	Yates Bar Acres	Habitat Acres In 2024 Assessment (from BBS)*	Habitat Acres Planted (Total Acres All Plantings 05-23)	Habitat as Percent of Yates Bar	Hatchery Seed Acres (05 to 23)	Fresh Shell Acres (05 to 23)	Wild Seed Acres (05 to 23)	Alt Sub Acres (05 to 23)
Patuxent River	168	Patuxent River Lower	8,803	11%	2,563	1,038	176	40.5%	59	109	64	0
	268	Patuxent River Middle	4,433	0.2%	1,204	1,072	23	89.0%	9	12	2	0
	368	Patuxent River Upper	18,157	79%	3,998	3,524	92	88.2%	39	47	6	0
North Mainstem	25	Bay Mainstem Upper	163,605	10%	25,923	21,116	535	81.5%	312	0	329	0
	27	Bay Mainstem Lower Middle	185,468	12%	34,153	11,507	73	33.7%	41	12	26	1
	127	Bay Mainstem Upper Middle	57,047	10%	17,367	4,888	176	28.1%	78	0	133	0
South Mainstem	129	Bay Mainstem Lower Eastern Shore	130,654	24%	7,827	3,213	14	41.0%	0	0	0	0
	229	Bay Mainstem Lower Western Shore	107,537	4%	23,586	2,672	316	11.3%	11	197	89	0

Table 2. (cont.)

Region	NOAA code	NOAA code name	NOAA code Acres	Percent of NOAA code in Sanctuary	Yates Bar Acres	Habitat Acres In 2024 Assessment (from BBS)*	Habitat Acres Planted (Total Acres All Plantings 05-23)	Habitat as Percent of Yates Bar	Hatchery Seed Acres (05 to 23)	Fresh Shell Acres (05 to 23)	Wild Seed Acres (05 to 23)	Alt Sub Acres (05 to 23)
Potomac River	78	St. Mary's River	6,023	21%	1,182	478	101	40.4%	37	59	7	9
	86	Smith Creek	846	0%	243	74	5	30.5%	0	5	0	0
	174	St. Clements And Breton Bay	7,063	46%	2,501	720	1	28.8%	1	0	0	0
	274	Wicomico River West	11,775	4%	4,396	2,687	176	61.1%	169	2	34	0
Western Shore	82	Severn River	7,552	98%	1,290	822	82	63.7%	78	3	1	3
	88	South River	5,996	38%	1,454	200	56	13.8%	50	1	12	1
Chester River	131	Chester River Lower	18,087	69%	3,900	1,345	223	34.5%	216	0	4	0
	231	Chester River Middle	15,287	53%	5,299	3,179	299	60.0%	296	0	6	0
	331	Chester River Upper	7,215	100%	549	1,005	32	182.9%	32	0	0	0

Table 2. (cont.)												
Region	NOAA code	NOAA code name	NOAA code Acres	Percent of NOAA code in Sanctuary	Yates Bar Acres	Habitat Acres In 2024 Assessment (from BBS)*	Habitat Acres Planted (Total Acres All Plantings 05-23)	Habitat as Percent of Yates Bar	Hatchery Seed Acres (05 to 23)	Fresh Shell Acres (05 to 23)	Wild Seed Acres (05 to 23)	Alt Sub Acres (05 to 23)
Tangier Sound	5	Big Annemessex River	7,137	10%	4,273	0	0	0.0%	0	0	0	0
	43	Fishing Bay	20,119	0%	11,932	2,018	199	16.9%	12	198	4	0
	47	Honga River	31,796	16%	20,048	3,938	197	19.6%	20	129	0	0
	57	Manokin River	20,187	80%	12,814	1,146	341	8.9%	227	4	0	128
	62	Nanticoke River	18,984	88%	1,258	644	313	51.2%	78	82	33	0
	72	Pocomoke Sound	16,287	7%	4,178	1,804	26	43.2%	0	26	0	0
	96	Wicomico River East	6,613	0%	712	200	53	28.1%	50	13	0	0
	192	Tangier Sound South	89,522	6%	38,818	10,534	406	27.1%	15	101	39	1
	292	Tangier Sound North	35,630	8%	18,721	2,909	470	15.5%	48	217	87	0

Table 3 Percent of reported harvest for each NOAA Code for the 19 season time series, only showing those NOAA Codes per season that were within the top 75% of total reported harvest. Season 1 corresponds to season 2005-06, season 2 is 2006-07, and season 19 is 2023-24.

NOAA Code	# Seasons in Top 75% Harvest	Season																		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
025	5	12%	9%	12%	7%		5%													
027	4	7%	7%	4%								3%								
039	8	33%	22%	10%	7%							3%	7%	5%	6%					
043	14					8%	12%	14%	15%	14%	10%	5%	6%	4%	4%	8%	10%	8%		8%
047	11				18%	15%	7%	9%	6%	6%	6%	3%	5%						7%	6%
062	3										4%		3%	4%						
072	4								10%	8%	5%		3%							
078	5												3%	10%	8%	4%				5%
127	1	5%																		
129	2				5%	7%														
137	7						3%				7%	7%	5%	4%	8%	5%				
168	11		4%							4%	10%	11%	8%	4%	6%	9%	5%	7%	10%	
192	16	4%		12%	20%	34%	25%	22%	9%	10%	7%	7%	4%	4%			8%	15%	31%	23%
229	2														6%	5%				
237	1													4%						

268	1	8%																		
292	17			6%	13%	14%	18%	23%	16%	17%	14%	17%	16%	18%	15%	31%	44%	39%	21%	12%
437	2			4%																5%
537	18	9%	33%	27%	6%		6%	10%	20%	18%	16%	18%	15%	18%	22%	15%	10%	7%	8%	17%

Table 4. Distribution of oyster harvest over NOAA code reporting units in the Maryland portion of Chesapeake Bay. Harvest with an unknown NOAA code is included in Oyster Landings.

Harvest Season	Oyster Landings (Bushels)	Number of NOAA Codes with Harvest	% of NOAA Codes with non-zero harvest	List of NOAA Codes without any harvest
2005-06	152,821	32	91%	82, 96, 331
2006-07	164,810	32	91%	43, 99, 174
2007-08	74,984	31	89%	82, 99, 174, 331
2008-09	100,622	34	97%	82
2009-10	133,995	34	97%	637
2010-11	108,367	32	91%	82, 99, 174
2011-12	117,548	33	94%	82, 99
2012-13	345,438	31	89%	25, 99, 268, 331
2013-14	426,588	30	86%	82, 99, 174, 231, 331
2014-15	397,273	34	97%	82
2015-16	383,911	33	94%	174, 331
2016-17	223,003	33	94%	82, 331
2017-18	182,132	34	97%	82
2018-19	145,292	31	89%	82, 99, 174, 331
2019-20	272,830	30	86%	82, 99, 174, 331, 337
2020-21	345,107	26	74%	25, 57, 60, 99, 131, 174, 331, 337, 368
2021-22	548,056	30	86%	99, 174, 331, 337, 368
2022-23	719,071	28	80%	60, 82, 99, 131, 174, 331, 337
2023-24	434,216	31	89%	99, 174, 331, 337

Table 5. Reported harvest by gear type from the Maryland portion of Chesapeake Bay.

Harvest Season	Reported Harvest of Oyster (Bushels) Per Gear Type						
	Diver	Hand Tong	Patent Tong	Power Dredge	Sail Dredge	Unknown	Annual Total
2005-06	38,326	27,782	48,848	33,613		4,252	152,821
2006-07	36,298	56,361	32,608	39,205		338	164,810
2007-08	11,298	23,253	12,018	28,147		268	74,984
2008-09	9,890	11,264	21,391	55,911		2,166	100,622
2009-10	3,171	5,726	36,270	87,404		1,424	133,995
2010-11	5,198	10,967	22,731	56,805	9,605	3,061	108,367
2011-12	2,791	11,071	19,651	74,393	7,309	2,333	117,548
2012-13	7,046	54,116	46,658	214,311	19,018	4,289	345,438
2013-14	24,068	65,048	76,419	238,908	18,009	4,136	426,588
2014-15	26,038	72,461	89,477	178,794	26,375	4,129	397,273
2015-16	39,515	79,102	103,207	120,993	38,774	2,321	383,911
2016-17	26,990	45,392	53,526	78,510	17,561	1,024	223,003
2017-18	23,396	37,533	31,288	78,138	11,135	643	182,132
2018-19	13,178	36,528	20,824	62,607	12,112	43	145,292
2019-20	20,940	45,181	68,803	112,691	25,083	132	272,830

2020-21	14,172	39,104	102,549	148,632	40,533	118	345,107
2021-22	15,439	45,137	177,496	261,761	48,175	49	548,056
2022-23	17,648	67,292	242,736	338,186	53,138	71	719,071
2023-24	17,091	69,557	77,219	238,274	31,950	127	434,216
Total	352,491	802,875	1,283,716	2,447,211	358,847	30,922	5,276,062

Table 6. The gear type used to harvest from the most productive areas within Maryland's portion of Chesapeake Bay varies by area.

NOAA code name	NOAA code	# of Year With Harvest	Primary Gear	NOAA Code Harvest Total (Bushels)	% of Total Harvest	Cumulative Harvest (Bushels)	Cumulative %
Tangier Sound North	292	19	Patent Tong	1,071,181	20%	1,071,181	20%
Broad Creek	537	19	Hand Tong	729,601	14%	1,800,782	34%
Tangier Sound South	192	19	Power Dredge	714,705	14%	2,515,487	48%
Fishing Bay	043	18	Power Dredge	417,627	8%	2,933,115	56%
Patuxent River Lower	168	19	Patent Tong	340,158	6%	3,273,272	62%
Honga River	047	19	Power Dredge	264,743	5%	3,538,015	67%
Eastern Bay	039	19	Diver	219,450	4%	3,757,465	71%
Choptank River Lower	137	19	Power Dredge	186,827	4%	3,944,292	75%

Table 7. Definition of variables used in population dynamics model.

Variable	Description	Value
	Indicator variables/subscripts	
y	year	2005-2023
t	season	1 = October-March 2 = April-September
r	region	1-35
s	stage	sp = spat sm = small mk = market
P	Indicator of penalty function for parameter estimation	
	Estimated parameters	
$\bar{R}$	mean recruitment	estimated
R_{dev}	deviations in recruitment	estimated
G	probability of transition from small to market stage	estimated
M	natural mortality	estimated
b	Box disarticulation rate	estimated
q_N	Catchability of live oysters	estimated
q_B	Catchability of boxes	estimated
N_{init}	Initial abundance of live oysters	estimated
B_{init}	Initial abundance of boxes	estimated
	Calculated/Specified quantities	
N	Abundance of live oysters	calculated
B	Abundance of boxes	
u	exploitation rate	calculated
$\hat{C}$	Estimated catch	calculated

Table 7. Definition of variables used in population dynamics model.

C	Observed Catch	from MD DNR database
P	hatchery spat planted	from MD DNR planting database
S_p	survival of hatchery spat from planting until October 1	0.15
R	Natural Recruitment	calculated
S_{sp}	annual survival of spat	0.61
W	wild seed planted	calculated
S_W	survival of wild seed from planting to October 1	0.9
δ	Proportion of boxes that disarticulate before the fall survey	0.2
$\hat{I}$	Estimated indices from fall dredge survey	calculated
u_{bd}	Proportion of population removed by fishing before fall dredge survey	calculated
C_{bd}	Observed catch that occurred before fall dredge survey	from MD DNR database
L	Likelihood component	calculated
n	Sample size	calculated
A	area of oyster habitat	from previous surveys
C	fishery catch in number of individuals	calculated
c_B	constant to convert catch from individuals to bushels	228
B	fishery catch in bushels	calculated
σ_X	Log-scale standard deviation for fall dredge survey indices	
$\bar{q}_{N_{s\neq sp}}$	mean for adult catchability prior	0.24
$\sigma_{q_{P,N_{s\neq sp}}}$	Standard deviation for adult catchability prior	0.02

Table 7. Definition of variables used in population dynamics model.

$ln(\bar{q}_{ratio,N,s=sp})$	mean for natural log of the ratio of spat catchability to adult catchability prior	-0.24
$\sigma_{q_{P,ratio,N,s=sp}}$	Log-scale standard deviation for Natural log of the ratio of spat catchability to adult catchability prior	0.10
$\ln(\bar{q}_{ratio,B,s\neq sp})$	mean for natural log of the ratio of small and market box catchability to adult catchability prior	-0.56
$\sigma_{q_{P,ratio,B,s\neq sp}}$	Log-scale standard deviation for Natural log of the ratio of small and market box catchability to adult catchability prior	0.12
$\bar{G}$	Mean of prior for probability of transition from small to market stage	0.35
σ_G	Standard deviation of prior for probability of transition from small to market stage	0.075
$\bar{b}$	Mean of prior for instantaneous box disarticulation rate	1.11
σ_b	Standard deviation of prior for instantaneous box disarticulation rate	0.02
σ_R	log-scale standard deviation for recruitment among years and regions	2.0
σ_M	log-scale standard deviation for natural mortality among years and regions	0.5
$\sigma_{C,s}$	Standard deviation for prior on observed catch of small and market oysters	$\begin{cases} 1 \quad, & if\ s = sm \\ 1{,}000, & if\ s = mk \end{cases}$
$N_{eq,s}$	Equilibrium abundance of live small and market oysters in the first year	calculated
$B_{eq,s}$	Equilibrium abundance of small and market boxes in the first year	calculated
$\sigma_{N_{P,s}}$	Standard deviation of prior for equilibrium abundance of live small and market oysters in the first year	0.2
$\sigma_{B_{P,s}}$	Standard deviation of prior equilibrium abundance of small and market boxes in the first year	0.2

Table 8. Summary of sensitivity analyses for assessment model.	
Analysis	Description
Spat M 0.4	Decrease spat mortality 20% to 0.4
Spat M 0.6	Increase spat mortality 20% to 0.6
One q per stage	One catchability parameter for adult, spat, and boxes across all NOAA codes
Low N per Bushel	Assume 350 oysters per bushel and
High N per Bushel	Assume 150 oysters per bushel and
No Harvest Before FDS	Assume no harvest occurs before the Fall Survey in all NOAA codes
SOS surv 0.05	Assume hatchery reared spat have 5% survival from planting to October 1
Reporting Rate 100%	Assume 100% reporting rate for harvest
Reporting Rate 80%	80% reporting rate for harvet
1/2 Adult mean q	Mean prior of 0.12 for adult catchability
Habitat 90%	90% of habitat in base model in each NOAA code
Habitat 80%	80% of habitat in base model in each NOAA code
Habitat 70%	70% of habitat in base model in each NOAA code
Habitat 60%	60% of habitat in base model in each NOAA code
Habitat 50%	50% of habitat in base model in each NOAA code
Habitat 37%	37% of habitat in base model in each NOAA code
2X SD R devs	SD prior of 4.0 for recruitment deviations
2X SD Adult q	SD prior of 0.04 for adult catchability
2X Adult mean q	Mean prior of 0.48 for adult catchability
2X SD Initial Live	SD prior of 0.6 for initial live abundance
2X SD M variation	SD prior of 1.0 for variation in M across NOAA codes
2X SD G	SD prior of 0.15 for transition probability
2X SD Initial Boxes	SD prior of 0.6 for initial box abundance
2X SD Box decay rate	SD prior of 0.04 for box decay rate
No Full Dredge	Remove all full dredge tows before calculating indices of abundance
30% Boxes Before FDS	30% of boxes not available to Fall Survey
10% Boxes Before FDS	10% of boxes not available to Fall Survey

Table 9. Estimates of the probability of transition from the small to market stage (G), small and market box catchability ($q_{\boldsymbol{B}}$), spat catchability ($q_{N,spat}$), and live adult (small and market) catchability ($q_{N,adult}$). The coefficient of variation of each estimate is in parentheses as a proportion.

NOAA Code	G	$q_{\boldsymbol{B}}$	$q_{N,spat}$	$q_{N,adult}$
25	0.22 (0.17)	0.11 (0.11)	0.16 (0.13)	0.22 (0.09)
27	0.30 (0.18)	0.14 (0.12)	0.17 (0.13)	0.24 (0.08)
39	0.41 (0.07)	0.13 (0.12)	0.11 (0.13)	0.21 (0.10)
43	0.25 (0.09)	0.11 (0.11)	0.24 (0.11)	0.25 (0.08)
47	0.17 (0.12)	0.10 (0.11)	0.21 (0.11)	0.24 (0.08)
53	0.29 (0.07)	0.13 (0.12)	0.12 (0.11)	0.21 (0.09)
57	0.22 (0.09)	0.11 (0.11)	0.24 (0.11)	0.24 (0.08)
60	0.47 (0.08)	0.12 (0.13)	0.12 (0.14)	0.20 (0.11)
62	0.41 (0.08)	0.16 (0.11)	0.14 (0.11)	0.24 (0.08)
72	0.22 (0.10)	0.09 (0.11)	0.23 (0.11)	0.25 (0.08)
78	0.11 (0.16)	0.14 (0.12)	0.17 (0.12)	0.24 (0.08)
82	0.44 (0.12)	0.13 (0.12)	0.18 (0.13)	0.23 (0.09)
86	0.18 (0.16)	0.14 (0.12)	0.17 (0.12)	0.24 (0.08)
88	0.45 (0.11)	0.10 (0.11)	0.16 (0.14)	0.21 (0.09)
96	0.41 (0.09)	0.14 (0.12)	0.15 (0.12)	0.23 (0.08)
99	0.65 (0.06)	0.16 (0.11)	0.16 (0.12)	0.24 (0.08)
127	0.20 (0.14)	0.08 (0.12)	0.13 (0.14)	0.19 (0.11)
129	0.22 (0.25)	0.13 (0.12)	0.18 (0.13)	0.24 (0.08)
131	0.49 (0.11)	0.10 (0.11)	0.16 (0.13)	0.20 (0.09)
137	0.19 (0.14)	0.12 (0.12)	0.16 (0.12)	0.23 (0.09)
168	0.19 (0.07)	0.16 (0.11)	0.13 (0.11)	0.24 (0.08)
174	0.42 (0.16)	0.14 (0.12)	0.18 (0.13)	0.24 (0.08)
192	0.21 (0.09)	0.09 (0.11)	0.25 (0.11)	0.24 (0.08)
229	0.29 (0.11)	0.14 (0.12)	0.16 (0.12)	0.23 (0.09)
231	0.45 (0.12)	0.13 (0.11)	0.18 (0.13)	0.22 (0.09)
237	0.48 (0.07)	0.14 (0.12)	0.13 (0.12)	0.22 (0.09)
268	0.34 (0.18)	0.14 (0.12)	0.17 (0.13)	0.24 (0.08)
274	0.17 (0.17)	0.12 (0.12)	0.17 (0.13)	0.23 (0.09)
292	0.25 (0.09)	0.14 (0.11)	0.17 (0.11)	0.24 (0.08)
331	0.44 (0.15)	0.14 (0.12)	0.19 (0.13)	0.24 (0.08)
337	0.37 (0.07)	0.13 (0.12)	0.13 (0.13)	0.22 (0.09)
368	0.28 (0.10)	0.15 (0.12)	0.16 (0.13)	0.24 (0.08)
437	0.20 (0.14)	0.10 (0.12)	0.16 (0.12)	0.21 (0.09)
537	0.11 (0.10)	0.14 (0.11)	0.18 (0.11)	0.25 (0.08)
637	0.42 (0.06)	0.13 (0.12)	0.10 (0.12)	0.20 (0.10)

Table 10. Status of NOAA codes relative to the abundance limit reference point in each sensitivity analysis. Orange shading indicates NOAA codes that were below the abundance limit reference point, and no shading indicates NOAA codes above the limit reference point.

	Spat M 0.4	Spat M 0.6	One q per stage	Low N per Bushel	High N per Bushel	No Harvest Before FDS	SOS surv 0.05	Reporting Rate 100%	Reporting Rate 80%	1/2 Adult mean q	Habitat 90%	Habitat 80%	Habitat 70%	Habitat 60%	Habitat 50%	Habitat 37%	2X SD R devs	2X SD Adult q	2X Adult mean q	2X SD Initial Live	2X SD M variation	2X SD G	2X SD Initial Boxes	2X SD Box decay rate	No Full Dredge	30% Boxes Before FDS	10% Boxes Before FDS	Base Model
25	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	4.7	2.3	2.4	2.4	2.5	2.6	2.8	2.4	2.8	1.1	2.3	2.4	2.3	2.3	2.3	4.2	2.3	2.3	2.3
27	1	1	1	1	1	1	1	1	1	1.9	1	1	1	1	1	1	1	1	0.5	1	1	1	1	1	1.3	1	1	1
39	9.2	9	8	9	9.4	9.1	8.4	9.1	9.1	21.6	9.3	9.5	9.9	10.4	11.3	13.5	9.4	17.3	4.2	9	9.3	9	9.1	9.1	11.1	9.1	9.1	9.1
43	39.3	38.1	46.4	39.4	38.2	38.7	38.7	38.8	38.5	73.6	38.5	38.4	38.2	37.9	37.7	37.5	38.9	34.2	19.9	38.7	38.8	38.9	38.7	38.7	50.4	39.3	38.2	38.7
47	30.8	29.8	33.6	30.2	30.3	30.3	30.3	30.3	30.3	59.5	30.3	30.3	30.4	30.4	30.5	30.7	30.4	29.4	15.5	30.4	31	30.5	30.3	30.3	35.5	30.7	29.9	30.3
53	68.1	65.8	59.2	66.9	67	66.9	60.4	66.9	66.9	140.5	68	69.4	71.2	73.6	77	84.6	66.9	96.7	32.3	65.4	69.2	67	66.5	66.9	73.9	66.4	67.4	66.9
57	59.5	58.2	68.7	58.8	58.9	58.8	58.4	58.8	58.8	117	59.1	59.4	59.9	60.7	62	64.9	58.6	59.9	30	59.7	60.6	59.1	59.1	58.8	67.5	58.3	59.5	58.8
62	68.5	65.5	62.1	67.7	66.7	66.9	67	67.1	66.8	133.4	66.8	66.6	66.4	66.3	66.4	67.9	67.6	65.8	32.8	66.2	66.5	67	67.1	67	81.3	66.1	67.7	67
72	16.7	16.2	19.3	16.6	16.3	16.4	16.4	16.5	16.4	31.8	16.4	16.3	16.3	16.2	16	15.8	16.5	15.1	8.4	16.5	16.6	16.5	16.5	16.4	20.7	16.7	16.3	16.4
78	47.2	45	46.6	45.6	46.2	46	46.1	45.9	46.3	92.7	46.2	46.5	46.8	47.2	47.8	49.2	47.1	48.6	23.1	46.2	48.3	47.1	46.2	46.1	58.5	45.9	46.2	46.1
82	7.8	7.7	7.9	7.8	7.8	7.8	7.7	7.8	7.8	16.1	7.8	7.8	7.7	7.8	8.3	9.6	8.9	8.6	4.1	7.7	7.8	7.9	7.8	7.8	9.8	7.7	7.8	7.8
86	32.8	31.5	33.7	31.8	32.5	31.9	32.1	32	32.3	63.3	32.2	32.4	32.6	32.9	33.3	34.2	33.4	32.4	16.4	32.2	31	32.4	32.2	32.1	31.4	32.7	31.7	32.1
88	18.4	18.3	16.4	18.1	18.4	18.3	18.2	18.3	18.4	38.2	18.7	19.1	19.7	20.3	21.4	24.2	19.1	26.3	8.7	18.3	17.4	18	18.3	18.3	26.3	18.7	18	18.3
96	35.2	33.7	33.9	34.8	34.3	34.2	32.8	34.5	34.4	68.6	34.7	35.1	35.7	36.6	37.9	41.2	35	37.4	17.7	34.1	35.3	34.4	34.4	34.4	39	34.6	34.2	34.4
99	12.3	12.1	12.9	12.2	12.2	12.2	12.3	12.2	12.2	24.3	12.2	12.3	12.3	12.3	12.4	12.4	12.7	12	6.2	12.1	12.4	12.1	12.2	12.2	14.6	12.3	12.1	12.2
127	3.8	3.8	3.2	3.8	3.8	3.8	3.6	3.8	3.8	13	3.9	3.9	4	4.5	4.4	5.4	4.6	45.7	1.6	3.8	3.9	3.9	3.8	3.8	4.4	3.8	3.9	3.8
129	25.7	25.3	26.9	25.5	25.5	25.5	25.5	25.5	25.5	50.8	25.5	25.5	25.5	25.5	25.5	25.5	26.9	25.4	12.8	25.5	25.5	27	25.5	25.5	30.5	26.1	25	25.5
131	1.2	1.2	1.1	1.2	1.2	1.2	1.1	1.2	1.2	2.6	1.3	1.3	1.4	1.5	1.6	2.1	1.2	1.9	0.5	1.2	1.2	1.2	1.2	1.2	1.4	1.2	1.3	1.2
137	15.3	14.8	15.2	15.2	15	15	14.6	15.1	15	31.8	15.1	15.1	15.1	15.2	15.2	15.4	15.4	16.6	7.4	15	14.8	15.1	15	15	18.9	15.2	14.9	15
168	28.9	28.6	29.9	26.8	30.5	28.4	28.6	28.2	29.6	49.9	29.4	30.3	31.5	33.3	36.1	42.9	28.7	28.5	16.6	28.8	28.9	29.1	28.8	28.8	29.3	29	28.6	28.8
174	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.8	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.2	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.4	0.4
192	23	22.4	25.6	22.5	22.7	22.6	22.7	22.6	22.7	44.2	22.7	22.8	22.9	23.1	23.4	24	22.8	22.1	11.8	22.7	22.9	22.8	22.7	22.7	25	23	22.4	22.7
229	5.3	5.2	5.2	5.3	5.3	5.3	5.3	5.3	5.3	10.9	5.3	5.3	5.4	5.5	5.6	6	5.3	6	2.6	5.2	5.4	5.3	5.3	5.3	6.2	5.3	5.3	5.3
231	2.4	2.3	2.3	2.4	2.4	2.4	2.2	2.4	2.4	4.9	2.4	2.5	2.5	2.6	2.8	3.2	2.4	2.9	1.2	2.4	2.5	2.4	2.4	2.4	4.3	2.4	2.4	2.4
237	27.1	26.4	25	26.6	27.1	26.7	25.4	26.7	26.8	61.9	26.9	27.2	27.4	27.7	28.2	29.1	27.4	39.1	12.7	26.6	26.7	26.7	26.8	26.8	27.5	26.8	26.7	26.8
268	44.6	43.6	47	43.9	44.4	44.1	44.1	44.1	44.2	88.2	44.1	44.2	44.3	44.3	44.4	44.7	48.8	44.4	22.1	43.9	43.4	43.8	44.1	44.1	55.8	45.6	42.8	44.1
274	26.5	25.7	26.4	26.2	26.1	26.1	25.7	26.1	26.1	55.1	26.2	26.4	26.5	26.8	27.2	27.9	28.3	29.9	12.6	26	27	26.4	26.2	26.1	19.6	26	26.2	26.1
292	24.9	24.3	25.6	23.9	25.2	24.5	24.6	24.4	25	46	24.9	25.4	26.1	27.2	29	33.4	24.6	24.5	13.9	24.7	25.1	24.8	24.8	24.6	29.2	24.9	24.4	24.6
331	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	1.3	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.7	0.3	0.7	0.7	0.6	0.7	0.7	1	0.7	0.6	0.7
337	19.6	18.8	17.7	19.2	19.2	19.2	18.2	19.2	19.2	44	19.4	19.7	20.2	20.9	22.3	26.1	19.7	26.4	9.4	19.2	18.3	19.2	19.2	19.2	23.7	18.9	19.5	19.2
368	22.9	22.6	23.6	22.7	22.7	22.7	22.7	22.7	22.7	45.6	22.7	22.8	22.8	22.8	22.8	22.8	23.4	23	11.3	22.7	24.1	22.7	22.8	22.7	26.8	22.8	22.7	22.7
437	67	62.4	61.5	65	64.4	64.6	55.7	64.7	64.5	124.7	66.6	69.2	72.8	78.2	86.9	109.9	65.2	86.8	31.9	65.4	64.8	65.5	64.5	64.6	74.9	62.5	66.8	64.6
537	207.5	203	223.8	207	206	202.7	205.2	205.5	205.1	386.6	204.8	204.5	204.6	205.4	207.9	217.2	207.6	186.8	104.5	196.6	200.8	208.3	204.1	205.2	259.4	205.9	204.8	205.2
637	64	60.9	52.5	62.4	62.4	62.3	53.6	62.4	62.3	136.2	64.5	67.6	72.2	79.3	90.8	121.3	62.5	108.7	32.9	61.9	62.1	62.2	62.2	62.3	70.9	61.5	63.2	62.4

Table 11. Status of NOAA codes relative to the exploitation rate limit reference point in each sensitivity analysis. Orange shading indicates NOAA codes that were above the exploitation rate limit reference point, and no shading indicates NOAA codes below the limit exploitation rate reference point.

	Spat M 0.4	Spat M 0.6	One q per stage	Low N per Bushel	High N per Bushel	No Harvest Before FDS	SOS surv 0.05	Reporting Rate 100%	Reporting Rate 80%	1/2 Adult mean q	Habitat 90%	Habitat 80%	Habitat 70%	Habitat 60%	Habitat 50%	Habitat 37%	2X SD R devs	2X SD Adult q	2X Adult mean q	2X SD Initial Live	2X SD M variation	2X SD G	2X SD Initial Boxes	2X SD Box decay rate	No Full Dredge	30% Boxes Before FDS	10% Boxes Before FDS	Base Model
Reference Point	0.13	0.13	0.12	0.07	0.15	0.13	0.13	0.12	0.14	0.07	0.14	0.16	0.18	0.21	0.25	0.33	0.13	0.13	0.26	0.13	0.13	0.13	0.13	0.13	0.11	0.13	0.13	0.13
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0.004	0	0.007	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	0.116	0.119	0.094	0.066	0.14	0.118	0.118	0.105	0.134	0.06	0.132	0.151	0.175	0.207	0.255	0.357	0.118	0.134	0.24	0.116	0.114	0.119	0.118	0.118	0.1	0.118	0.117	0.118
47	0.087	0.089	0.079	0.051	0.102	0.088	0.088	0.079	0.099	0.044	0.098	0.11	0.127	0.148	0.179	0.244	0.088	0.091	0.176	0.088	0.078	0.09	0.088	0.088	0.07	0.087	0.089	0.088
53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
57	0.001	0.001	0.001	0	0.001	0.001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.001	0.001	0.001	0.001
62	0.022	0.019	0.023	0	0.031	0.021	0.024	0.014	0.024	0.009	0.021	0.024	0.027	0.032	0.038	0.051	0.019	0.019	0.039	0.019	0.019	0.019	0.019	0.019	0.017	0.022	0.02	0.021
72	0.042	0.043	0.036	0.025	0.05	0.043	0.043	0.038	0.048	0.022	0.048	0.054	0.062	0.072	0.088	0.12	0.043	0.047	0.084	0.042	0.042	0.043	0.042	0.043	0.035	0.043	0.043	0.043
78	0.195	0.194	0.19	0.105	0.231	0.196	0.199	0.173	0.221	0.092	0.217	0.246	0.283	0.332	0.401	0.549	0.194	0.184	0.416	0.192	0.17	0.196	0.192	0.195	0.163	0.195	0.194	0.195
82	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
86	0.04	0.041	0.039	0.023	0.048	0.041	0.041	0.037	0.046	0.02	0.046	0.052	0.059	0.069	0.084	0.113	0.041	0.041	0.085	0.04	0.038	0.042	0.041	0.041	0.038	0.041	0.041	0.041
88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
96	0.024	0.016	0.021	0.003	0.034	0.021	0.034	0.016	0.026	0.01	0.023	0.025	0.028	0.032	0.038	0.048	0.02	0.019	0.041	0.021	0.018	0.02	0.02	0.02	0.02	0.021	0.02	0.02
99	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
127	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
129	0.014	0.014	0.013	0.008	0.016	0.014	0.014	0.012	0.015	0.007	0.015	0.017	0.019	0.023	0.027	0.037	0.014	0.014	0.027	0.014	0.01	0.014	0.014	0.014	0.011	0.014	0.014	0.014
131	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
137	0.021	0.021	0.021	0.011	0.025	0.021	0.022	0.019	0.024	0.01	0.024	0.027	0.031	0.036	0.043	0.06	0.021	0.019	0.045	0.021	0.022	0.021	0.021	0.021	0.017	0.021	0.021	0.021
168	0.2	0.2	0.19	0.114	0.231	0.204	0.205	0.181	0.222	0.115	0.218	0.238	0.262	0.29	0.321	0.365	0.201	0.202	0.35	0.2	0.194	0.2	0.199	0.2	0.188	0.197	0.202	0.2
174	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
192	0.154	0.157	0.144	0.091	0.18	0.156	0.156	0.14	0.175	0.079	0.173	0.194	0.221	0.257	0.306	0.406	0.156	0.159	0.304	0.154	0.149	0.157	0.156	0.156	0.125	0.154	0.158	0.156
229	0.107	0.107	0.109	0.035	0.134	0.107	0.108	0.094	0.123	0.05	0.119	0.134	0.153	0.177	0.21	0.274	0.106	0.093	0.228	0.108	0.1	0.107	0.107	0.107	0.09	0.108	0.106	0.107
231	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
237	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
268	0.002	0.002	0.002	0	0.003	0.002	0.002	0.001	0.003	0.001	0.002	0.002	0.003	0.003	0.004	0.005	0.002	0.002	0.004	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
274	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
292	0.245	0.246	0.235	0.142	0.281	0.248	0.246	0.221	0.276	0.125	0.273	0.305	0.345	0.394	0.455	0.558	0.245	0.247	0.481	0.244	0.23	0.246	0.245	0.246	0.207	0.243	0.248	0.246
331	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
337	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
368	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
437	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
537	0.079	0.08	0.074	0.045	0.093	0.082	0.08	0.072	0.09	0.044	0.088	0.099	0.112	0.129	0.153	0.197	0.079	0.087	0.152	0.082	0.079	0.08	0.08	0.08	0.064	0.08	0.08	0.08
637	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 12. Estimated abundance or density relative to the abundance reference points in each NOAA code for 2023 (old model) or the mean of the three most recent years (new model). Abundance is in millions of market oysters, and densities are densities of adult oysters.							
	Old Model (abundance)			New Model (density)			
NOAA Code	Limit	Target	2023	Limit	Cautionary level	Target	2023
25	7.0	-	9.9	4.5	9.0	94.2	2.3
27	2.4	-	4.3	4.5	9.0	94.2	1.0
39	4.4	-	29.8	4.5	9.0	94.2	9.1
43	0.3	-	15.4	4.5	9.0	94.2	38.7
47	2.1	-	11.7	4.5	9.0	94.2	30.3
53	1.1	-	97.6	4.5	9.0	94.2	66.9
57	1.4	-	10.1	4.5	9.0	94.2	58.8
60	4.6	-	7.3	4.5	9.0	94.2	7.3
62	2.1	-	29.9	4.5	9.0	94.2	67.0
72	2.0	-	4.0	4.5	9.0	94.2	16.4
78	0.3	-	10.6	4.5	9.0	94.2	46.1
82	2.1	-	3.5	4.5	9.0	94.2	7.8
86	0.1	-	0.9	4.5	9.0	94.2	32.1
88	1.0	-	2.6	4.5	9.0	94.2	18.3
96	0.3	-	3.3	4.5	9.0	94.2	34.4
99	0.3	-	1.2	4.5	9.0	94.2	12.2
127	9.1	-	6.3	4.5	9.0	94.2	3.8
129	1.2	-	3.6	4.5	9.0	94.2	25.5
131	5.5	-	2.3	4.5	9.0	94.2	1.2
137	0.6	-	8.3	4.5	9.0	94.2	15.0
168	3.2	-	13.8	4.5	9.0	94.2	28.8
174	1.3	-	1.1	4.5	9.0	94.2	0.4
192	9.7	-	33.0	4.5	9.0	94.2	22.7
229	2.5	-	7.2	4.5	9.0	94.2	5.3
231	7.5	-	6.6	4.5	9.0	94.2	2.4
237	1.9	-	18.4	4.5	9.0	94.2	26.8
268	0.3	-	2.0	4.5	9.0	94.2	44.1
274	4.5	-	7.6	4.5	9.0	94.2	26.1
292	9.6	-	50.6	4.5	9.0	94.2	24.6
331	0.6	-	0.1	4.5	9.0	94.2	0.7
337	8.7	-	15.1	4.5	9.0	94.2	19.2
368	2.4	-	5.3	4.5	9.0	94.2	22.7
437	2.9	-	28.9	4.5	9.0	94.2	64.6
537	6.5	-	65.2	4.5	9.0	94.2	205.2
637	6.4	-	52.2	4.5	9.0	94.2	62.4

Table 13. Comparison of estimated adjusted exploitation rates relative to the exploitation rate reference points in each NOAA code for the most recent year (old model) or the mean of the three most recent years (new model). Exploitation rates are presented as proportions. The method for adjusting the exploitation rate for plantings in the old model allowed calculation of negative exploitation rates.

	Old Model			New Model		
NOAA Code	Limit	Target	2023	Limit	Target	2023
25	0.00	0.00	-0.35	0.13	0.09	0.00
27	0.10	0.05	-0.07	0.13	0.09	0.00
39	0.04	0.02	-0.16	0.13	0.09	0.00
43	0.50	0.25	0.48	0.13	0.09	0.12
47	0.36	0.18	0.49	0.13	0.09	0.09
53	0.04	0.02	-0.71	0.13	0.09	0.00
57	0.12	0.06	-0.08	0.13	0.09	0.00
60	0.00	0.00	-0.08	0.13	0.09	0.00
62	0.01	0.00	-0.02	0.13	0.09	0.02
72	0.25	0.12	0.26	0.13	0.09	0.04
78	0.35	0.17	0.42	0.13	0.09	0.19
82	0.00	0.00	-6.50	0.13	0.09	0.00
86	0.24	0.12	0.13	0.13	0.09	0.04
88	0.00	0.00	-0.73	0.13	0.09	0.00
96	0.10	0.05	0.02	0.13	0.09	0.02
99	0.00	0.00	0.00	0.13	0.09	0.00
127	0.00	0.00	-1.01	0.13	0.09	0.00
129	0.24	0.12	0.08	0.13	0.09	0.01
131	0.00	0.00	-0.99	0.13	0.09	0.00
137	0.29	0.14	0.45	0.13	0.09	0.02
168	0.17	0.09	0.29	0.13	0.09	0.20
174	0.00	0.00	-0.99	0.13	0.09	0.00
192	0.28	0.14	0.70	0.13	0.09	0.16
229	0.12	0.06	0.30	0.13	0.09	0.11
231	0.00	0.00	-1.66	0.13	0.09	0.00
237	0.00	0.00	-0.12	0.13	0.09	0.00
268	0.12	0.06	0.02	0.13	0.09	0.00
274	0.00	0.00	-1.23	0.13	0.09	0.00
292	0.00	0.00	0.24	0.13	0.09	0.25
331	0.00	0.00	0.00	0.13	0.09	0.00
337	0.00	0.00	-0.29	0.13	0.09	0.00
368	0.00	0.00	-0.07	0.13	0.09	0.00
437	0.01	0.01	0.02	0.13	0.09	0.00
537	0.19	0.10	0.24	0.13	0.09	0.08

637	0.00	0.00	-1.41	0.13	0.09	0.00

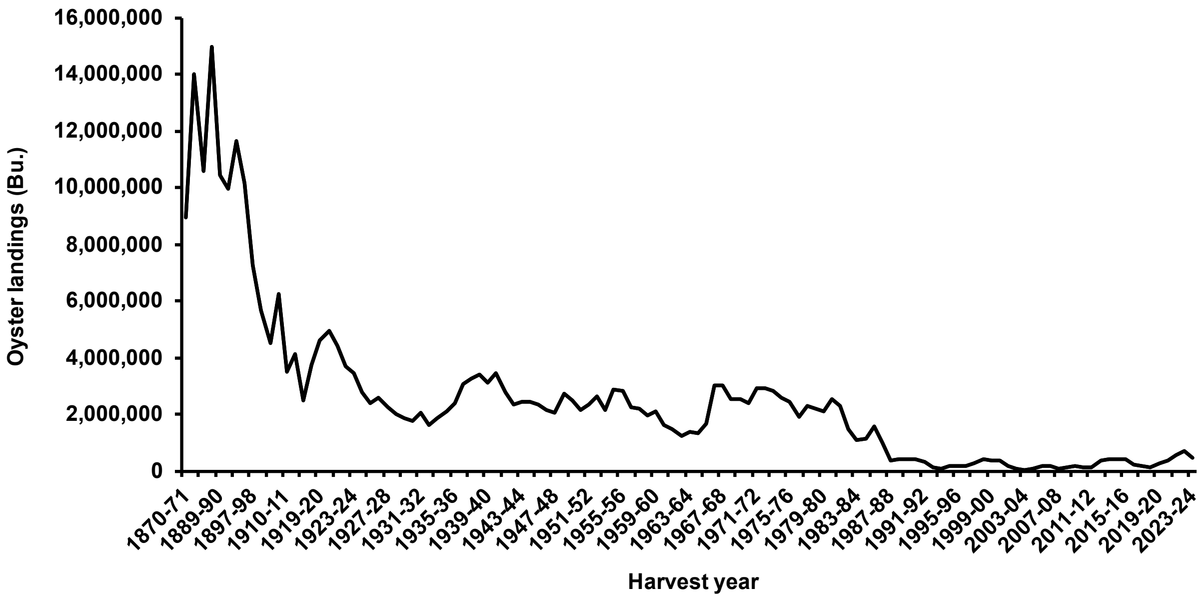

Figure 1. The harvest of oysters (bushels) from the Maryland portion of Chesapeake Bay from the 1870-71 through the 2023-2024 harvest seasons.

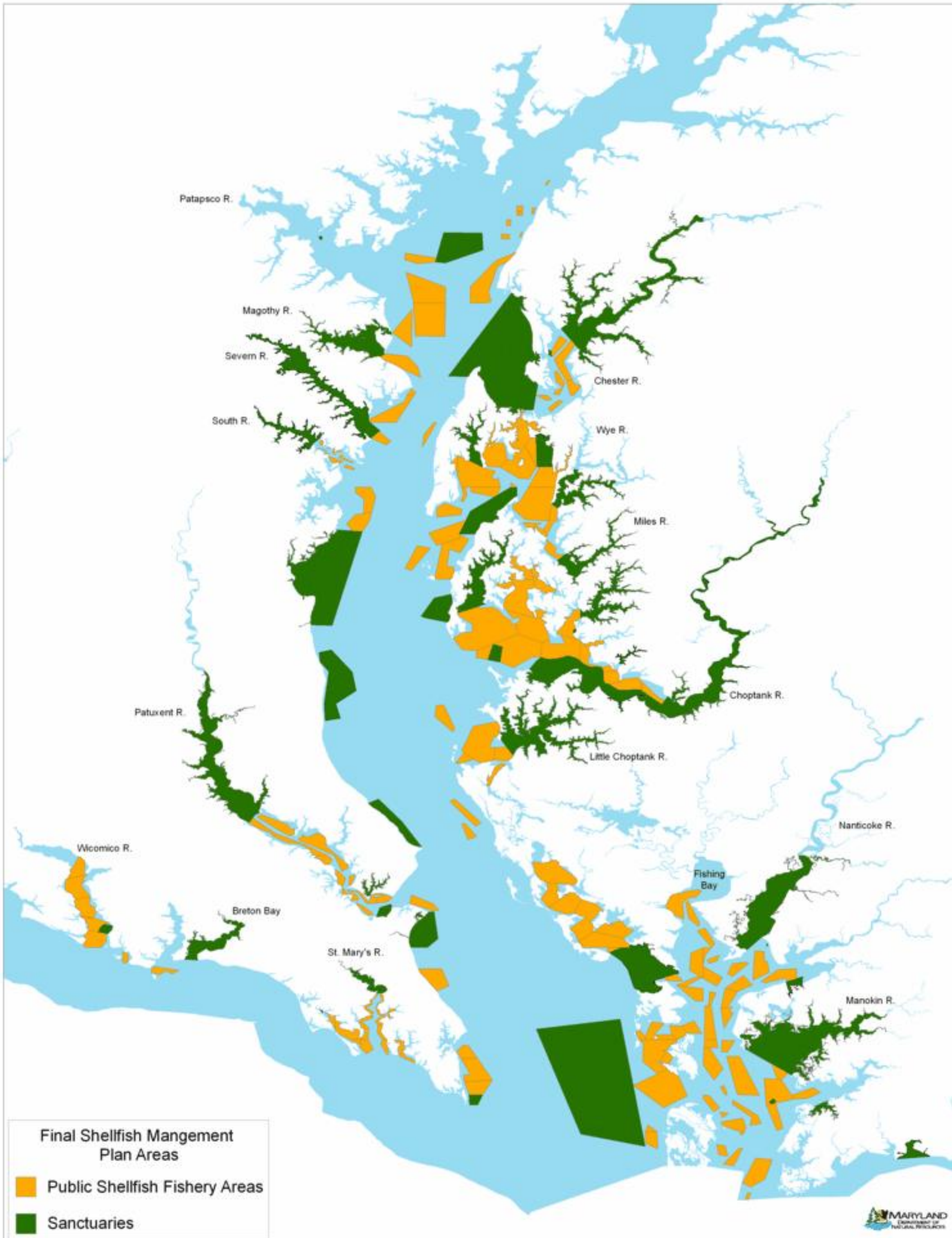

Figure 2. Map of current oyster sanctuaries and public shellfish fishery areas in Maryland.

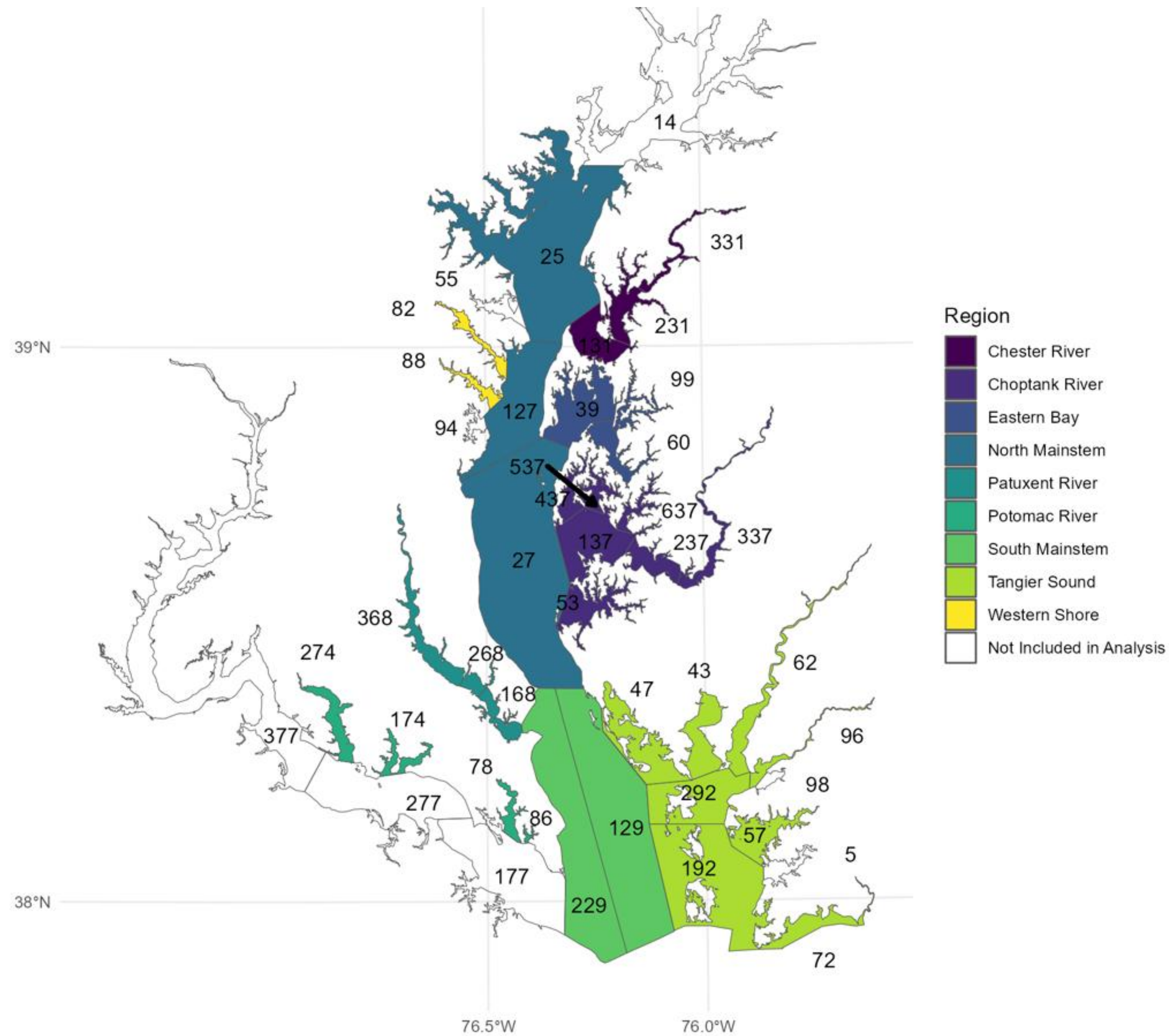

Figure 3. NOAA code harvest reporting areas in the Maryland portion of Chesapeake Bay and the regions used to summarize assessment model results.

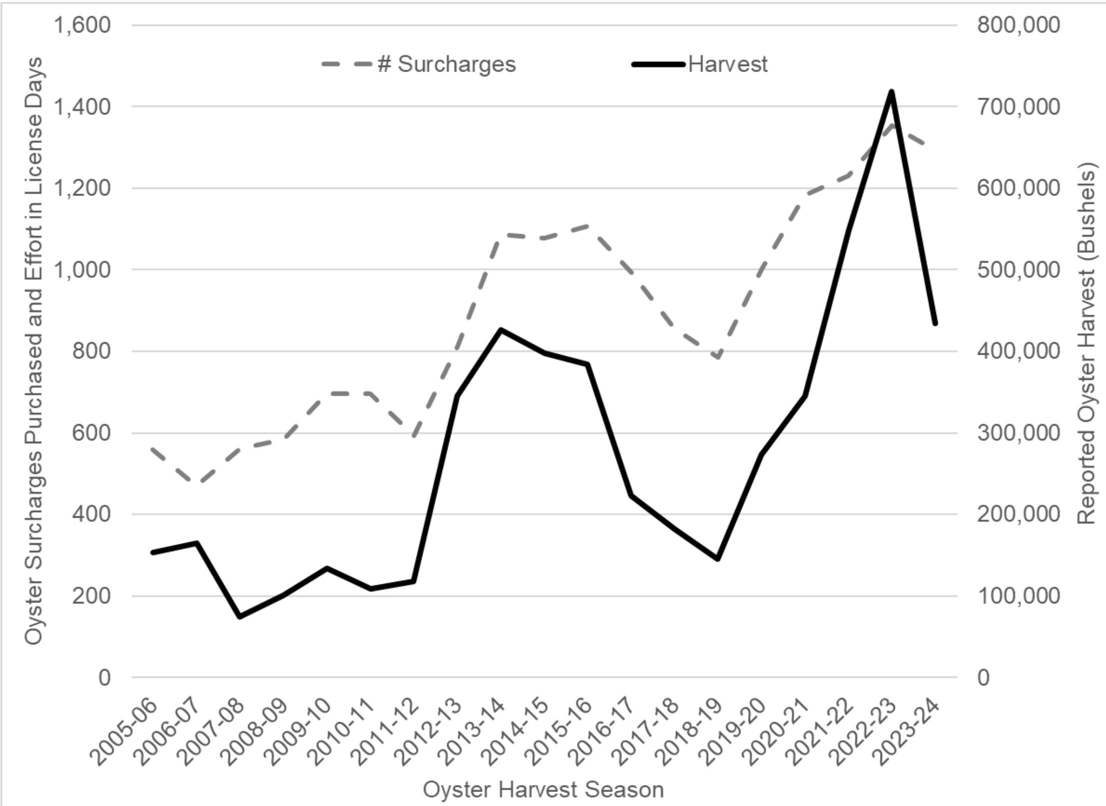

Figure 4. Effort in the oyster fishery represented by the number of surcharges sold each year and the bushels harvested from the Maryland portion of Chesapeake Bay during 2005-2023.

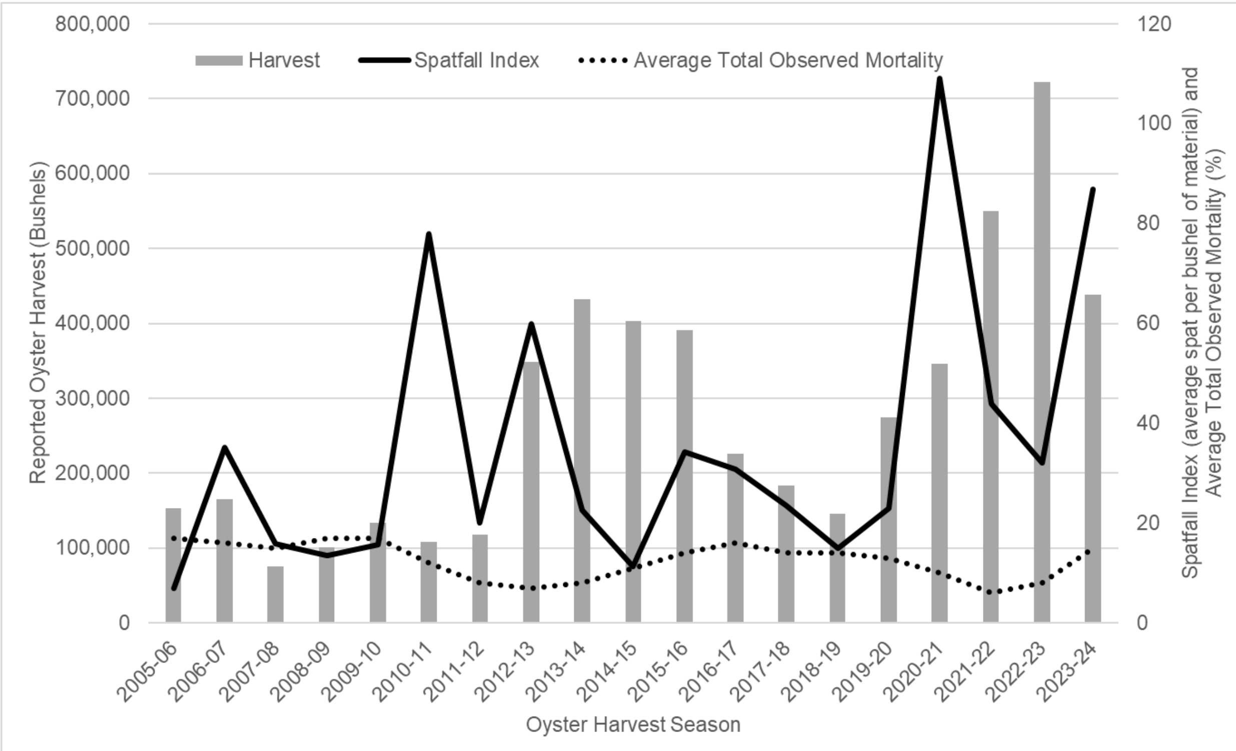

Figure 5. Oyster harvest from the Maryland portion of Chesapeake Bay along with an index of spatfall and mortality from the Maryland Department of Natural Resources fall dredge survey.

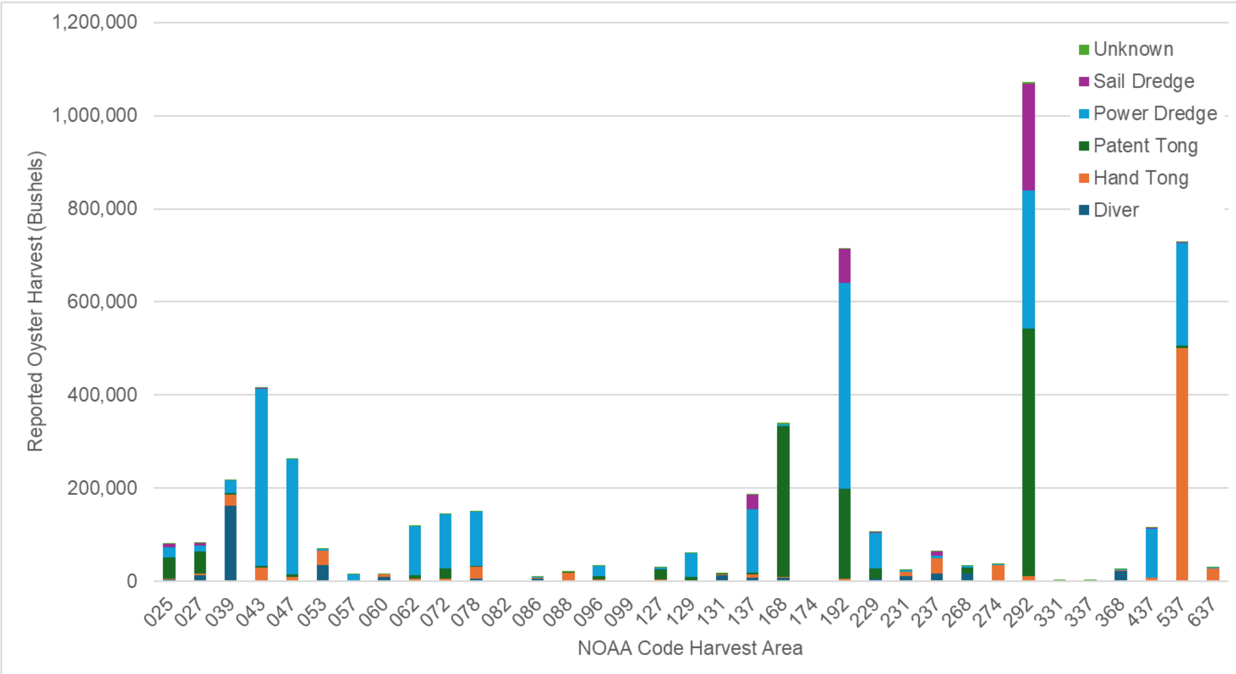

Figure 6. Oyster harvest by gear for each NOAA code reporting area in the Maryland portion of Chesapeake Bay. Harvest is totaled over the 2005-2006 through 2023-2024 seasons.

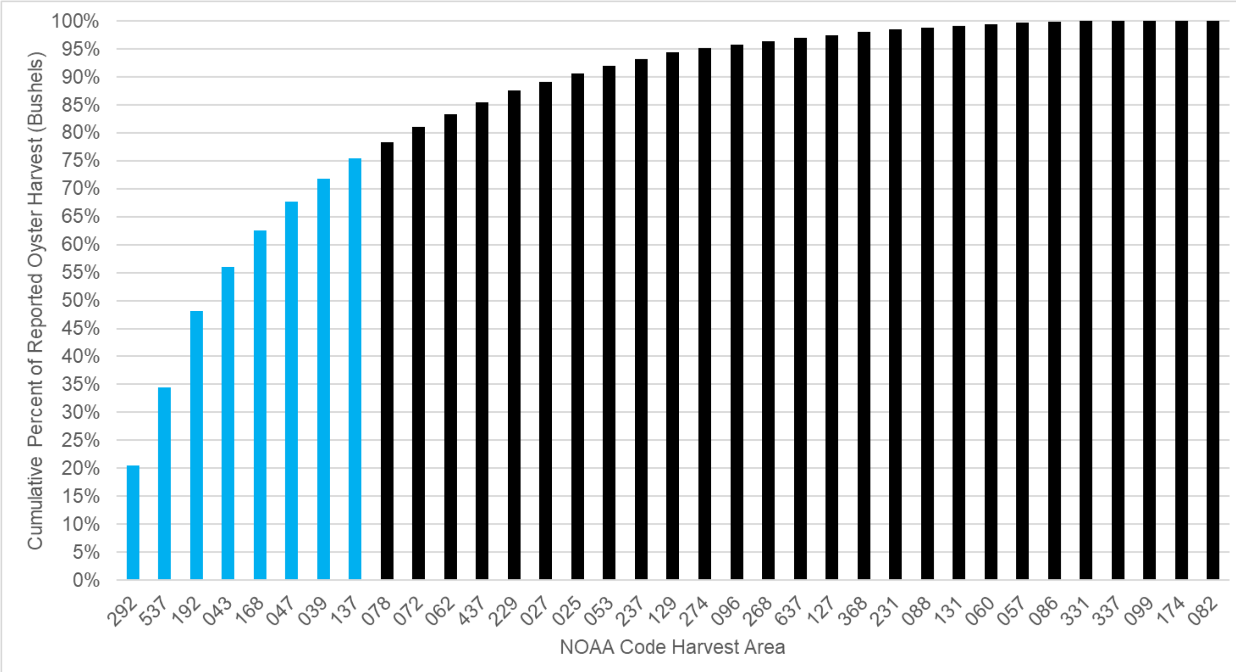

Figure 7. The cumulative distribution of the oyster harvest during the 2005-2006 to 2023-2024 harvest seasons over the NOAA code harvest reporting areas in the Maryland portion of Chesapeake Bay. Blue bars indicate the NOAA codes that make up 75% of the reported harvest.

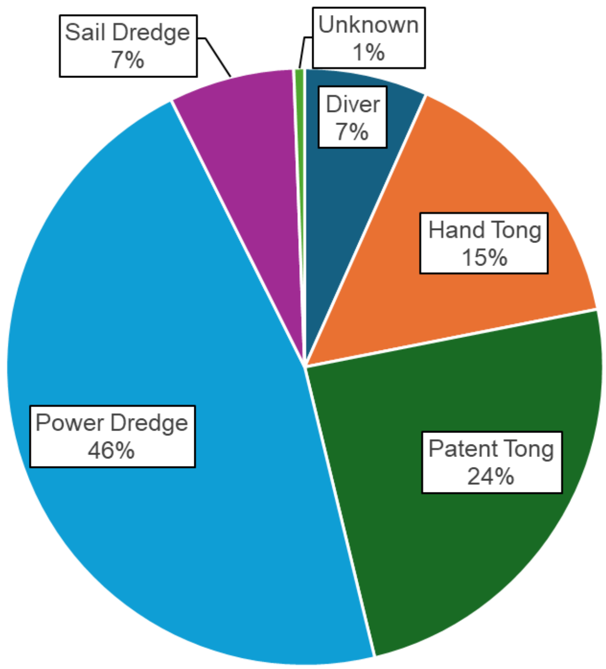

Figure 8. The fraction of oyster harvest by gear type in the Maryland portion of Chesapeake Bay during the 2005-2006 to 2023-2024 harvest seasons.

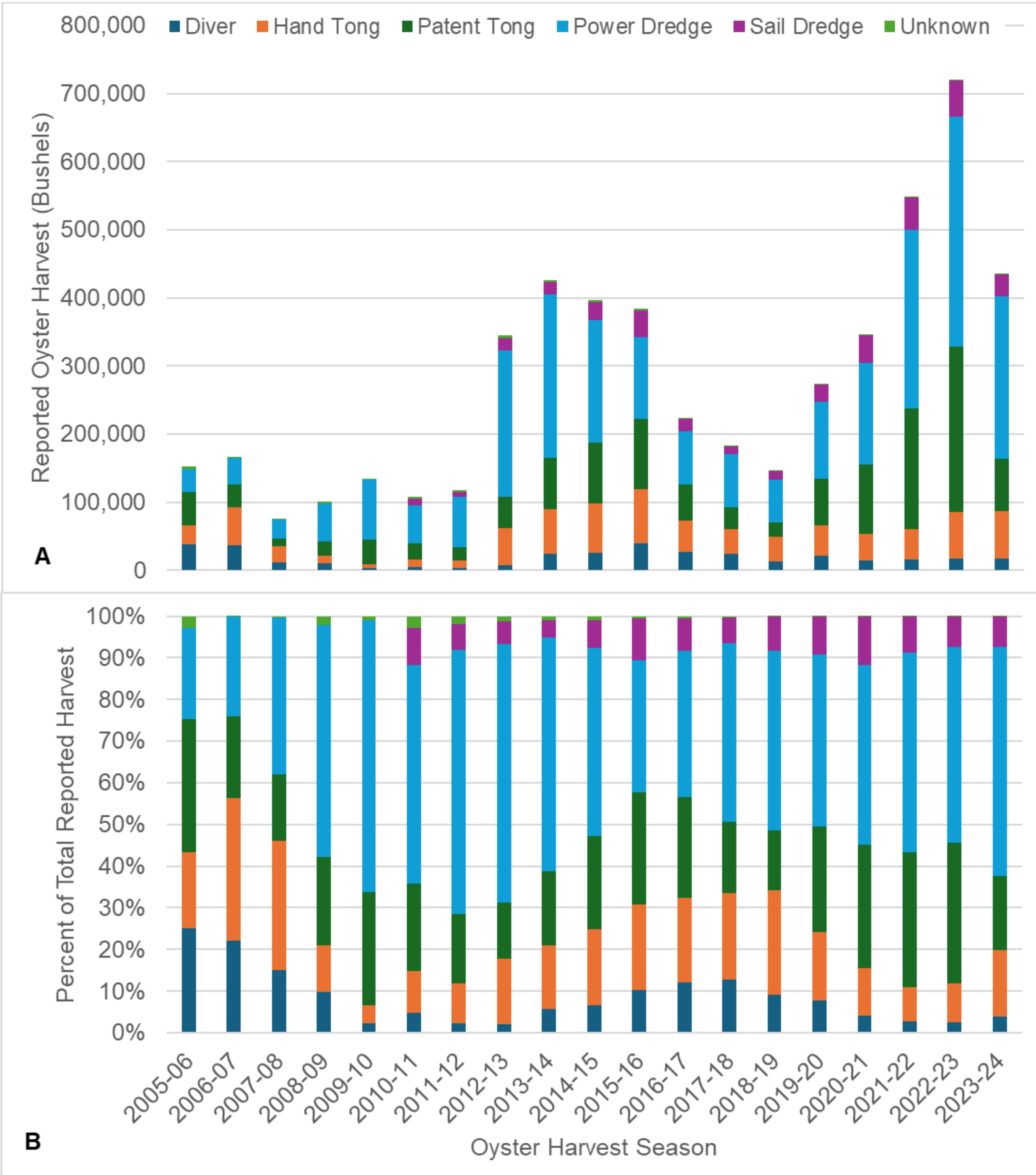

Figure 9. Annual oyster harvest by gear from the Maryland portion of Chesapeake Bay a) in bushels, b) as a percentage of the annual harvest during the 2005-2006 to 2023-2024 harvest seasons.

Figure 10. A comparison of three sources of reported oyster harvest from the Maryland portion of Chesapeake Bay: harvester reports, buy tickets and the oyster severance tax (i.e., bushel tax).

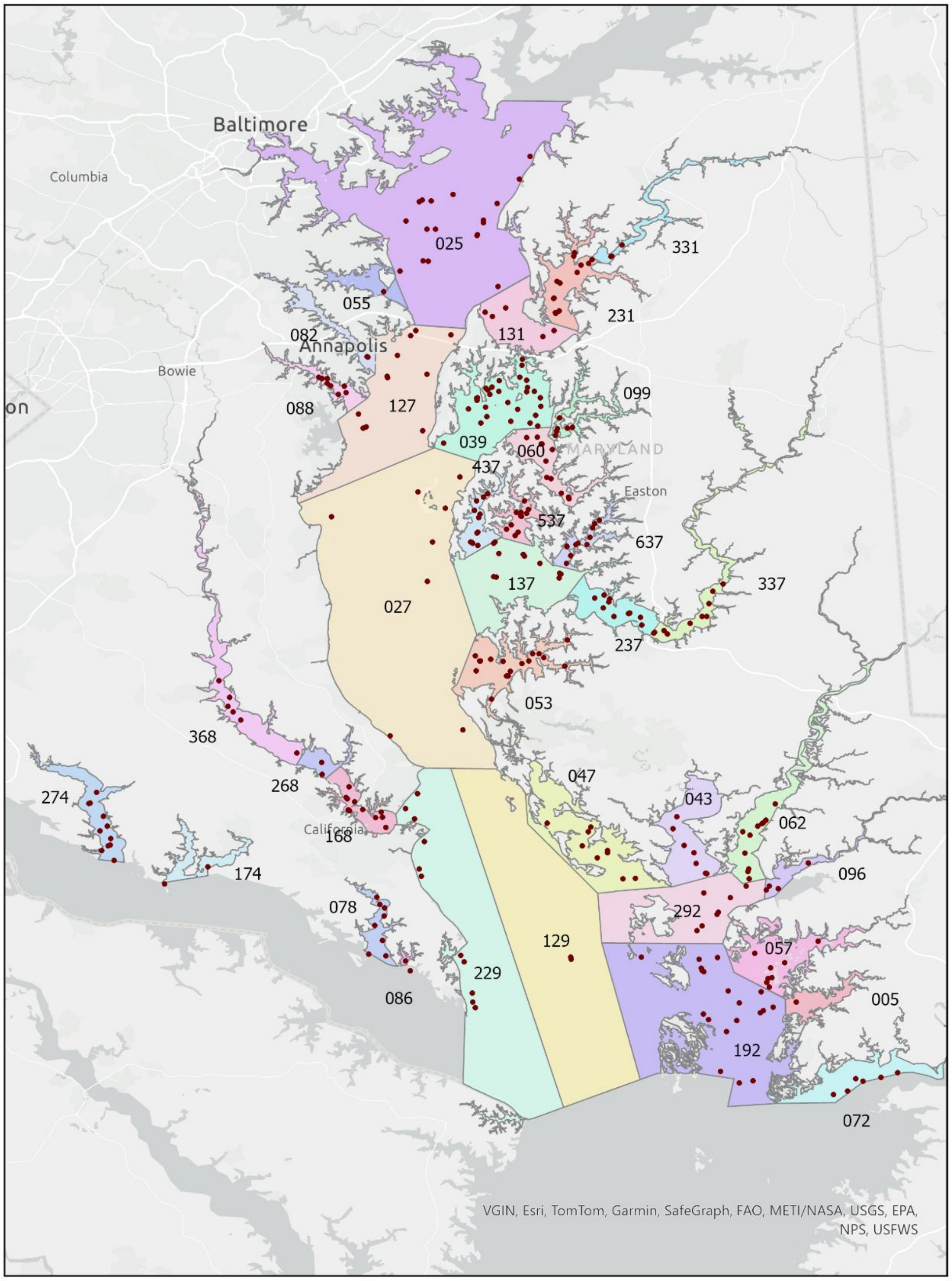

Figure 11. Map of the Maryland portion of Chesapeake Bay showing NOAA codes and sampling sites for the Maryland Department of Natural Resources fall dredge survey.

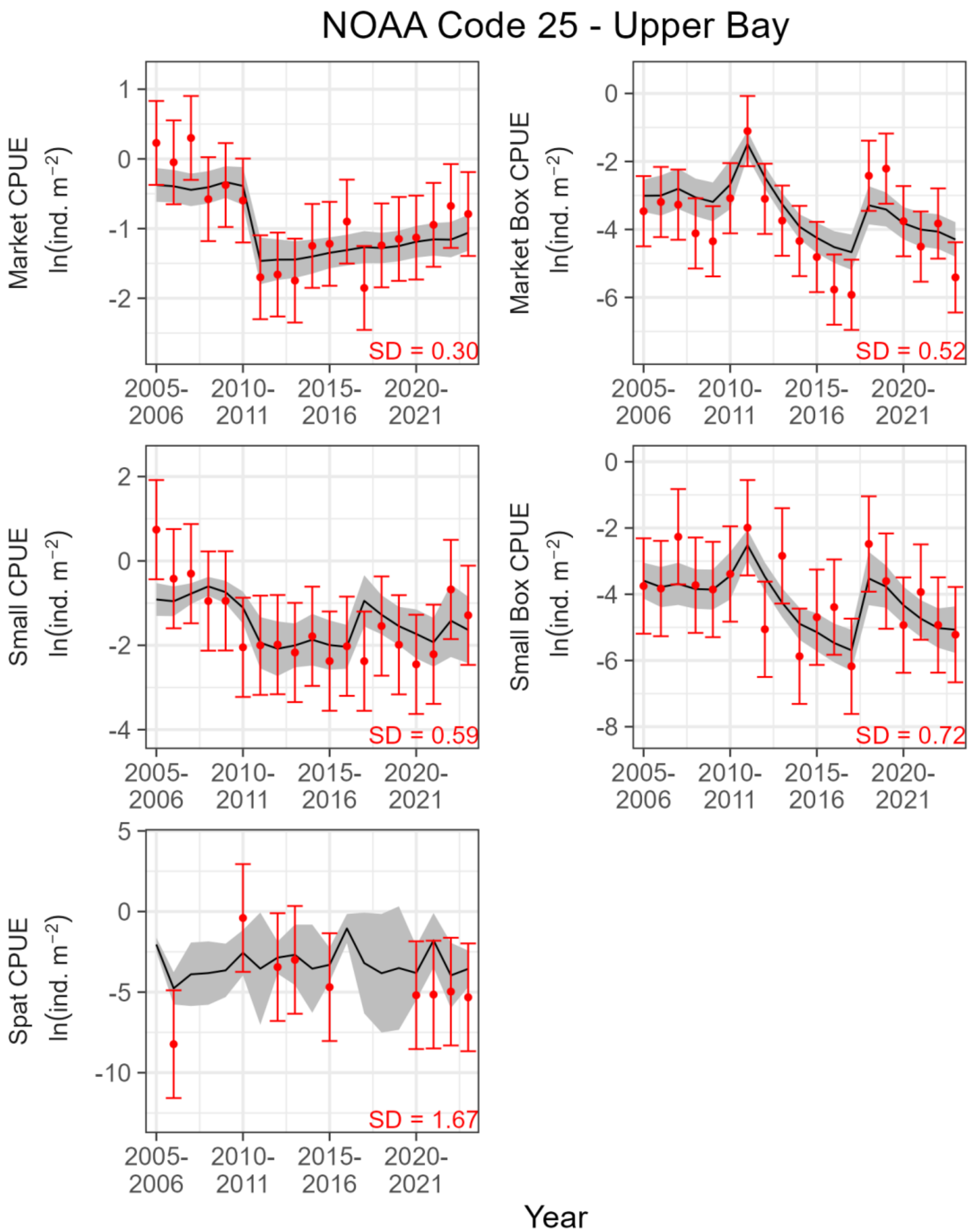

Figure 12. Estimated (black line) and observed (red points) indices of abundance (ln individuals per m^2) of live market, market box, live small, small box, and spat, during 2005-2023 in the Upper Bay. Red whiskers indicate 95% confidence intervals (CIs) on the observations (given the standard deviations (SDs) used in model fitting), and the shaded areas indicate approximate 95% CIs of the model estimates.

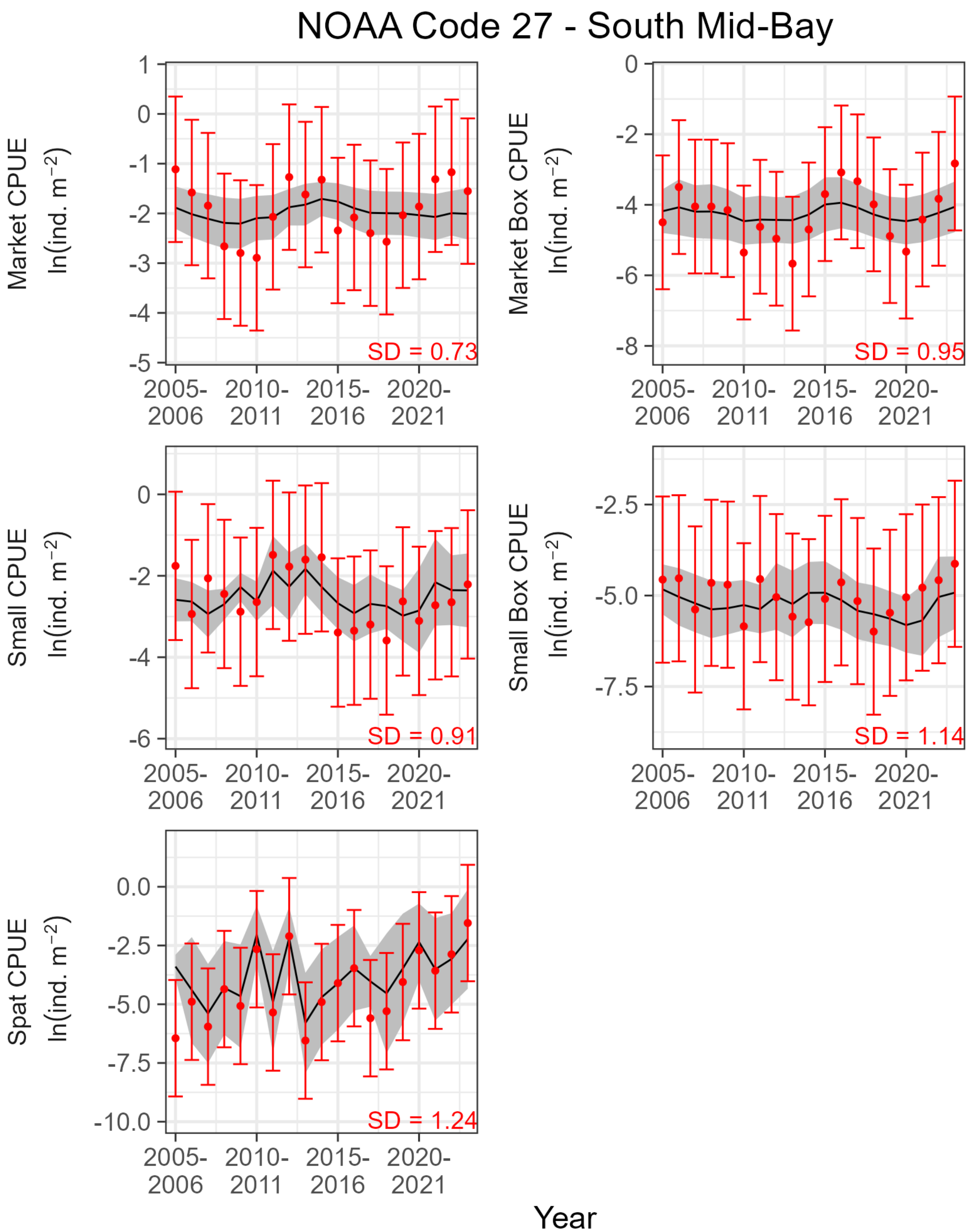

Figure 13. Estimated (line) and observed (points) values for South Mid-Bay. Variable and symbol definitions are the same as Figure 12.

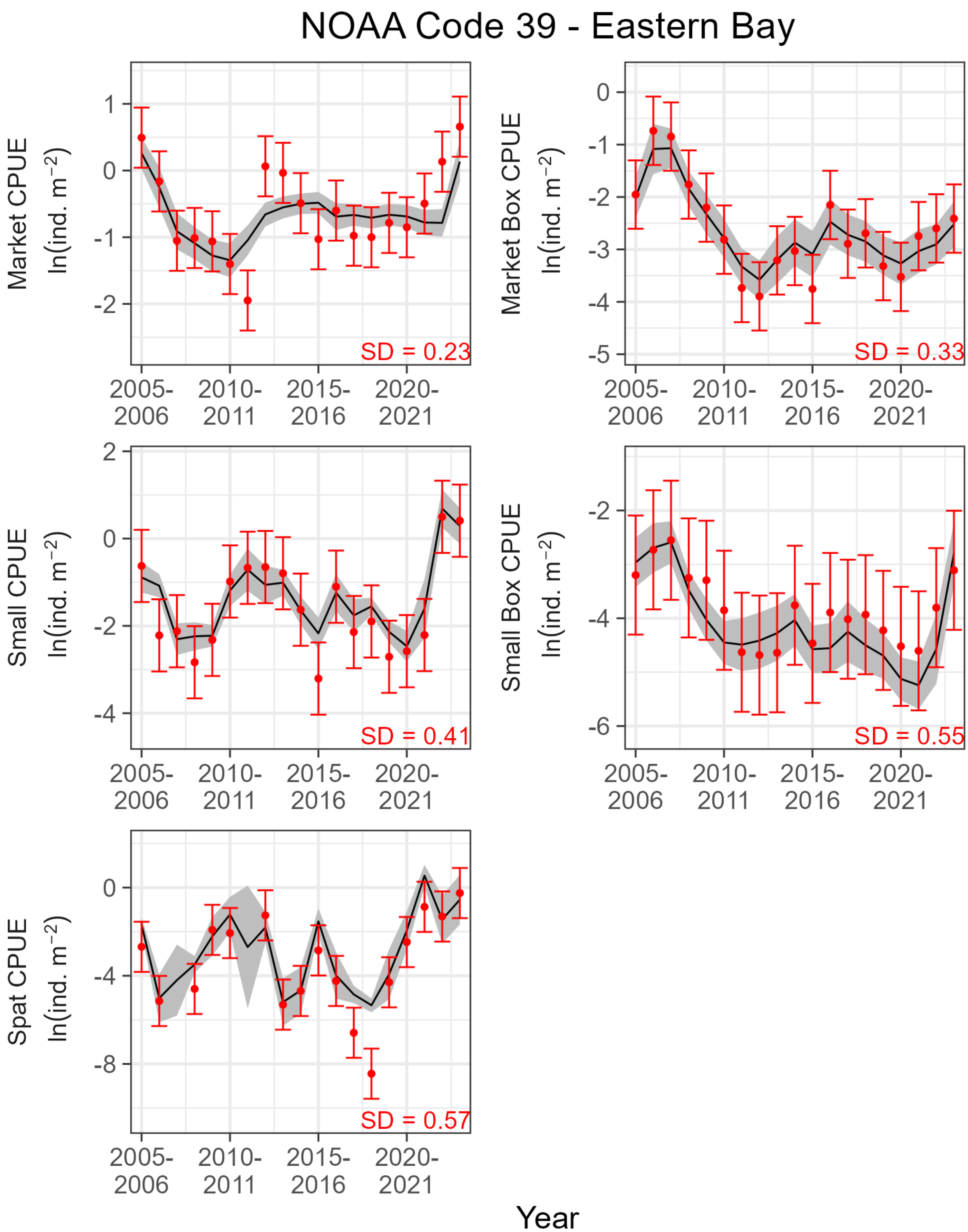

Figure 14. Estimated (line) and observed (points) values for Eastern Bay. Variable and symbol definitions are the same as Figure 12.

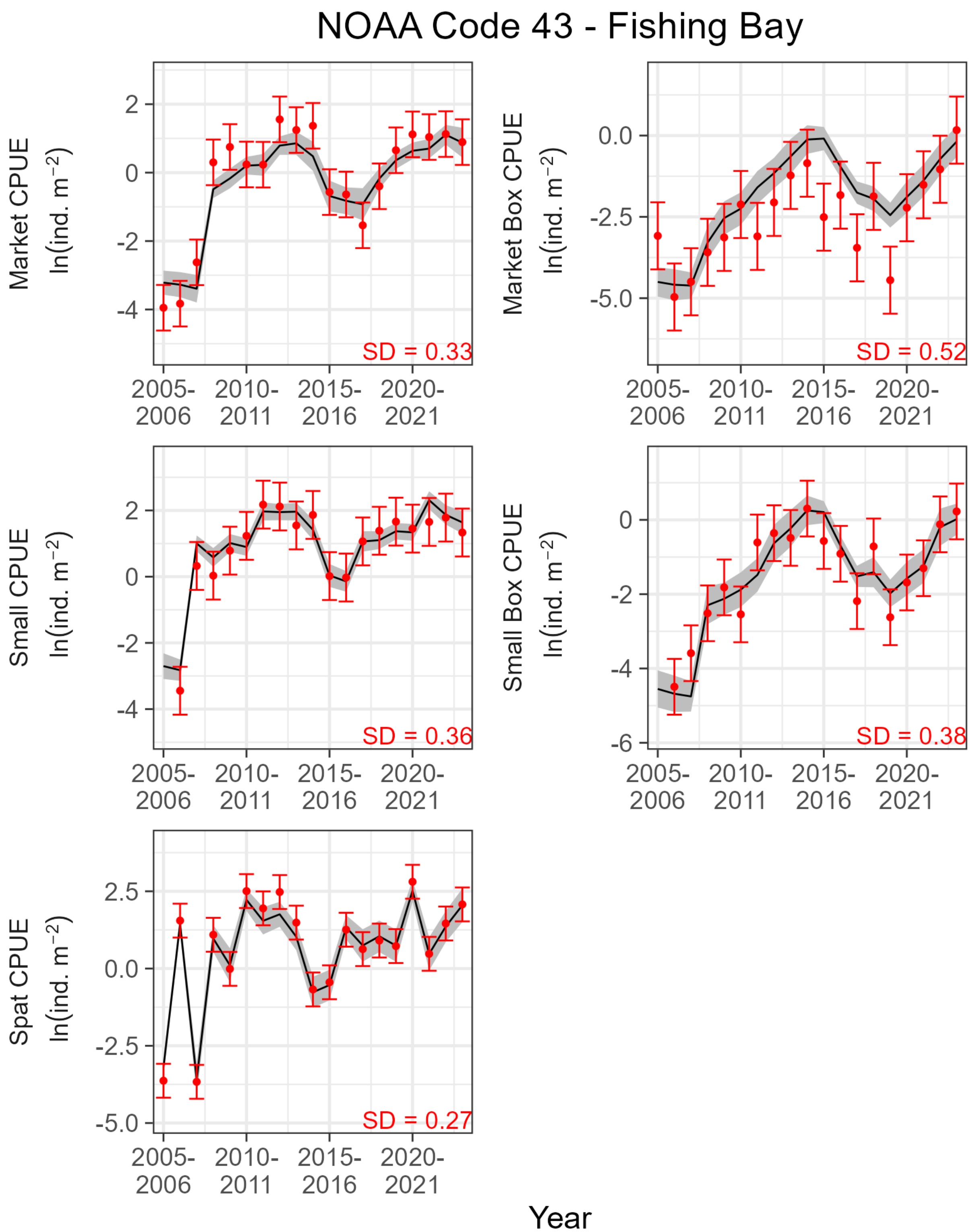

Figure 15. Estimated (line) and observed (points) values for Fishing Bay. Variable and symbol definitions are the same as Figure 12.

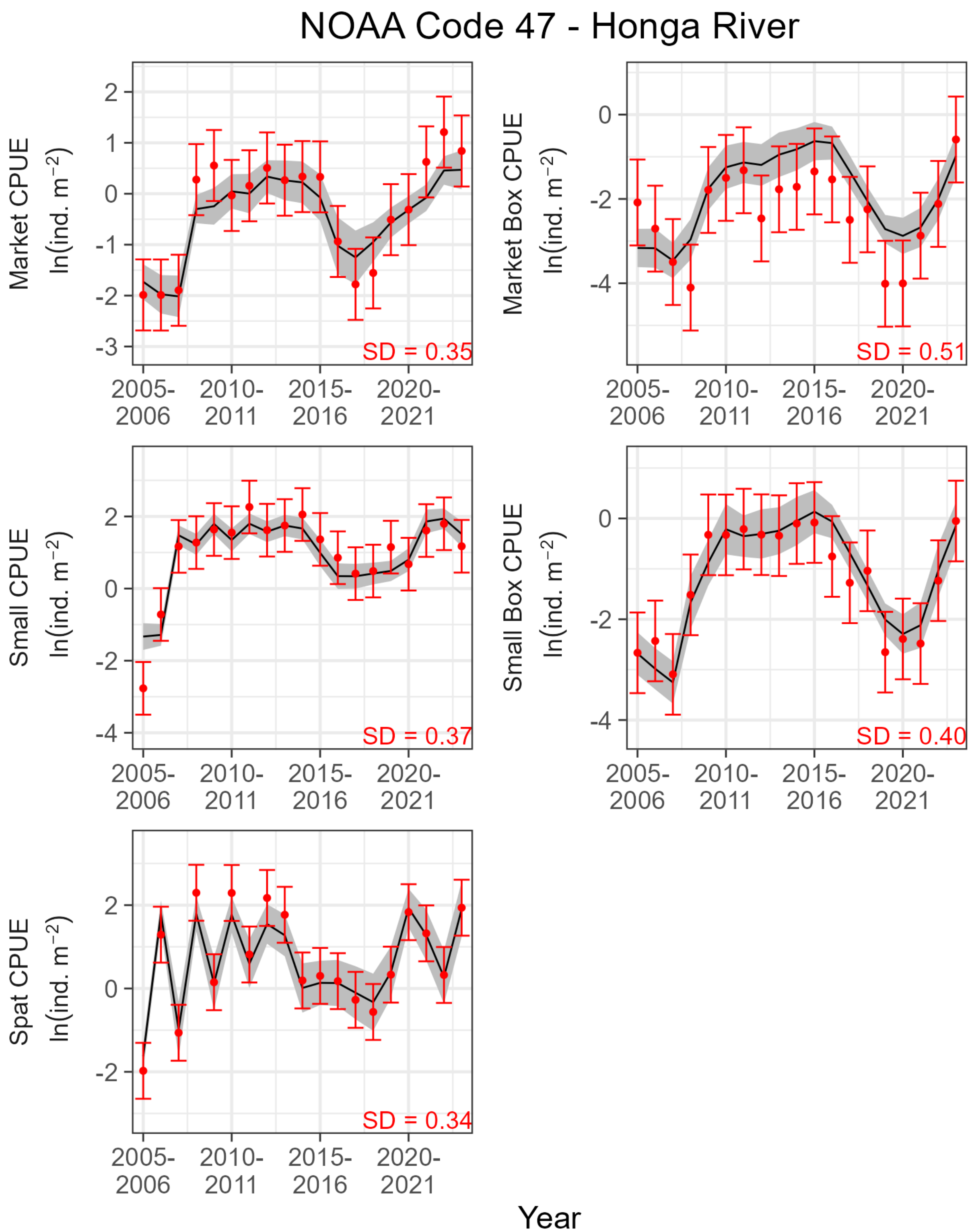

Figure 16. Estimated (line) and observed (points) values for Honga River. Variable and symbol definitions are the same as Figure 12.

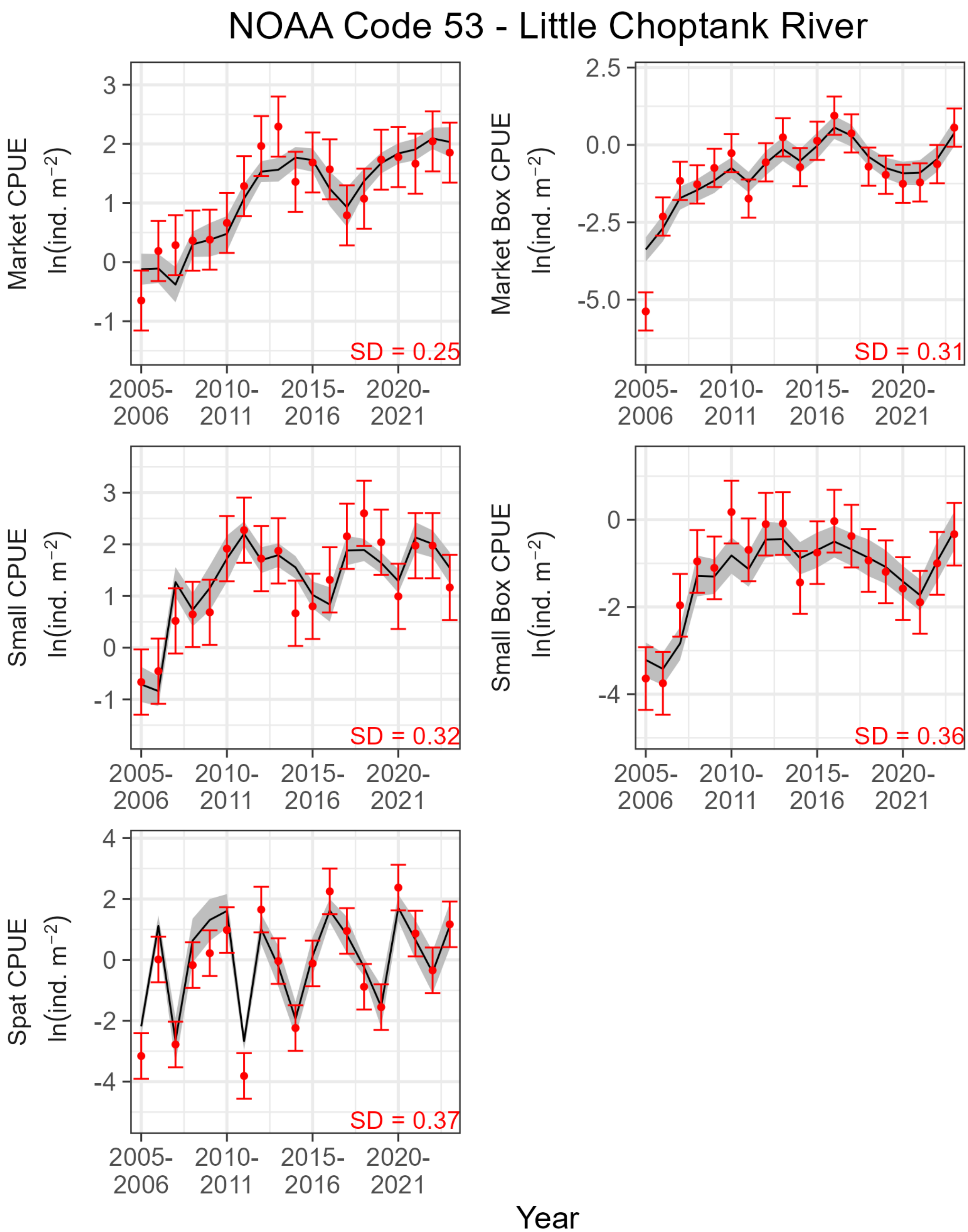

Figure 17. Estimated (line) and observed (points) values for the Little Choptank River. Variable and symbol definitions are the same as Figure 12.

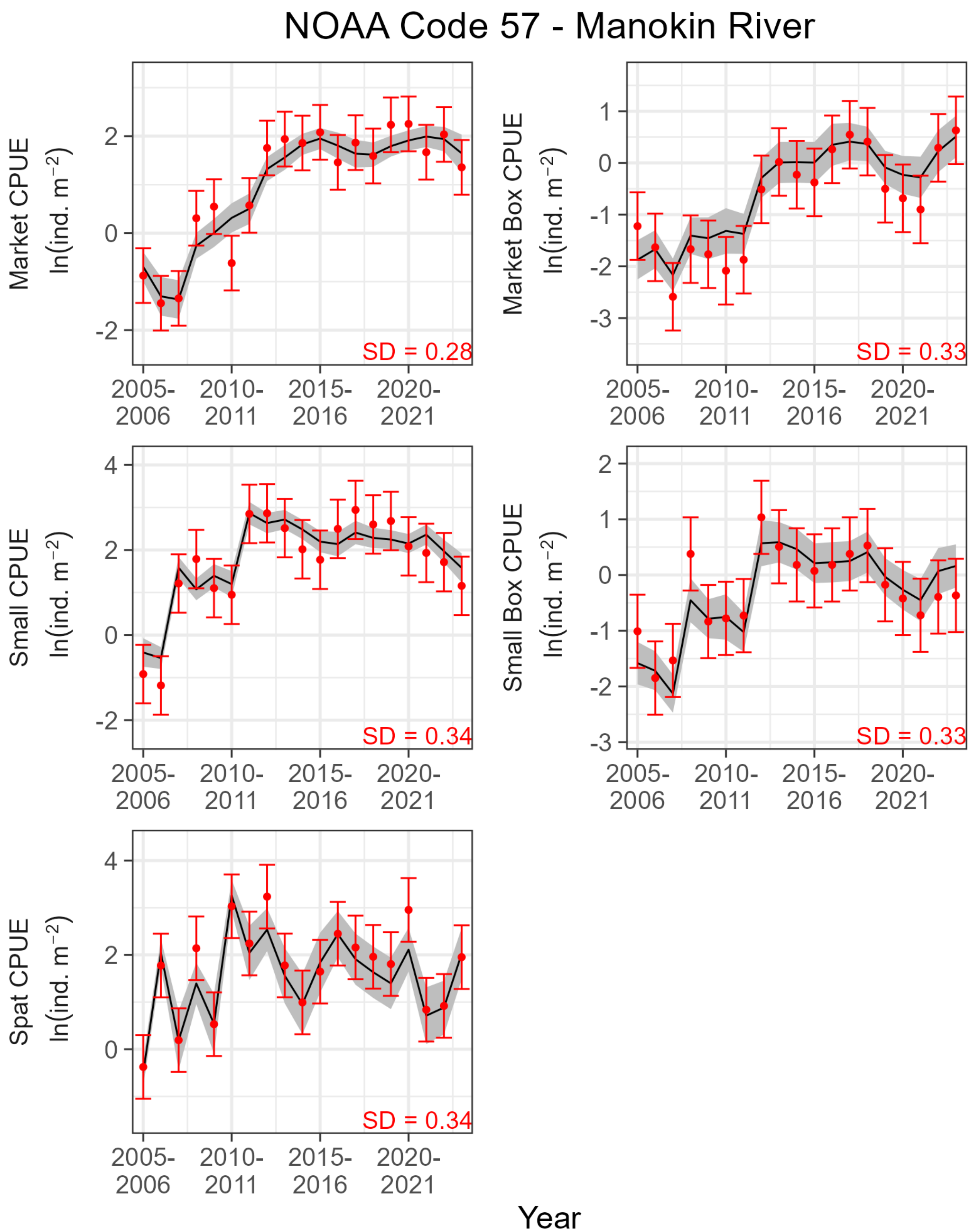

Figure 18. Estimated (line) and observed (points) values for the Manokin River. Variable and symbol definitions are the same as Figure 12.

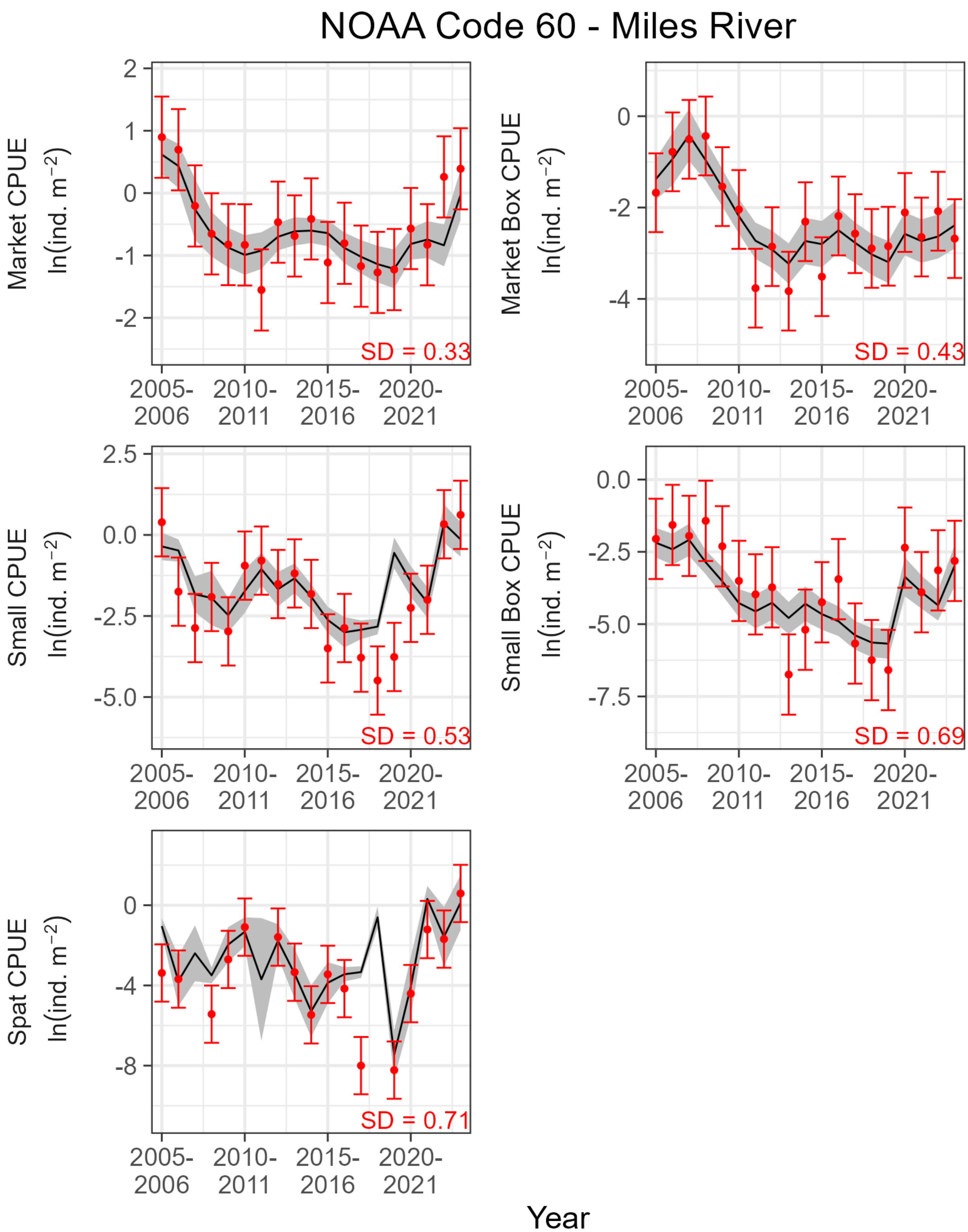

Figure 19. Estimated (line) and observed (points) values for the Miles River (NOAA code 60). Variable and symbol definitions are the same as Figure 12.

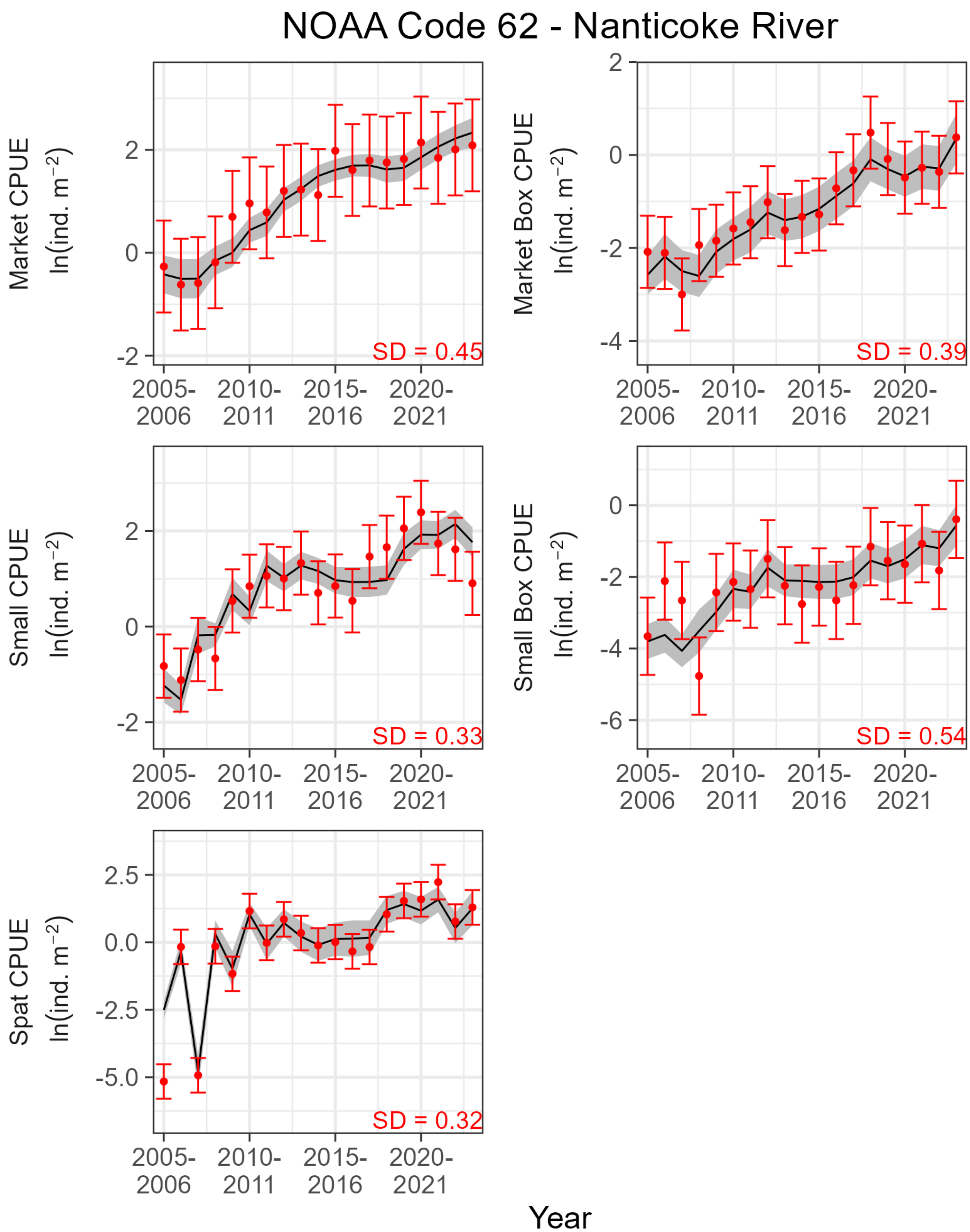

Figure 20. Estimated (line) and observed (points) values for the Nanticoke River (NOAA code 62). Variable and symbol definitions are the same as Figure 12.

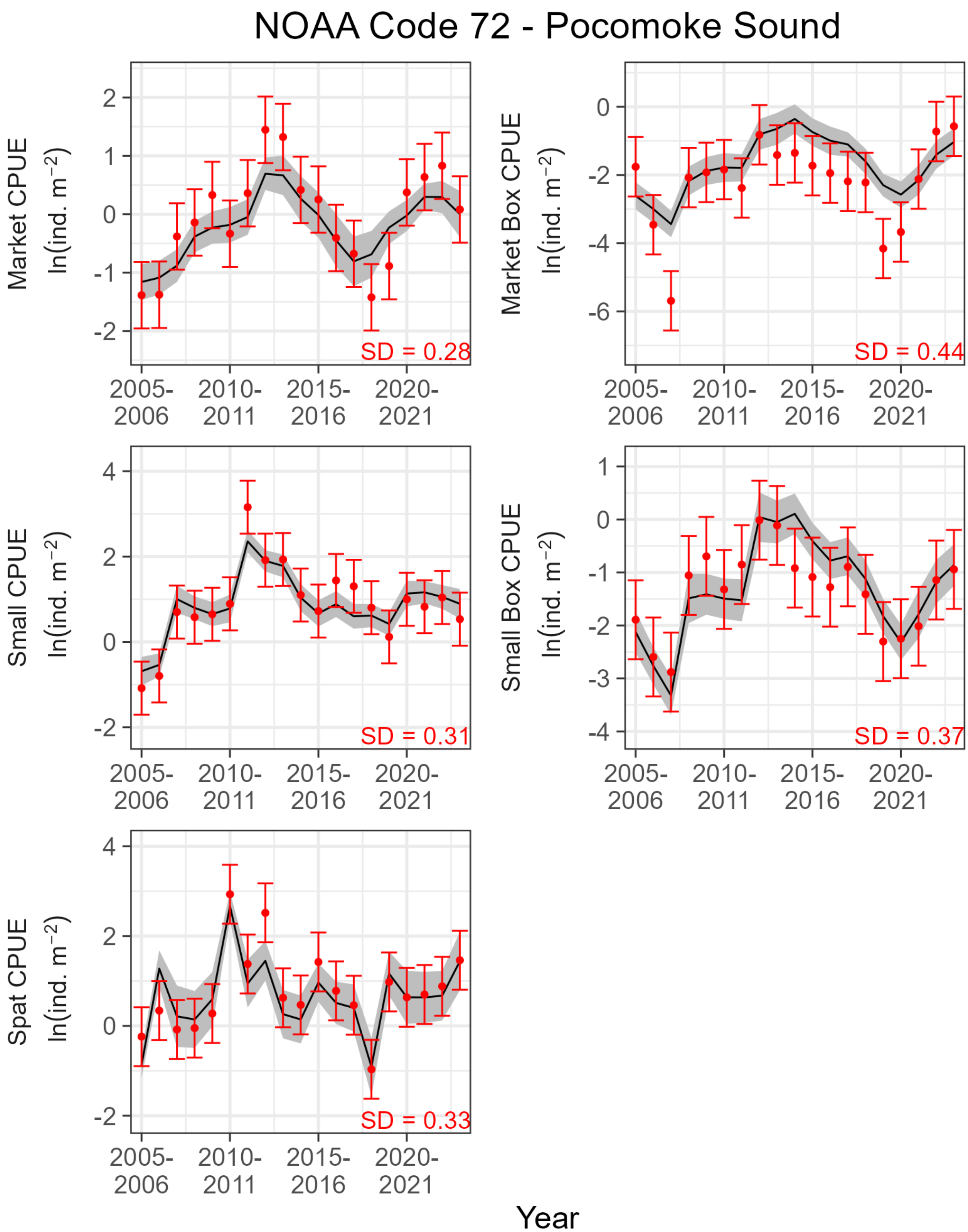

Figure 21. Estimated (line) and observed (points) values for Pocomoke Sound (NOAA code 72). Variable and symbol definitions are the same as Figure 12.

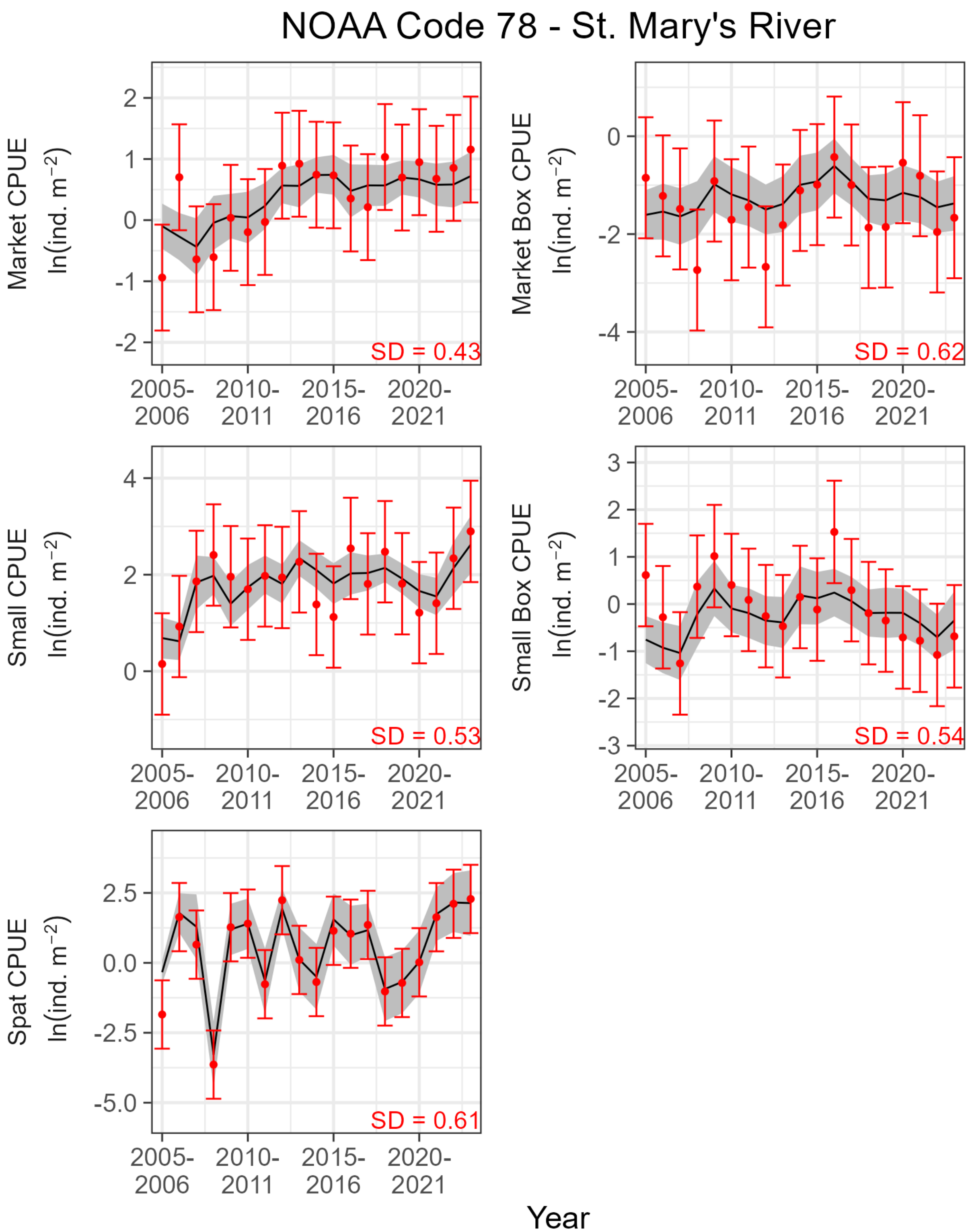

Figure 22. Estimated (line) and observed (points) values for St. Mary's River. Variable and symbol definitions are the same as Figure 12.

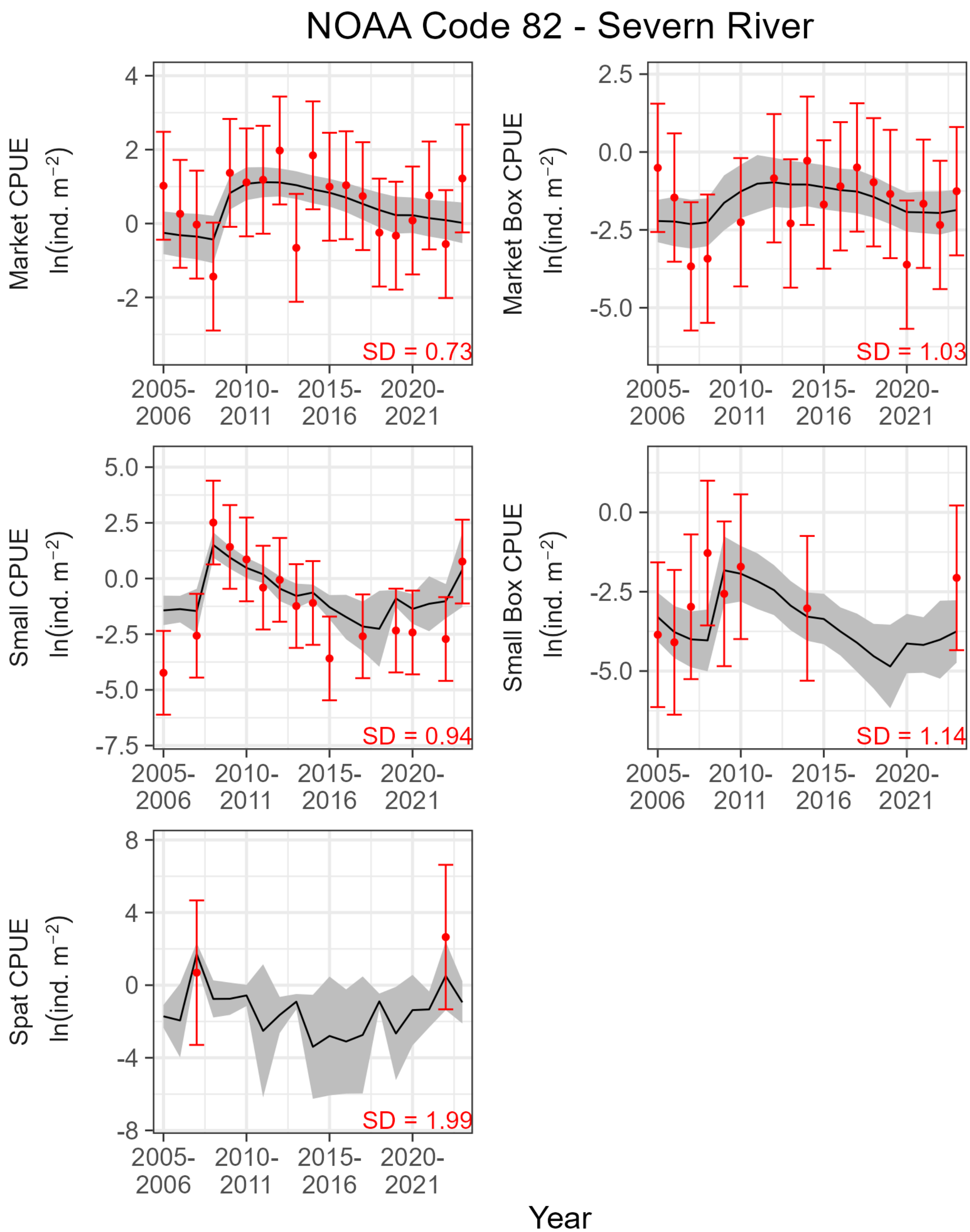

Figure 23. Estimated (line) and observed (points) values for Severn River. Variable and symbol definitions are the same as Figure 12.

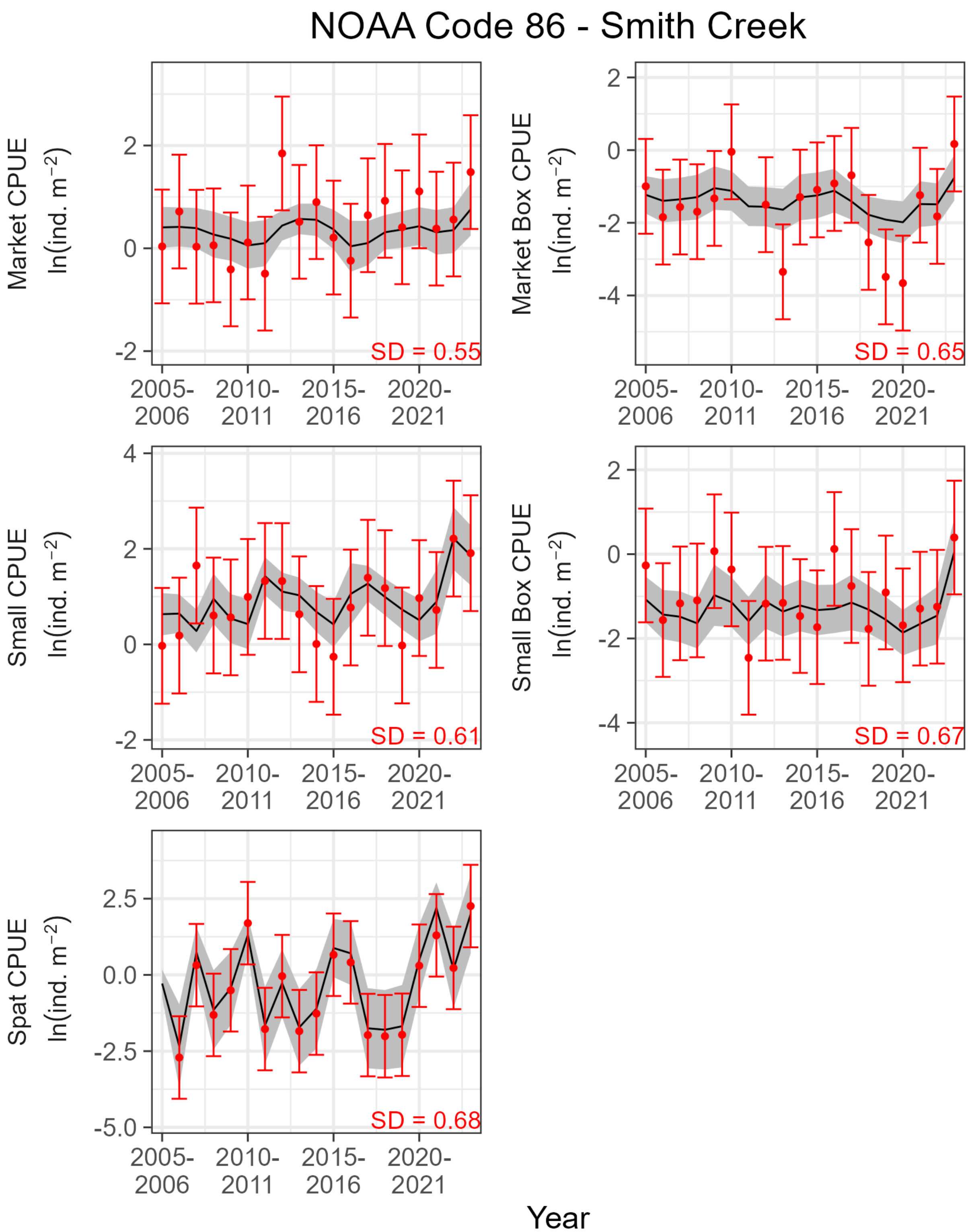

Figure 24. Estimated (line) and observed (points) values for Smith Creek. Variable and symbol definitions are the same as Figure 12.

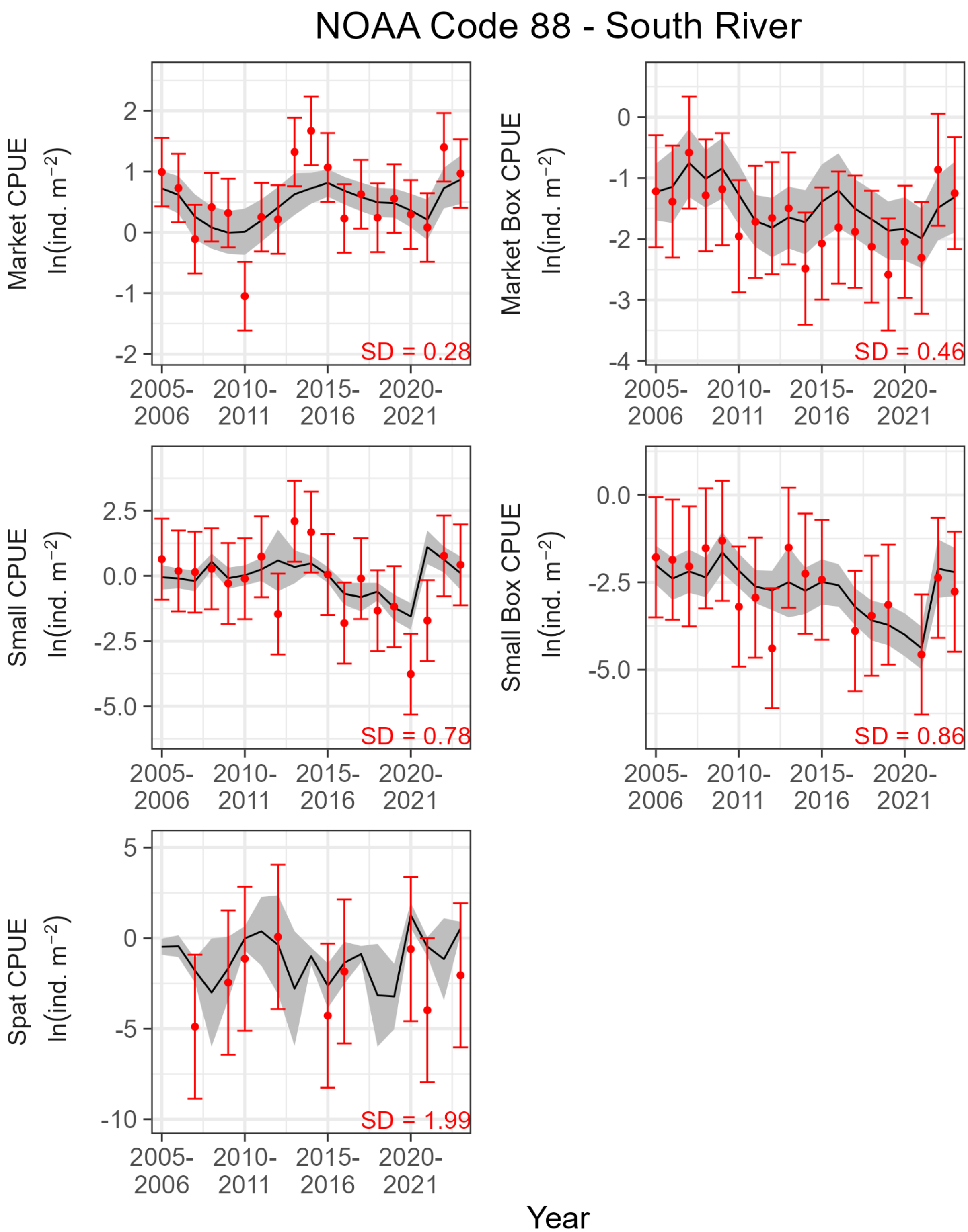

Figure 25. Estimated (line) and observed (points) values for South River. Variable and symbol definitions are the same as Figure 12.

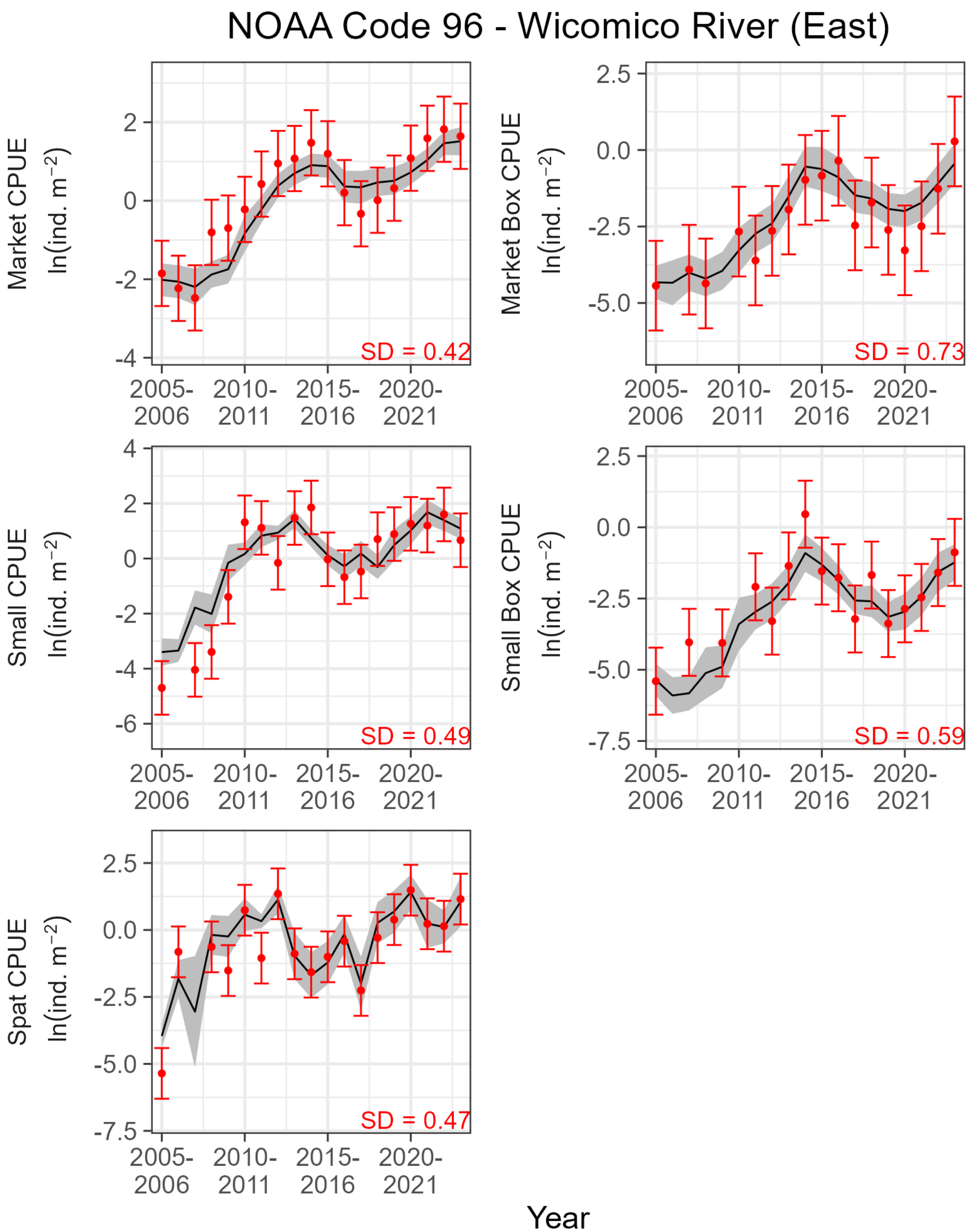

Figure 26. Estimated (line) and observed (points) values for Wicomico River (East). Variable and symbol definitions are the same as Figure 12.

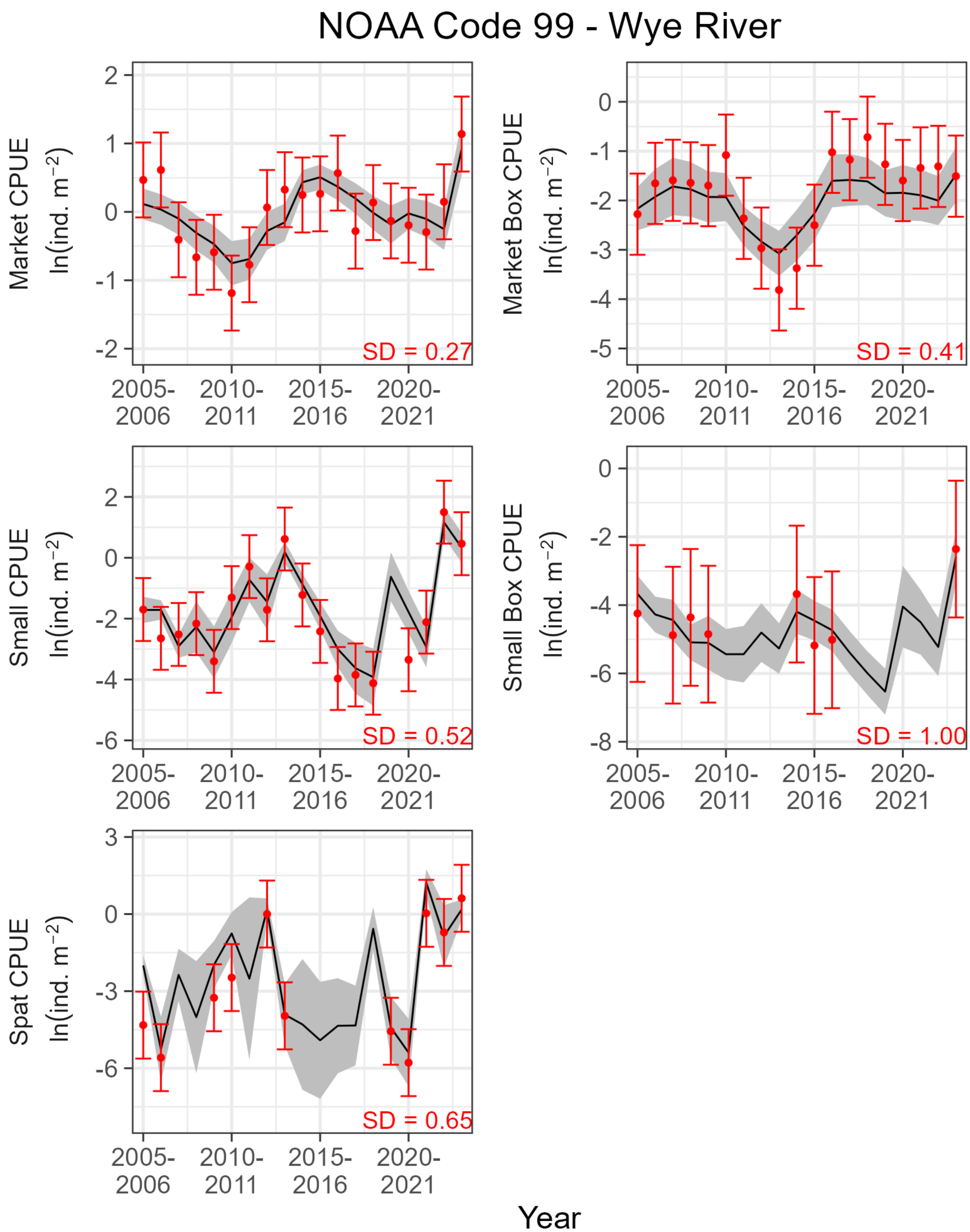

Figure 27. Estimated (line) and observed (points) values for Wye River. Variable and symbol definitions are the same as Figure 12.

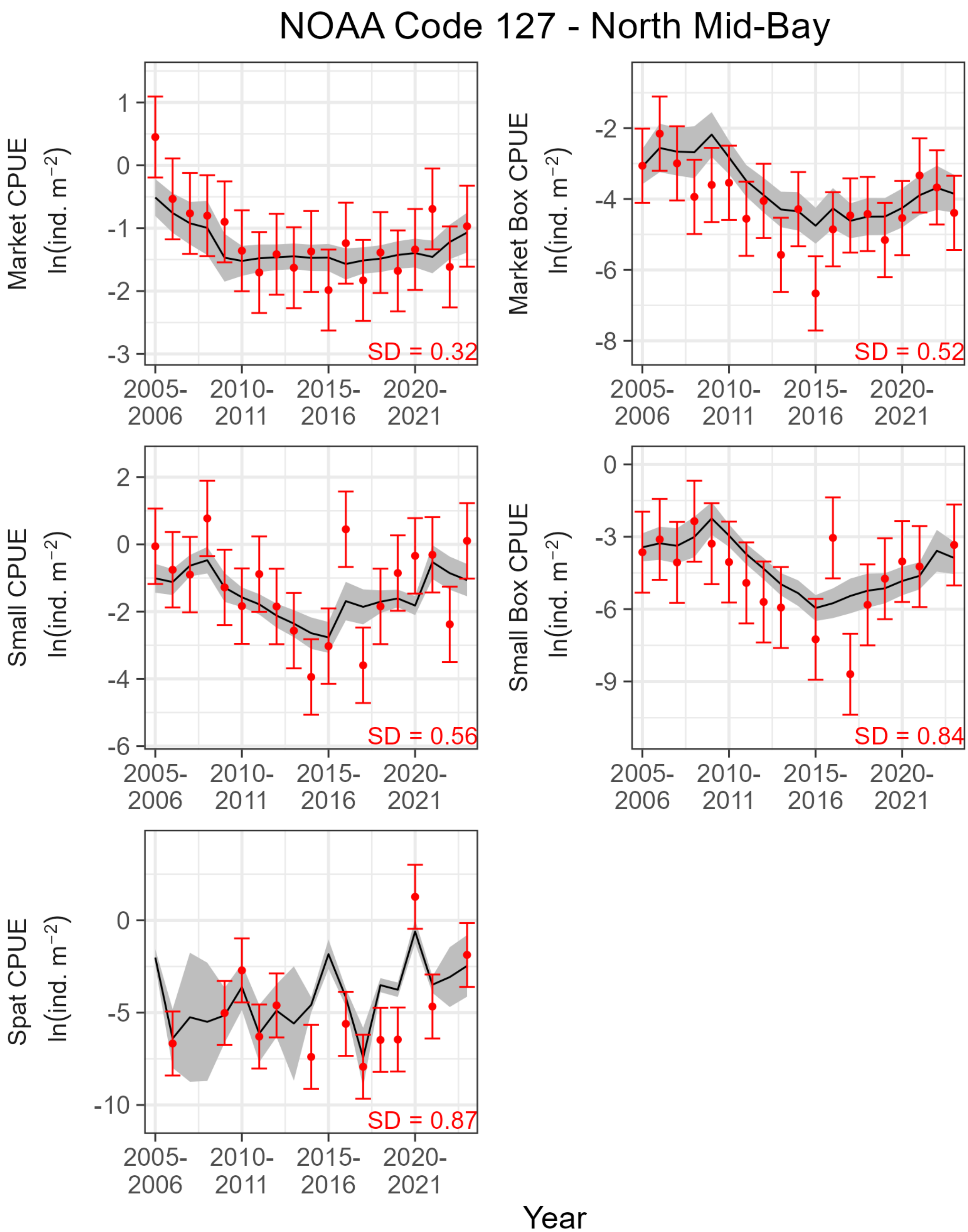

Figure 28. Estimated (line) and observed (points) values for North Mid-Bay. Variable and symbol definitions are the same as Figure 12.

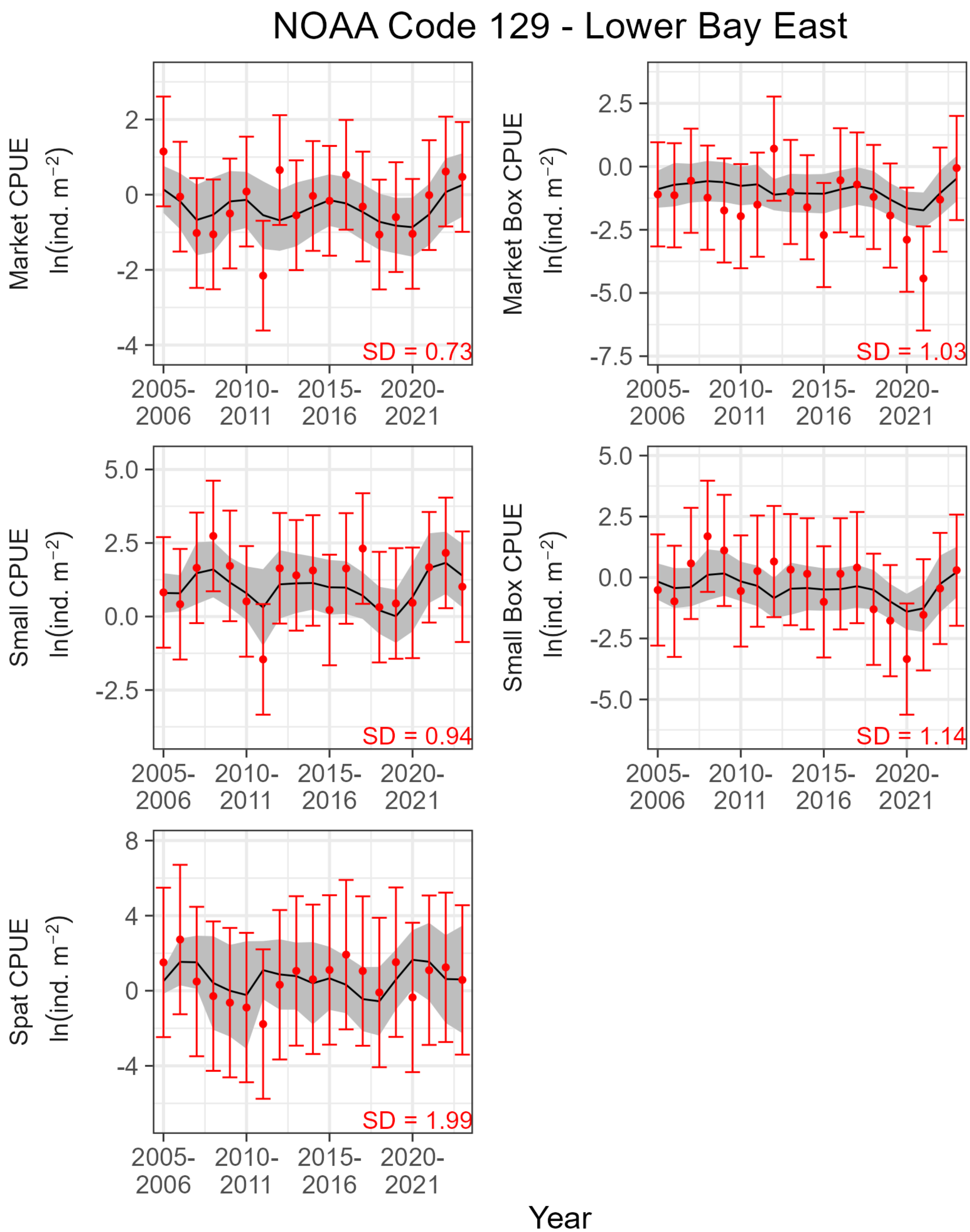

Figure 29. Estimated (line) and observed (points) values for Lower Bay East. Variable and symbol definitions are the same as Figure 12.

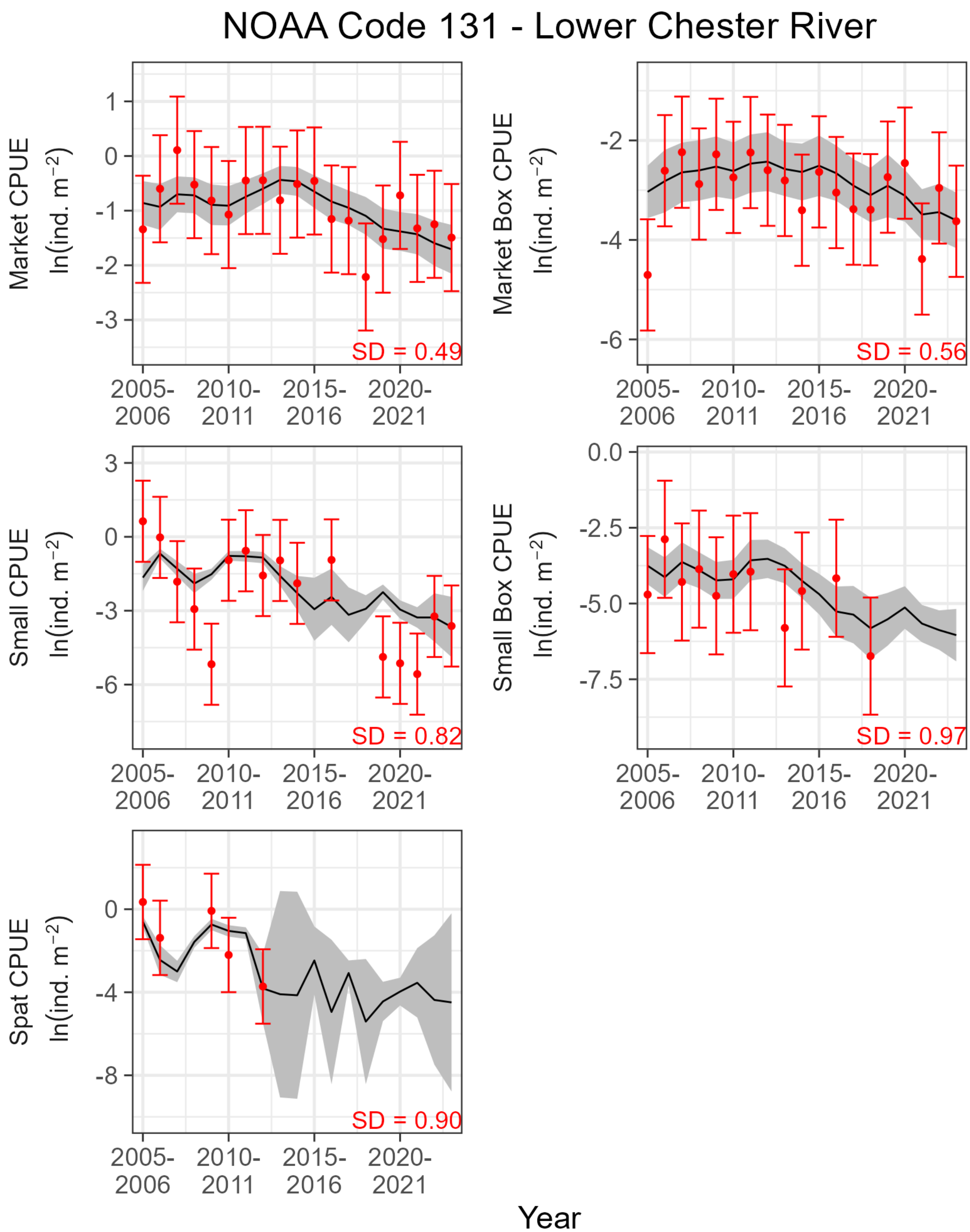

Figure 30. Estimated (line) and observed (points) values for Lower Chester River. Variable and symbol definitions are the same as Figure 12.

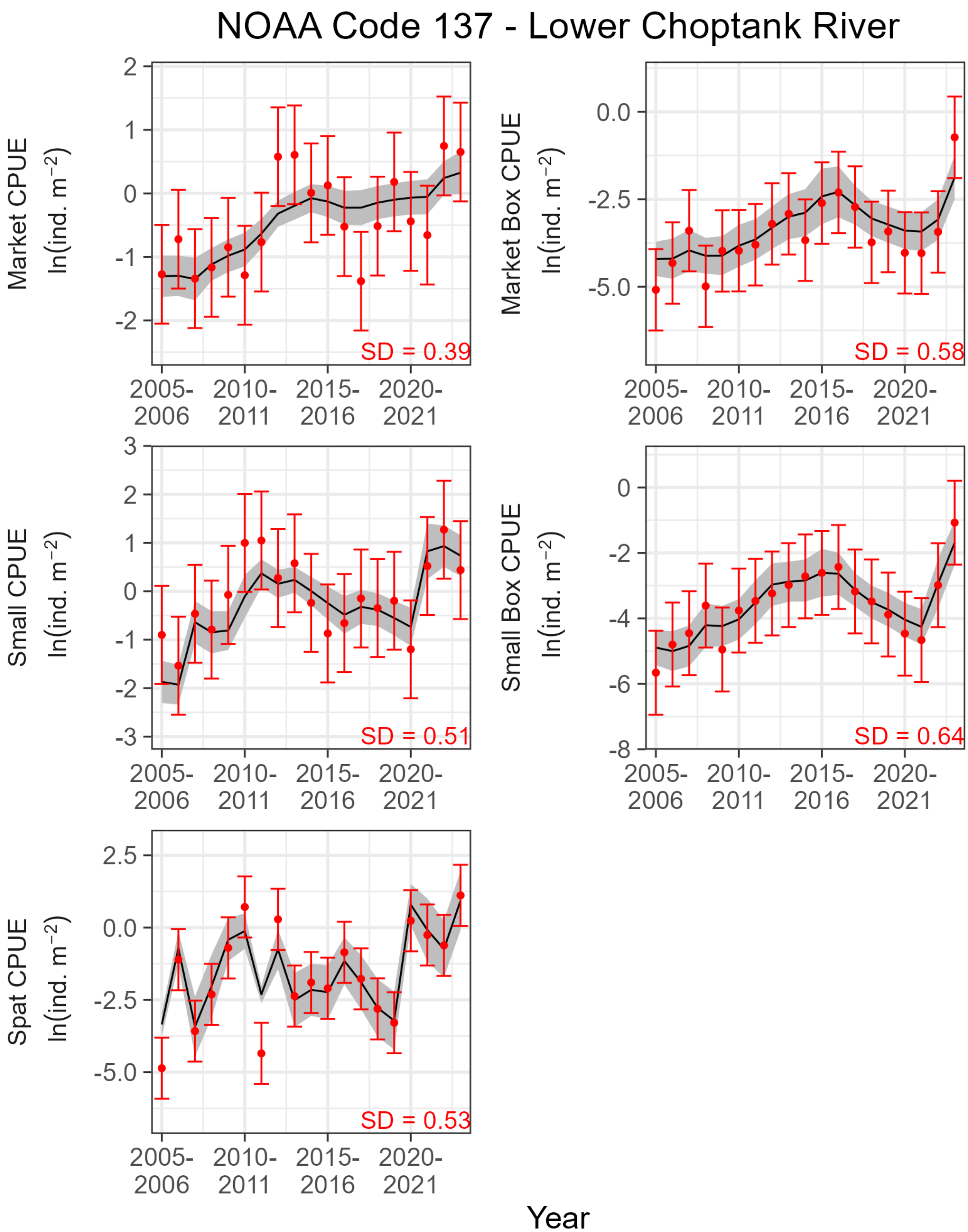

Figure 31. Estimated (line) and observed (points) values for Lower Choptank River. Variable and symbol definitions are the same as Figure 12.

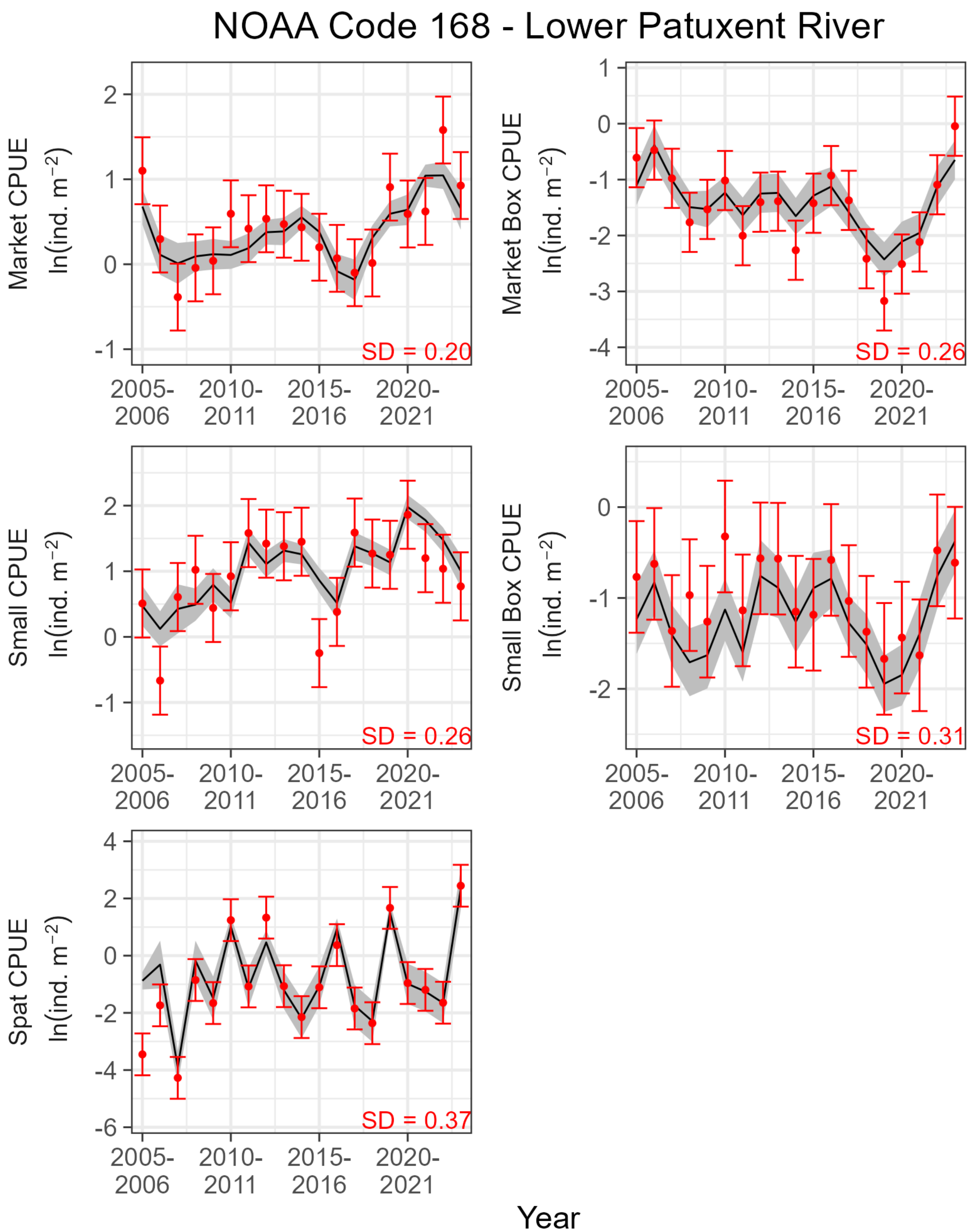

Figure 32. Estimated (line) and observed (points) values for Lower Patuxent River. Variable and symbol definitions are the same as Figure 12.

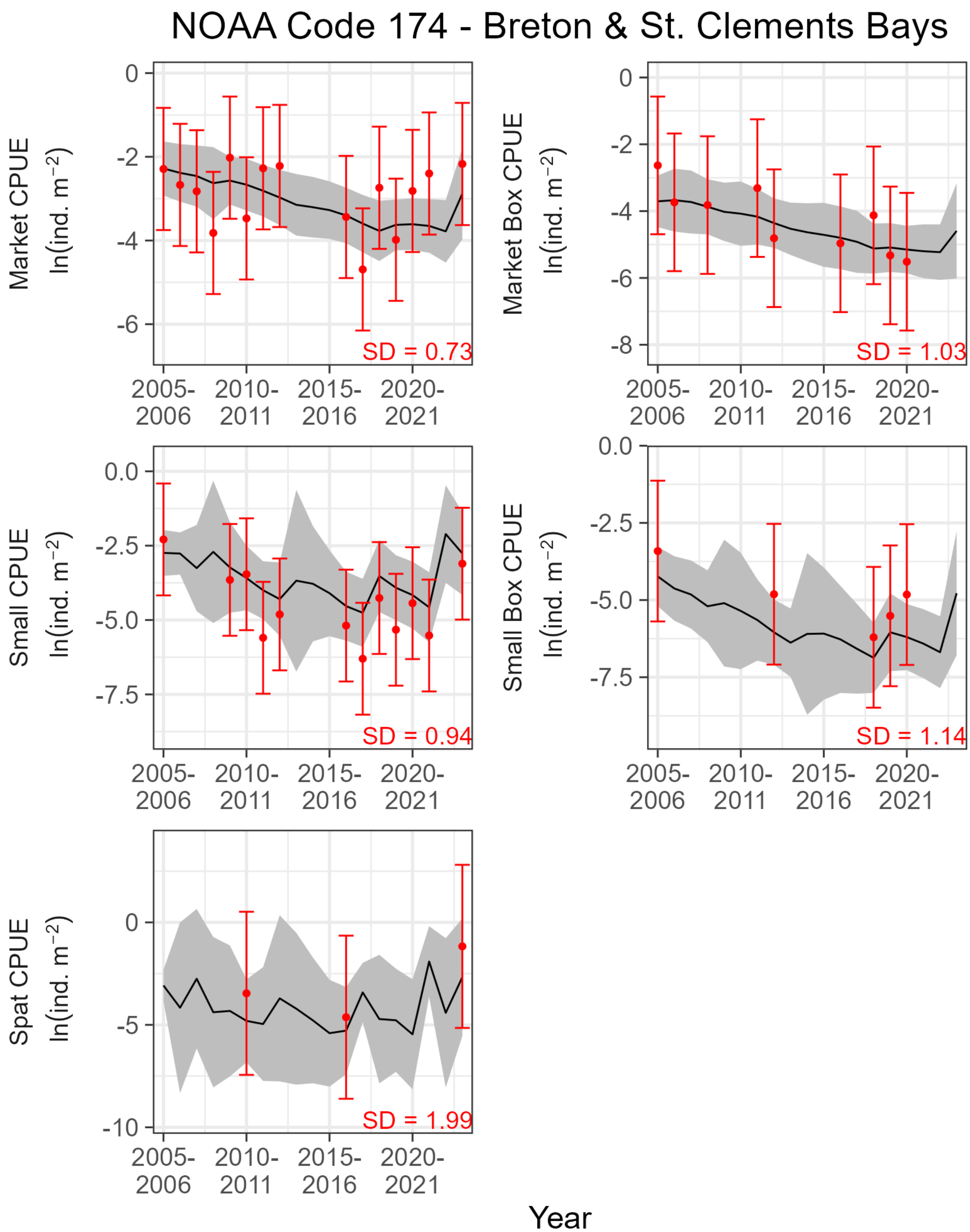

Figure 33. Estimated (line) and observed (points) values for Breton & St. Clement's Bay. Variable and symbol definitions are the same as Figure 12.

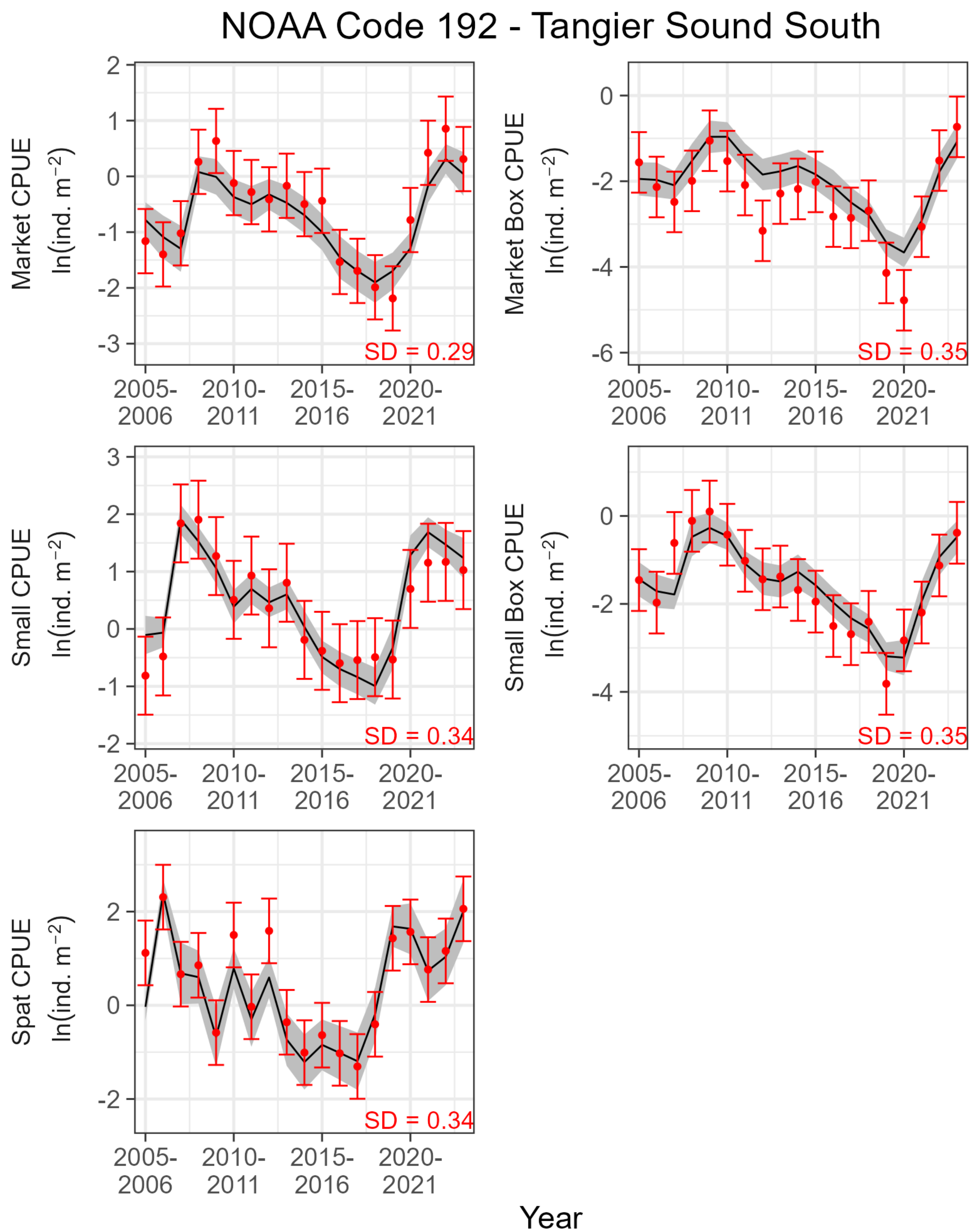

Figure 34. Estimated (line) and observed (points) values for Tangier Sound South. Variable and symbol definitions are the same as Figure 12.

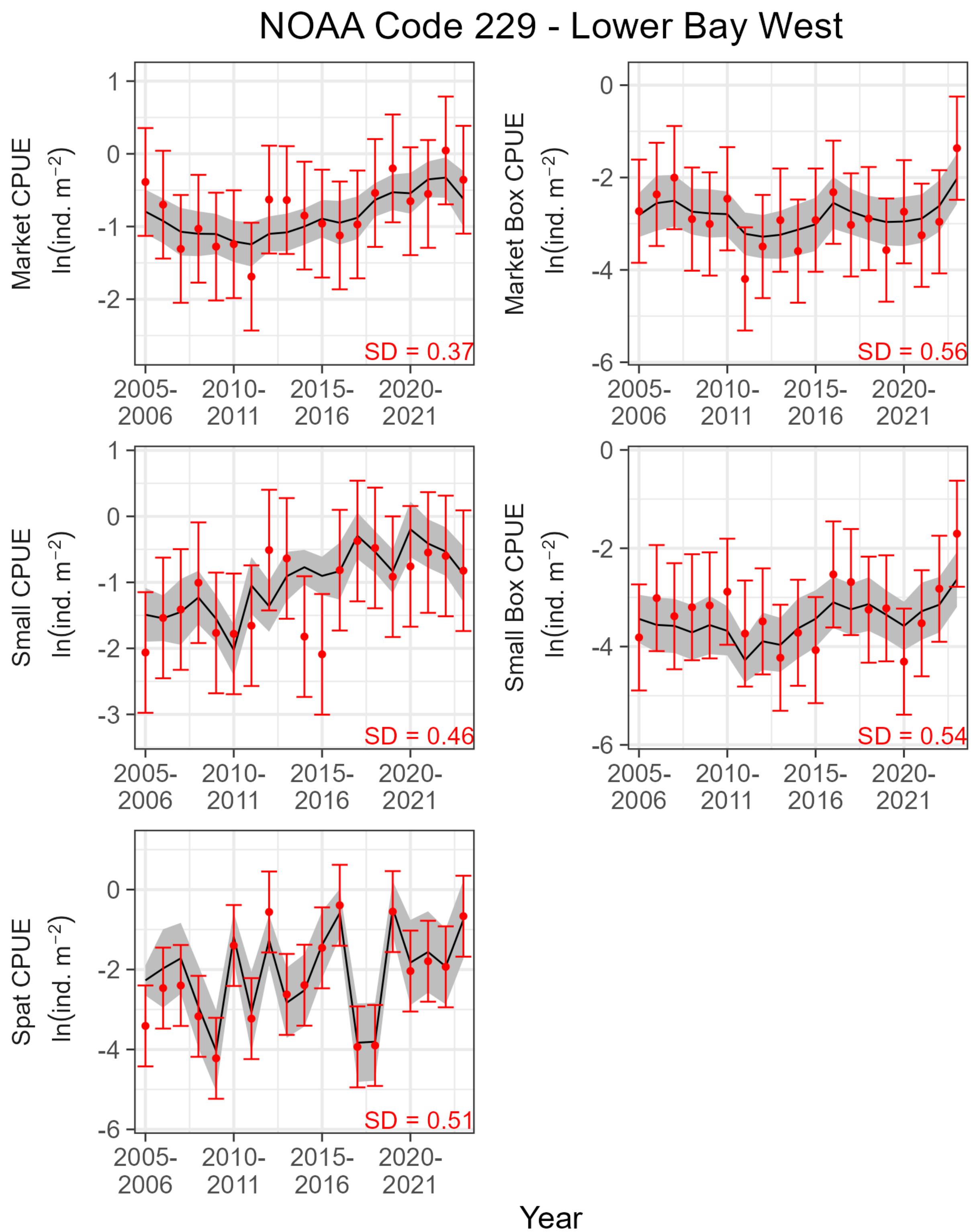

Figure 35. Estimated (line) and observed (points) values for Lower Bay West. Variable and symbol definitions are the same as Figure 12.

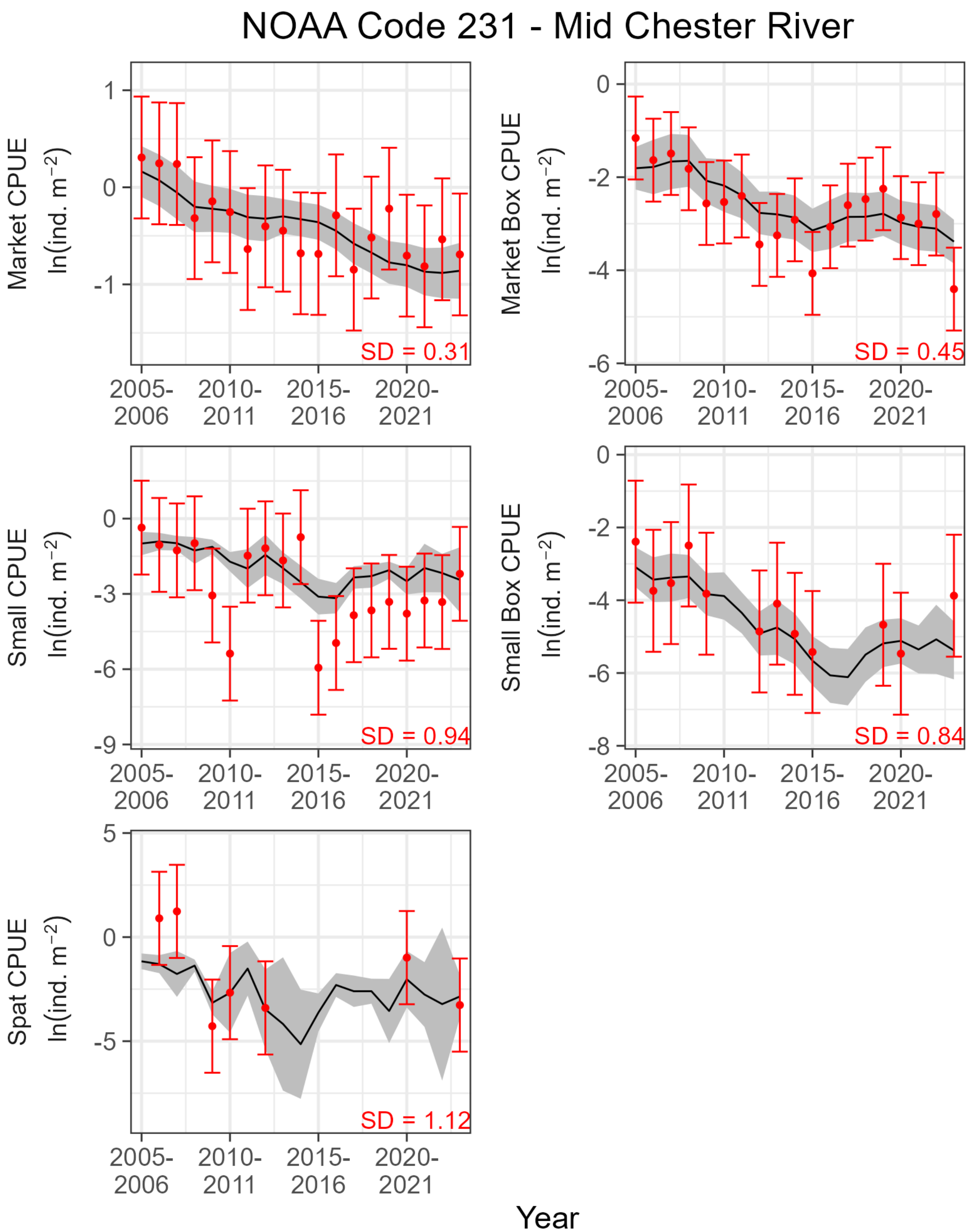

Figure 36. Estimated (line) and observed (points) values for Mid Chester River. Variable and symbol definitions are the same as Figure 12.

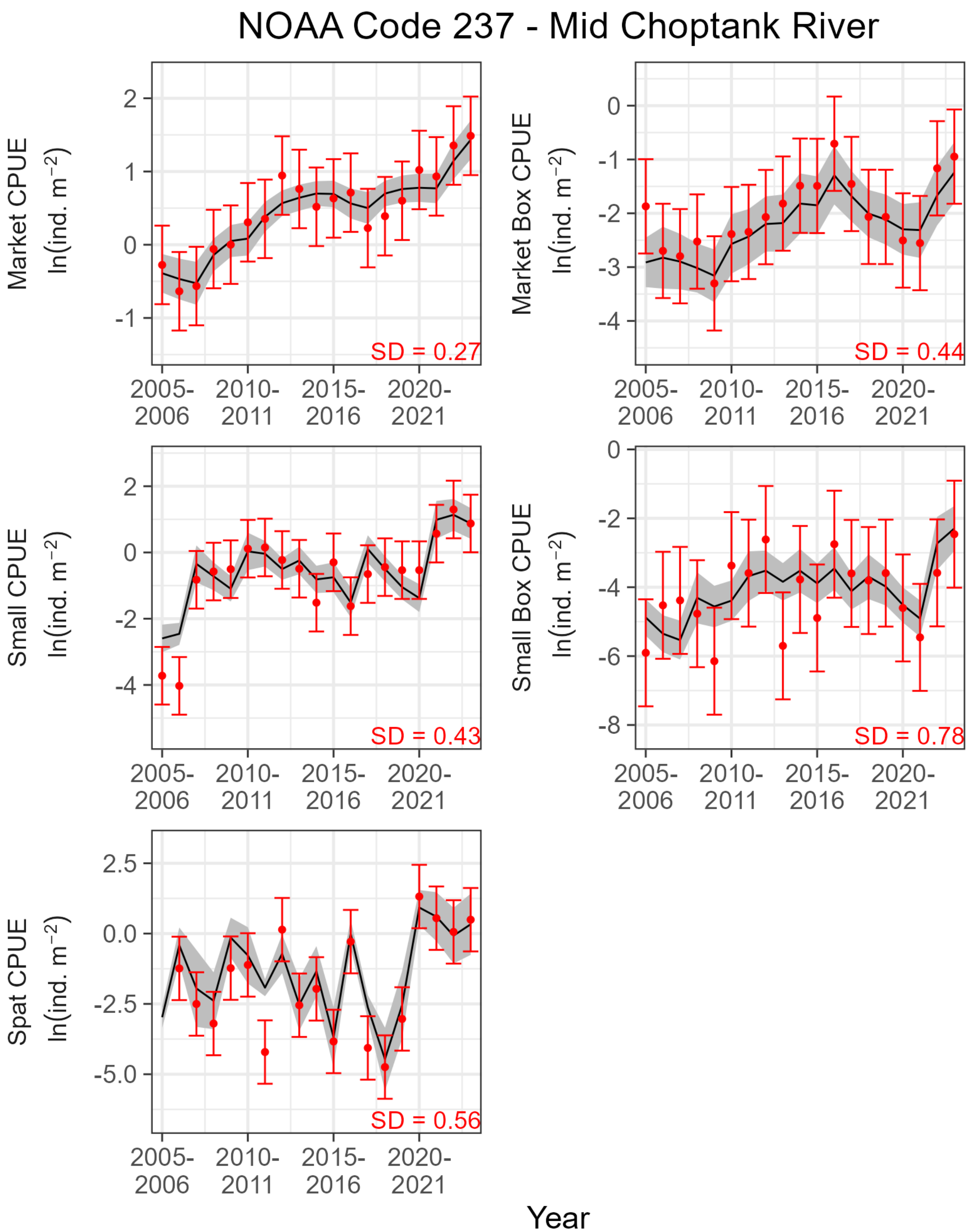

Figure 37. Estimated (line) and observed (points) values for Mid Choptank River. Variable and symbol definitions are the same as Figure 12.

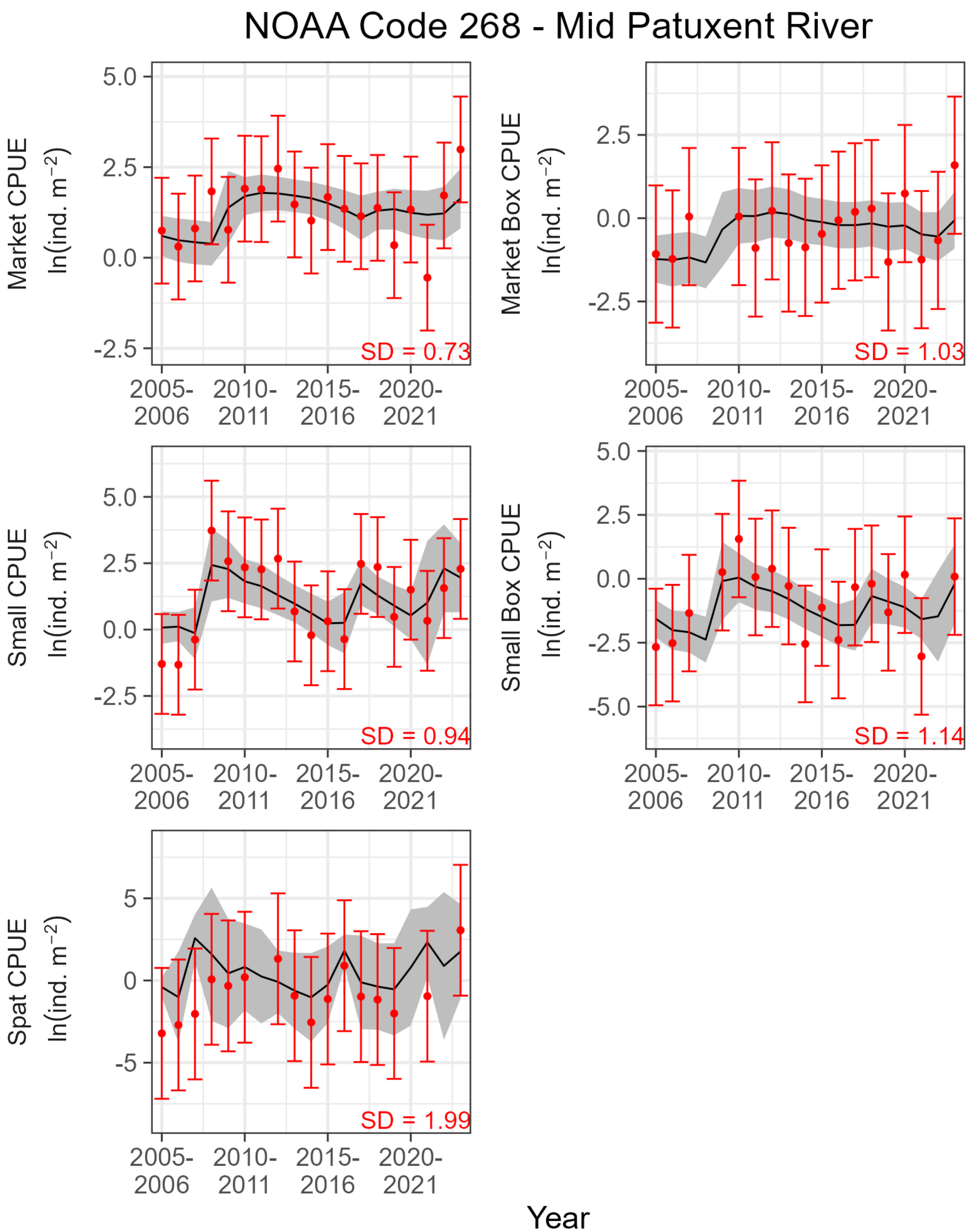

Figure 38. Estimated (line) and observed (points) values for Mid Patuxent River. Variable and symbol definitions are the same as Figure 12.

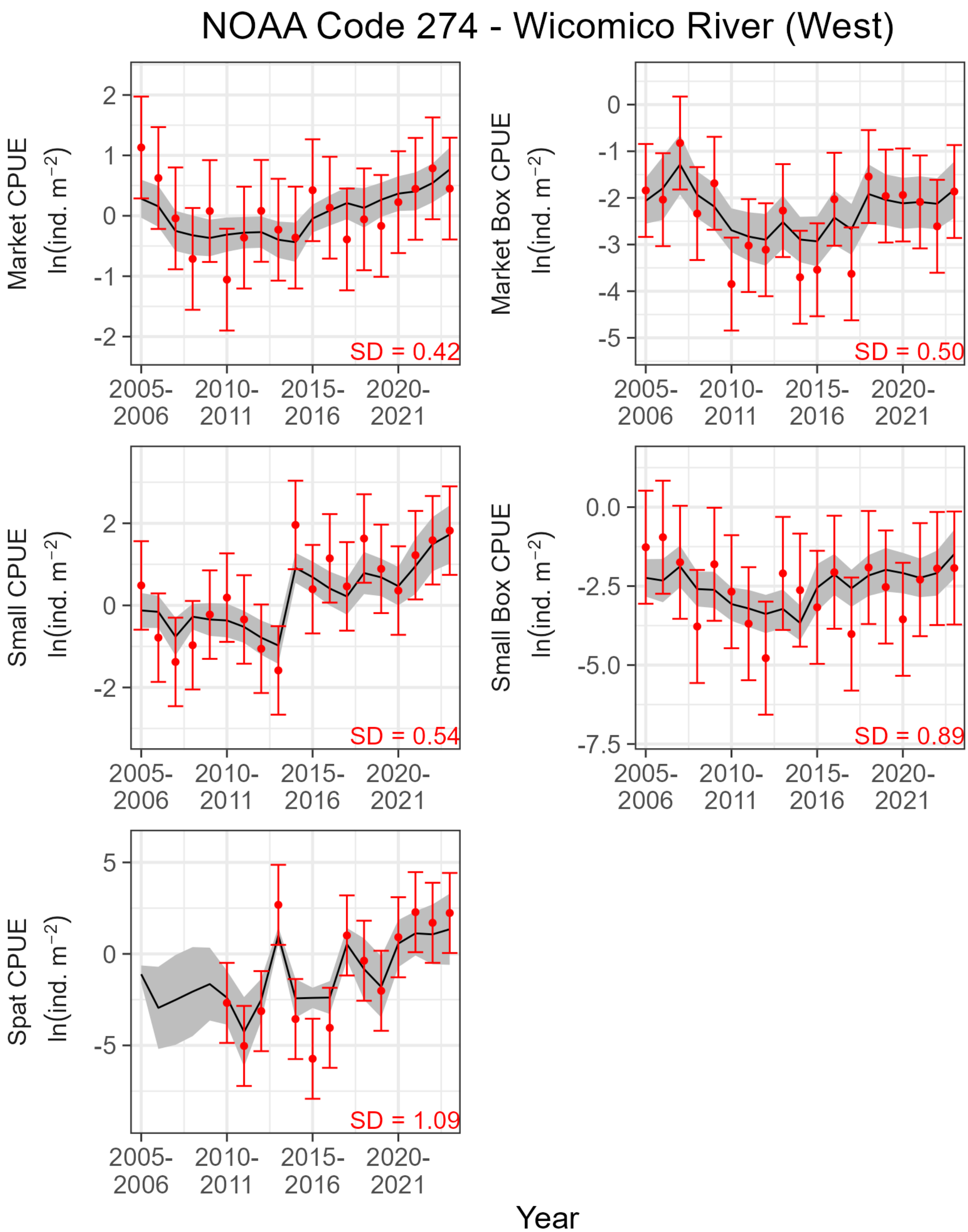

Figure 39. Estimated (line) and observed (points) values for Wicomico River (West). Variable and symbol definitions are the same as Figure 12.

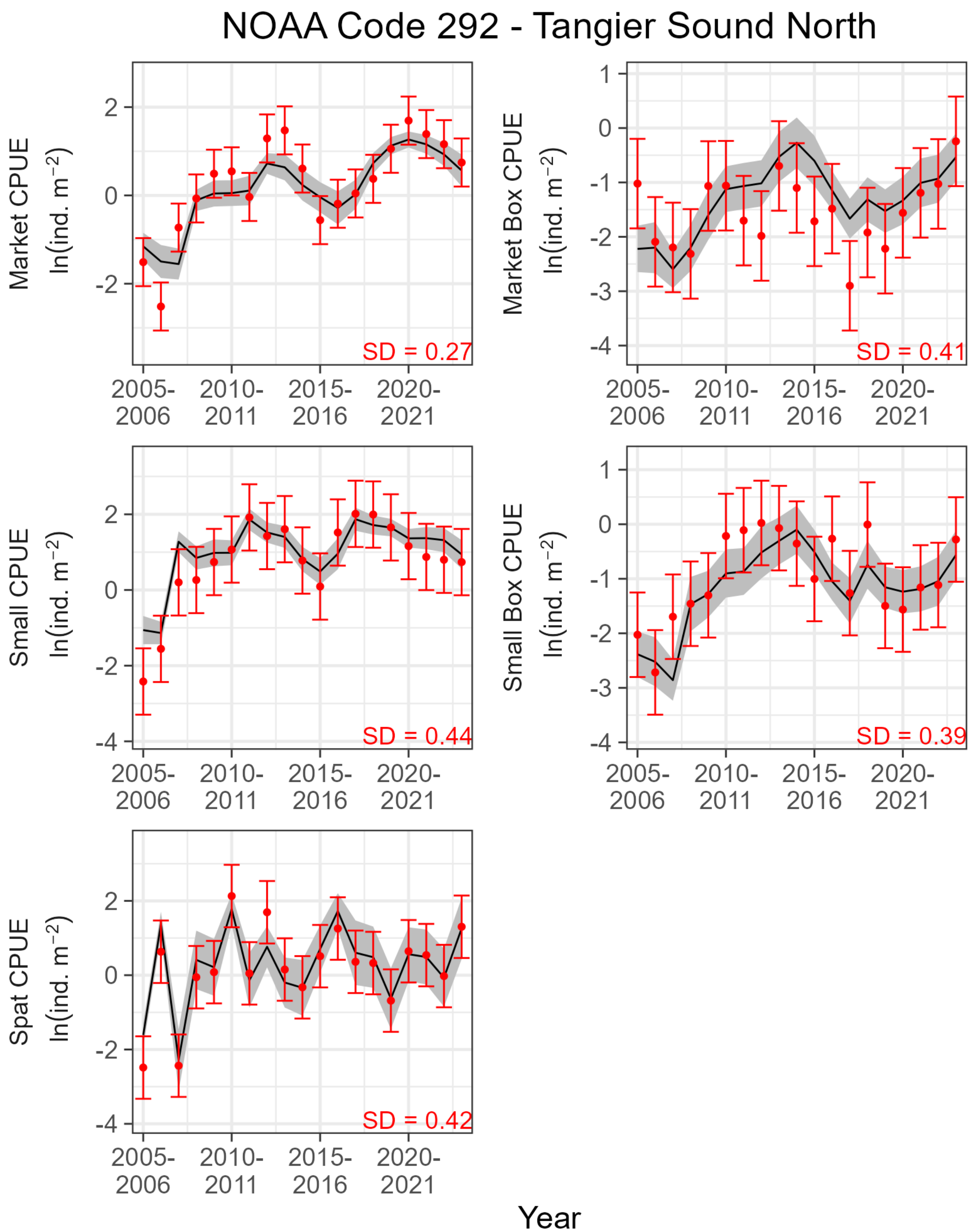

Figure 40. Estimated (line) and observed (points) values for Tangier Sound North. Variable and symbol definitions are the same as Figure 12.

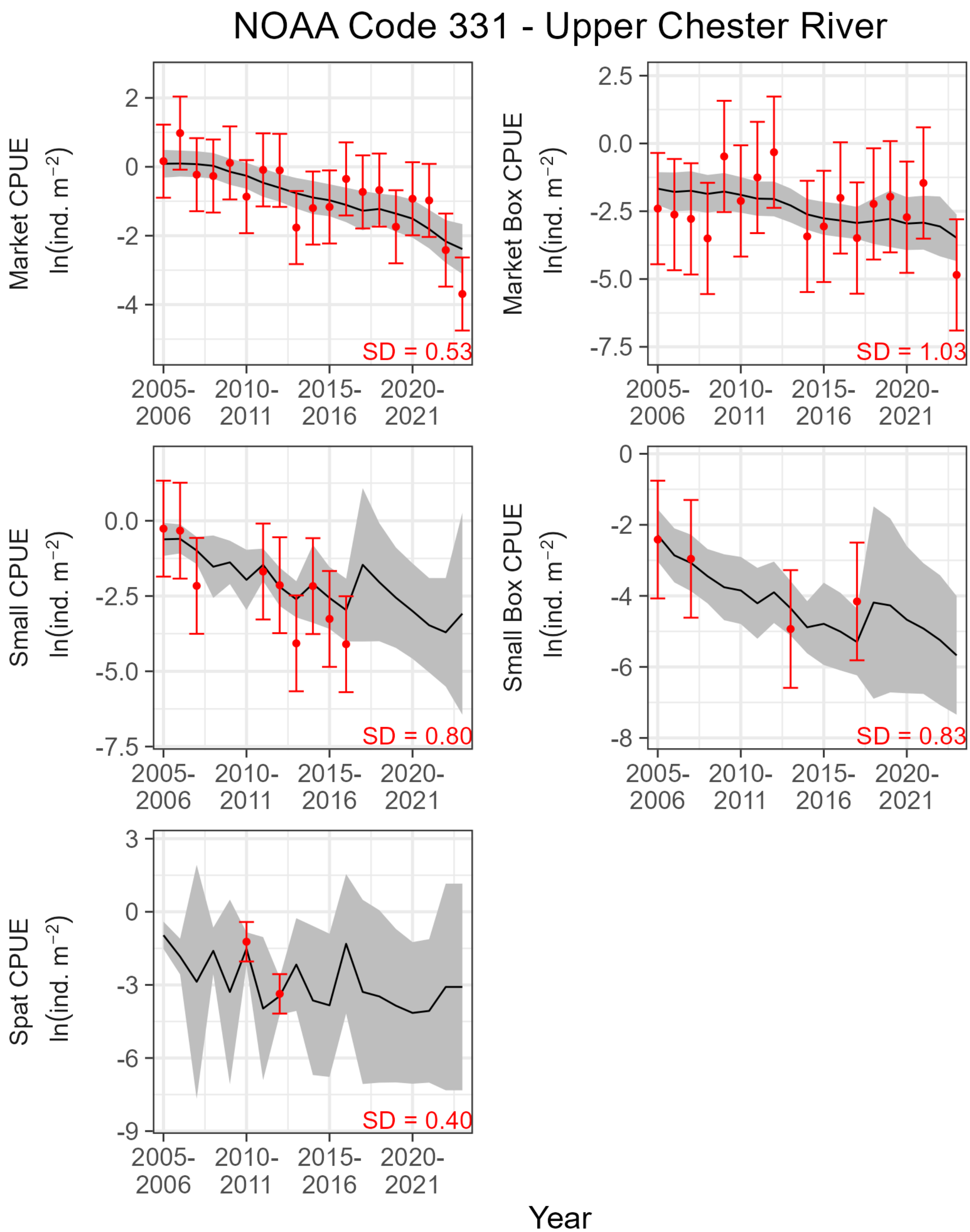

Figure 41. Estimated (line) and observed (points) values for Upper Chester River. Variable and symbol definitions are the same as Figure 12.

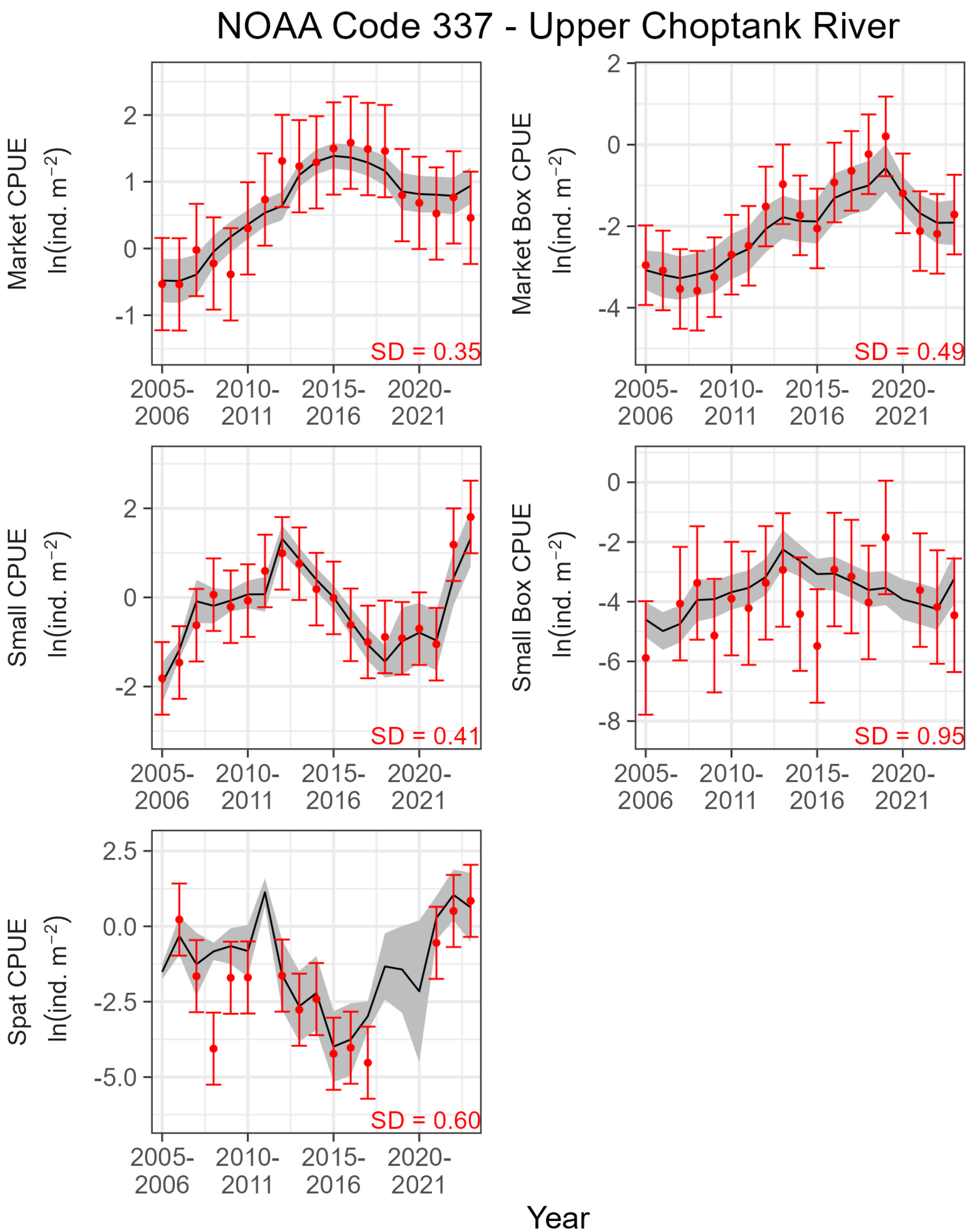

Figure 42. Estimated (line) and observed (points) values for Upper Choptank River. Variable and symbol definitions are the same as Figure 12.

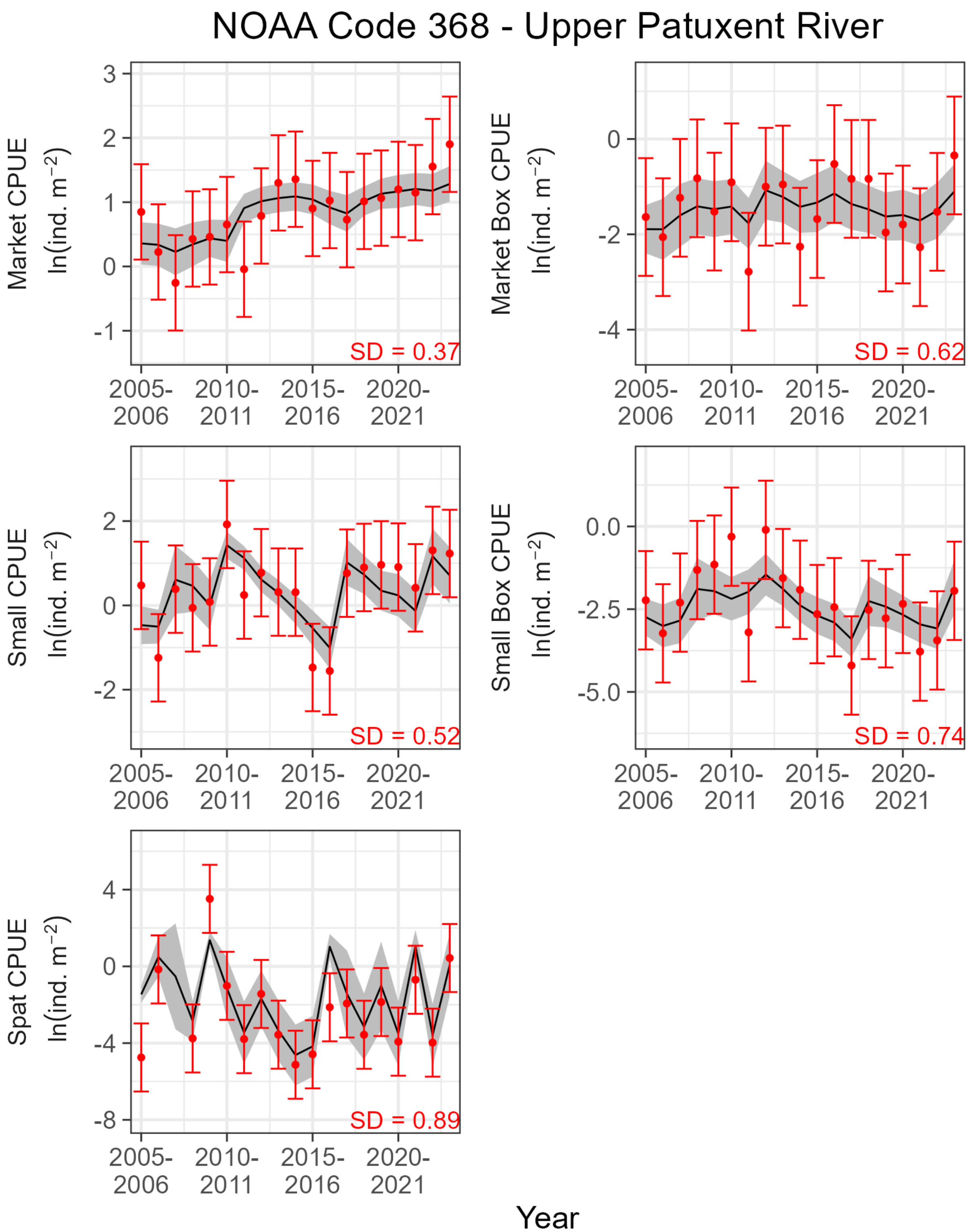

Figure 43. Estimated (line) and observed (points) values for Upper Patuxent River. Variable and symbol definitions are the same as Figure 12.

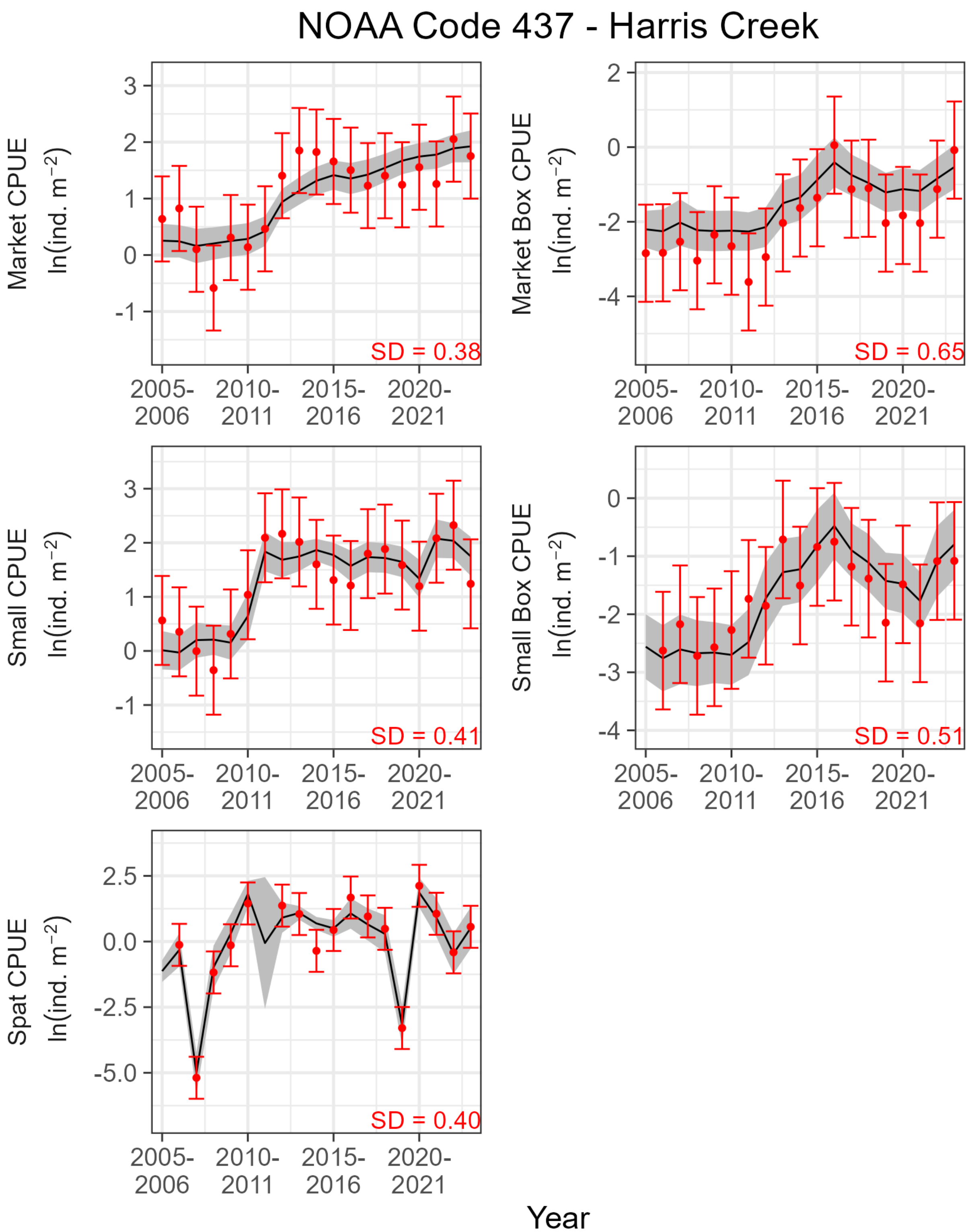

Figure 44. Estimated (line) and observed (points) values for Harris Creek. Variable and symbol definitions are the same as Figure 12.

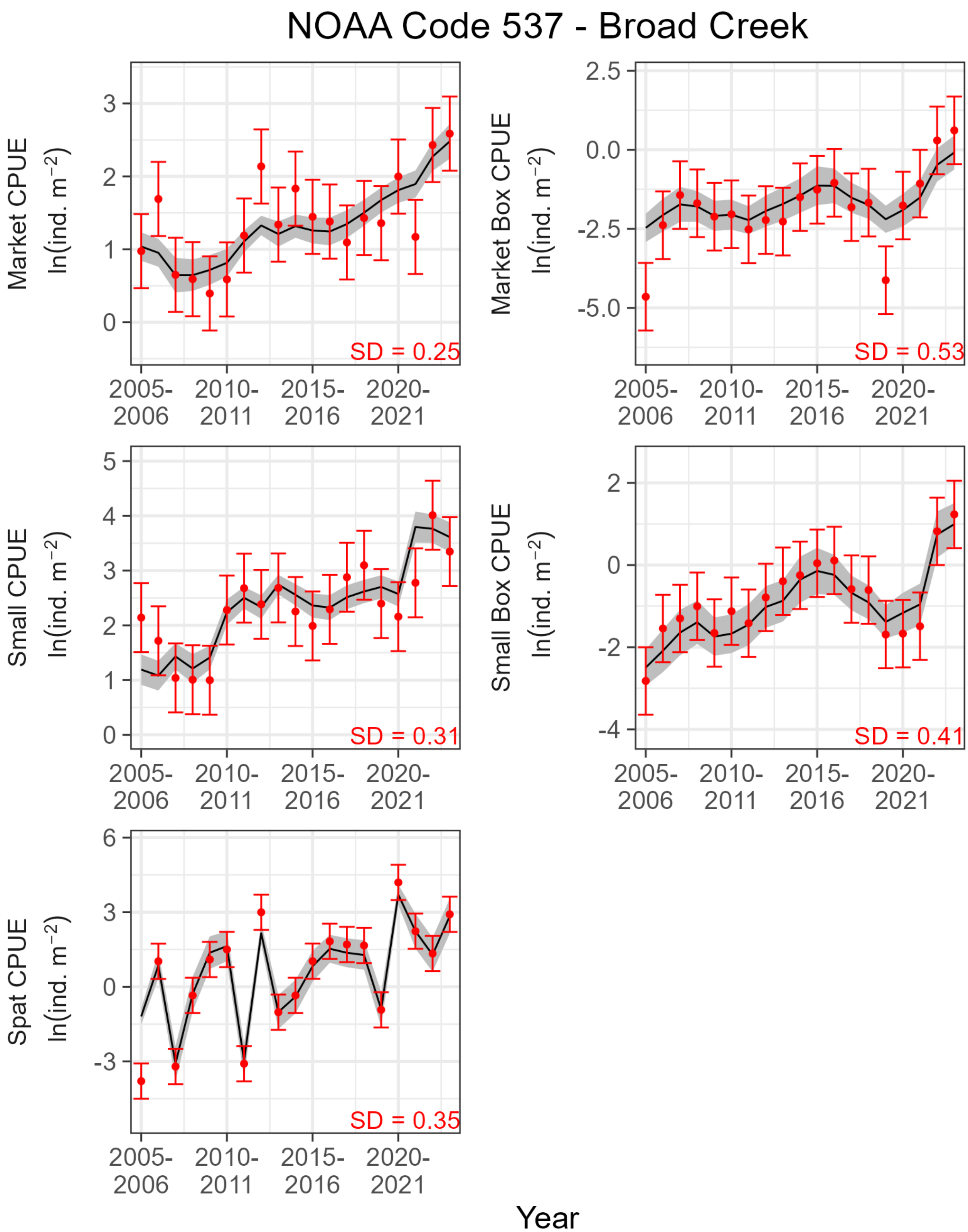

Figure 45. Estimated (line) and observed (points) values for Broad Creek. Variable and symbol definitions are the same as Figure 12.

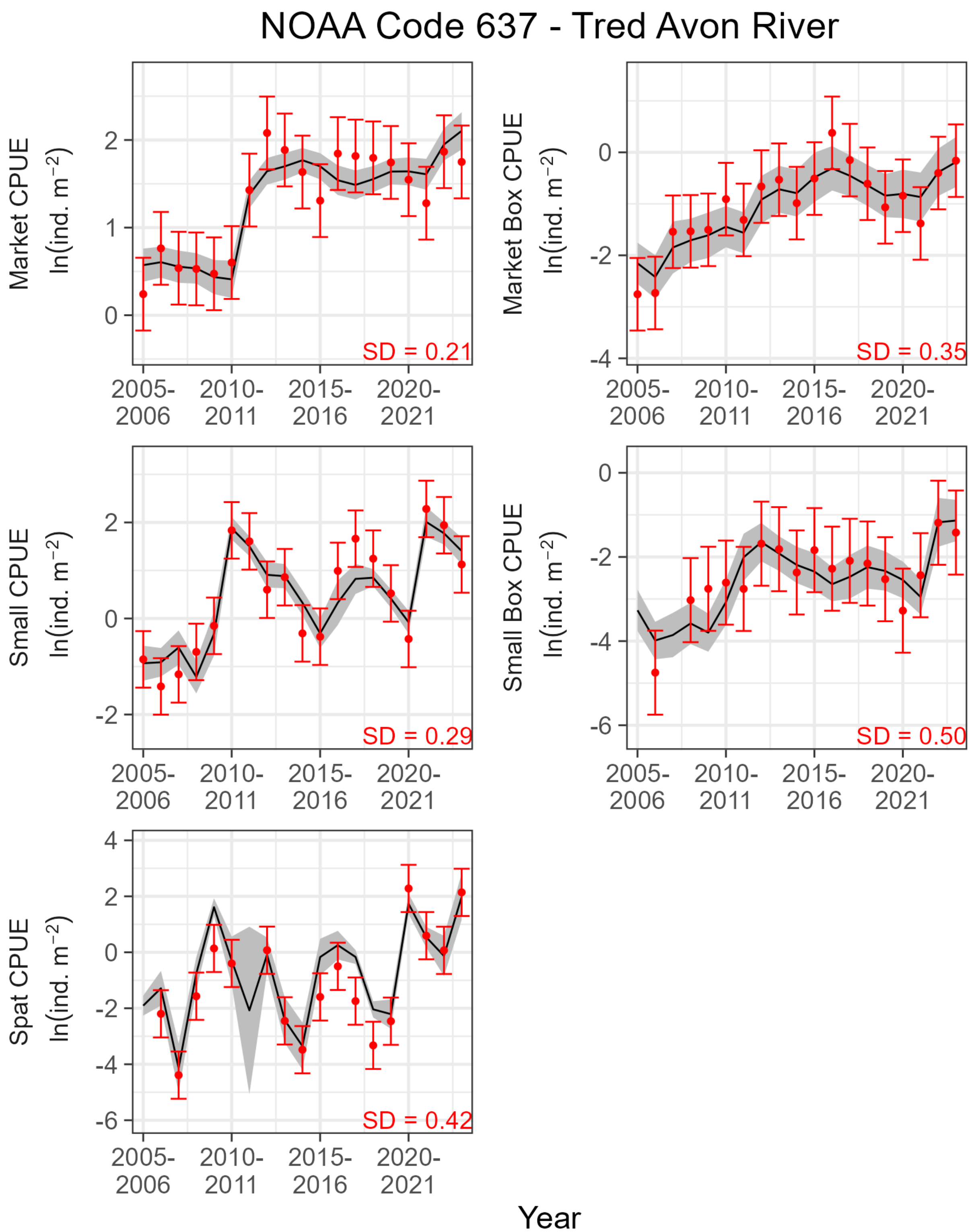

Figure 46. Estimated (line) and observed (points) values for Tred Avon River. Variable and symbol definitions are the same as Figure 12.

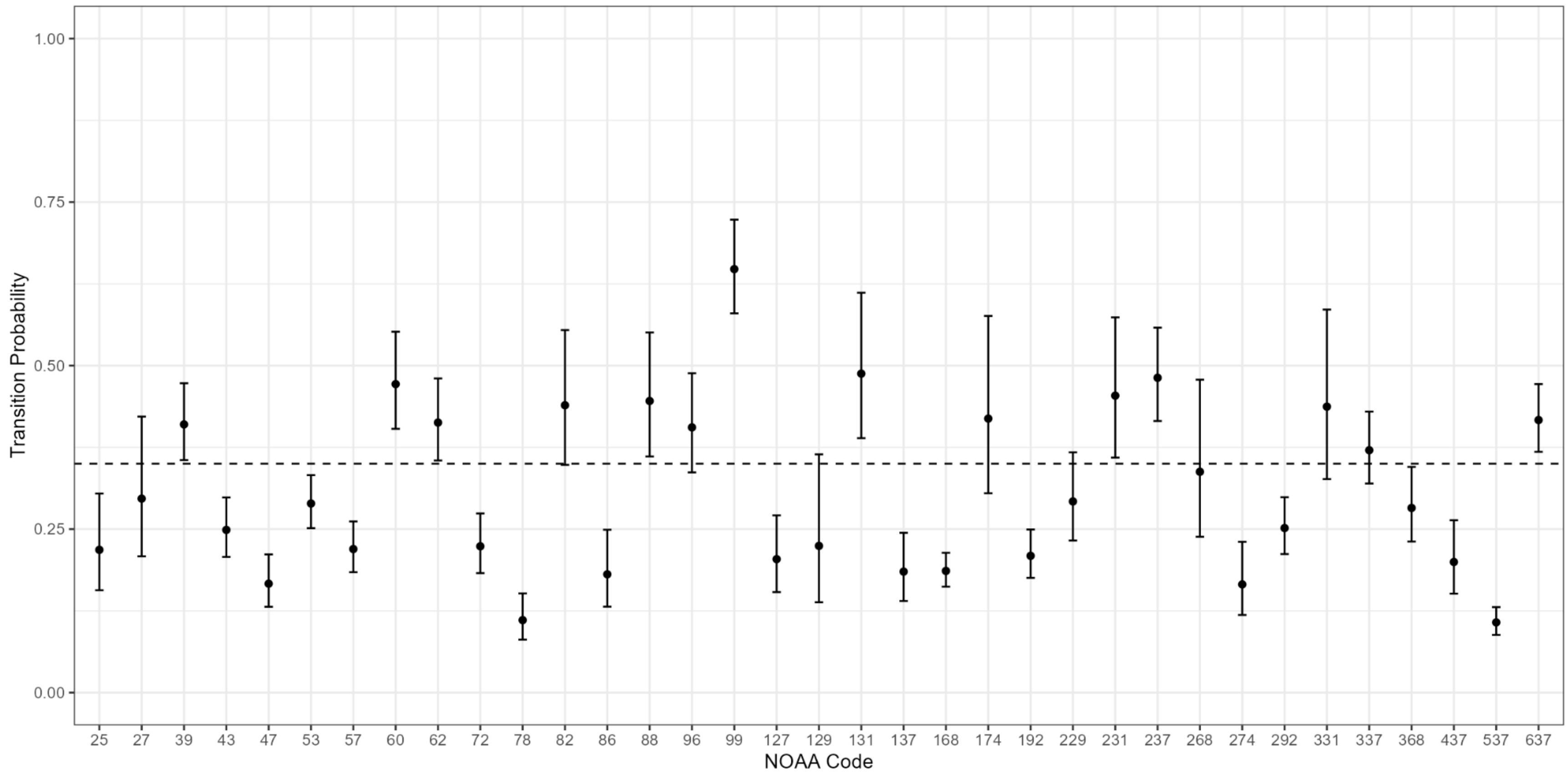

Figure 47. Estimated transition probabilities from small to market stage in each NOAA code (points) with approximate 95% confidence intervals (whiskers). The dashed line represents the mean of the penalty included in the model.

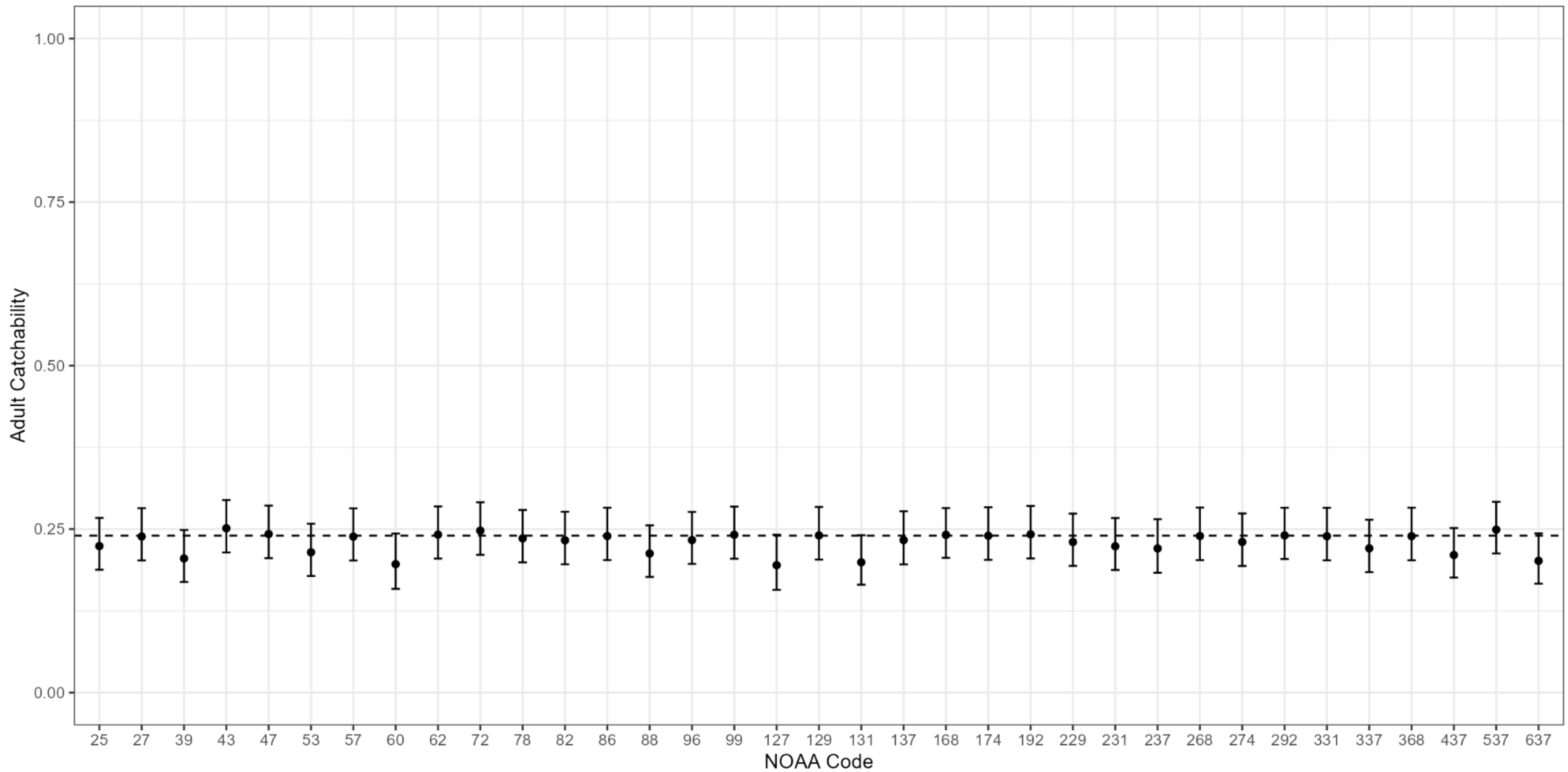

Figure 48. Estimated adult (small and market) catchability for the Fall Dredge Survey in each NOAA code (points) with approximate 95% confidence intervals (whiskers). The dashed line represents the median of the penalty included in the model.

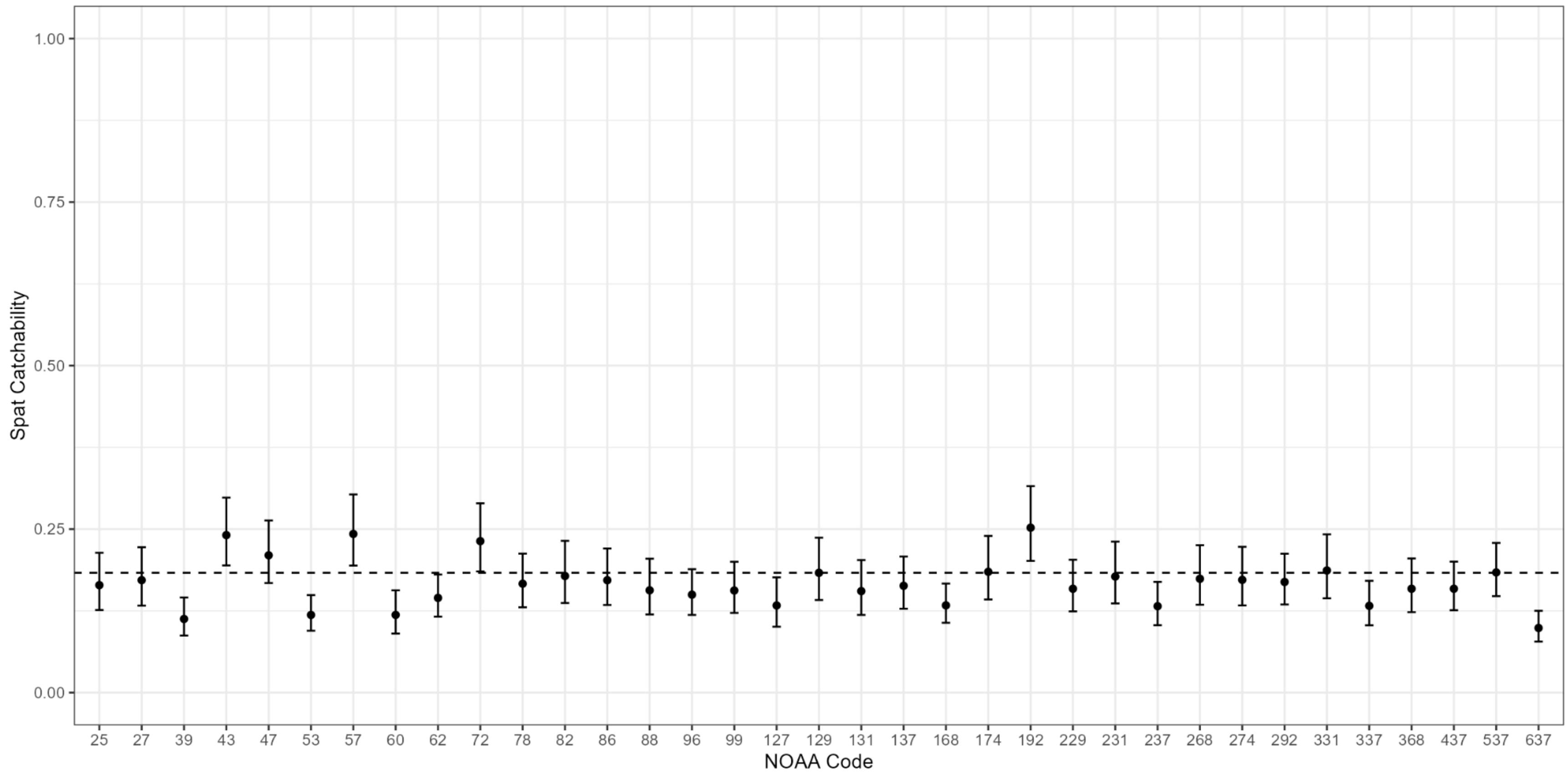

Figure 49. Estimated spat catchability for the Fall Dredge Survey in each NOAA code (points) with approximate 95% confidence intervals (whiskers). The dashed line represents the median of the penalty included in the model.

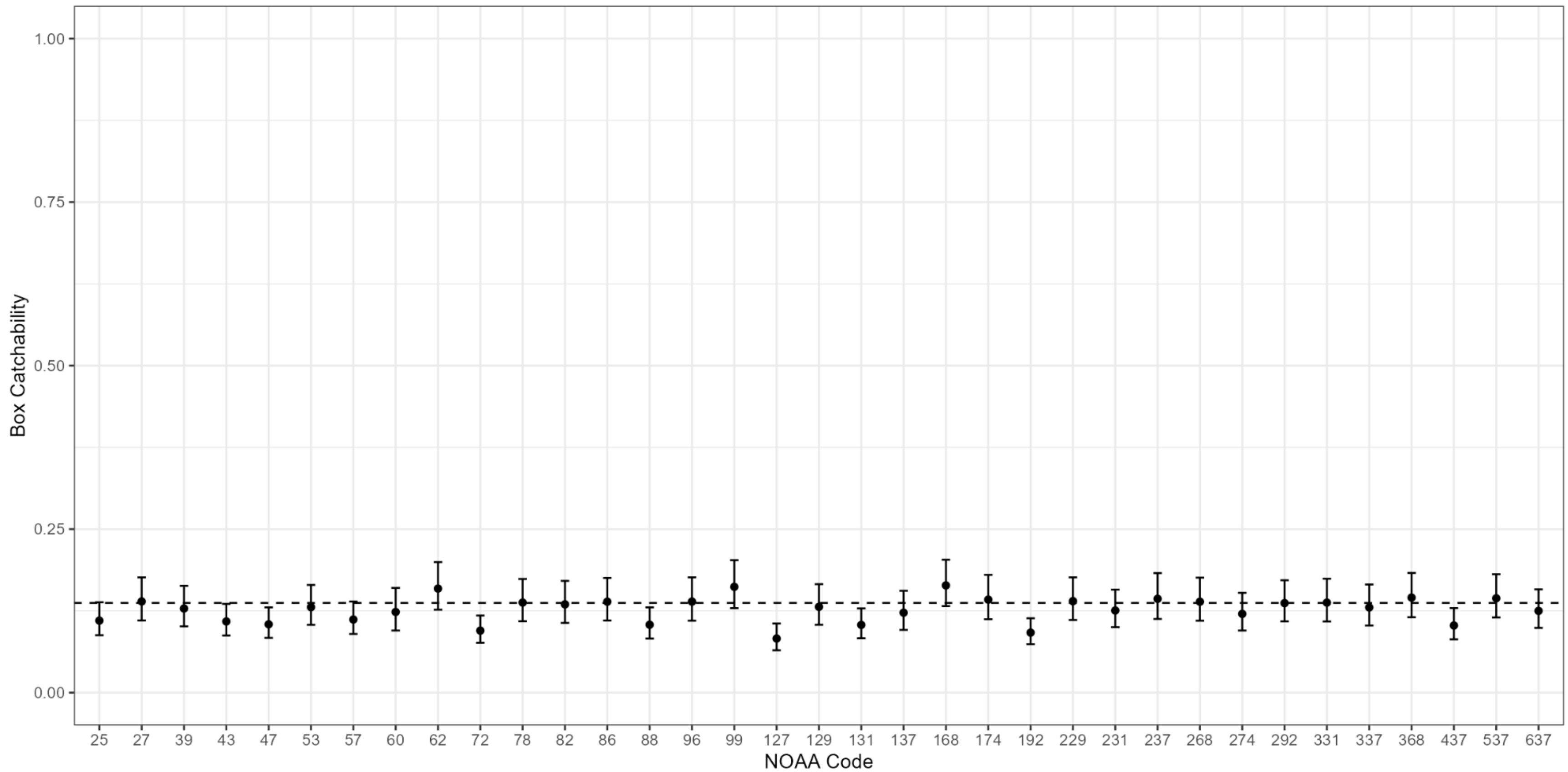

Figure 50. Estimated box (small and market) catchability in each NOAA code (points) with approximate 95% confidence intervals (whiskers). The dashed line represents the median of the penalty included in the model.

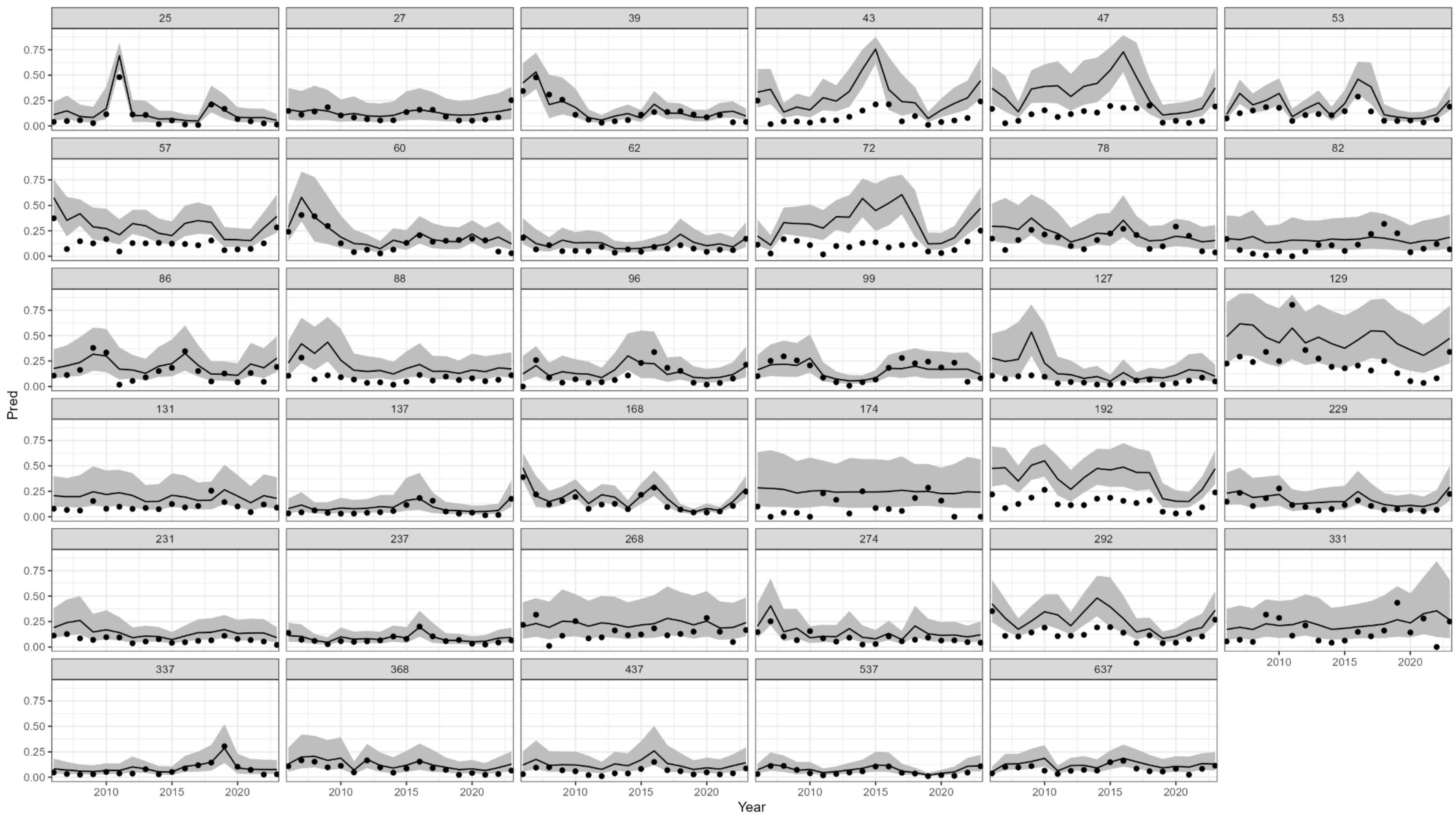

Figure 51. Comparison of natural mortality rates from the stage-structured model (black lines) and box count natural mortality rate estimates (black dots) for each NOAA code. The shaded areas indicate approximate 95% confidence intervals of the model estimates.

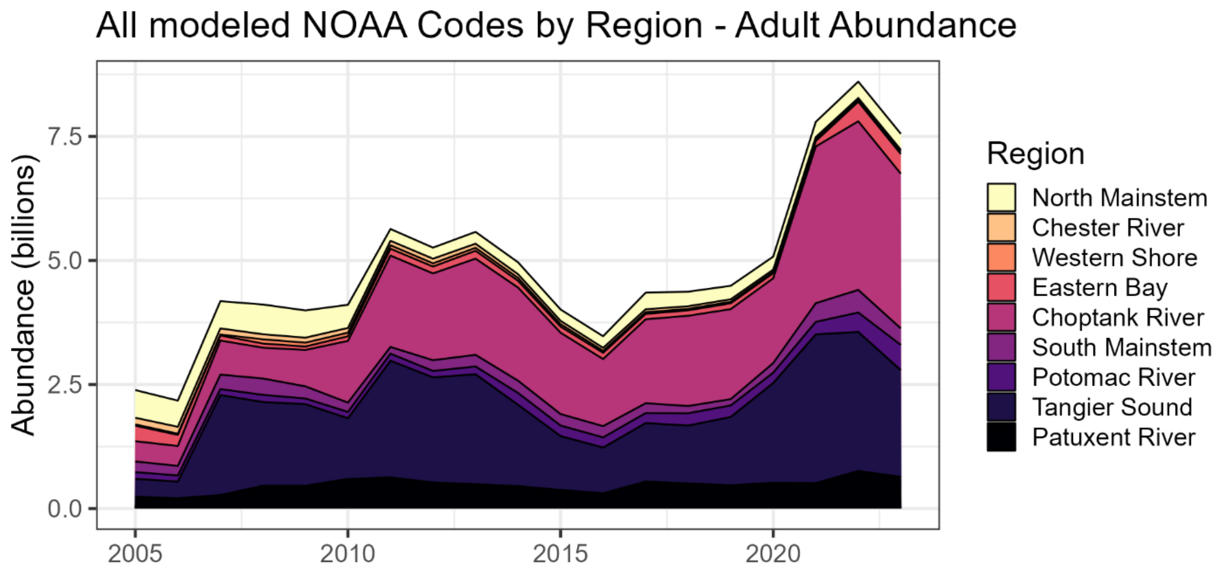

Figure 52. Estimated adult (small + market) oyster abundance among regions in the portion of the Chesapeake Bay under Maryland management during 2005-2023.

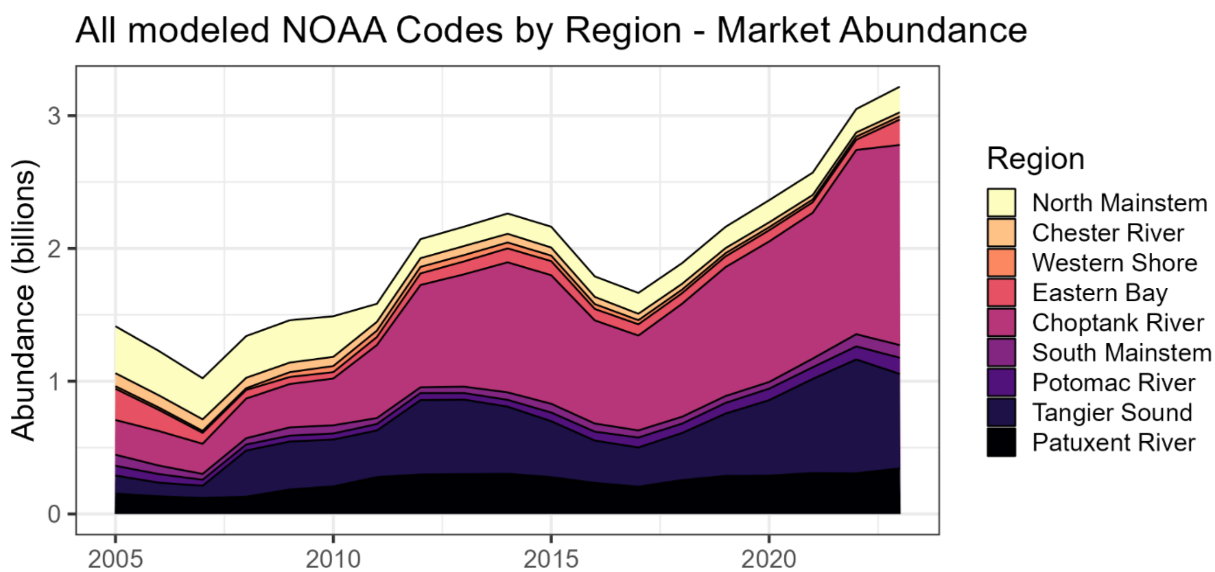

Figure 53. Estimated market oyster abundance among regions in the portion of the Chesapeake Bay under Maryland management during 2005-2023.

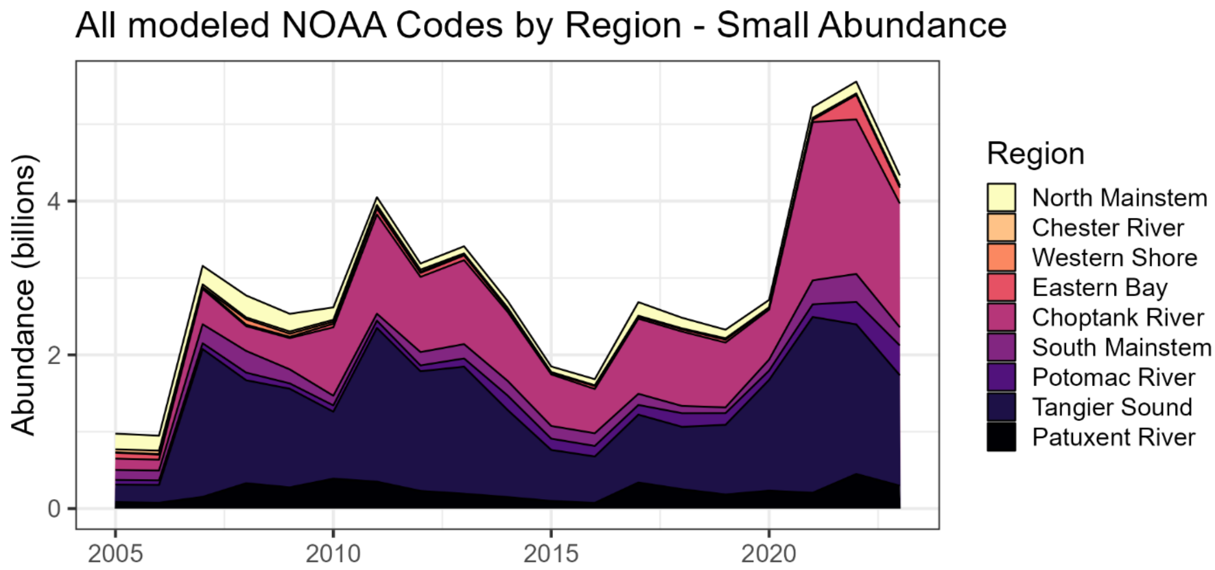

Figure 54. Estimated small oyster abundance among regions in the portion of the Chesapeake Bay under Maryland management during 2005-2023.

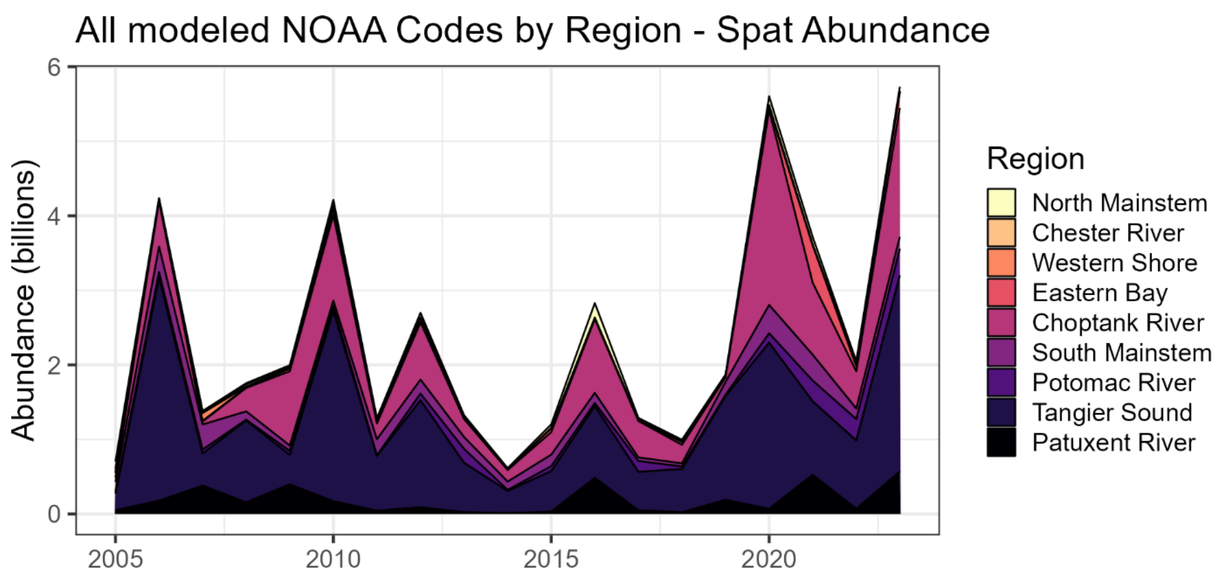

Figure 55. Estimated spat oyster abundance among regions in the portion of the Chesapeake Bay under Maryland management during 2005-2023.

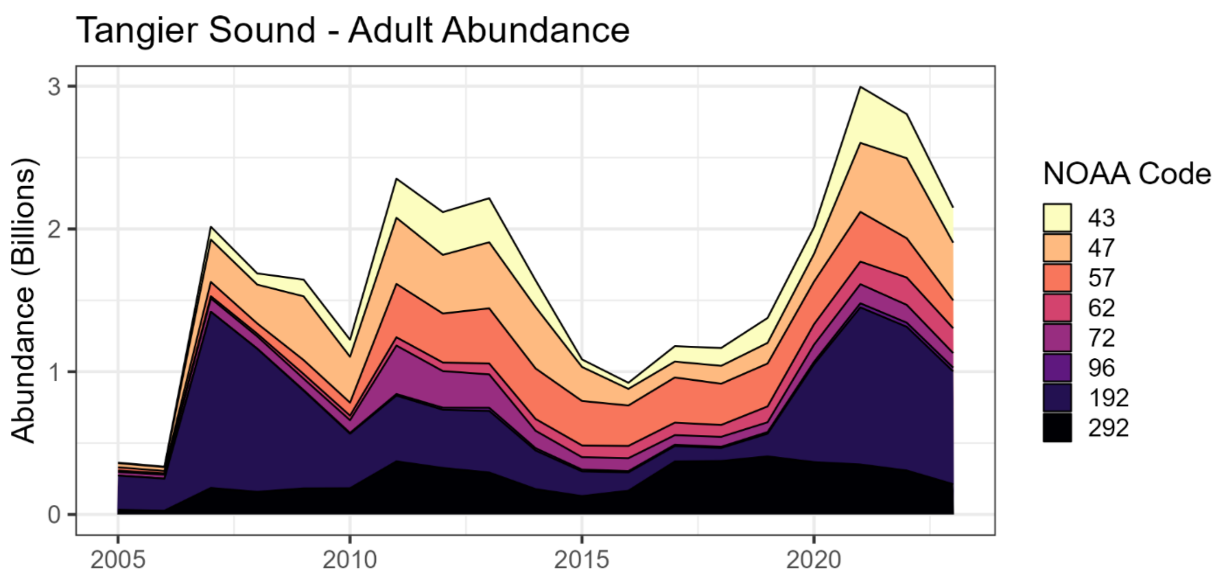

Figure 56. Estimated adult oyster abundance among modeled NOAA codes in the Tangier Sound Region under Maryland management during 2005-2023.

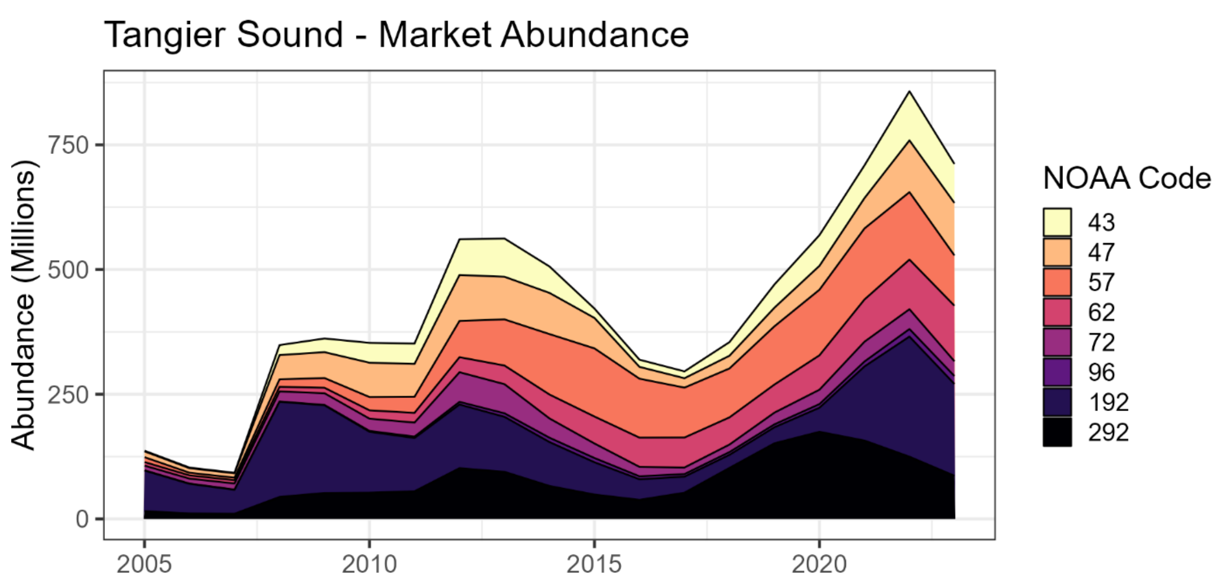

Figure 57. Estimated market oyster abundance among modeled NOAA codes in the Tangier Sound Region under Maryland management during 2005-2023.

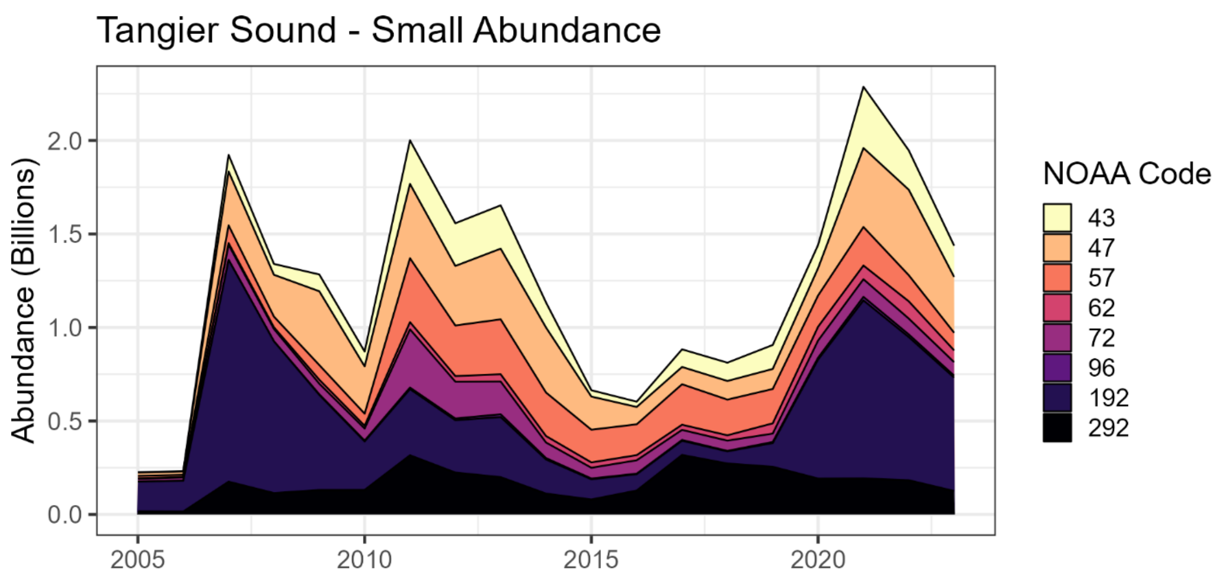

Figure 58. Estimated small oyster abundance among modeled NOAA codes in the Tangier Sound Region under Maryland management during 2005-2023.

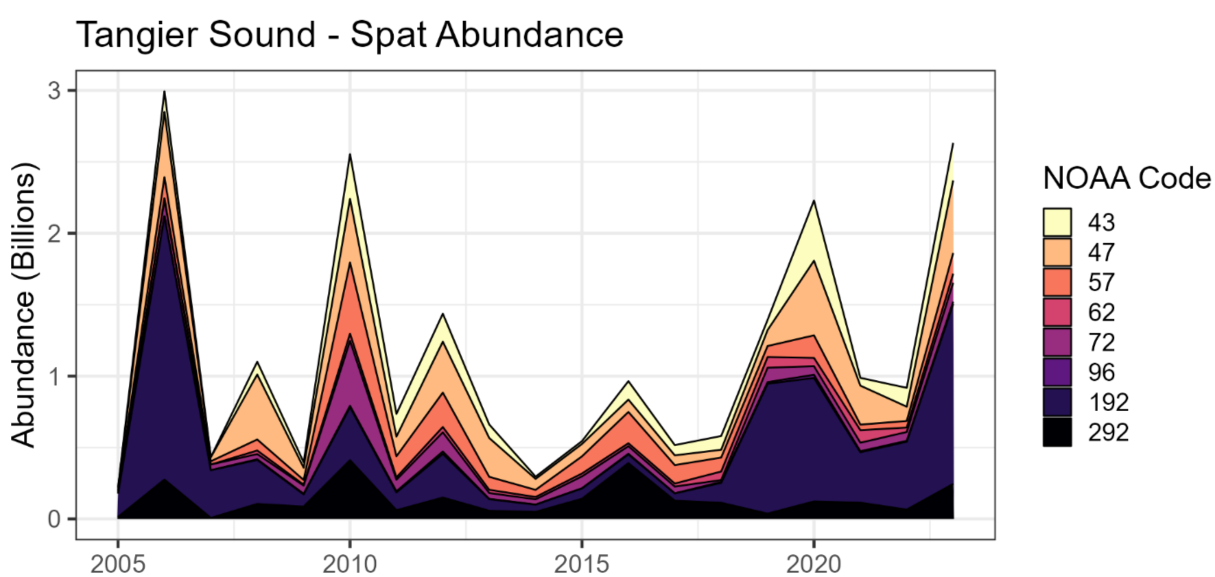

Figure 59. Estimated spat oyster abundance among modeled NOAA codes in the Tangier Sound Region under Maryland management during 2005-2023.

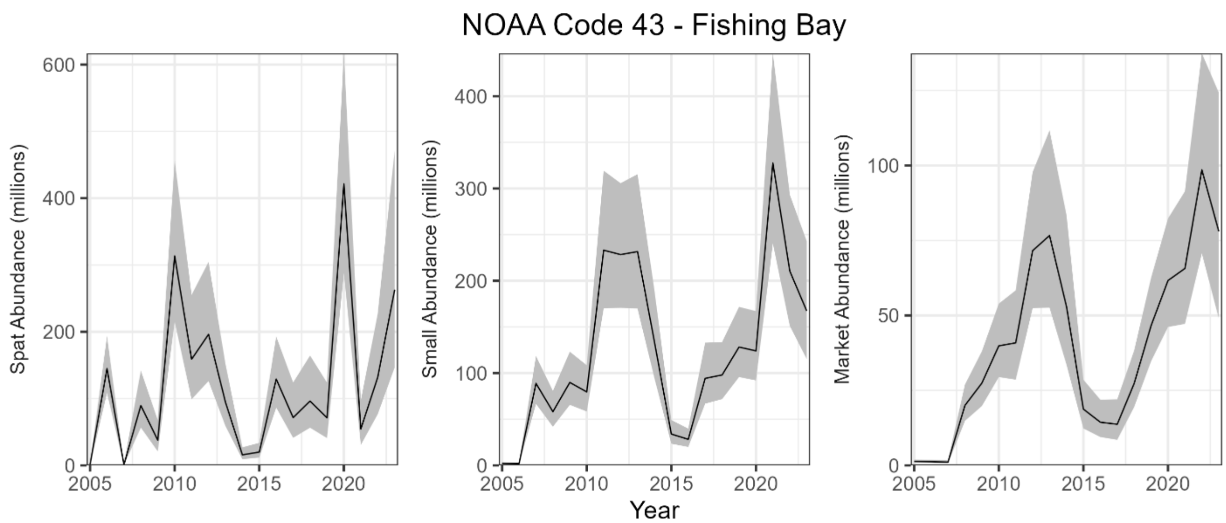

Figure 60. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Fishing Bay. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

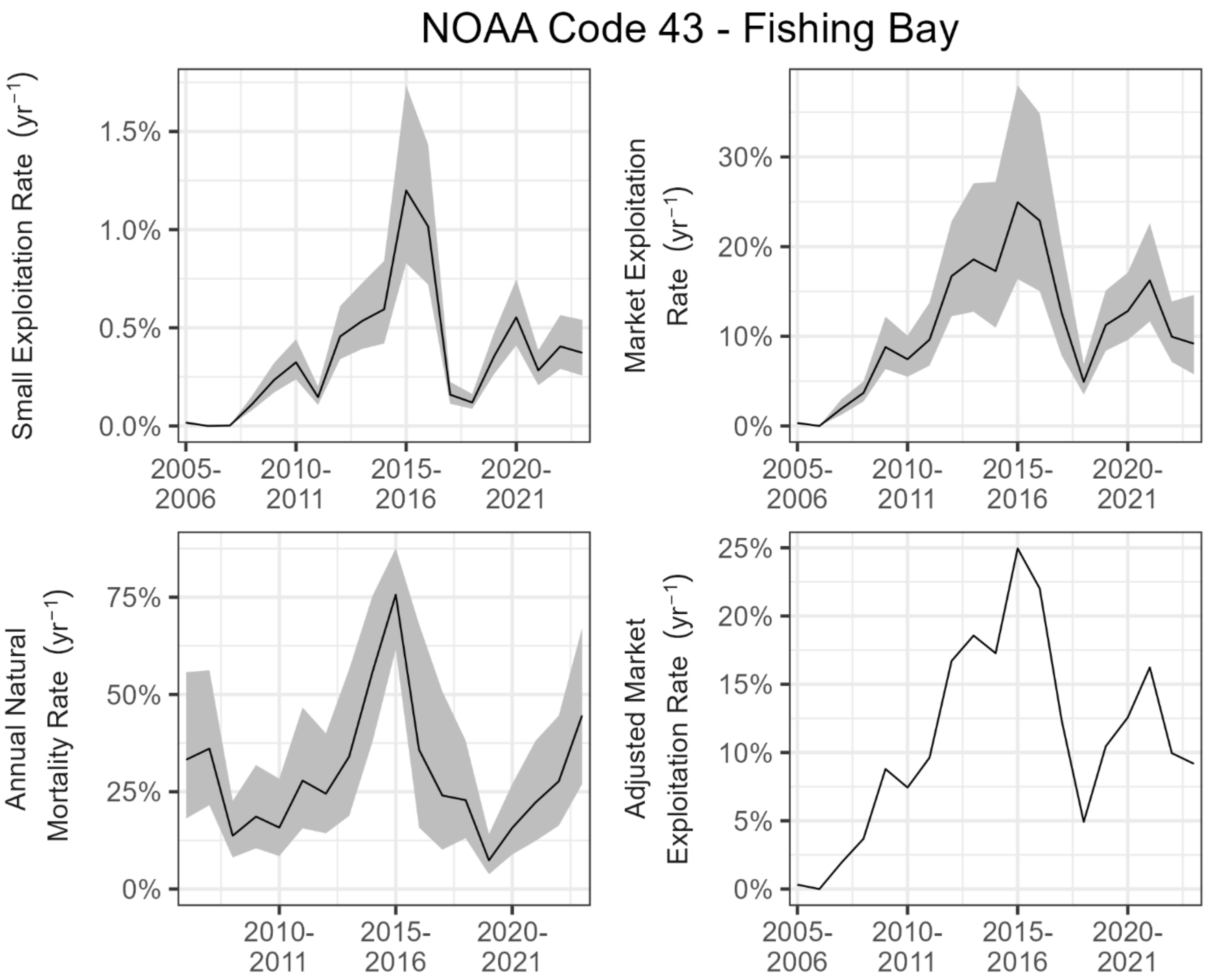

Figure 61. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Fishing Bay. The shaded areas indicate approximate 95% confidence intervals.

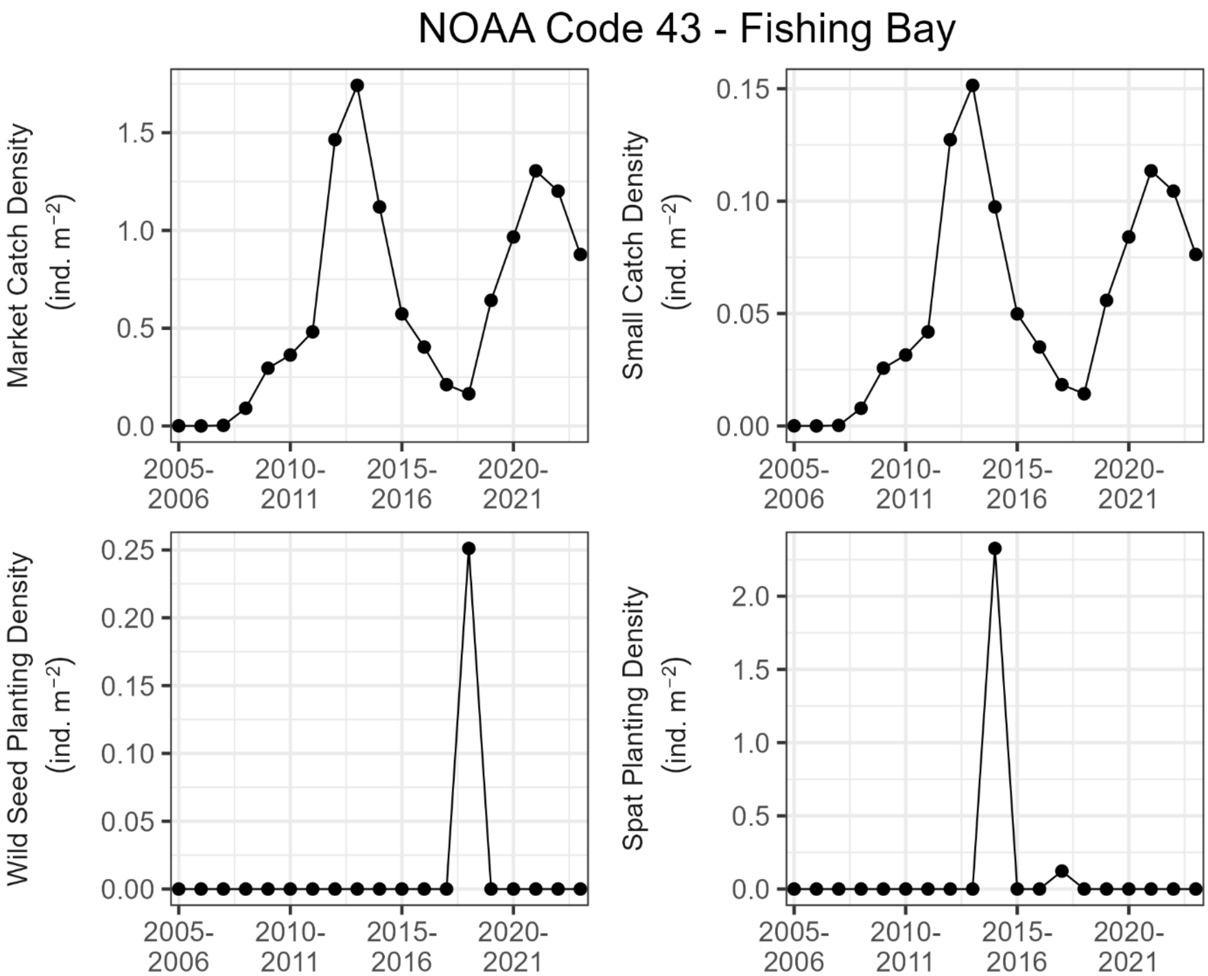

Figure 62. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Fishing Bay. Density was calculated as the number of individuals divided by habitat area for each data source.

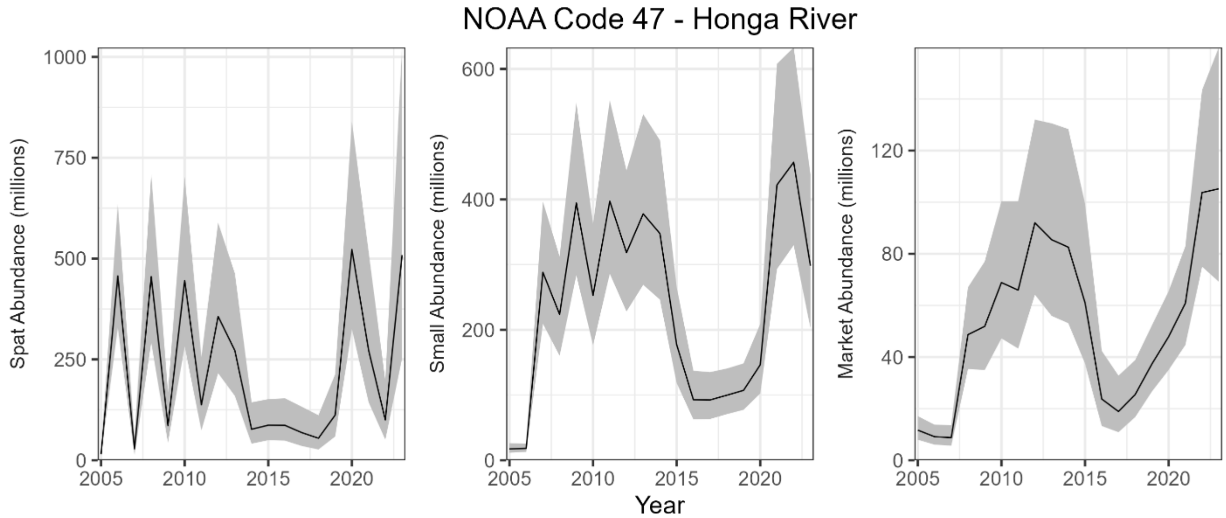

Figure 63. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Honga River. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

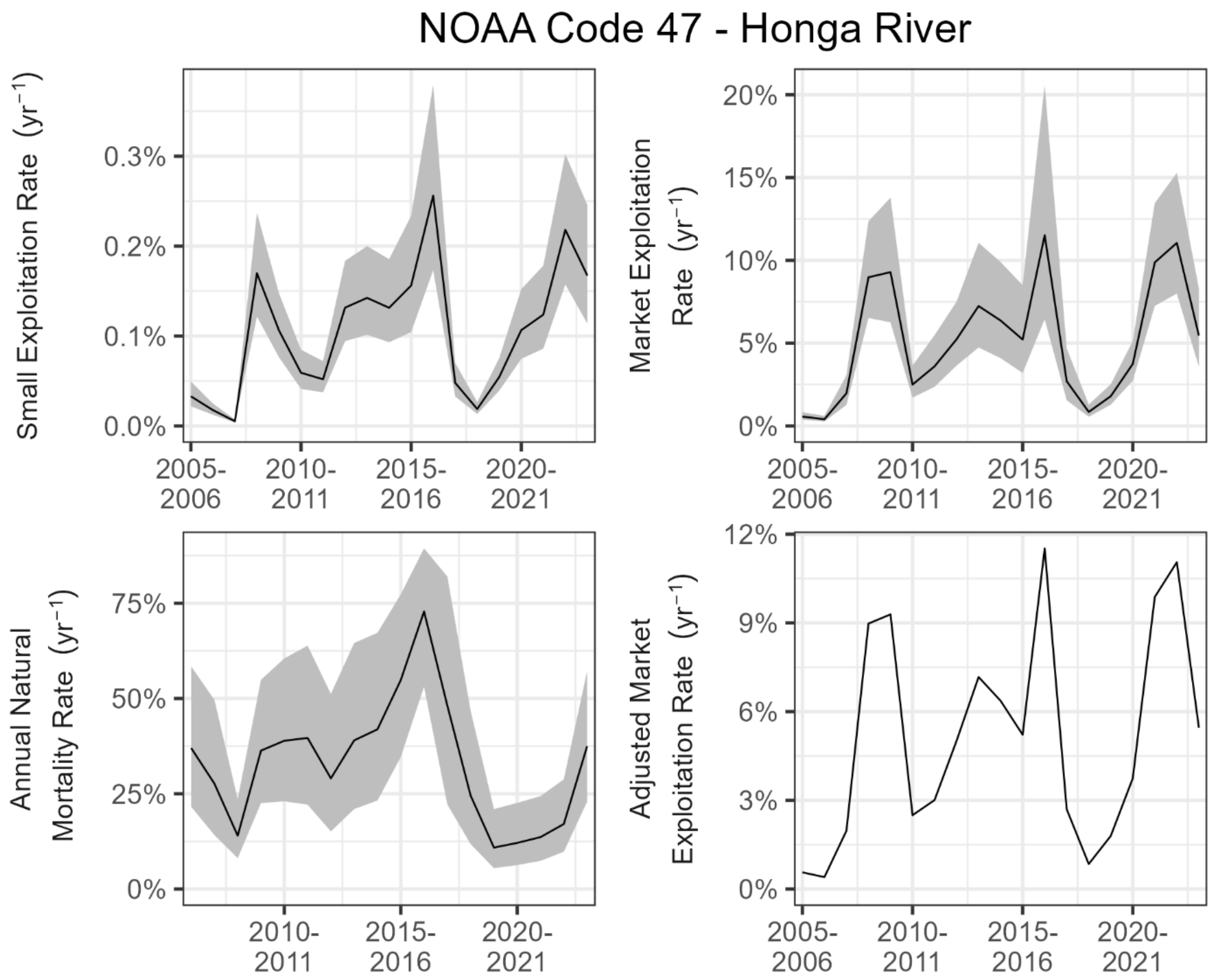

Figure 64. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Honga River. The shaded areas indicate approximate 95% confidence intervals.

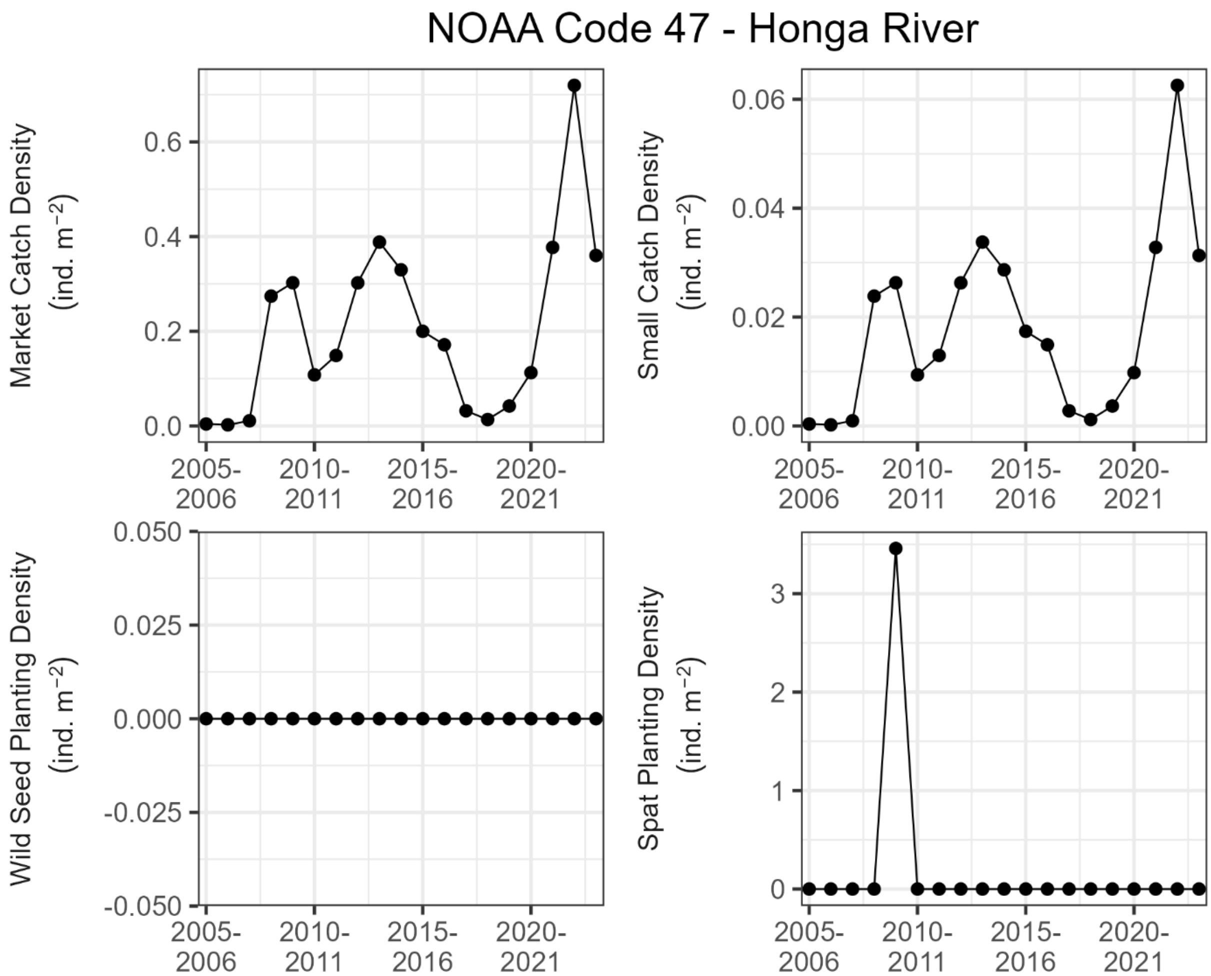

Figure 65. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Honga River. Density was calculated as the number of individuals divided by habitat area for each data source.

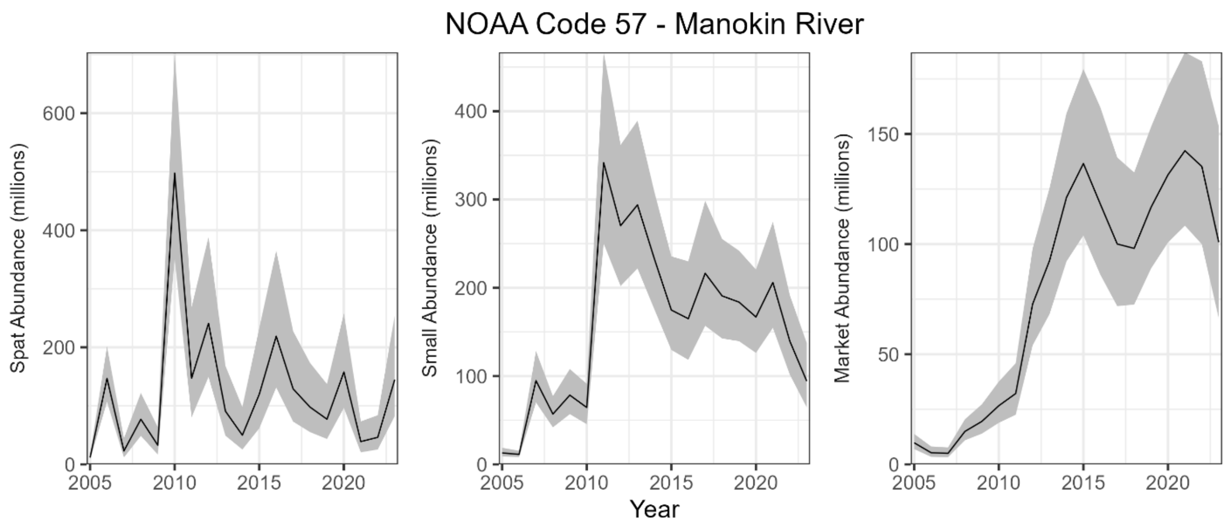

Figure 66. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Manokin River. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

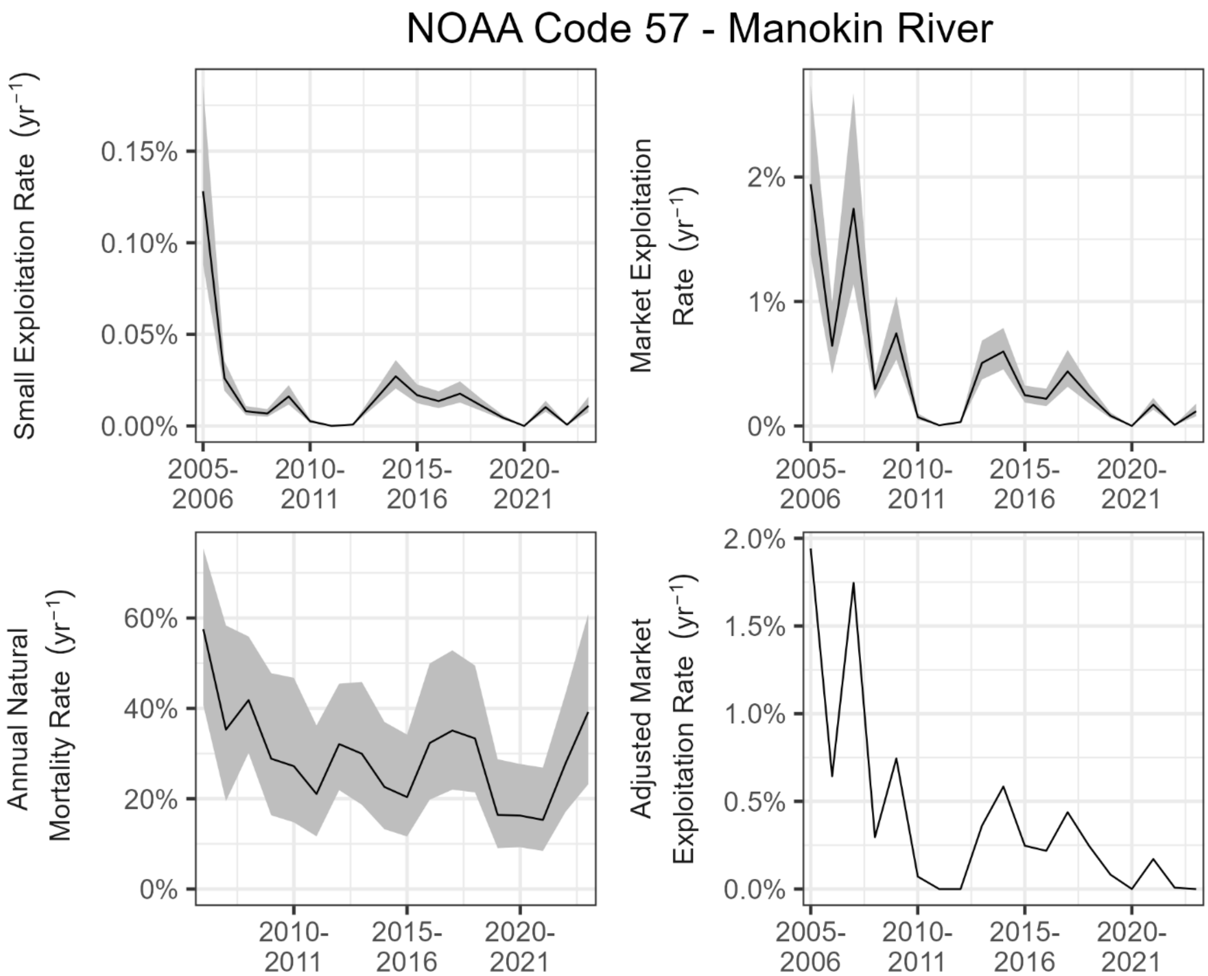

Figure 67. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Manokin River. The shaded areas indicate approximate 95% confidence intervals.

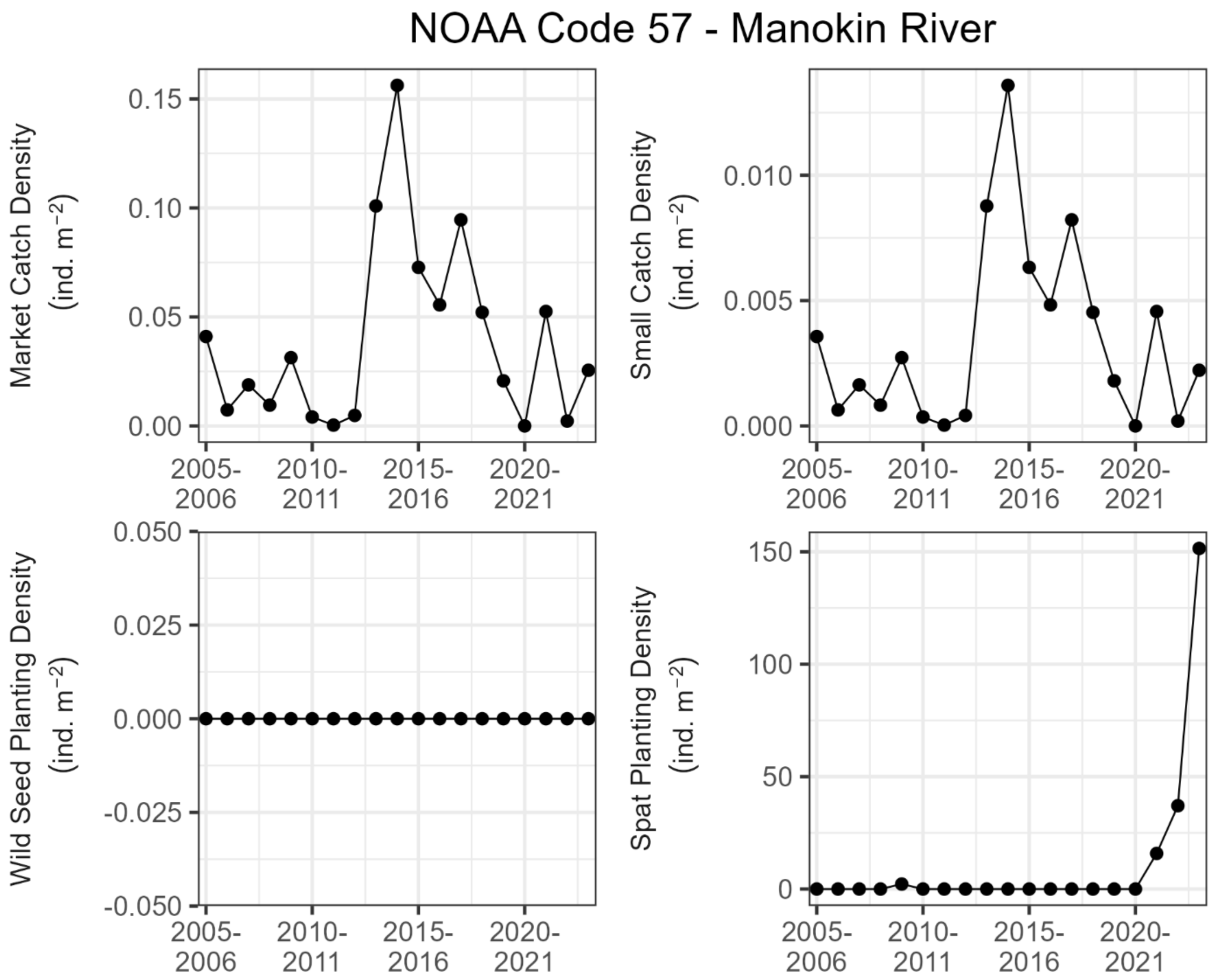

Figure 68. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Manokin River. Density was calculated as the number of individuals divided by habitat area for each data source.

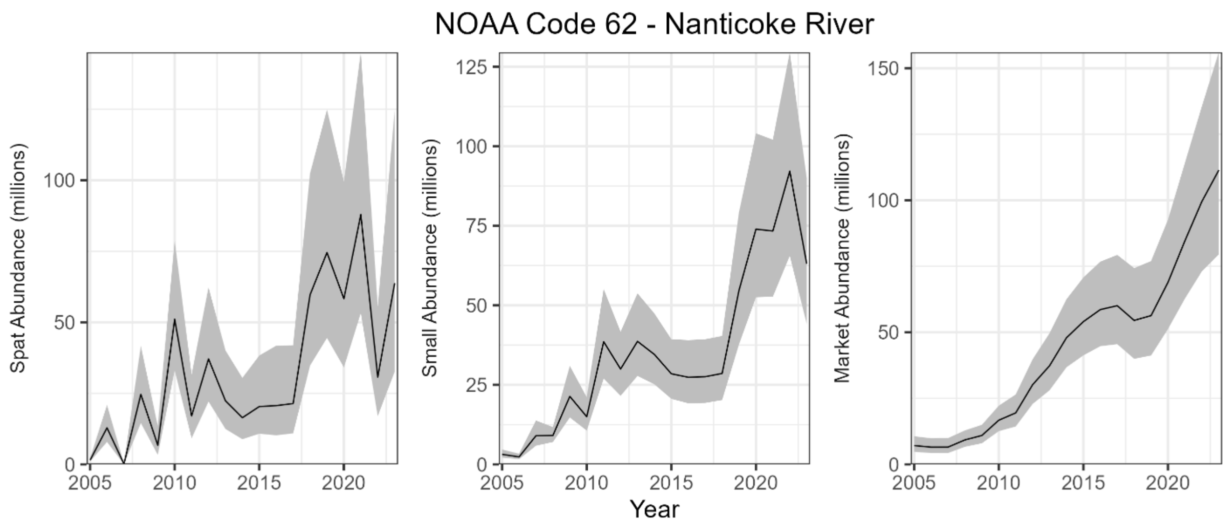

Figure 69. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Nanticoke River. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

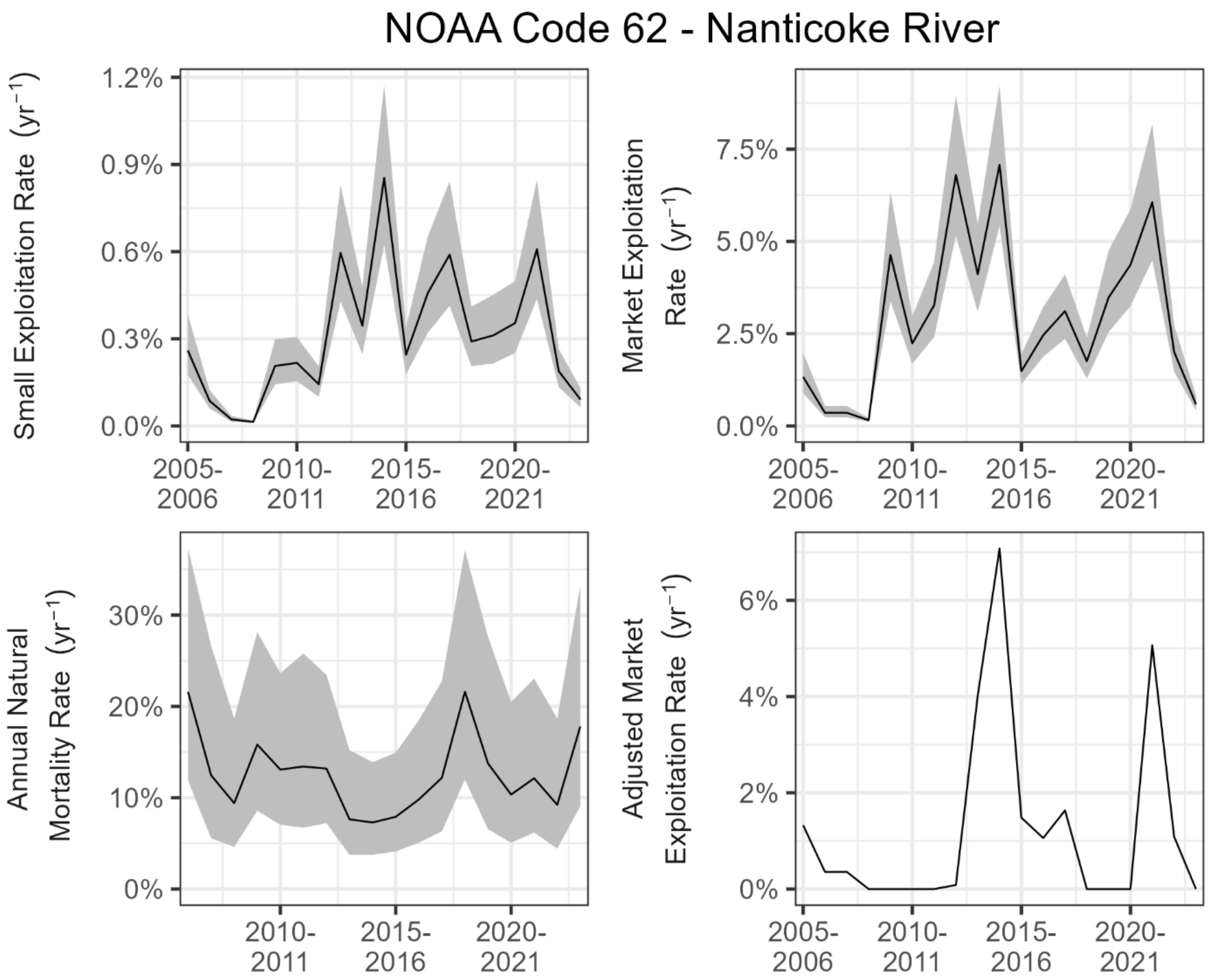

Figure 70. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Nanticoke River. The shaded areas indicate approximate 95% confidence intervals.

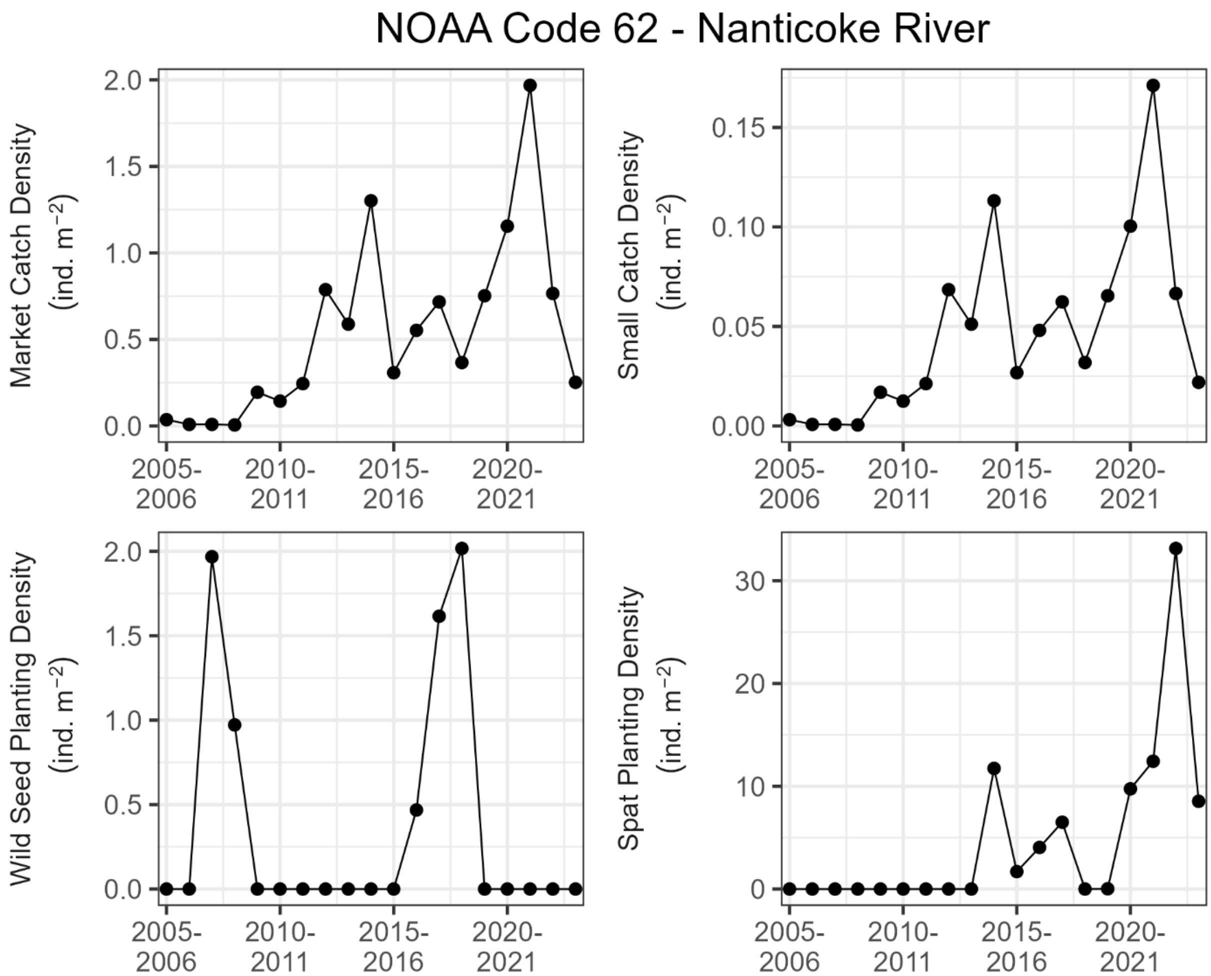

Figure 71. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Nanticoke River. Density was calculated as the number of individuals divided by habitat area for each data source.

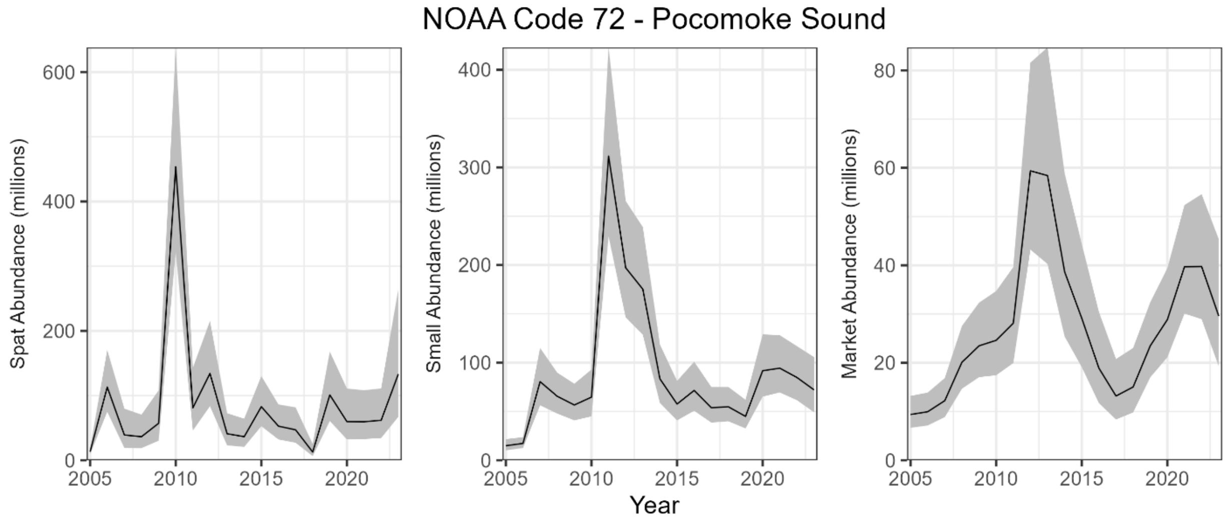

Figure 72. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Pocomoke Sound. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

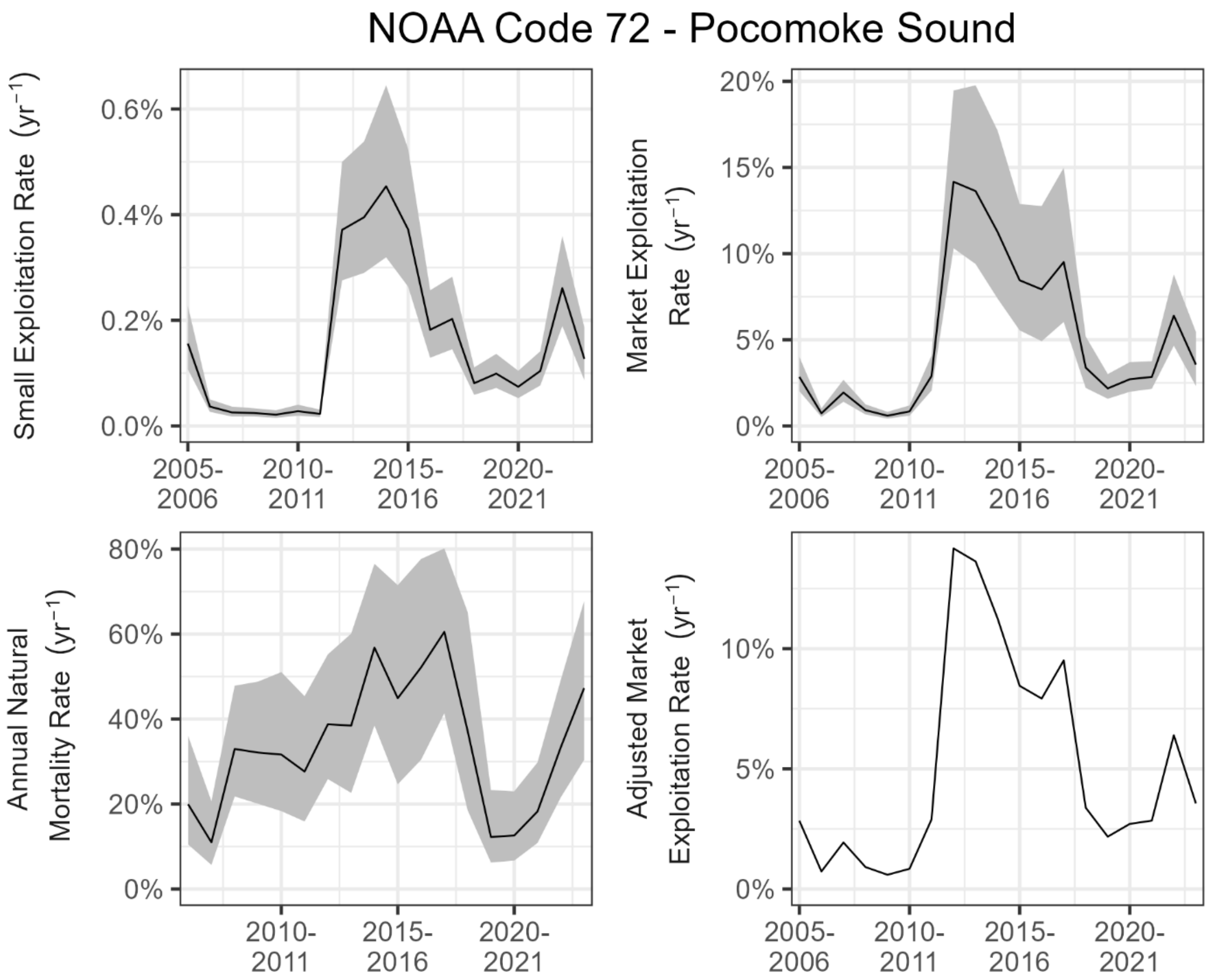

Figure 73. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Pocomoke Sound. The shaded areas indicate approximate 95% confidence intervals.

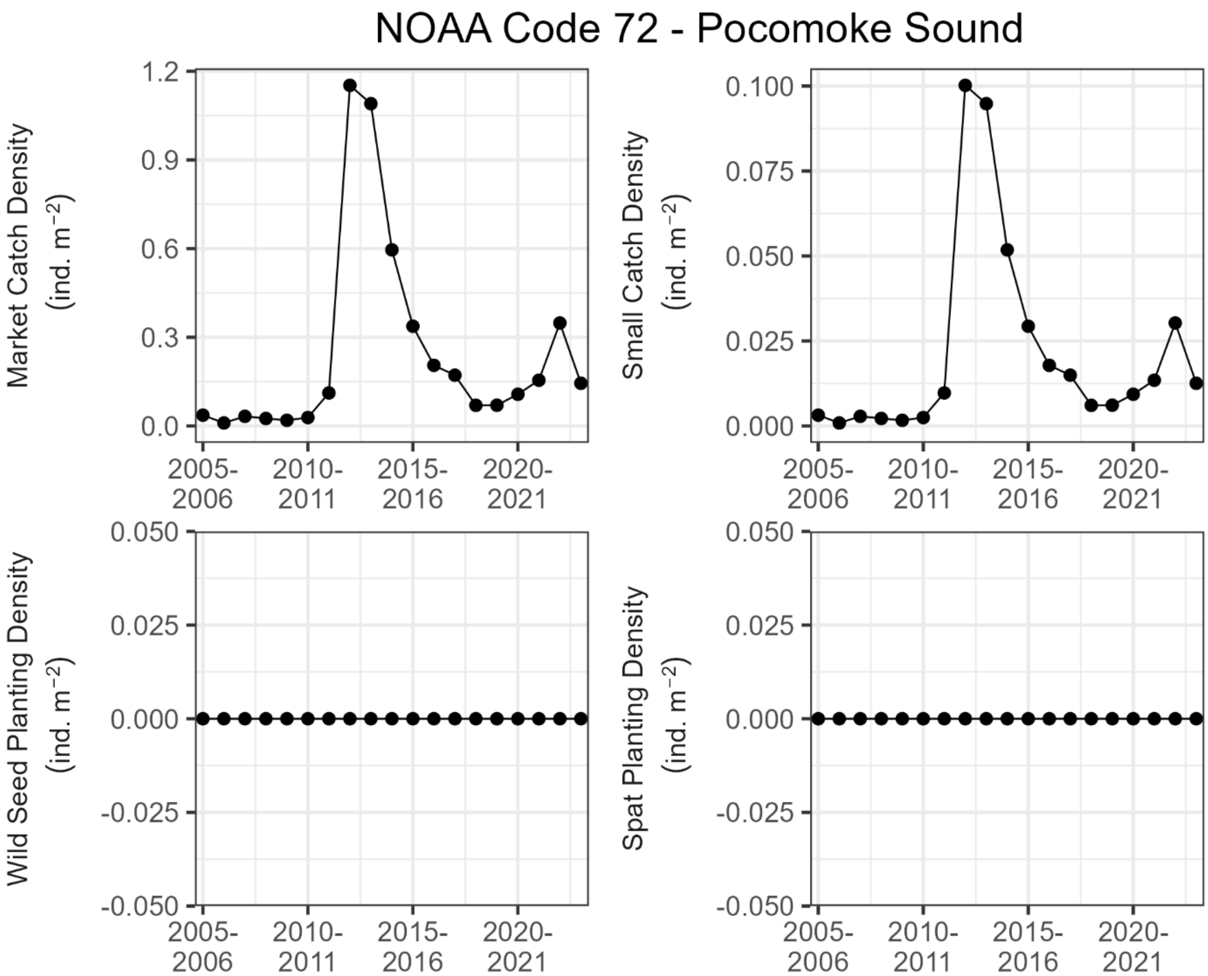

Figure 74. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Pocomoke Sound. Density was calculated as the number of individuals divided by habitat area for each data source.

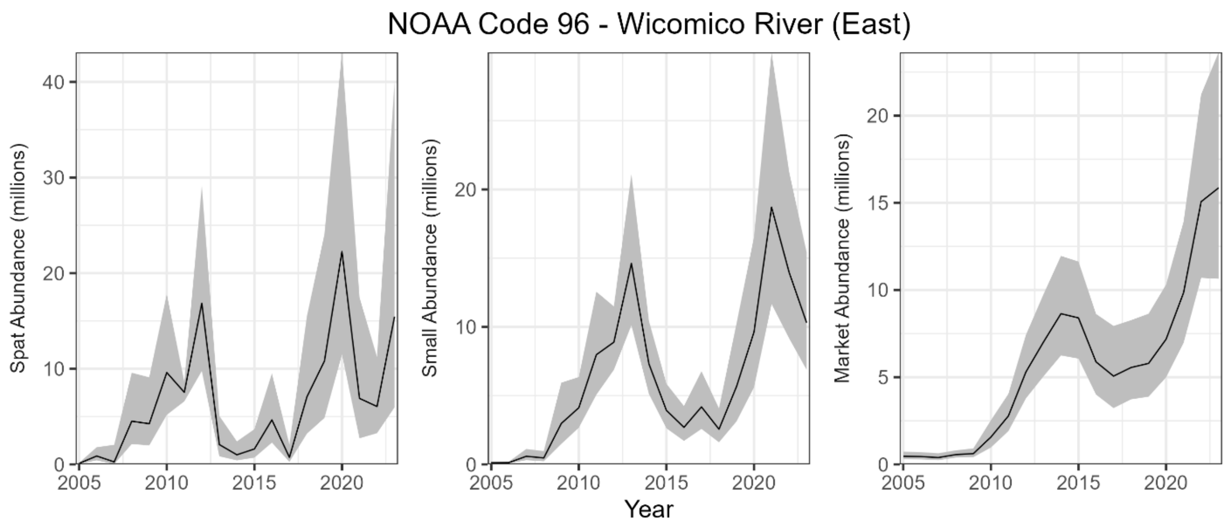

Figure 75. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Wicomico River (East). The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

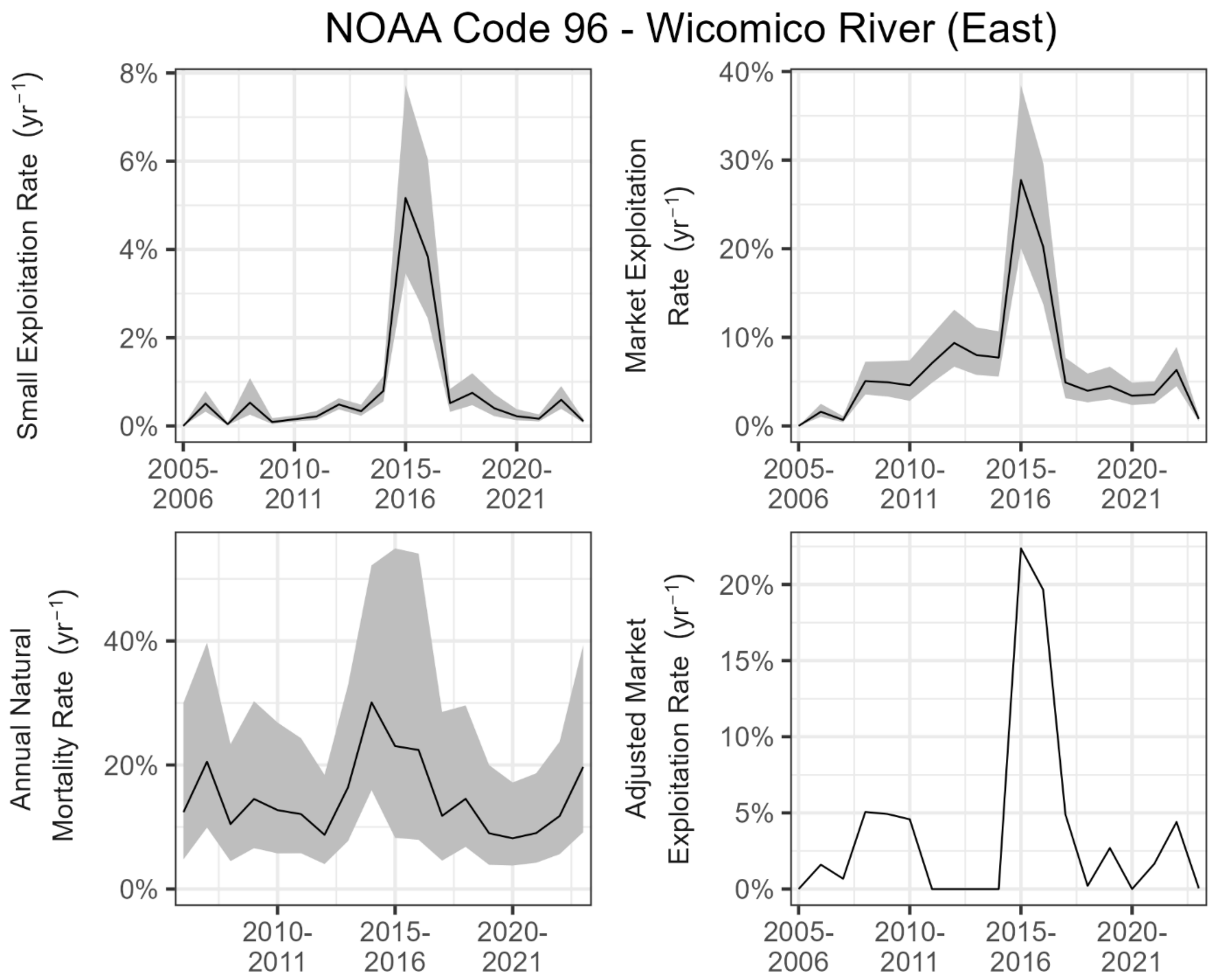

Figure 76. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Wicomico River (East). The shaded areas indicate approximate 95% confidence intervals.

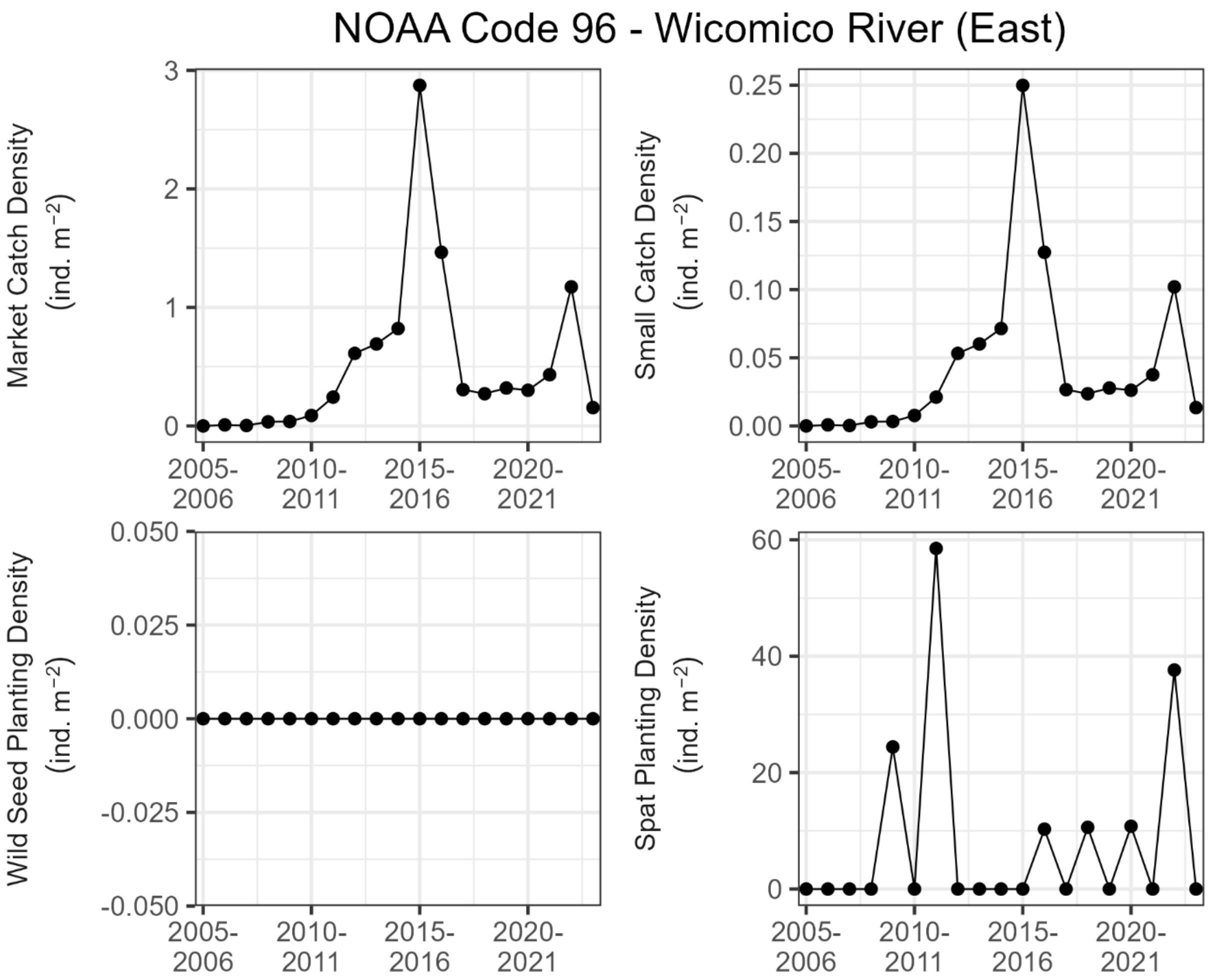

Figure 77. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Wicomico River (East). Density was calculated as the number of individuals divided by habitat area for each data source.

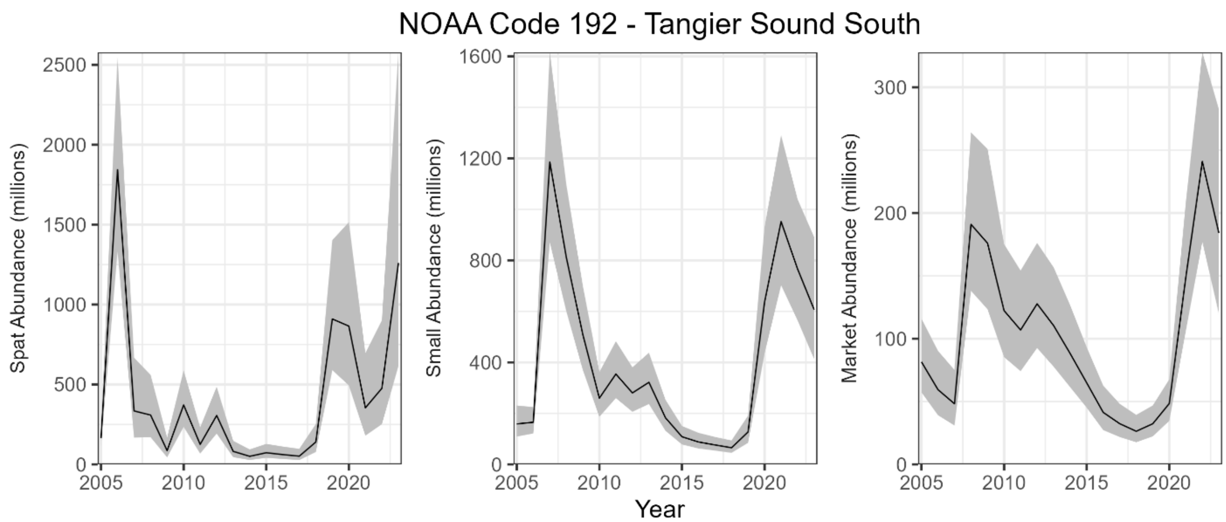

Figure 78. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Tangier Sound South. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

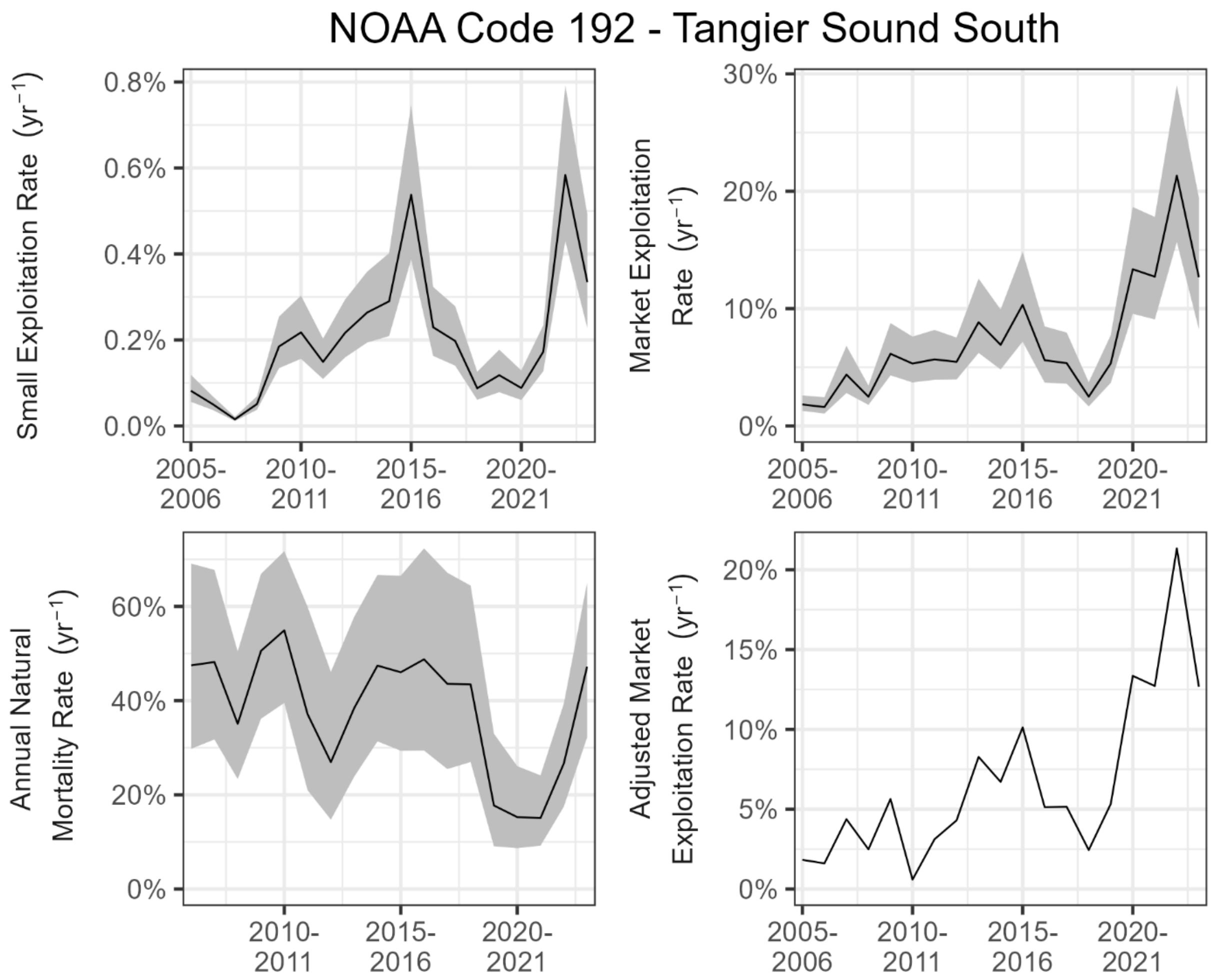

Figure 79. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Tangier Sound South. The shaded areas indicate approximate 95% confidence intervals.

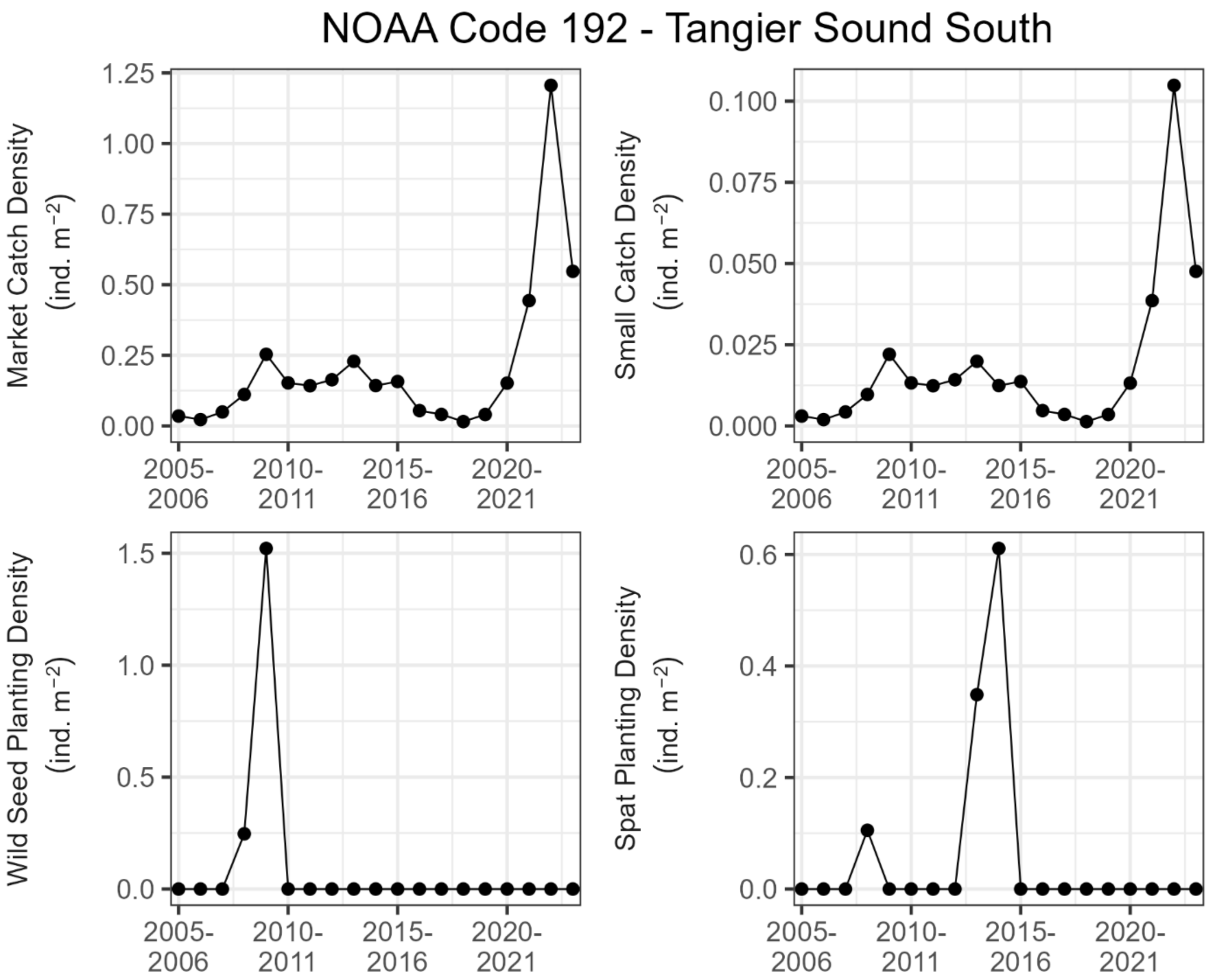

Figure 80. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Tangier Sound South. Density was calculated as the number of individuals divided by habitat area for each data source.

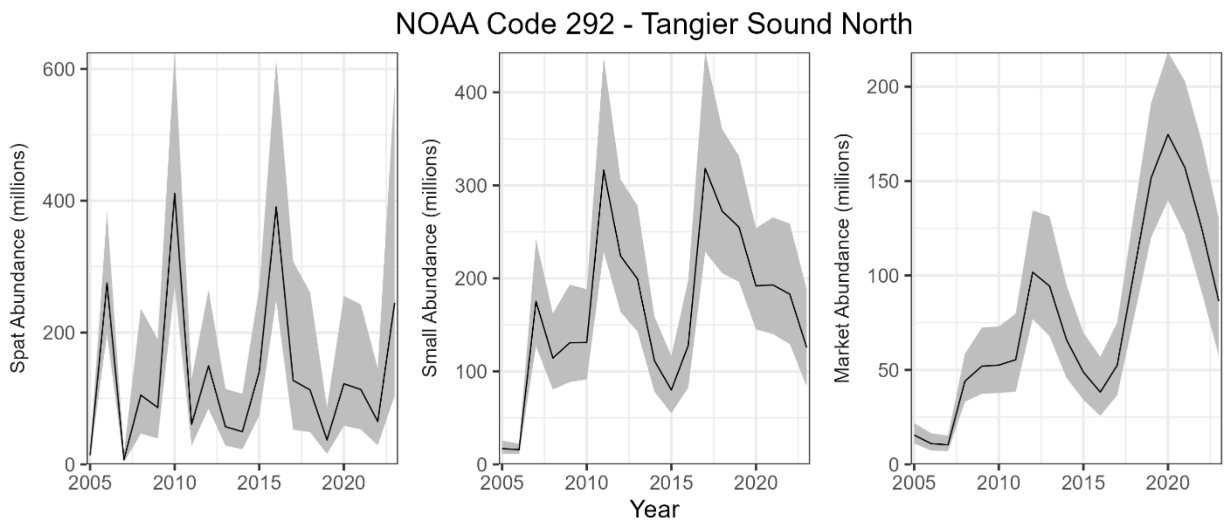

Figure 81. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Tangier Sound North. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

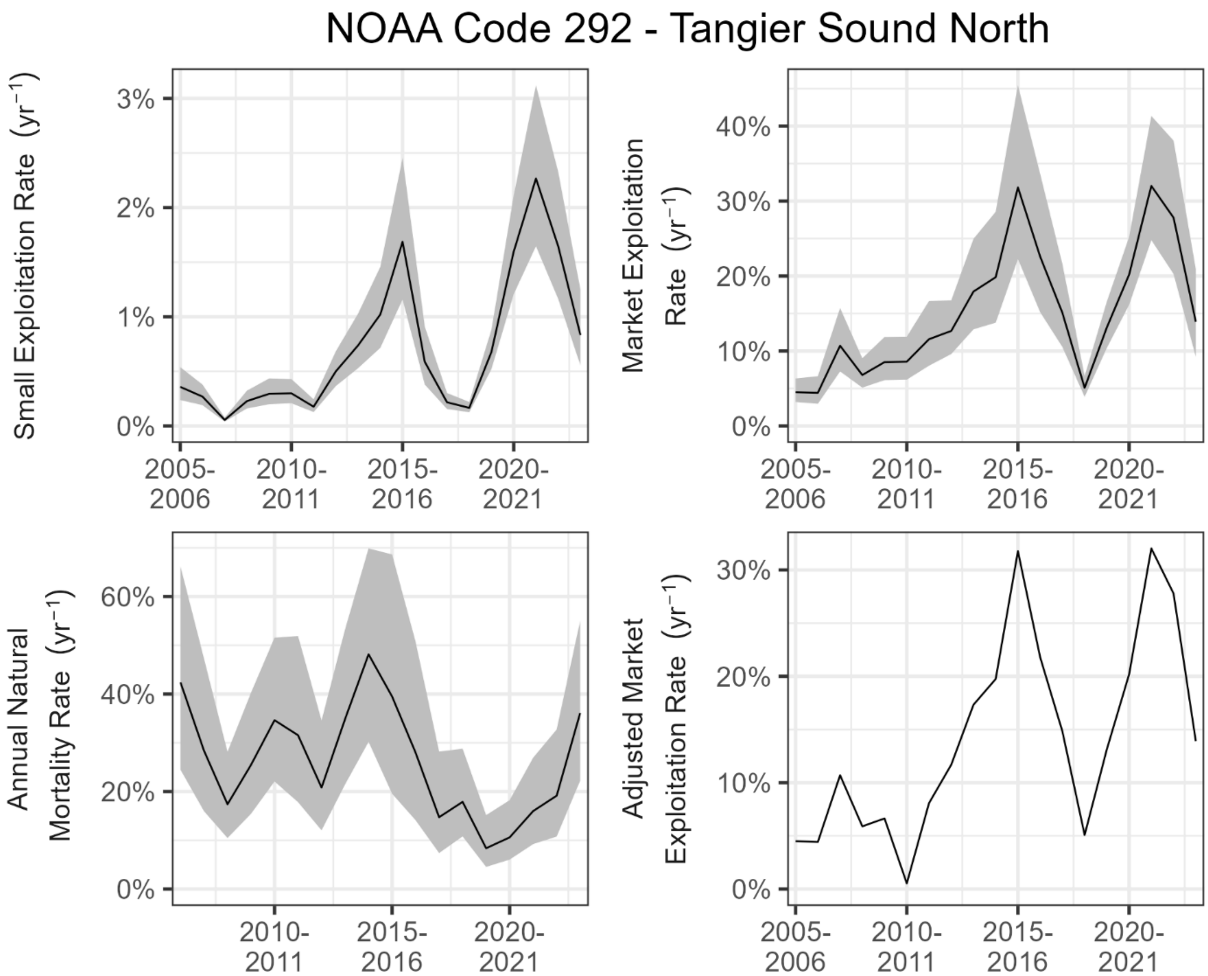

Figure 82. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Tangier Sound North. The shaded areas indicate approximate 95% confidence intervals.

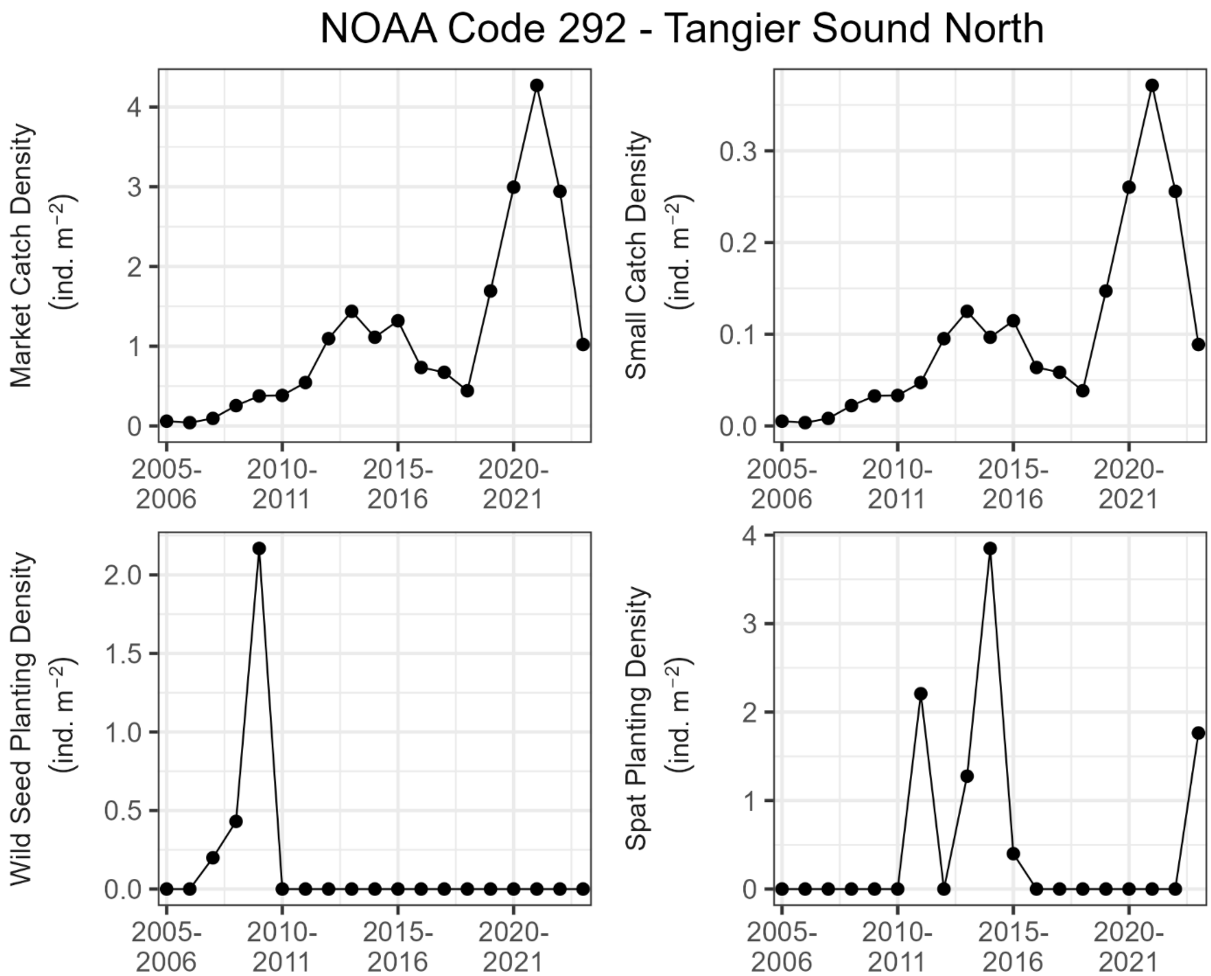

Figure 83. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Tangier Sound North. Density was calculated as the number of individuals divided by habitat area for each data source.

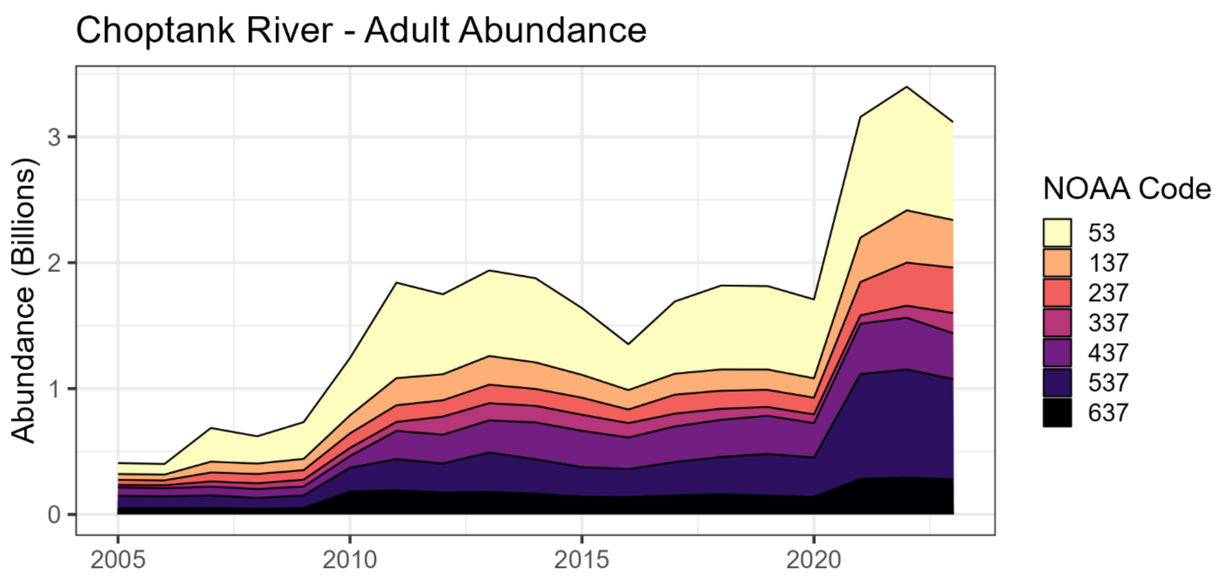

Figure 84. Estimated adult oyster abundance among modeled NOAA codes in the Choptank River Region under Maryland management during 2005-2023.

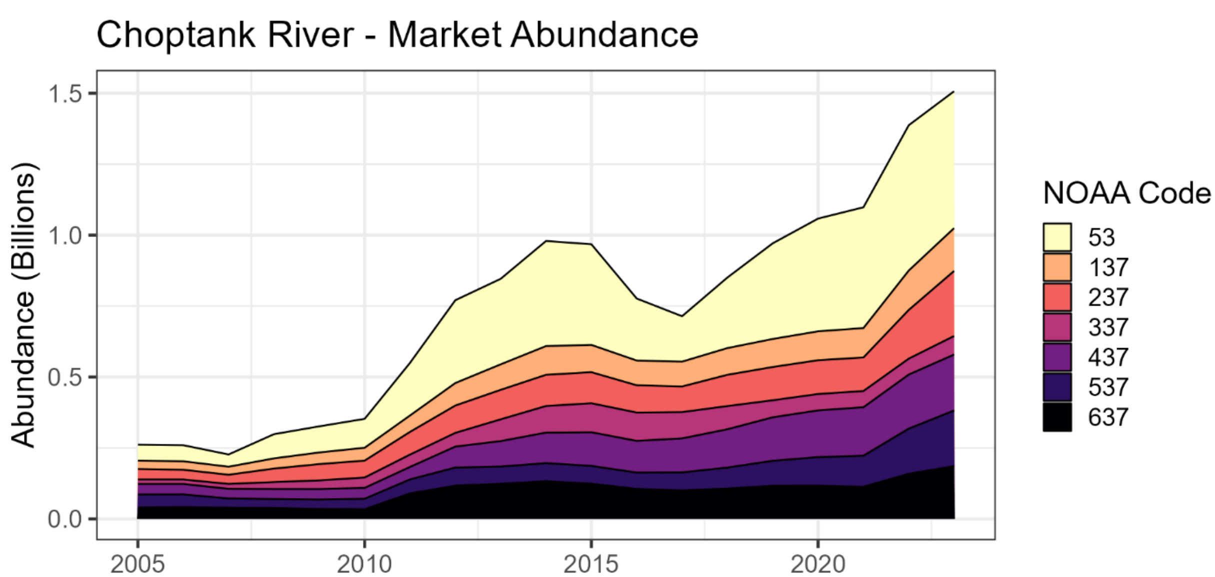

Figure 85. Estimated market oyster abundance among modeled NOAA codes in the Choptank River Region under Maryland management during 2005-2023.

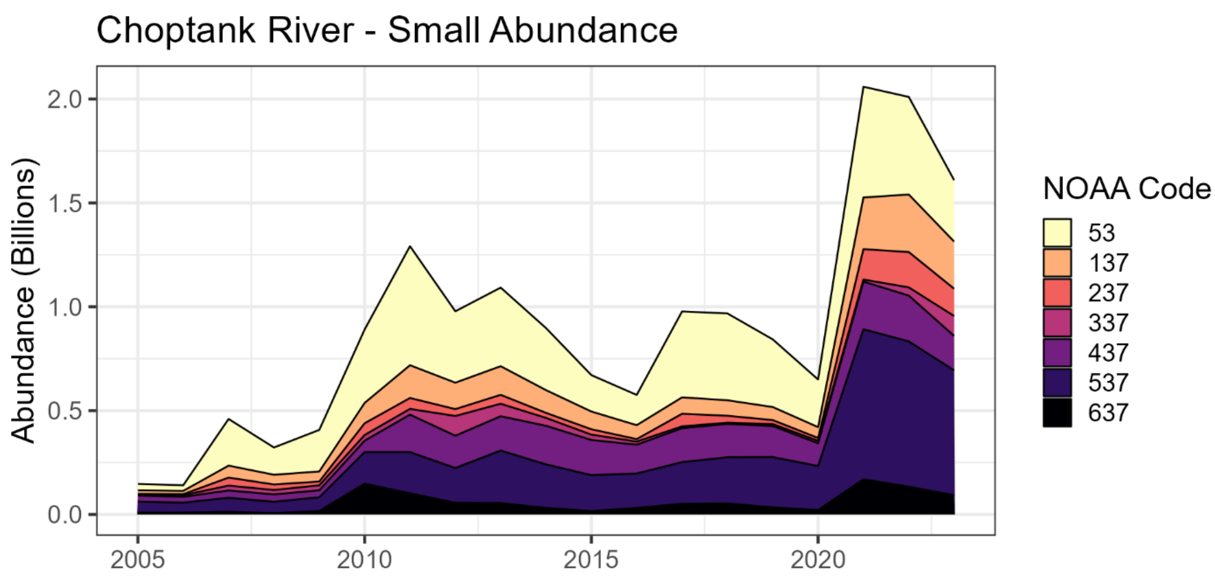

Figure 86. Estimated small oyster abundance among modeled NOAA codes in the Choptank River Region under Maryland management during 2005-2023.

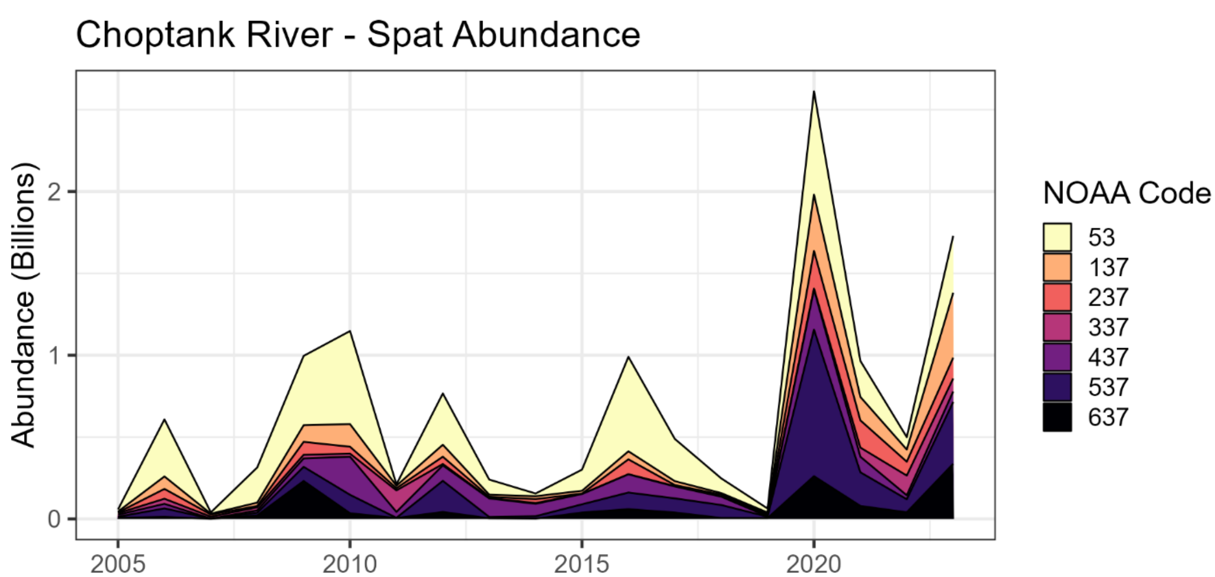

Figure 87. Estimated spat oyster abundance among modeled NOAA codes in the Choptank River Region under Maryland management during 2005-2023.

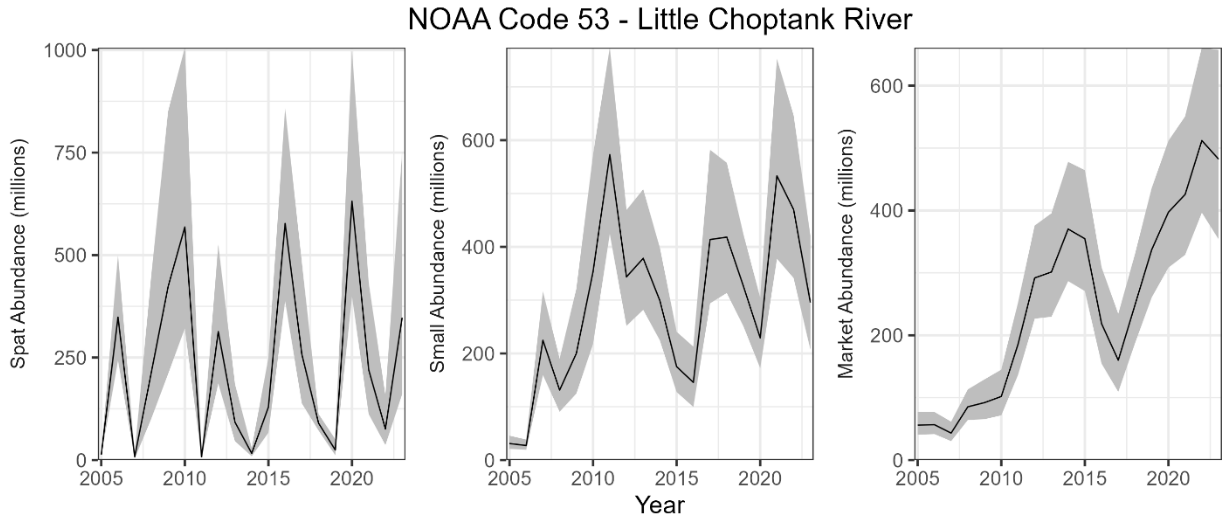

Figure 88. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Little Choptank River. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

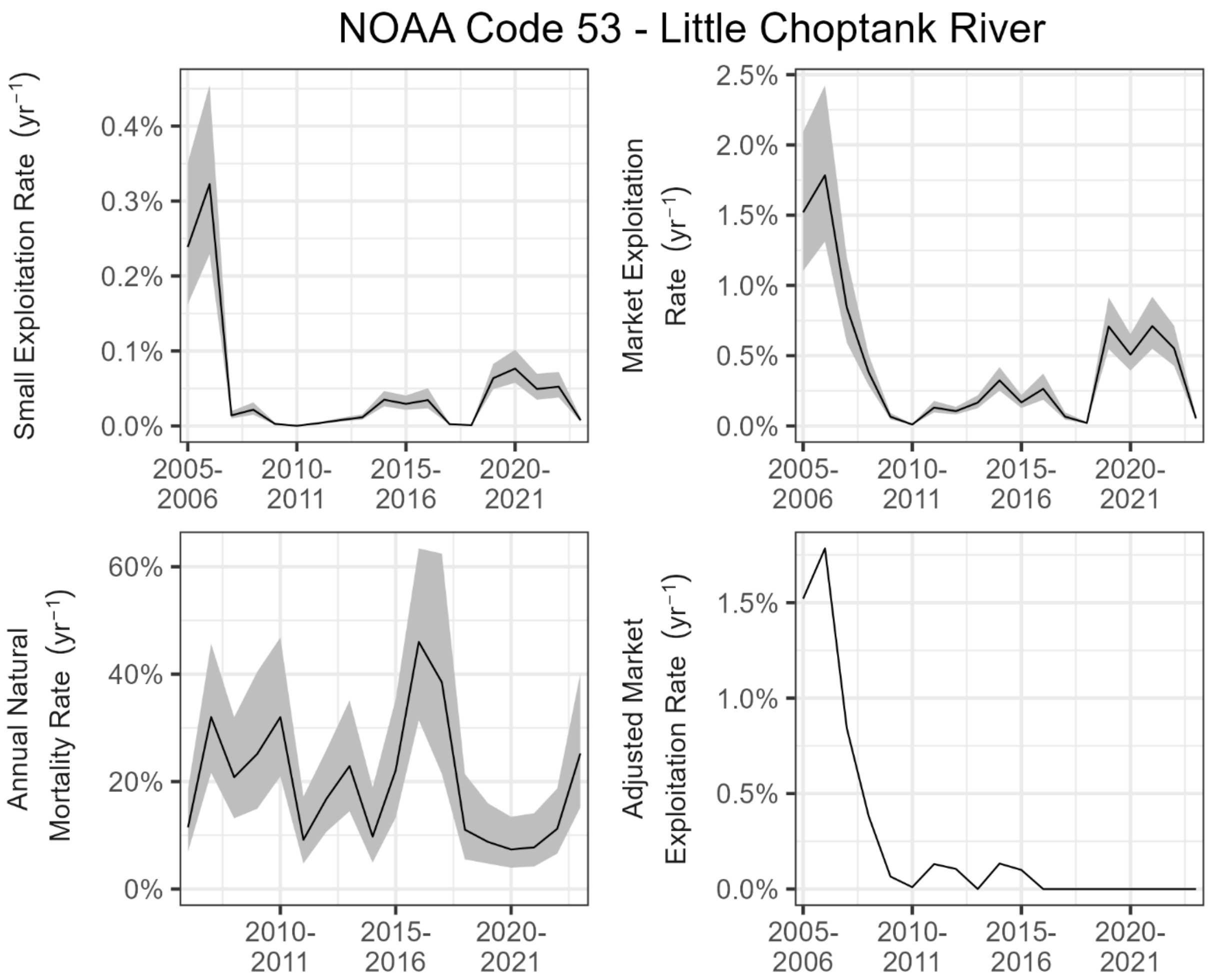

Figure 89. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Little Choptank River. The shaded areas indicate approximate 95% confidence intervals.

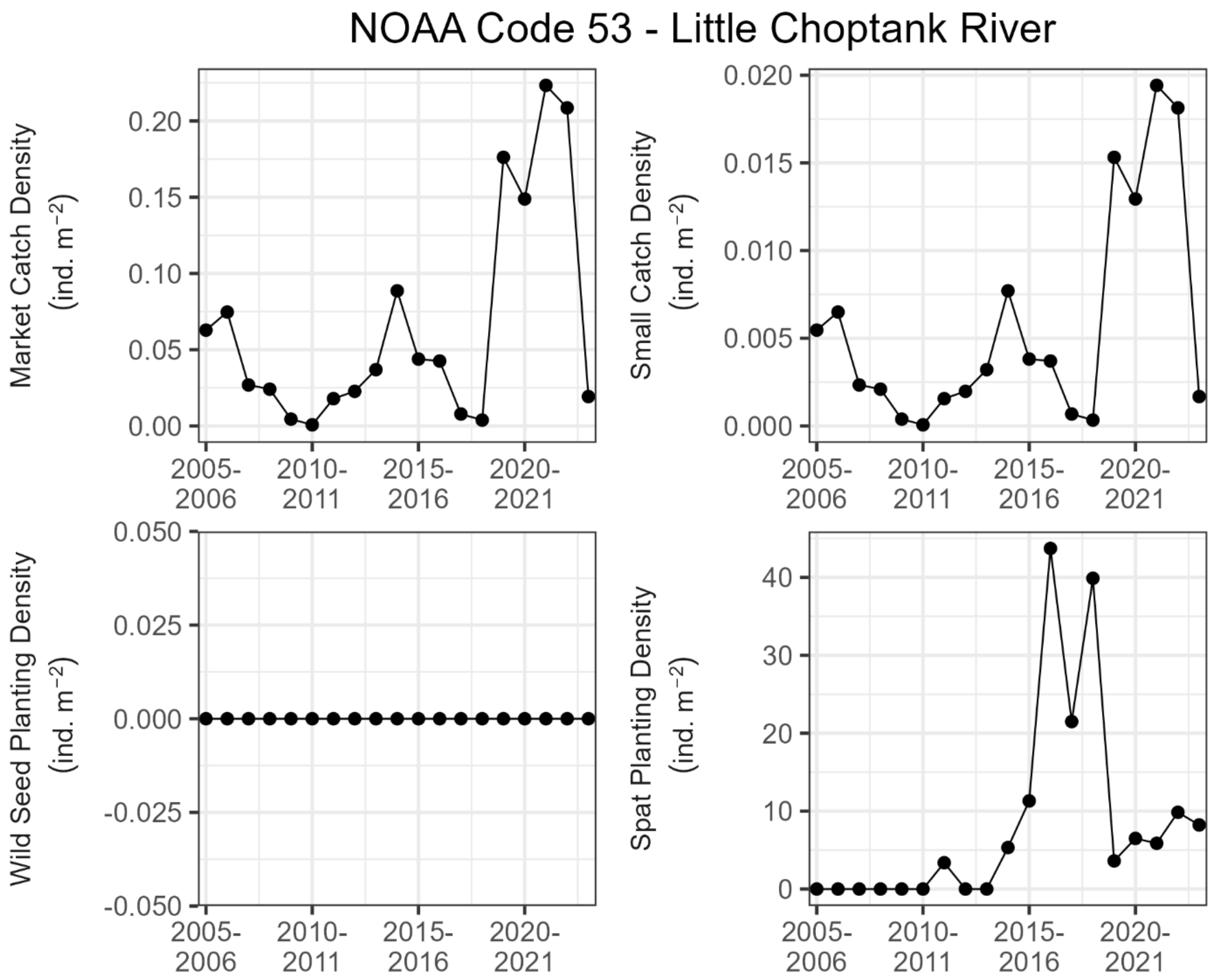

Figure 90. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Little Choptank River. Density was calculated as the number of individuals divided by habitat area for each data source.

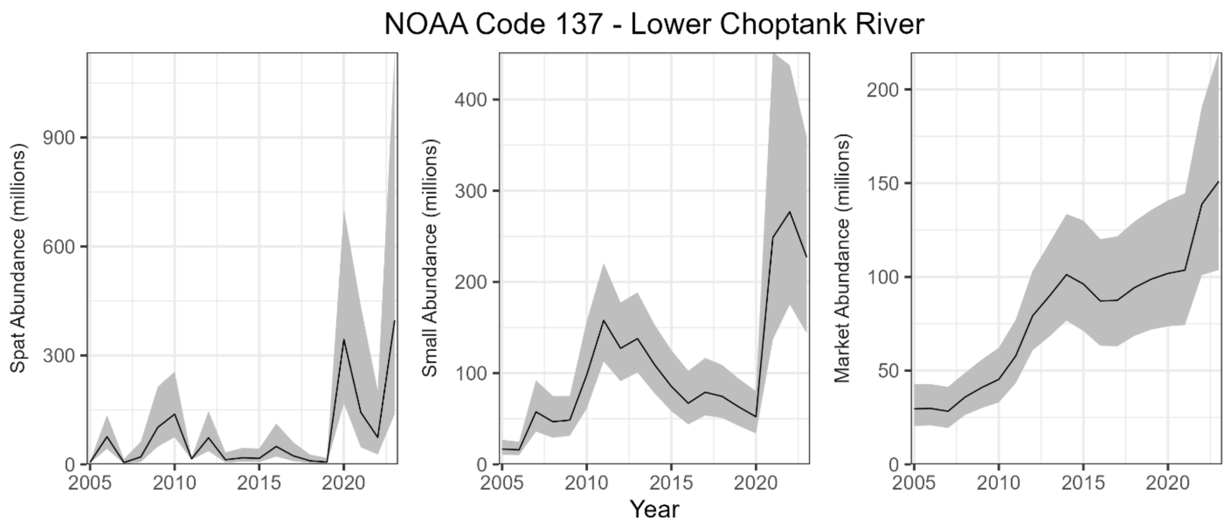

Figure 91. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Lower Choptank River. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

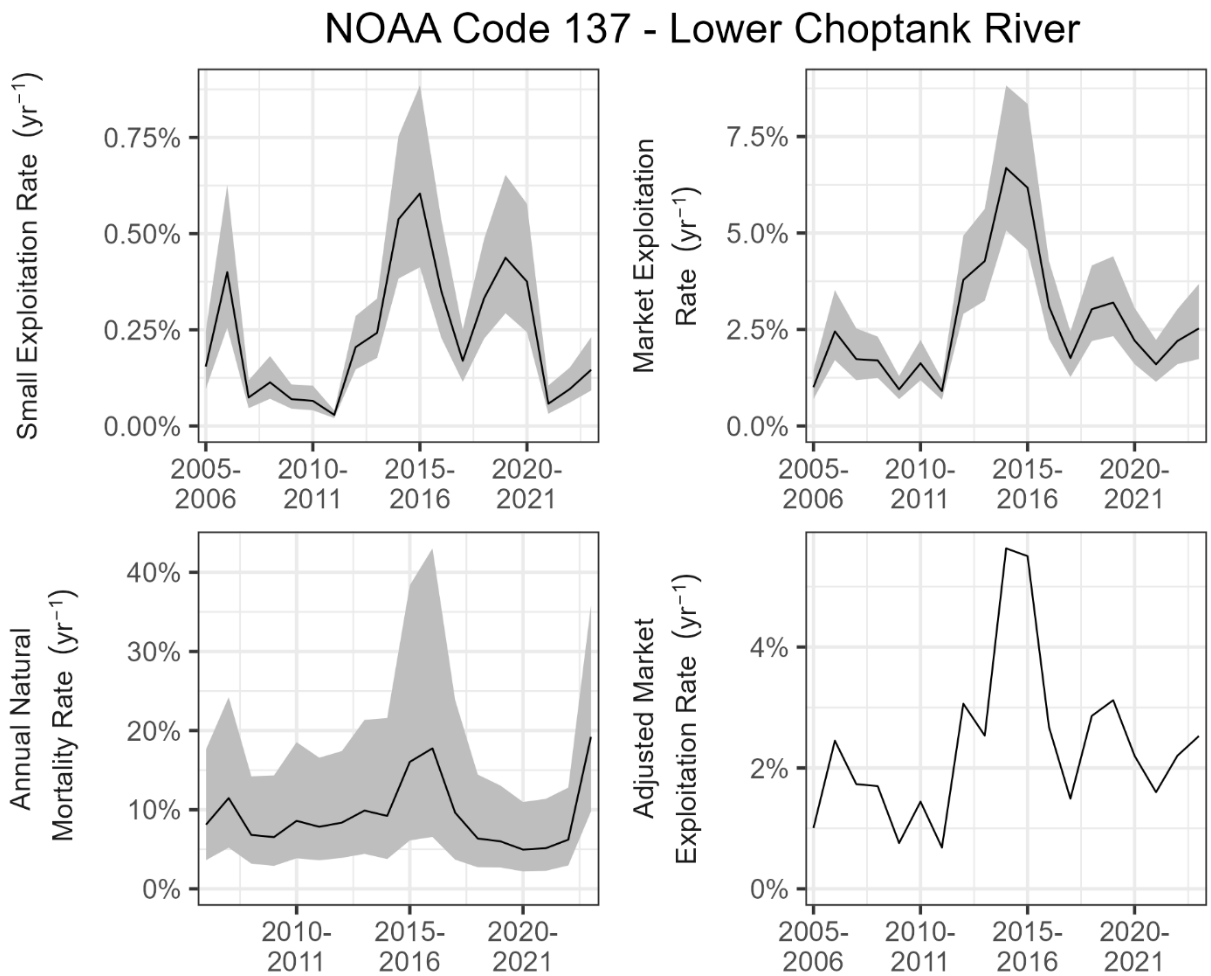

Figure 92. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Lower Choptank River. The shaded areas indicate approximate 95% confidence intervals.

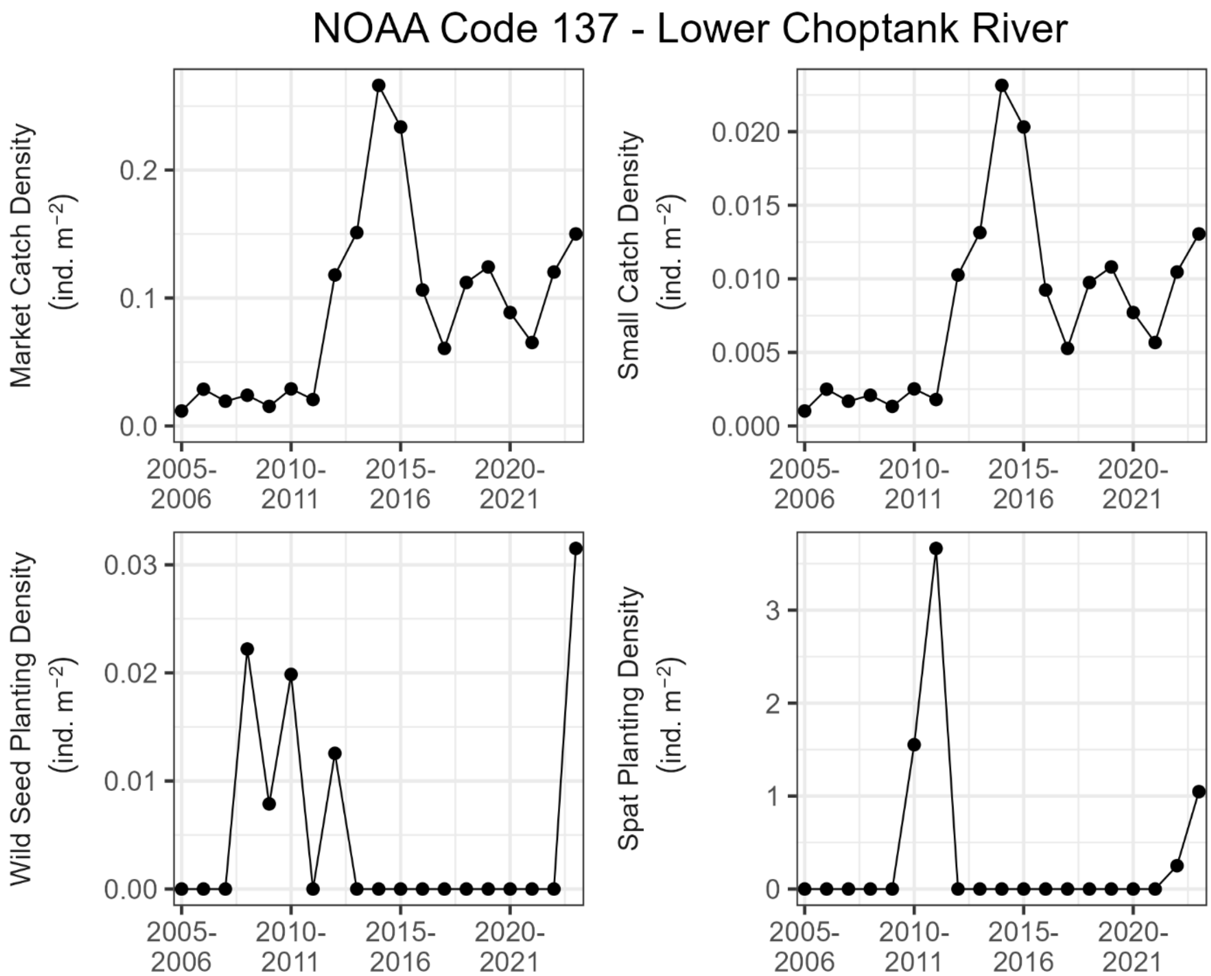

Figure 93. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Lower Choptank River. Density was calculated as the number of individuals divided by habitat area for each data source.

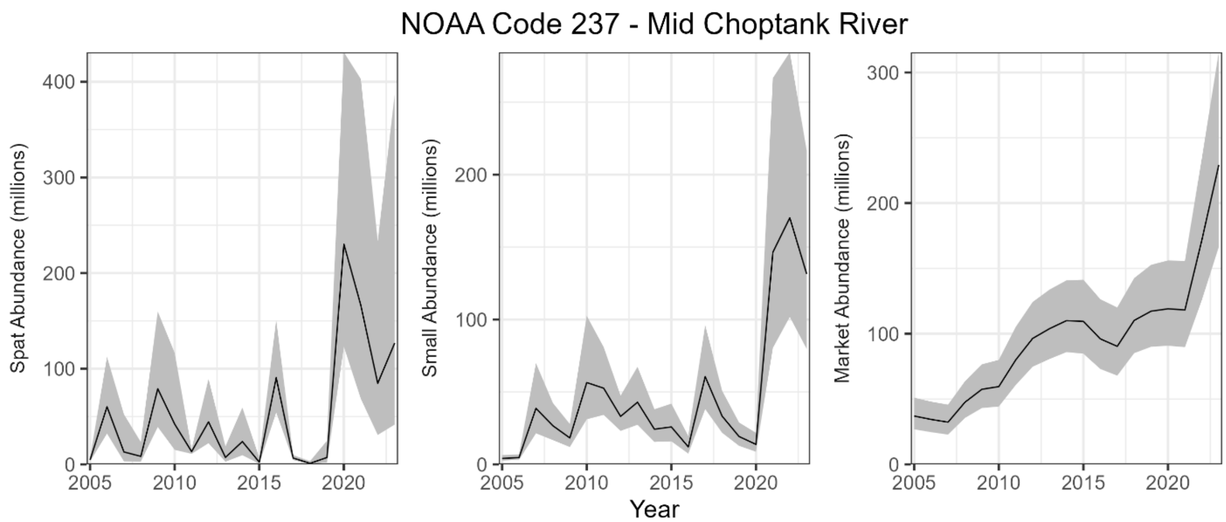

Figure 94. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Mid Choptank River. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

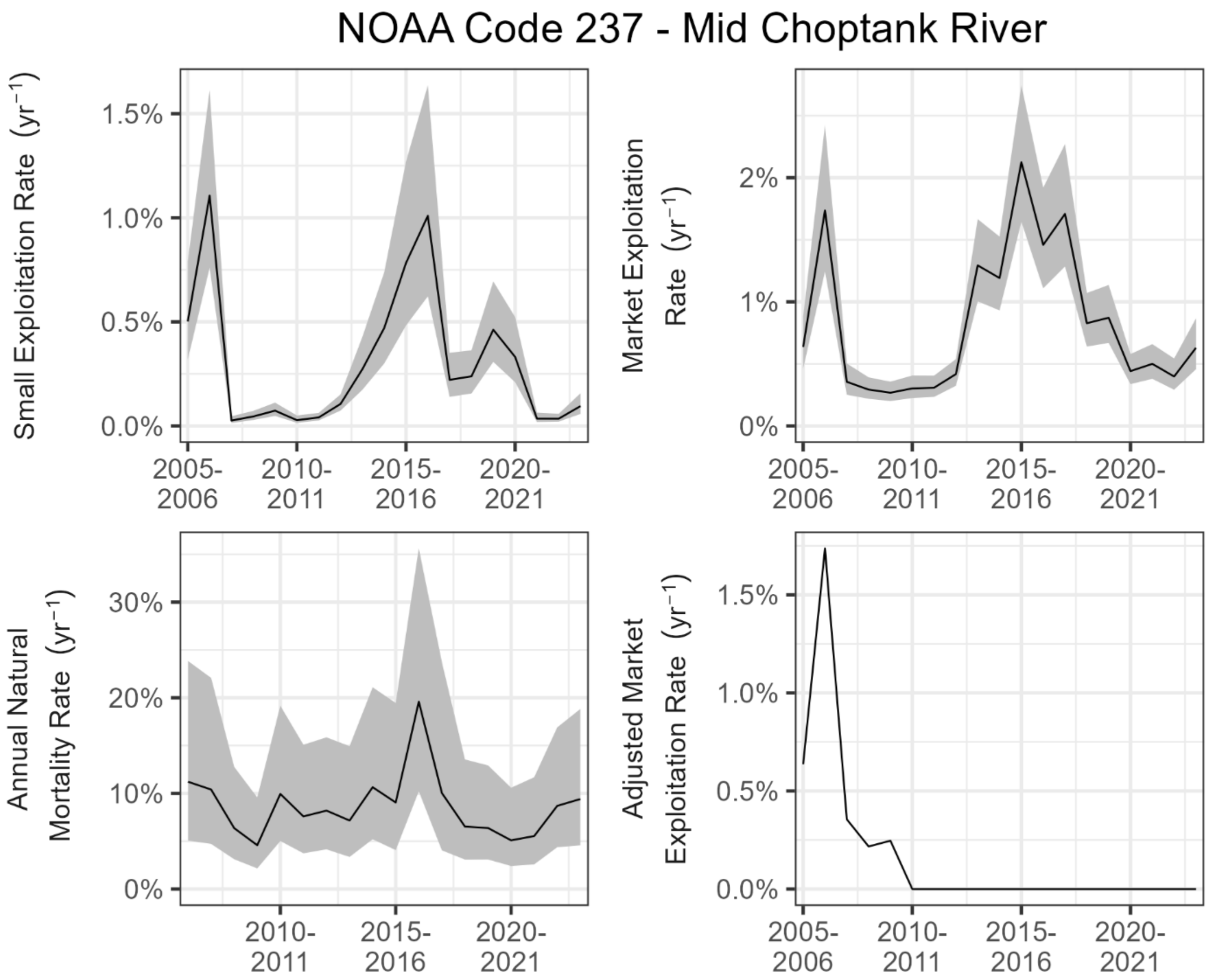

Figure 95. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Mid Choptank River. The shaded areas indicate approximate 95% confidence intervals.

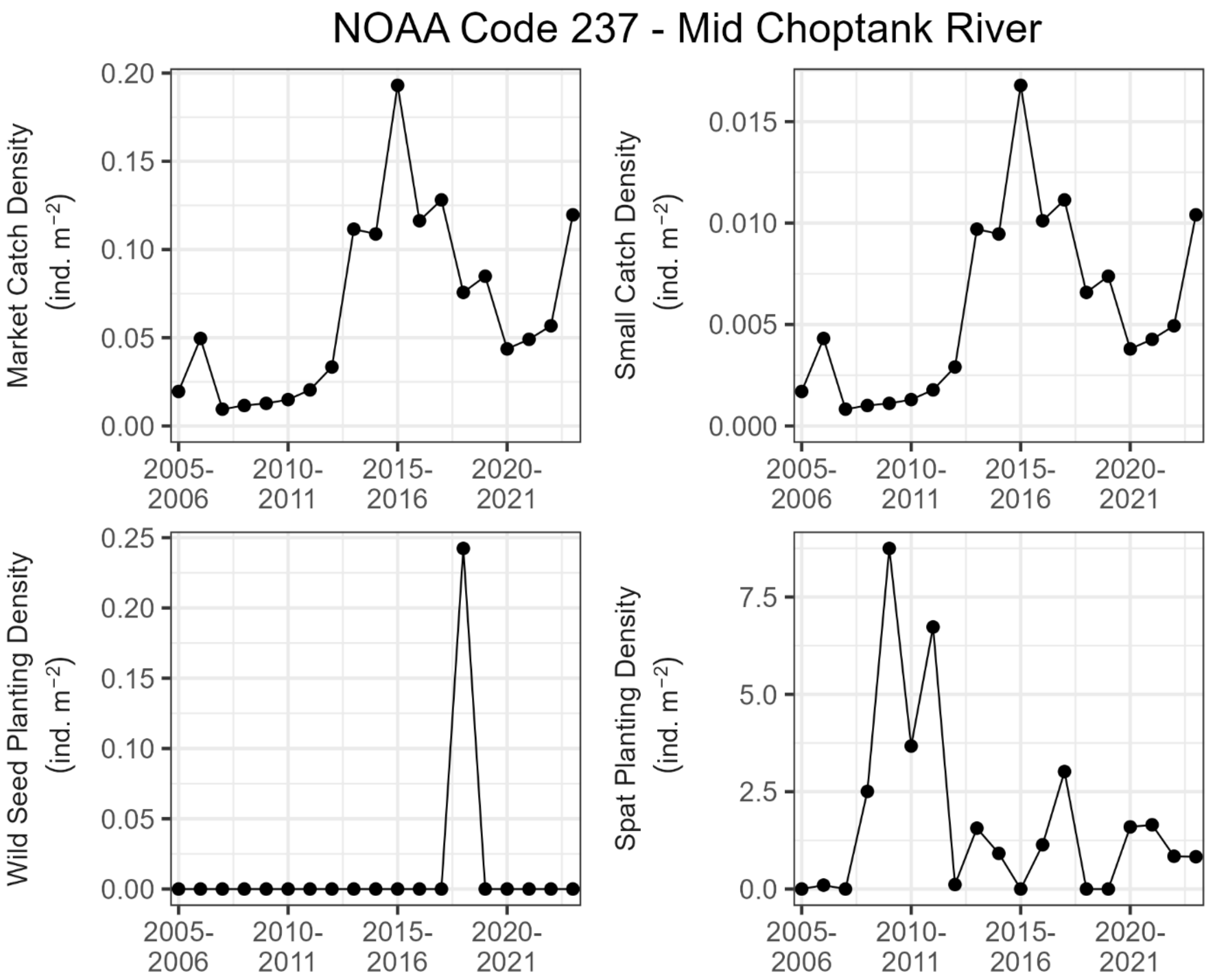

Figure 96. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Mid Choptank River. Density was calculated as the number of individuals divided by habitat area for each data source.

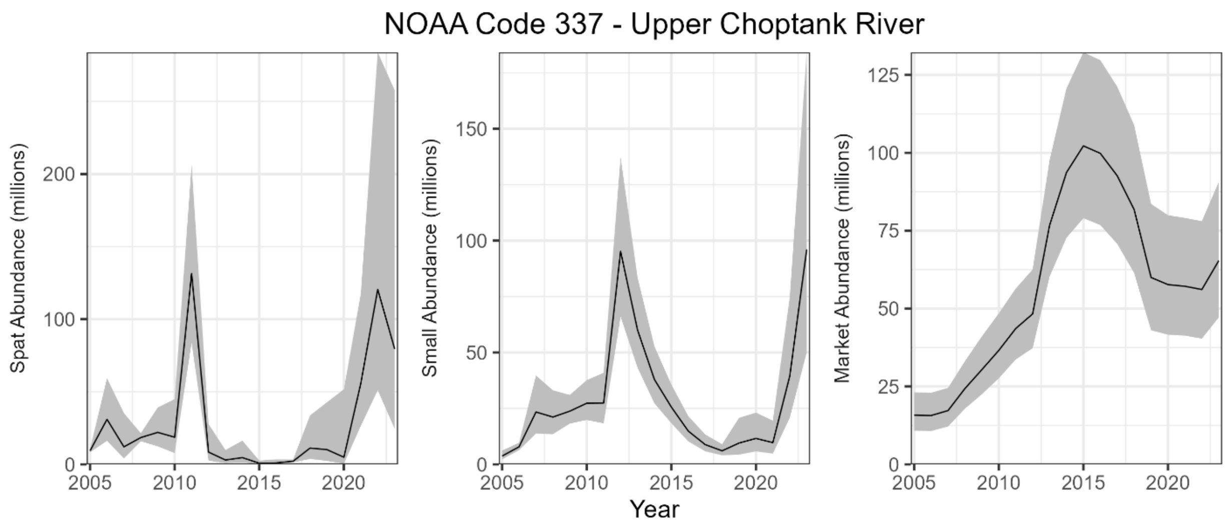

Figure 97. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Upper Choptank River. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

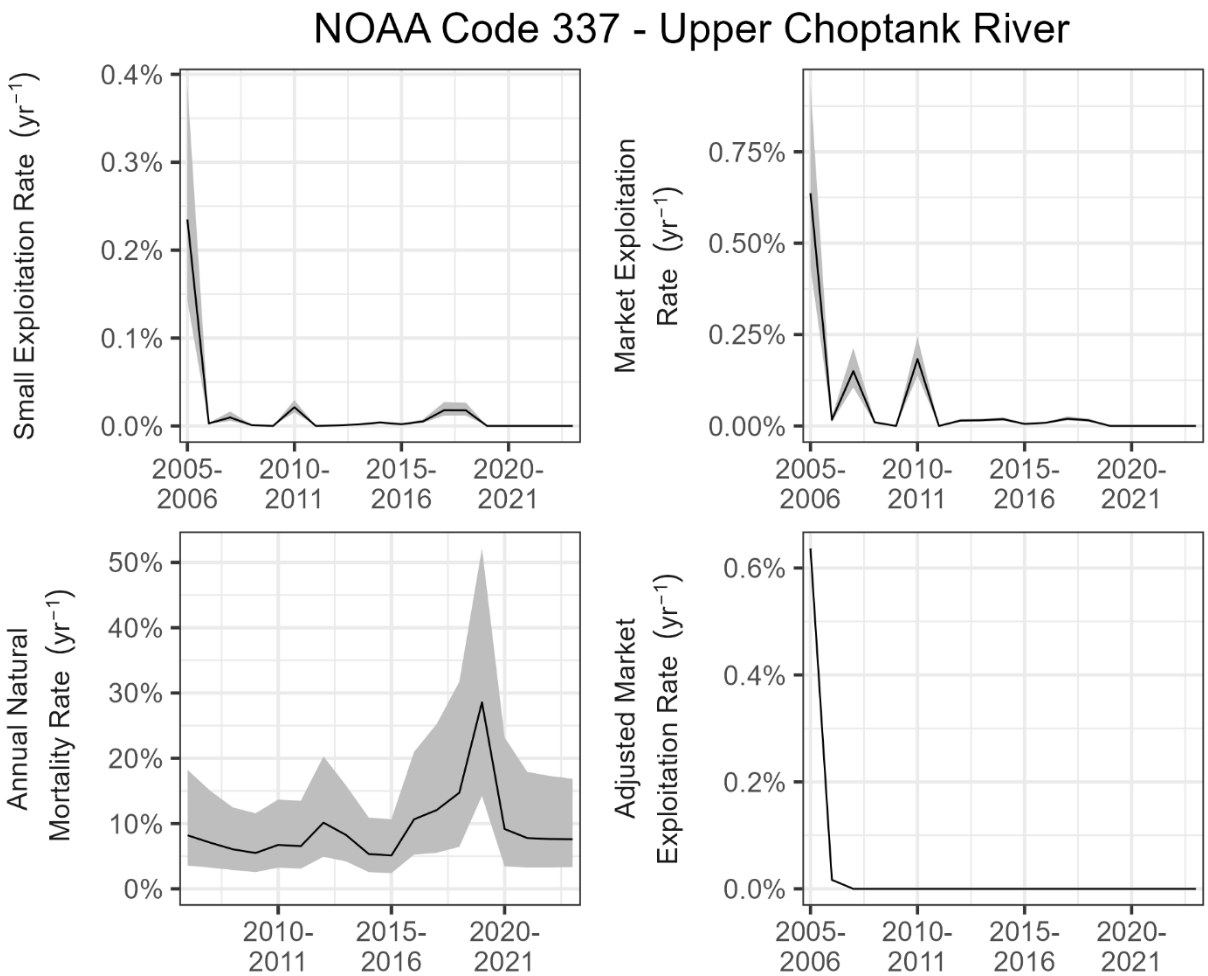

Figure 98. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Upper Choptank River. The shaded areas indicate approximate 95% confidence intervals.

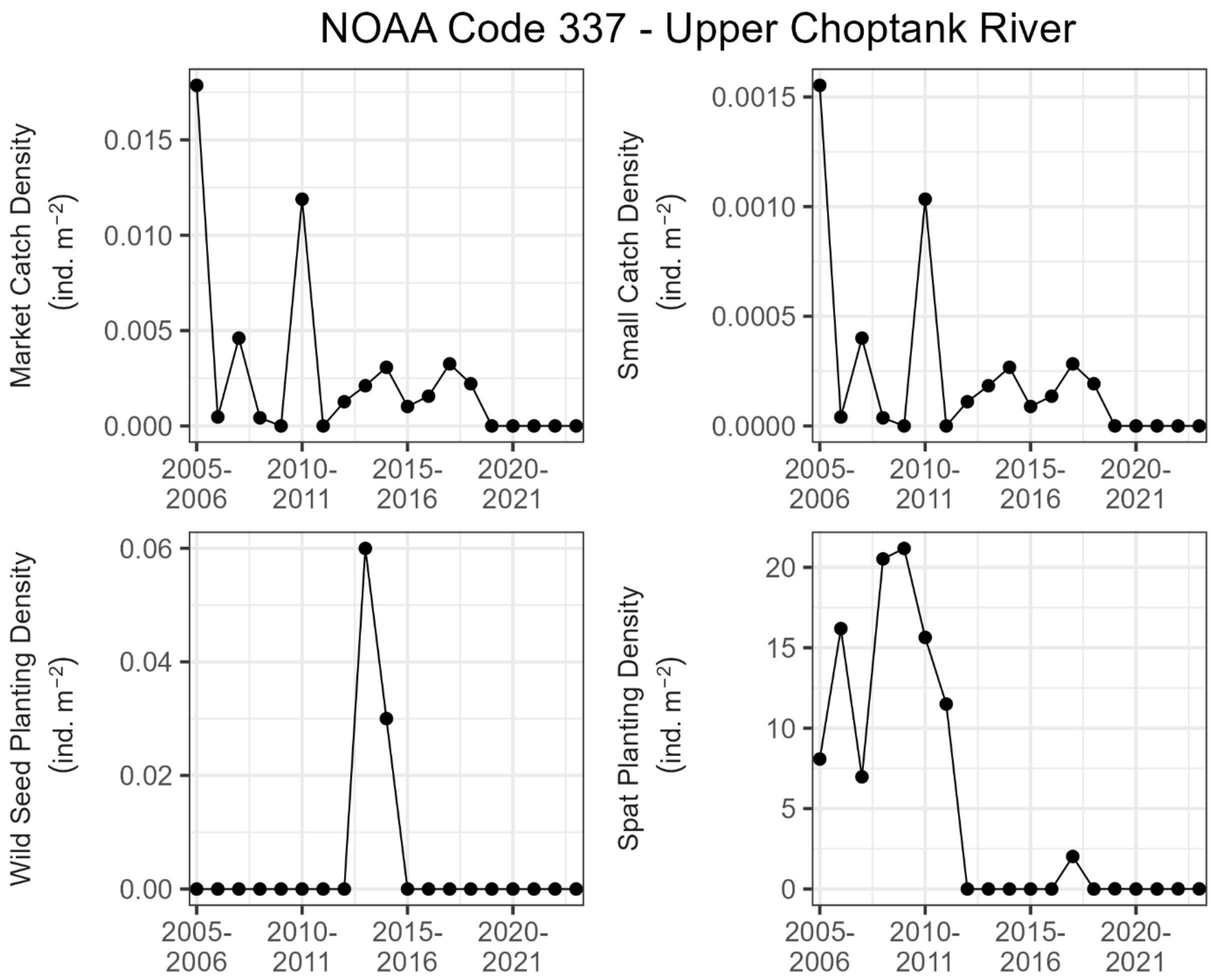

Figure 99. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Upper Choptank River. Density was calculated as the number of individuals divided by habitat area for each data source.

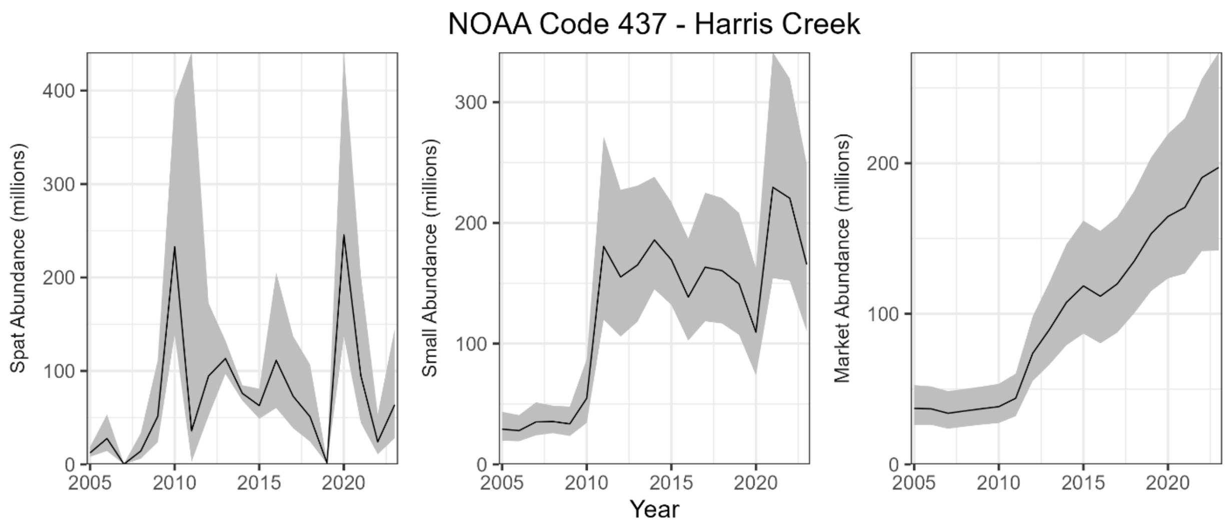

Figure 100. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Harris Creek. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

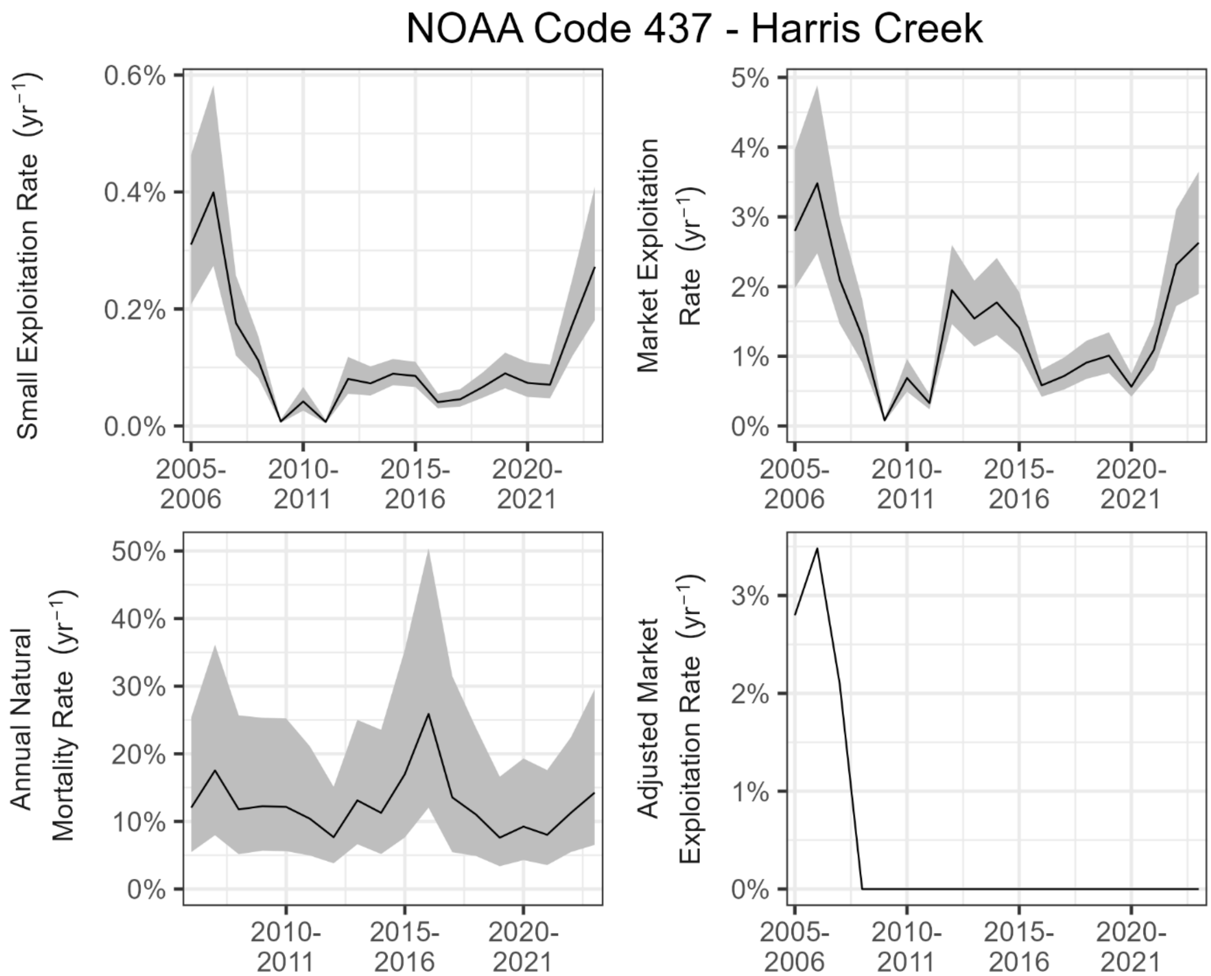

Figure 101. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Harris Creek. The shaded areas indicate approximate 95% confidence intervals.

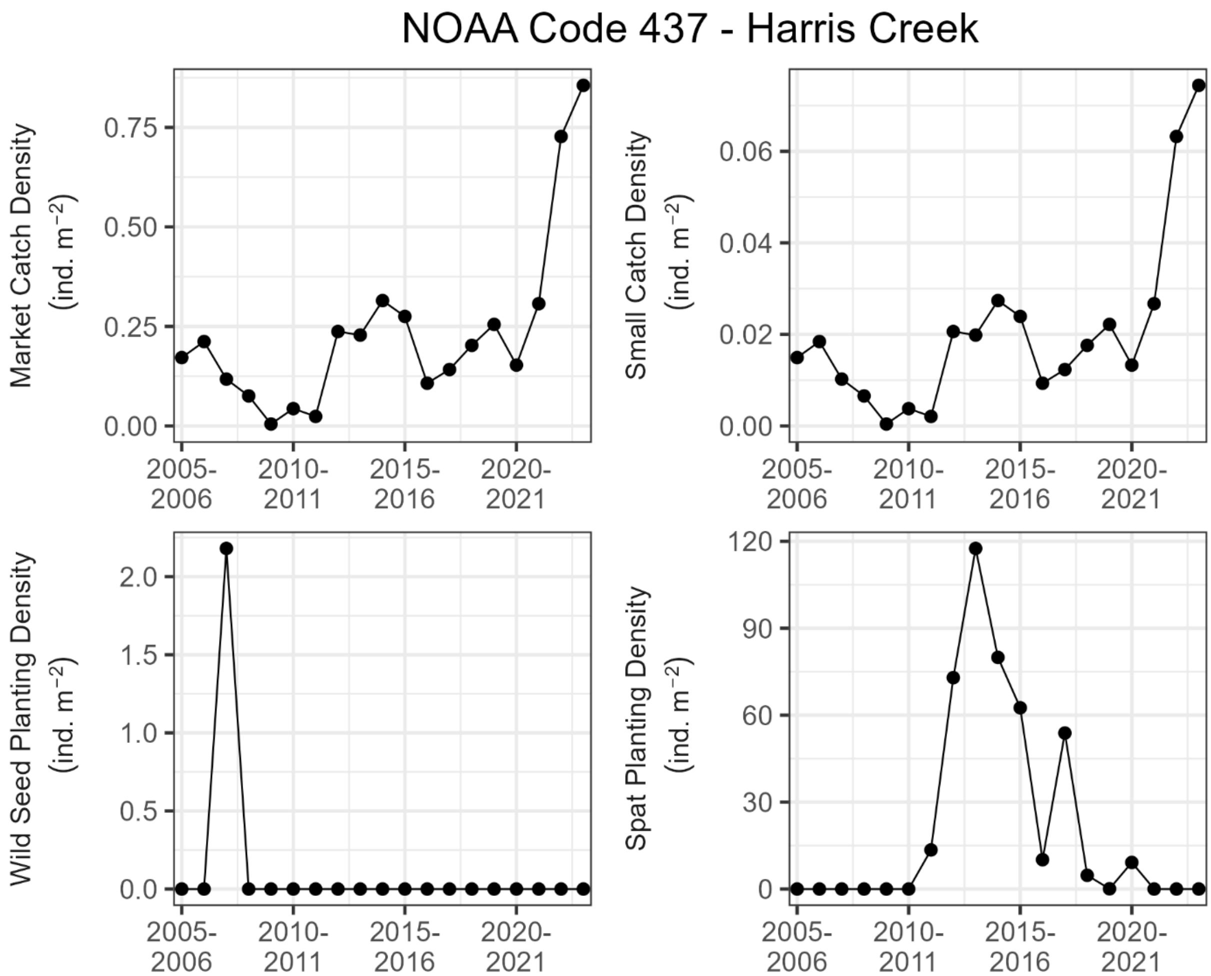

Figure 102. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Harris Creek. Density was calculated as the number of individuals divided by habitat area for each data source.

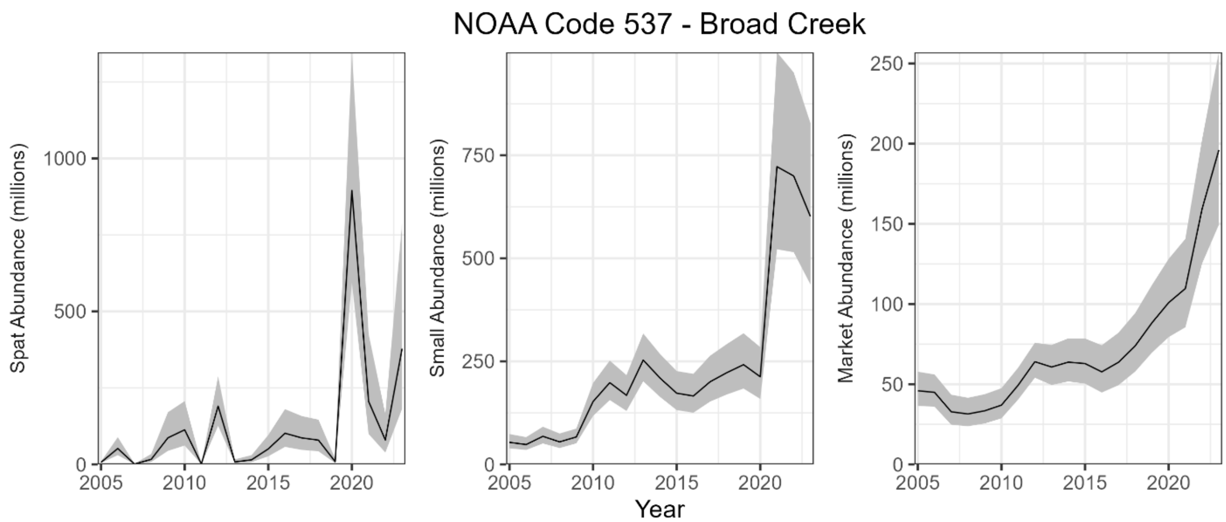

Figure 103. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Broad Creek. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

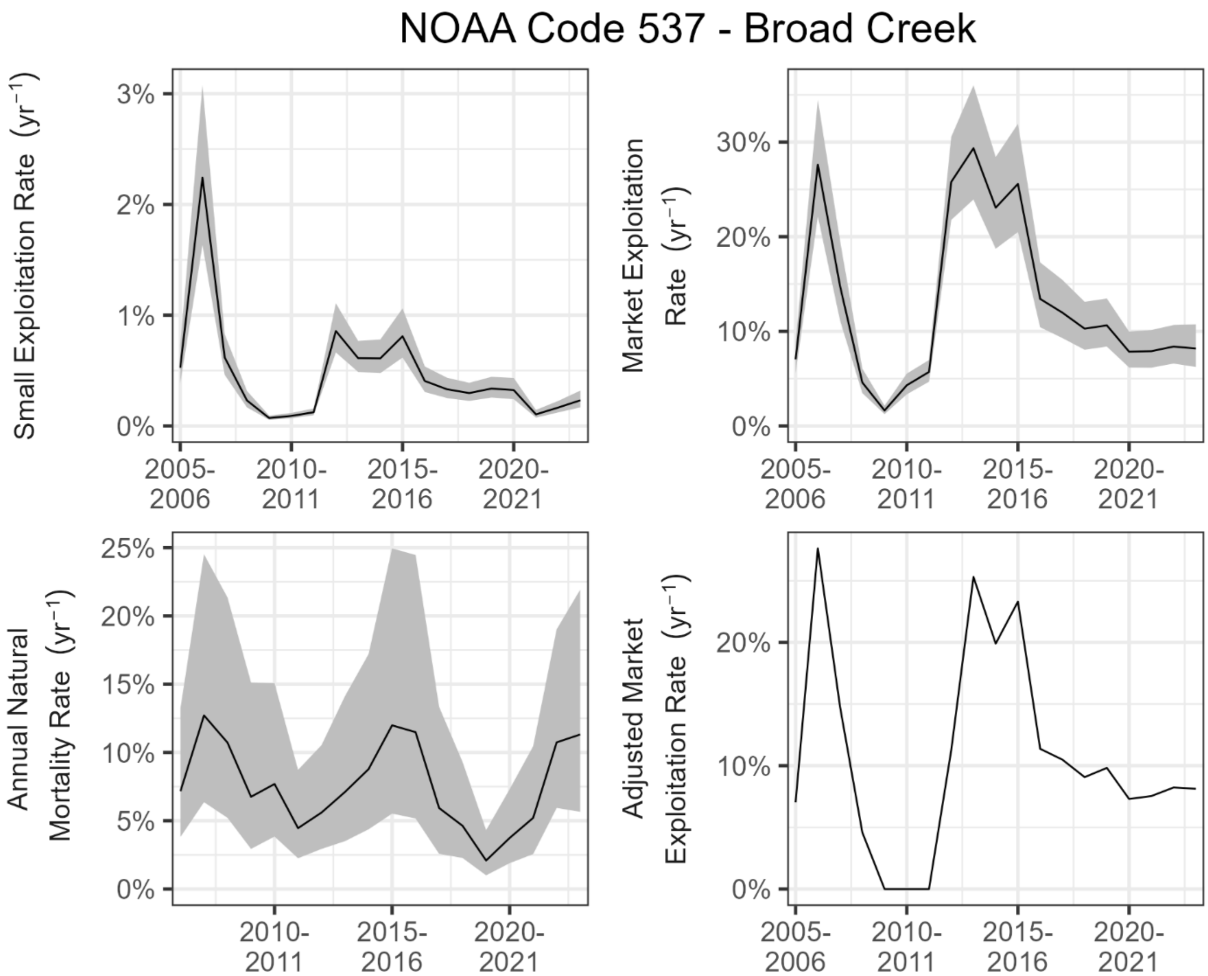

Figure 104. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Broad Creek. The shaded areas indicate approximate 95% confidence intervals.

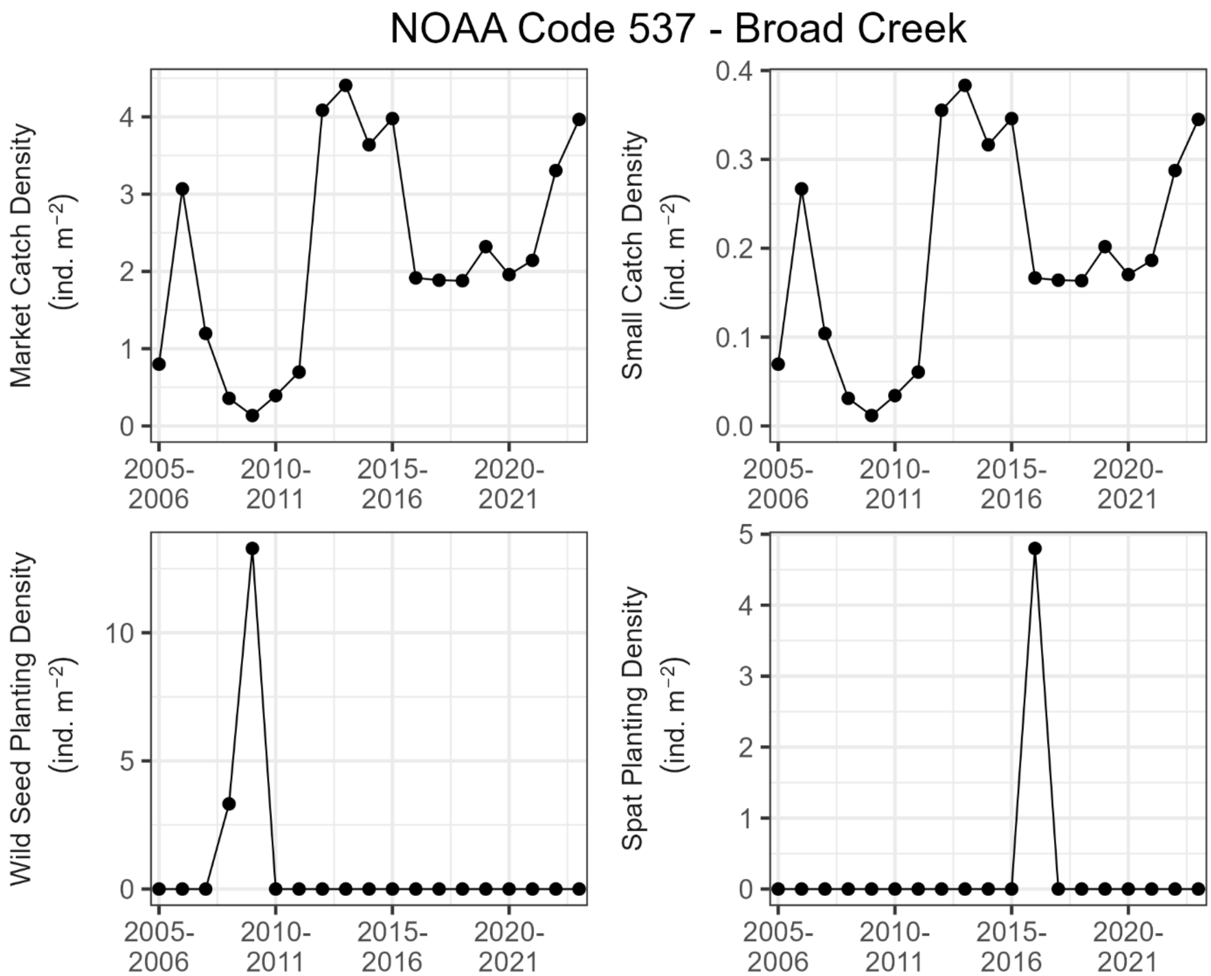

Figure 105. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Broad Creek. Density was calculated as the number of individuals divided by habitat area for each data source.

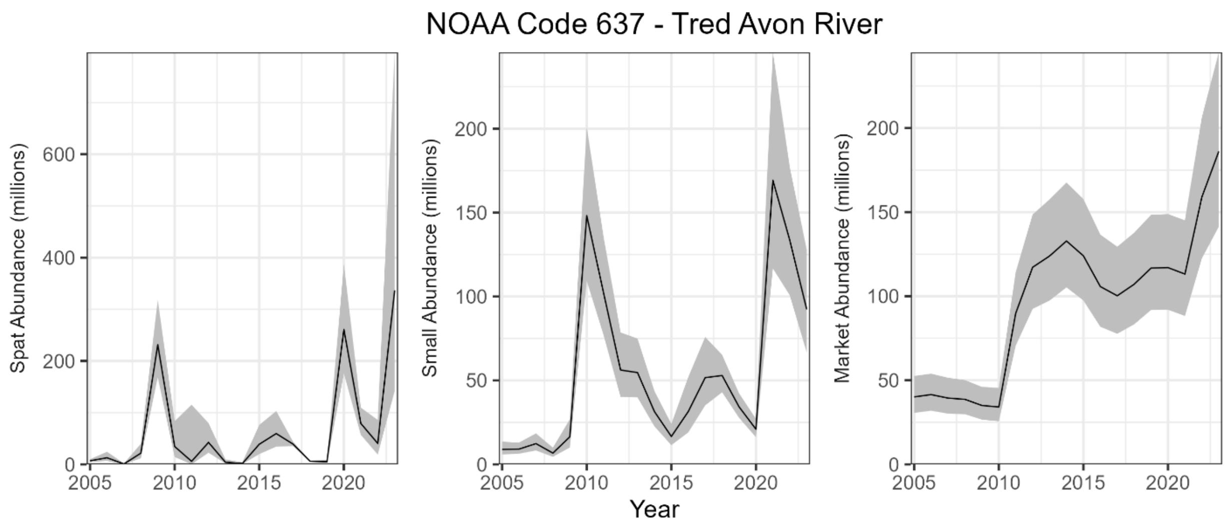

Figure 106. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Tred Avon River. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

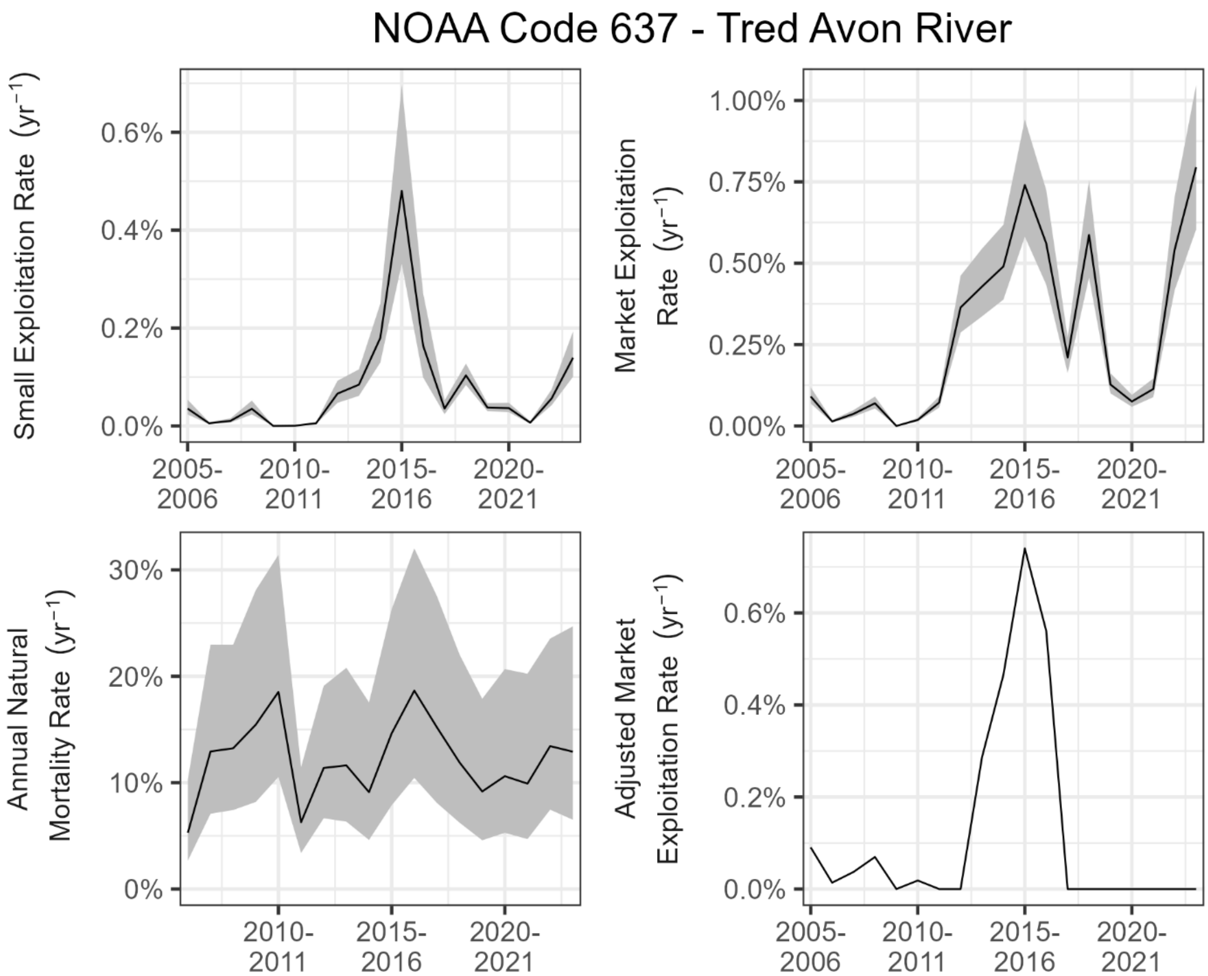

Figure 107. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Tred Avon River. The shaded areas indicate approximate 95% confidence intervals.

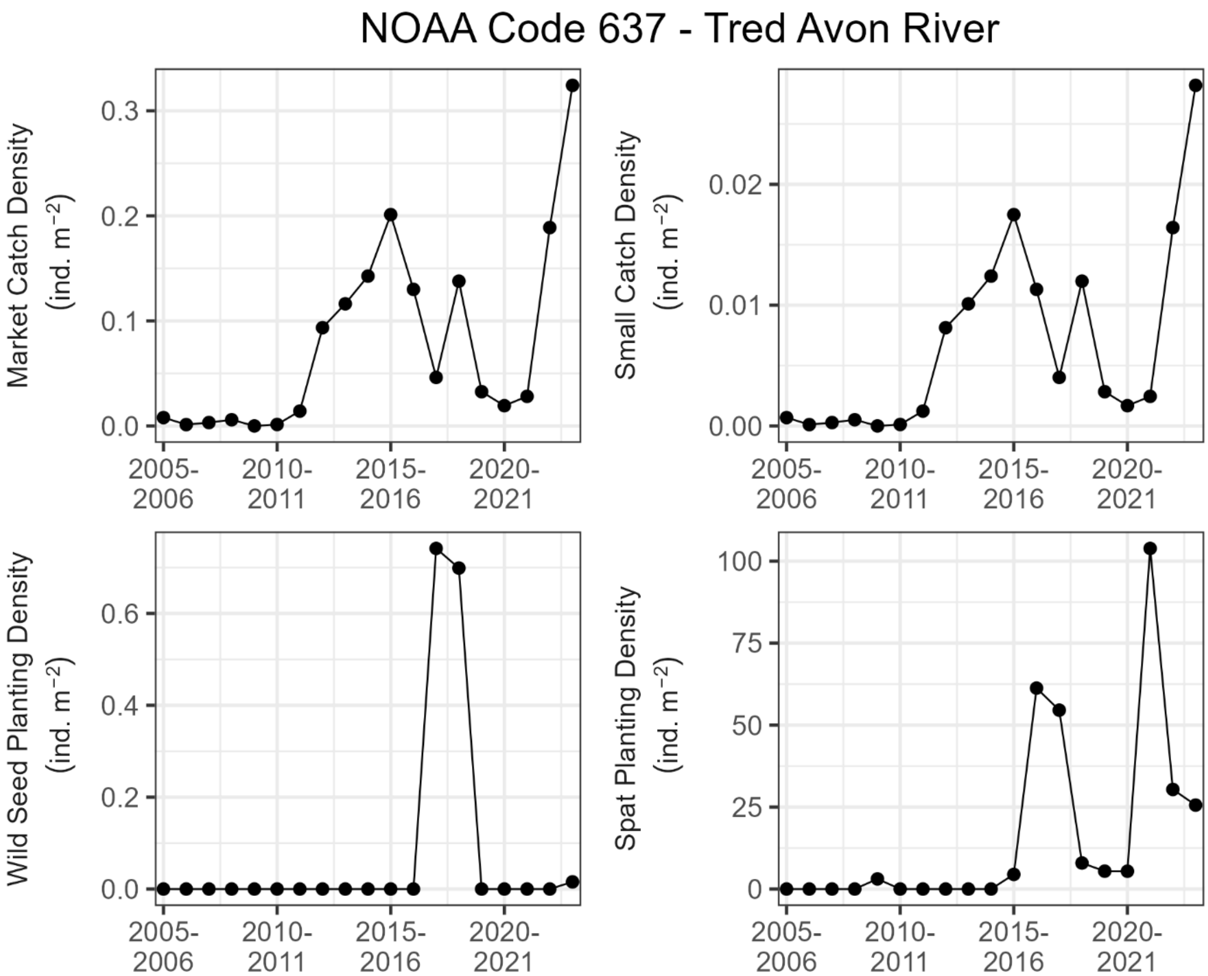

Figure 108. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Tred Avon River. Density was calculated as the number of individuals divided by habitat area for each data source.

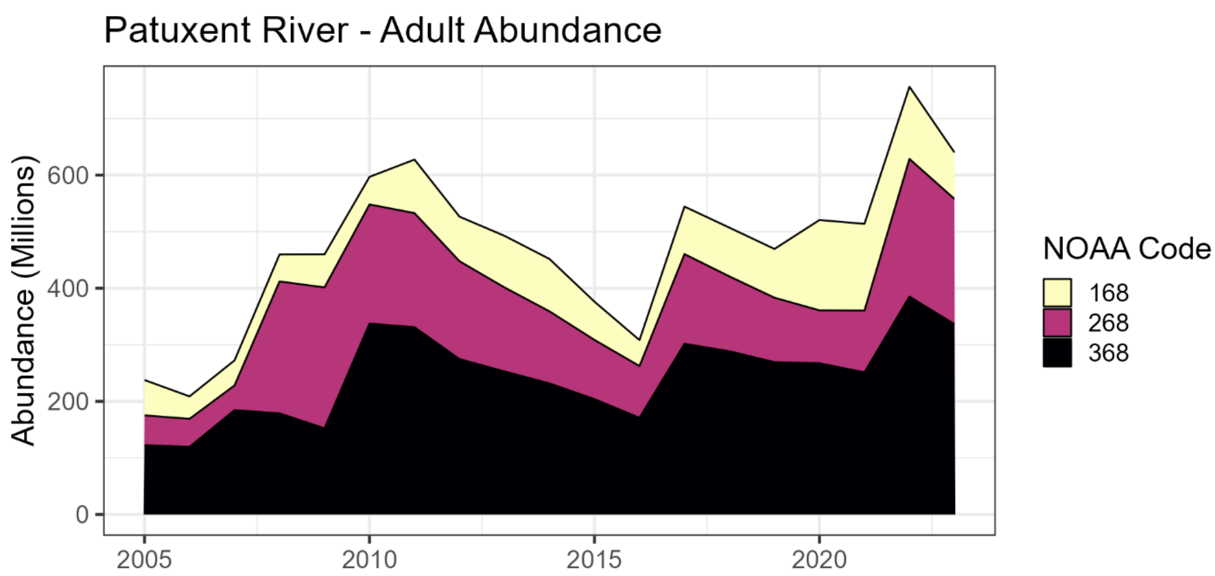

Figure 109. Estimated adult oyster abundance among modeled NOAA codes in the Patuxent River Region under Maryland management during 2005-2023.

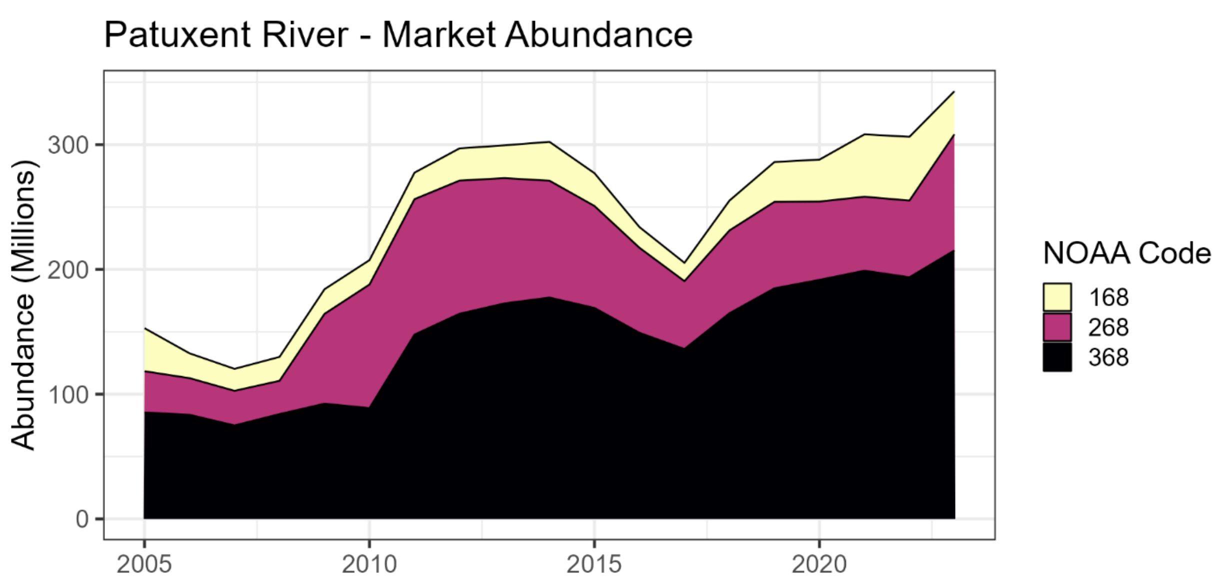

Figure 110. Estimated market oyster abundance among modeled NOAA codes in the Patuxent River Region under Maryland management during 2005-2023.

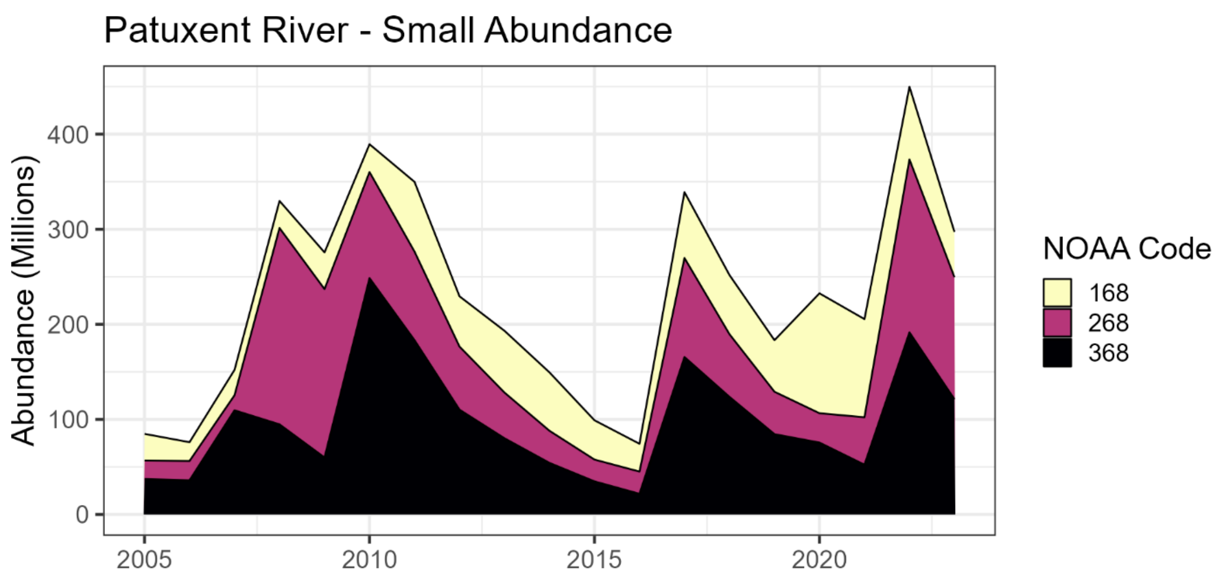

Figure 111. Estimated small oyster abundance among modeled NOAA codes in the Patuxent River Region under Maryland management during 2005-2023.

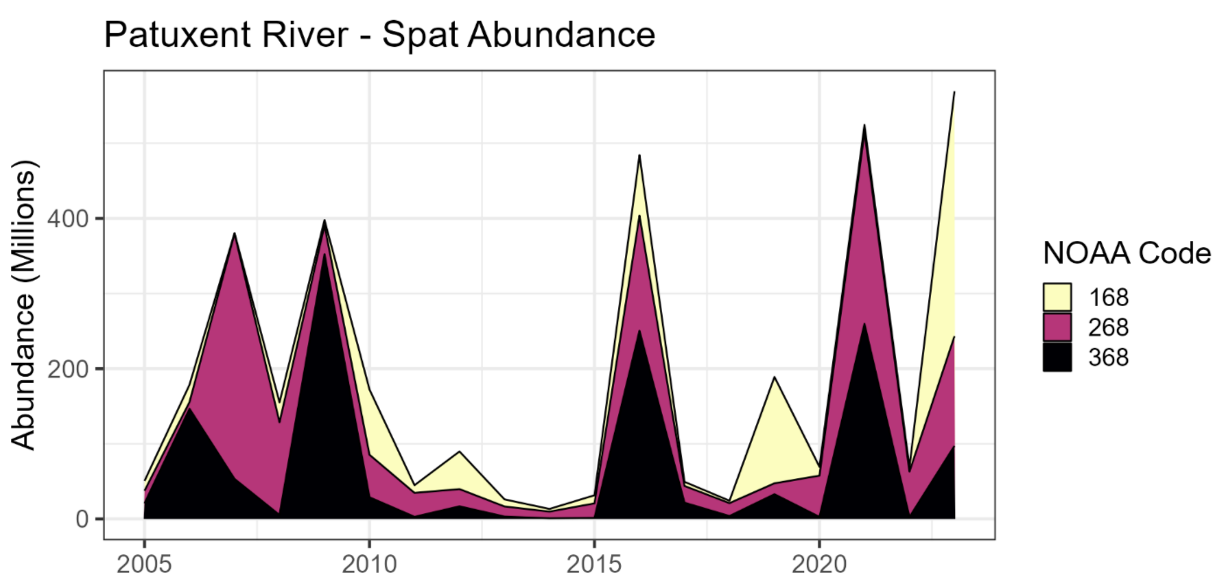

Figure 112. Estimated spat oyster abundance among modeled NOAA codes in the Patuxent River Region under Maryland management during 2005-2023.

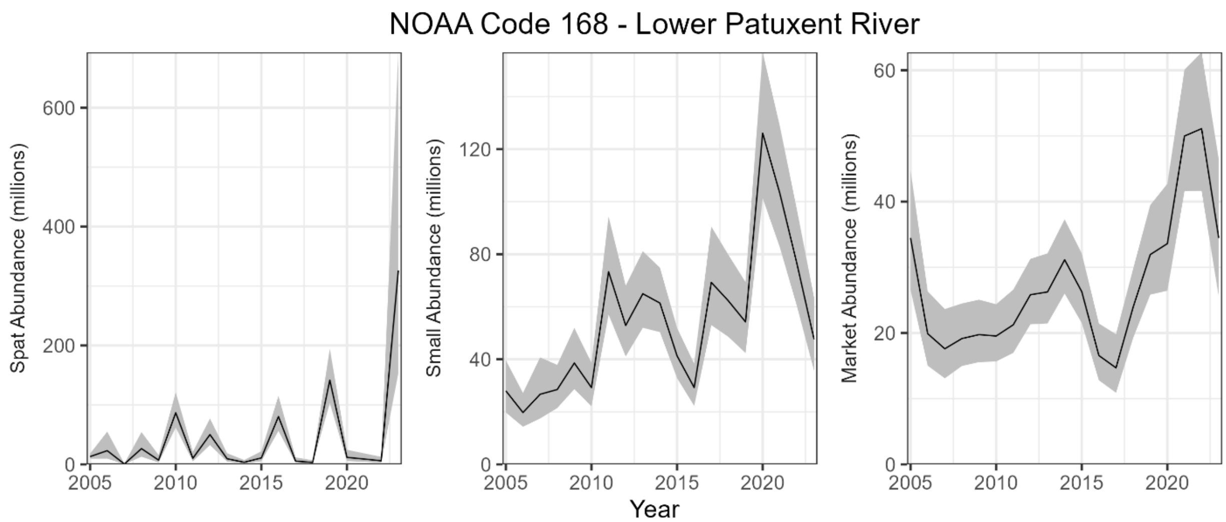

Figure 113. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Lower Patuxent River. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

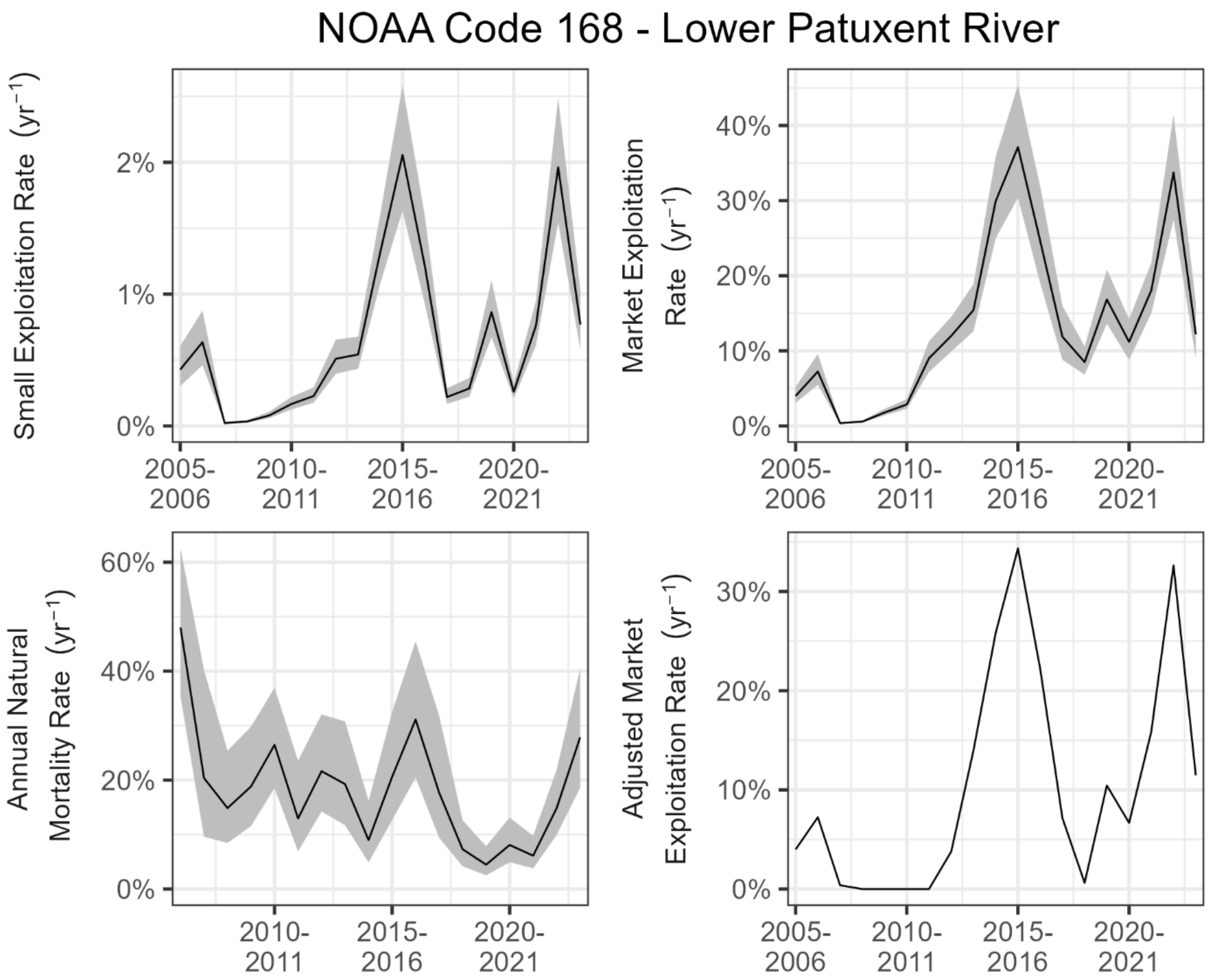

Figure 114. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Lower Patuxent River. The shaded areas indicate approximate 95% confidence intervals.

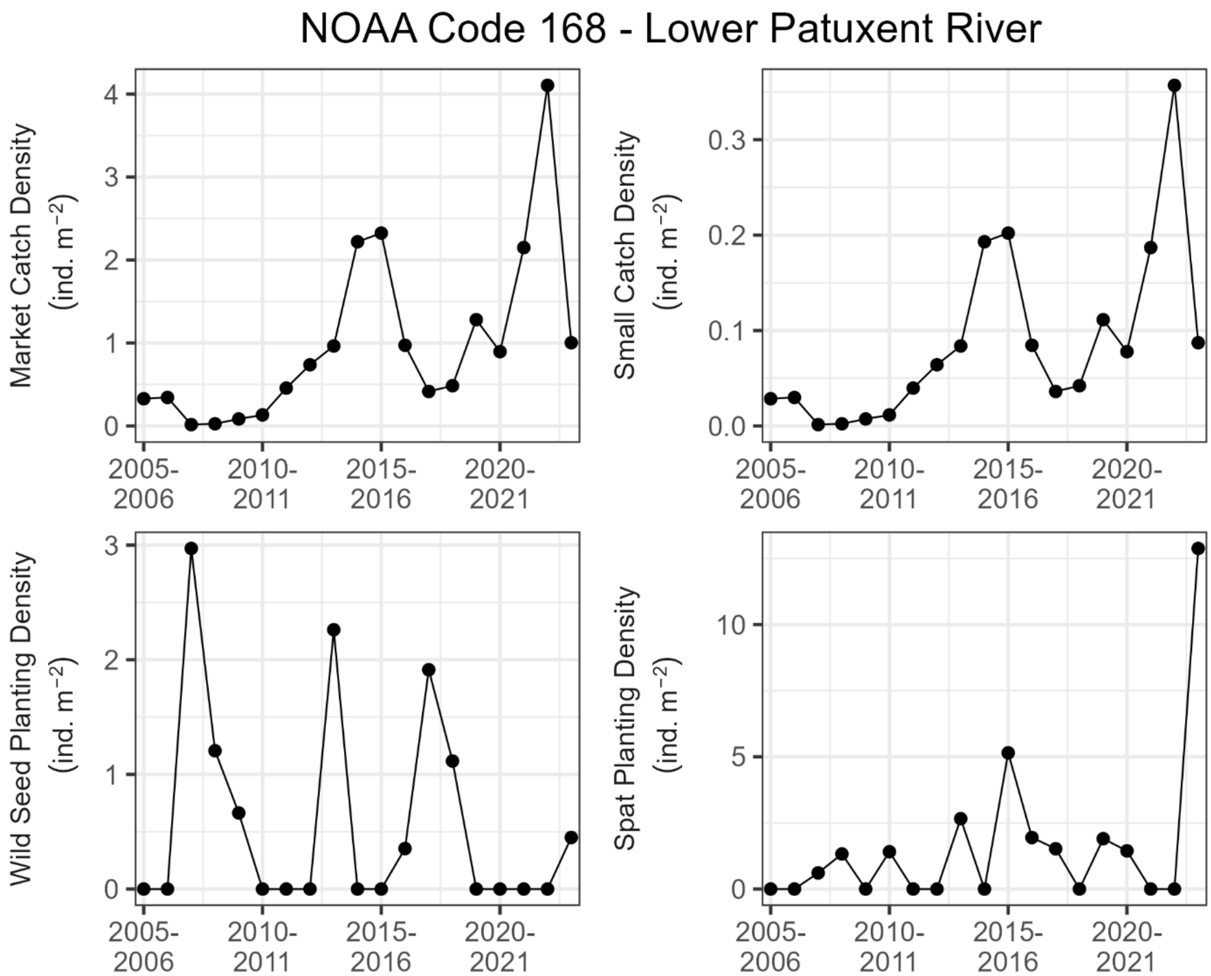

Figure 115. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Lower Patuxent River. Density was calculated as the number of individuals divided by habitat area for each data source.

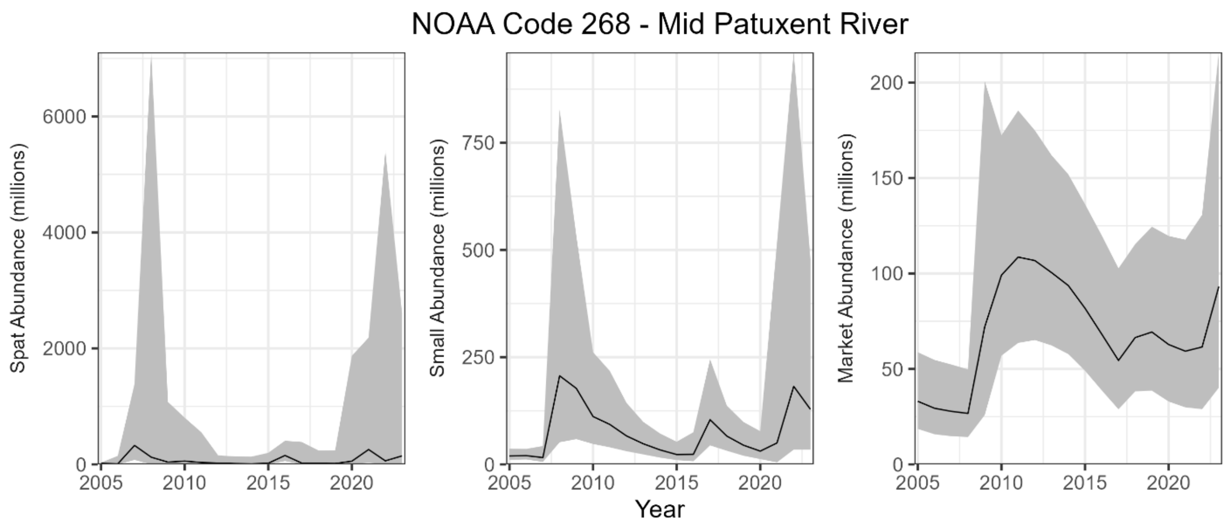

Figure 116. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Mid Patuxent River. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

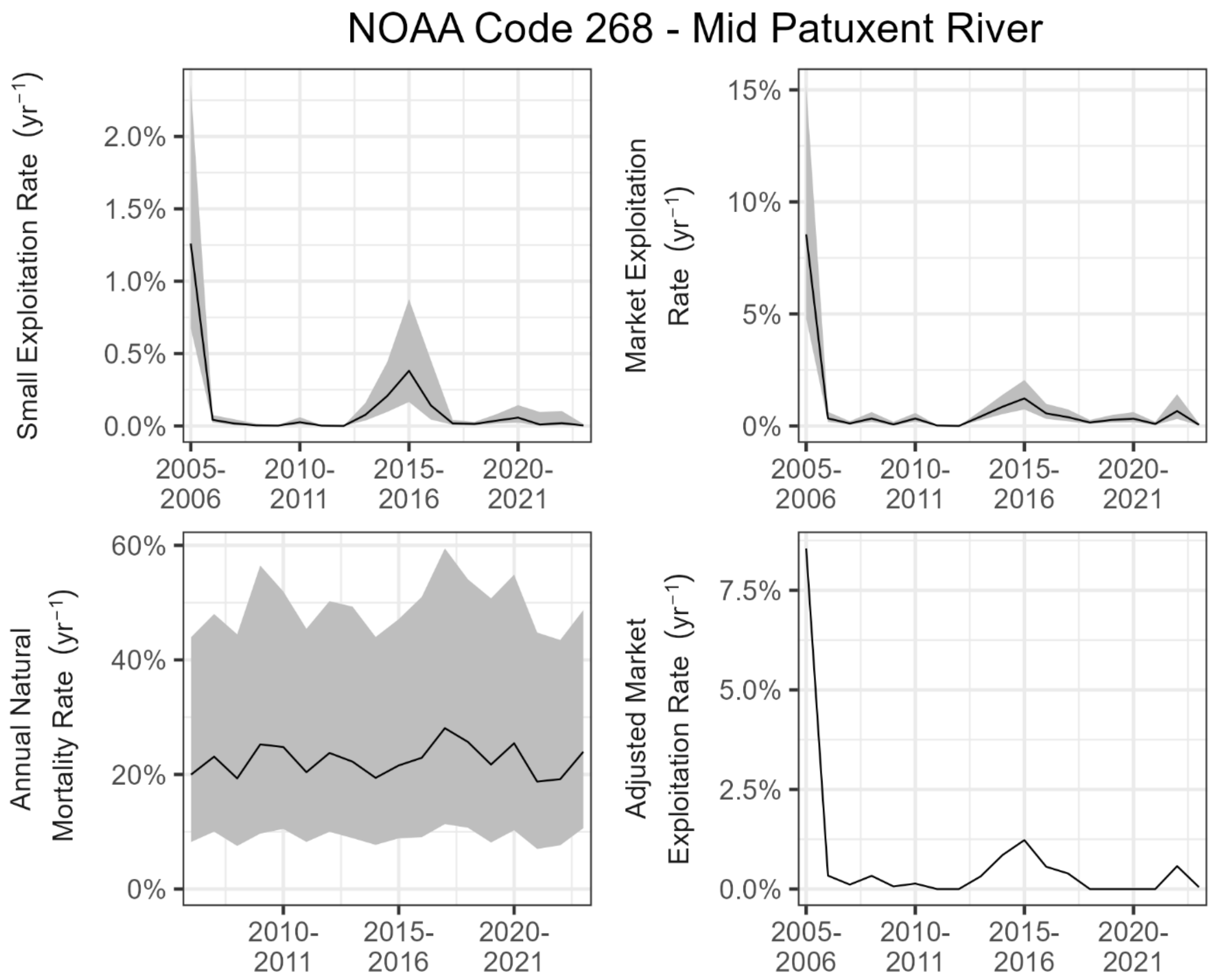

Figure 117. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Mid Patuxent River. The shaded areas indicate approximate 95% confidence intervals.

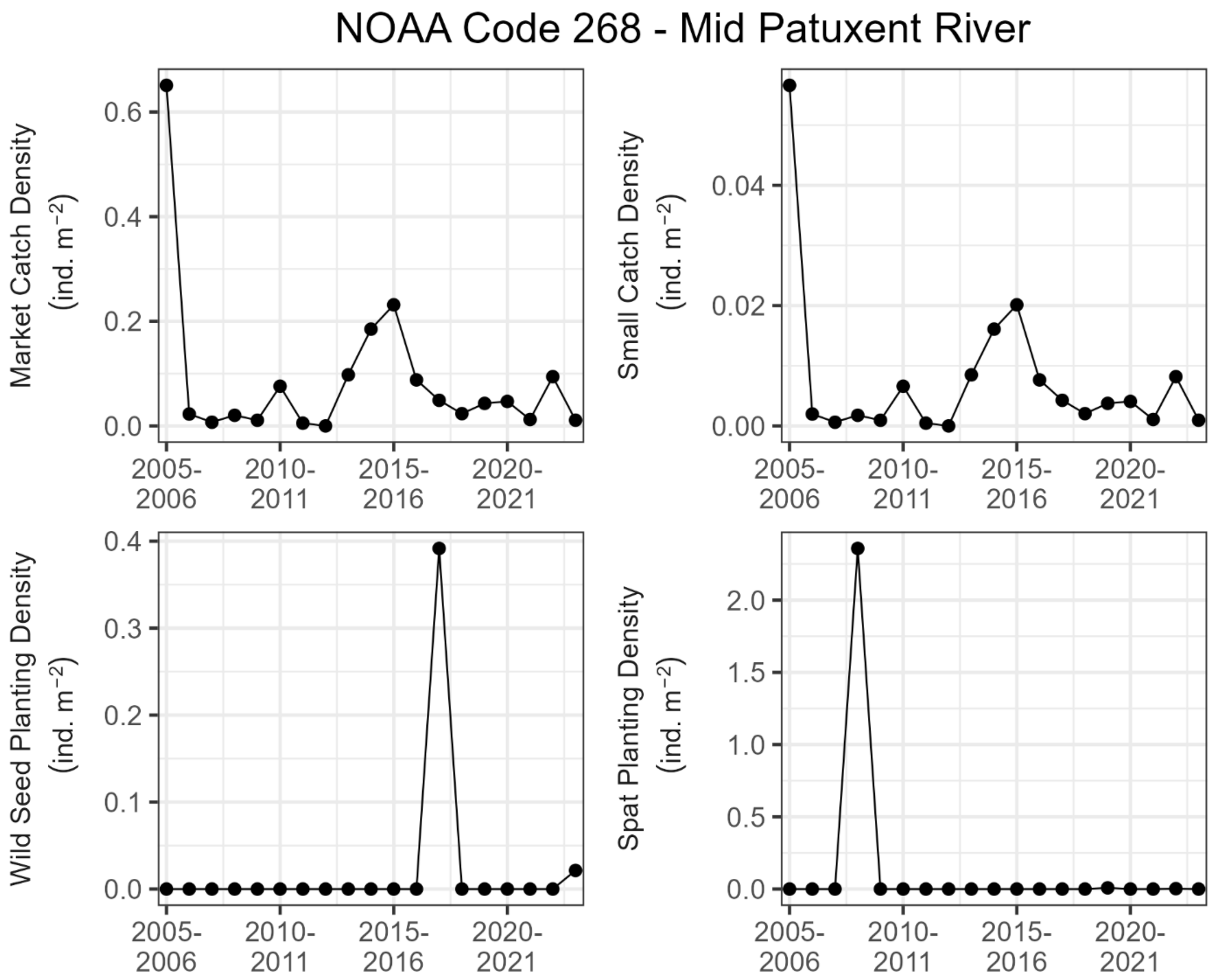

Figure 118. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Mid Patuxent River. Density was calculated as the number of individuals divided by habitat area for each data source.

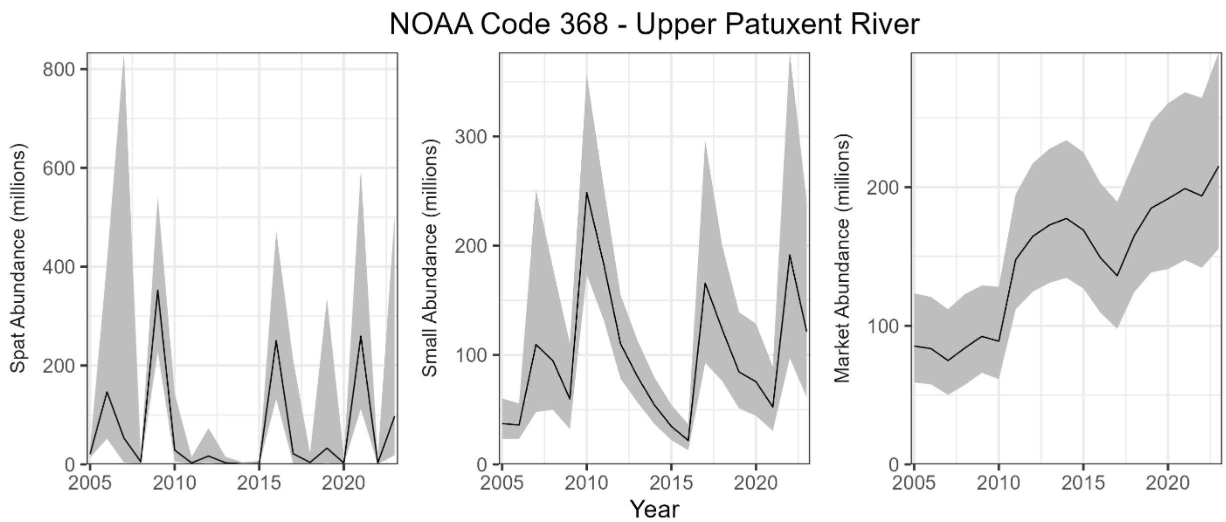

Figure 119. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Upper Patuxent River. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

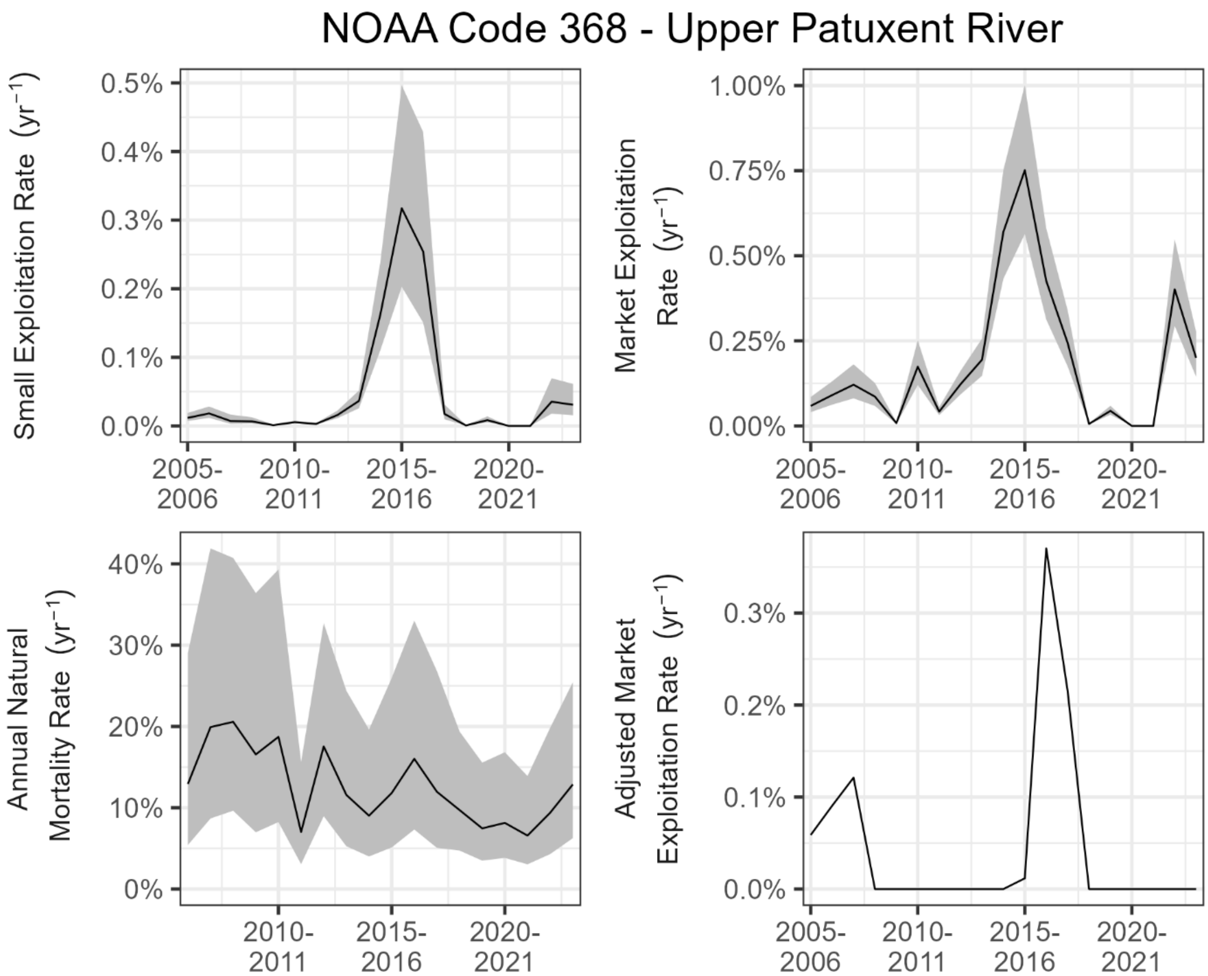

Figure 120. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Upper Patuxent River. The shaded areas indicate approximate 95% confidence intervals.

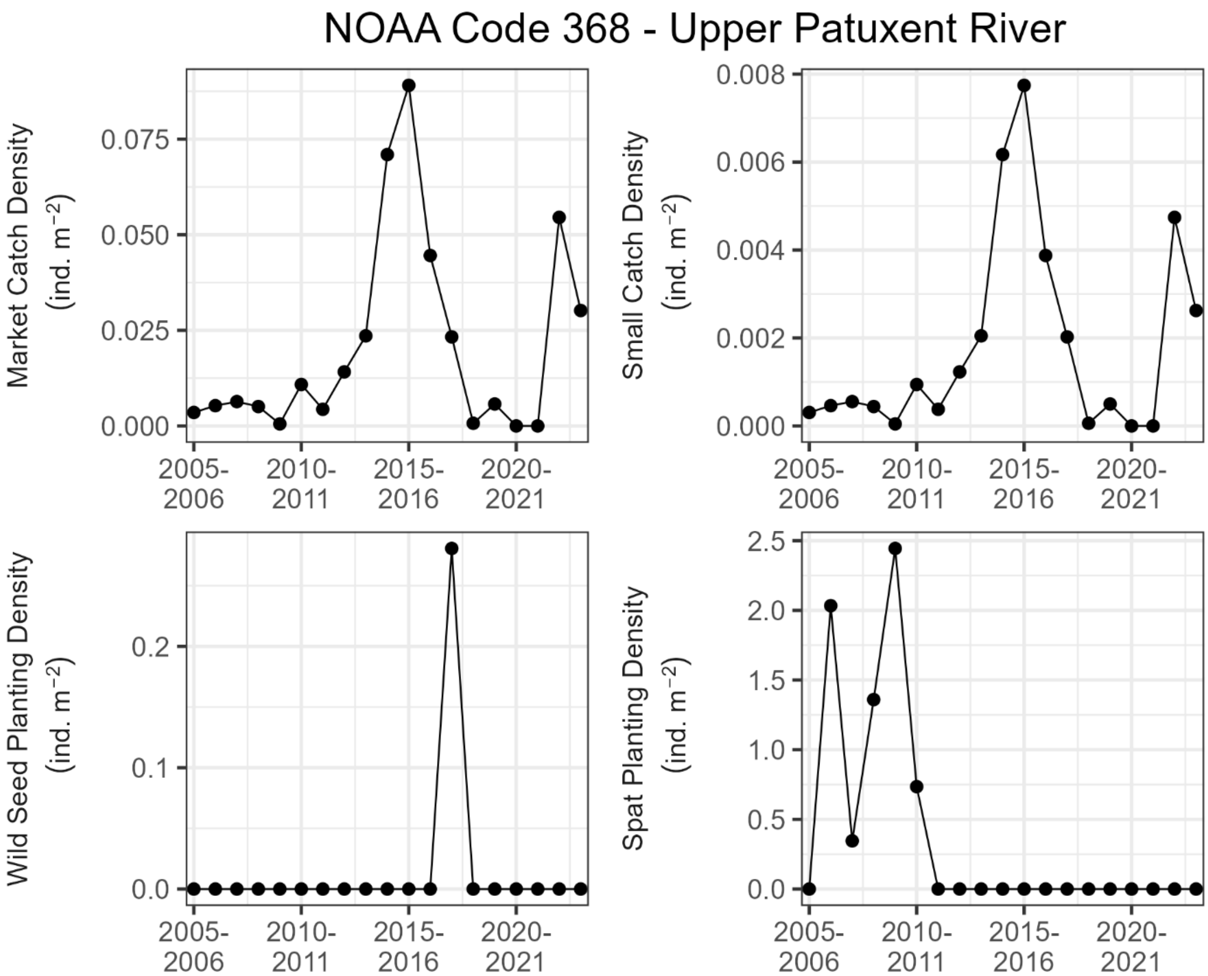

Figure 121. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Upper Patuxent River. Density was calculated as the number of individuals divided by habitat area for each data source.

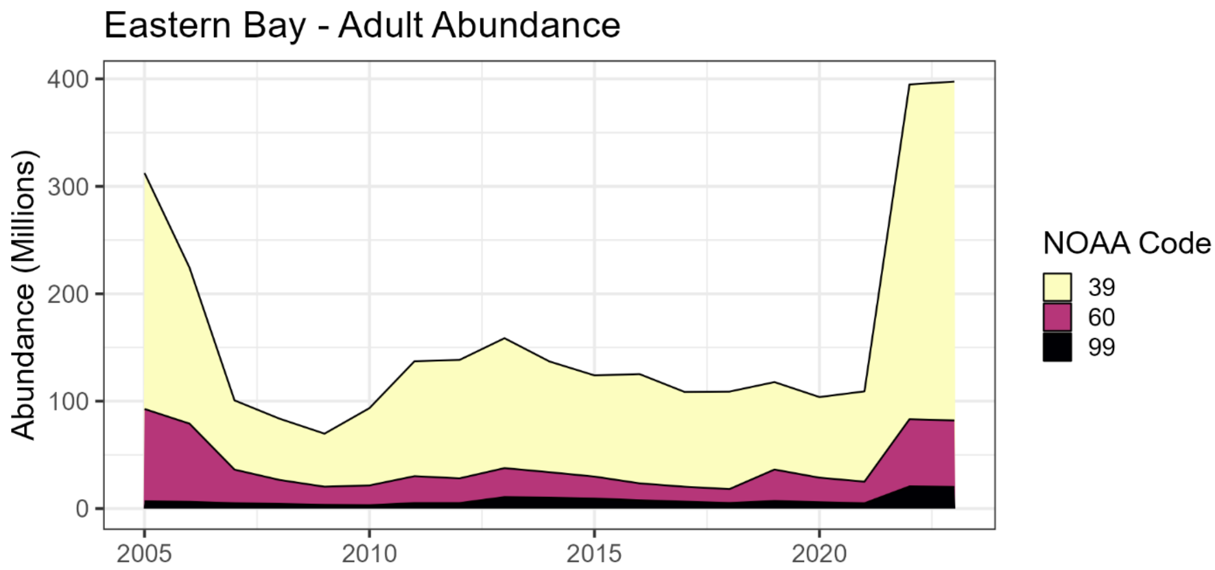

Figure 122. Estimated adult oyster abundance among modeled NOAA codes in the Eastern Bay Region under Maryland management during 2005-2023.

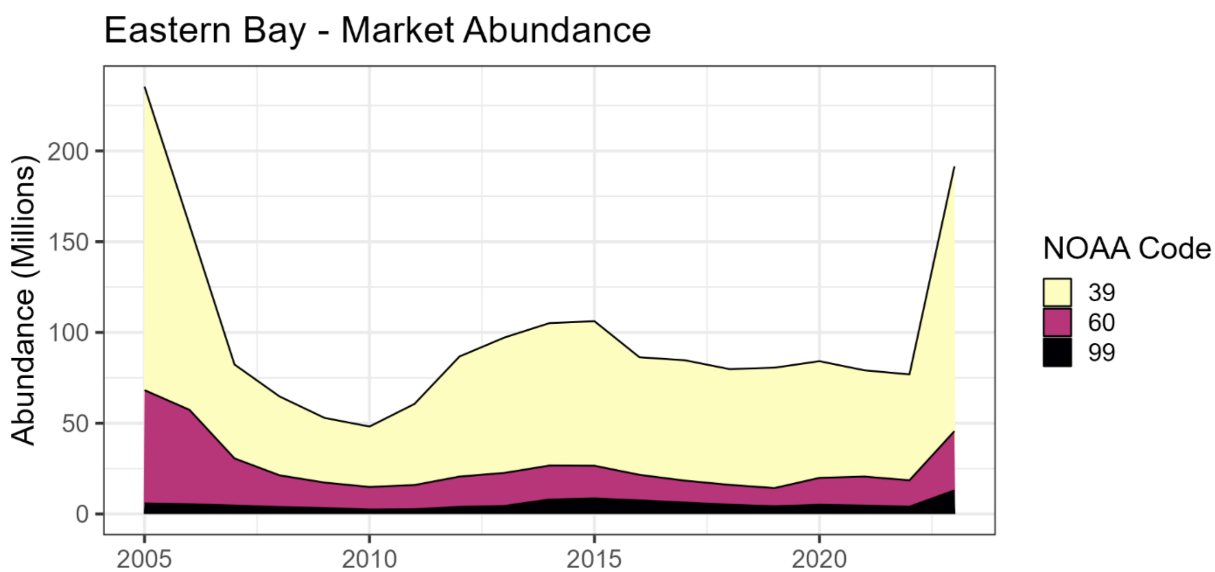

Figure 123. Estimated market oyster abundance among modeled NOAA codes in the Eastern Bay Region under Maryland management during 2005-2023.

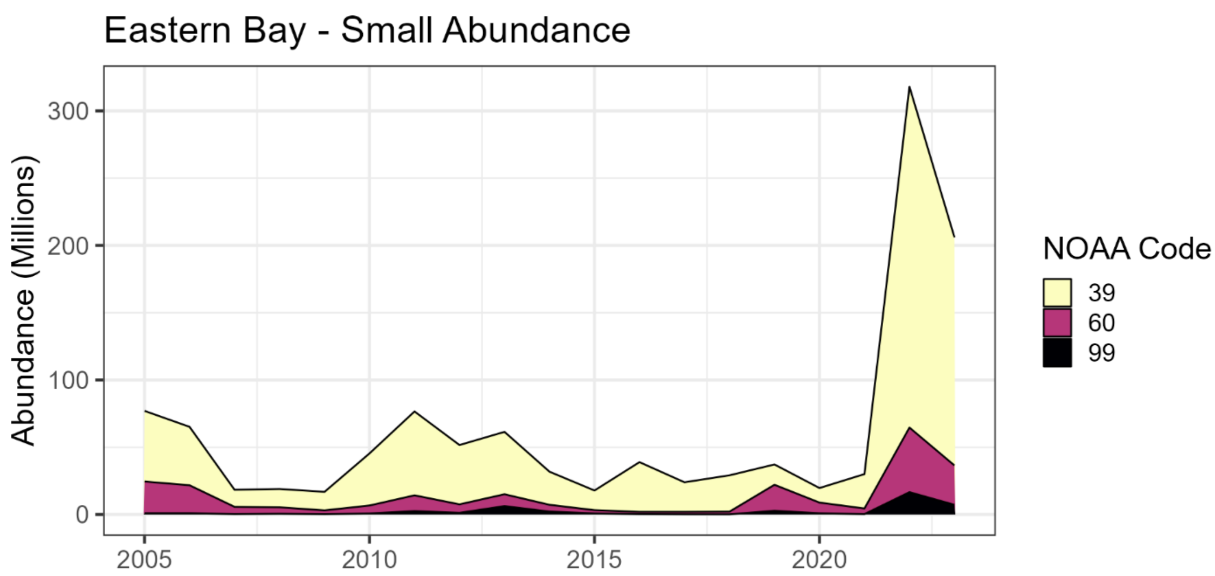

Figure 124. Estimated small oyster abundance among modeled NOAA codes in the Eastern Bay Region under Maryland management during 2005-2023.

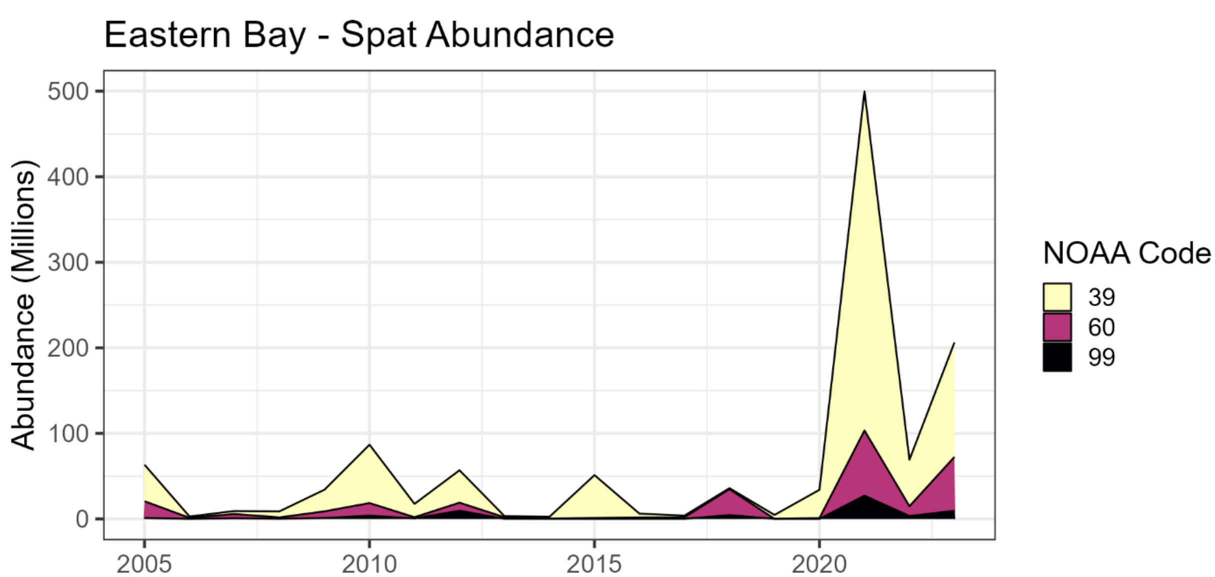

Figure 125. Estimated spat oyster abundance among modeled NOAA codes in the Eastern Bay Region under Maryland management during 2005-2023.

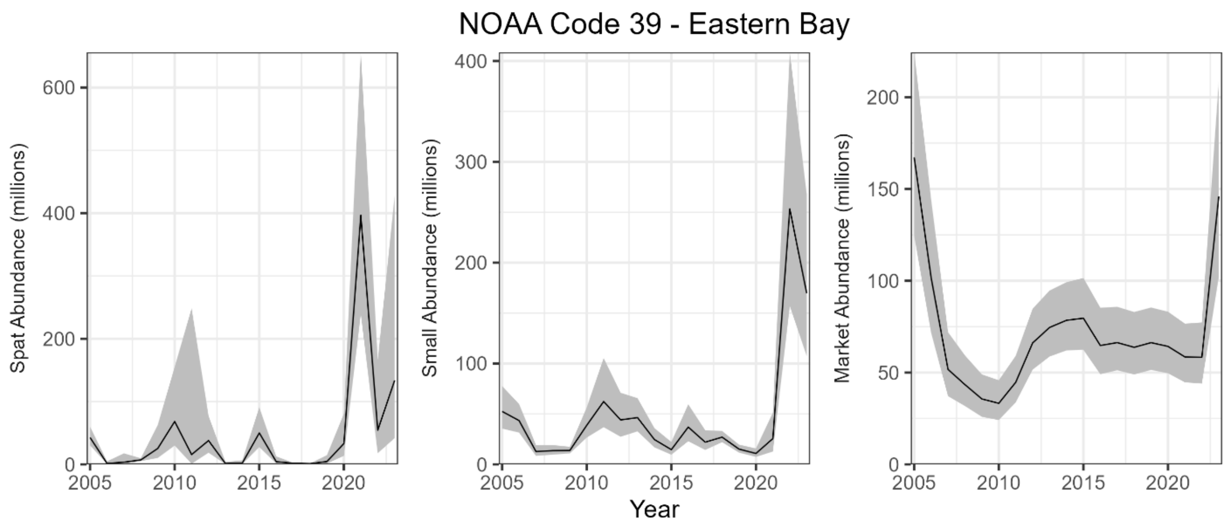

Figure 126. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Eastern Bay. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

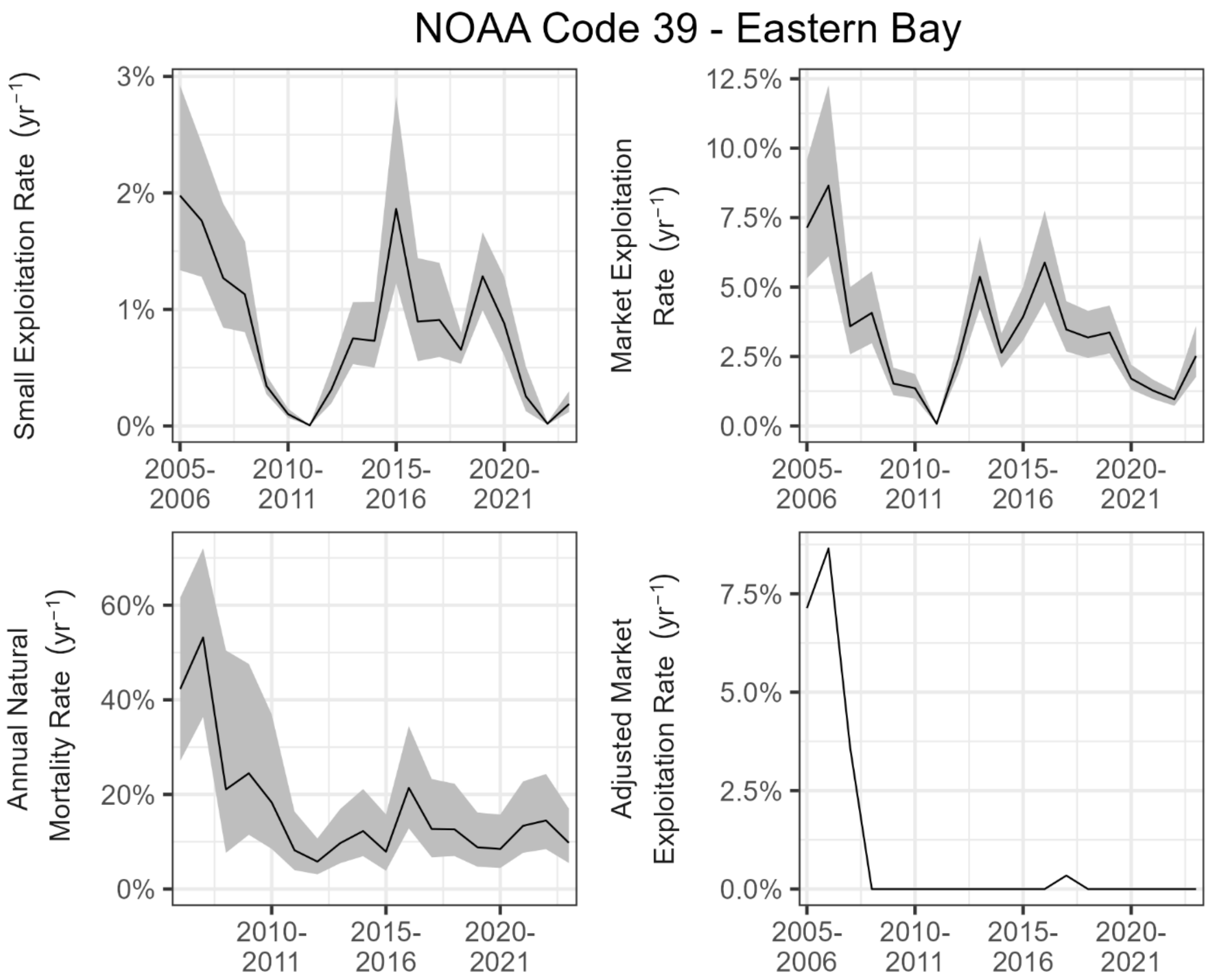

Figure 127. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Eastern Bay. The shaded areas indicate approximate 95% confidence intervals.

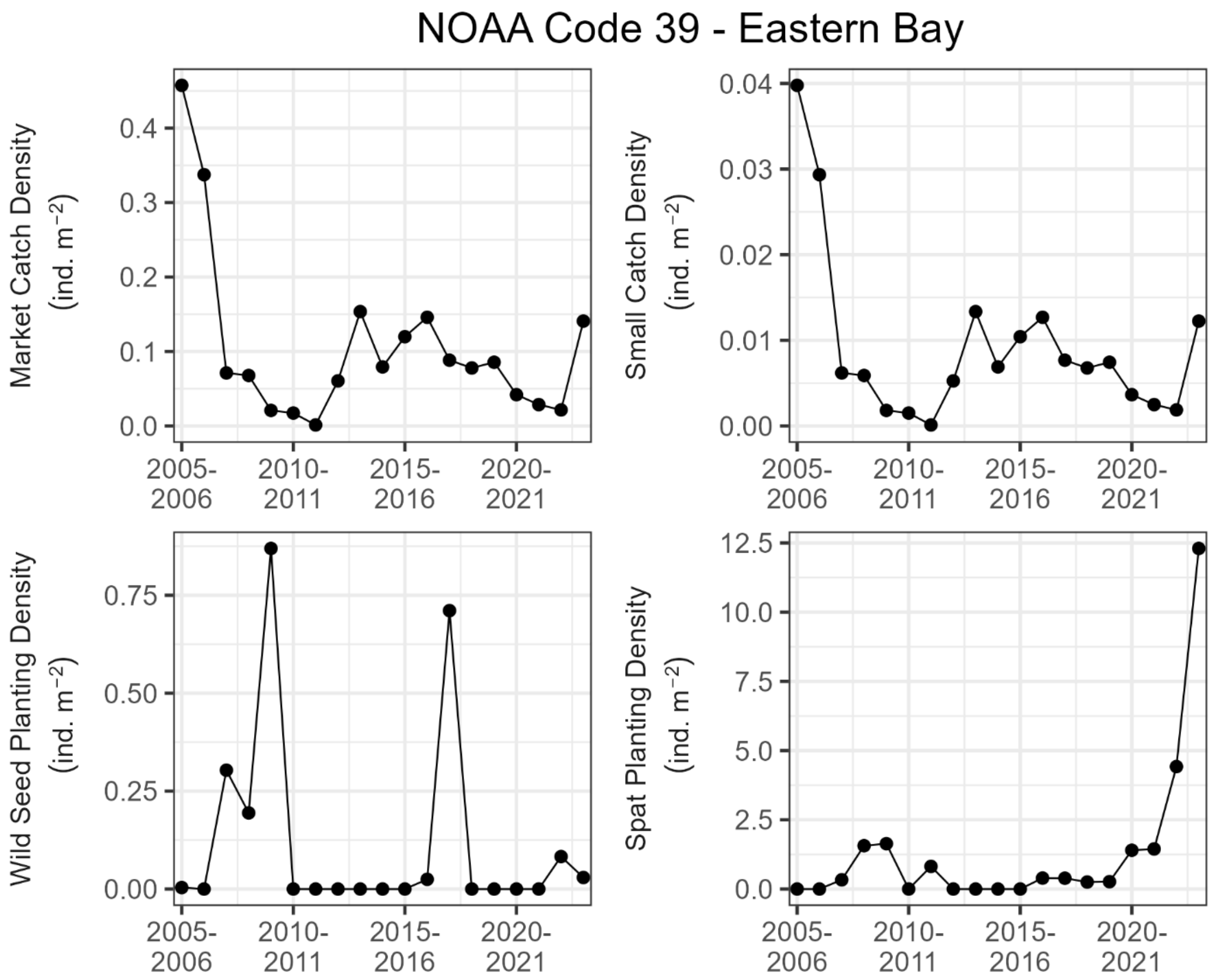

Figure 128. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Eastern Bay. Density was calculated as the number of individuals divided by habitat area for each data source.

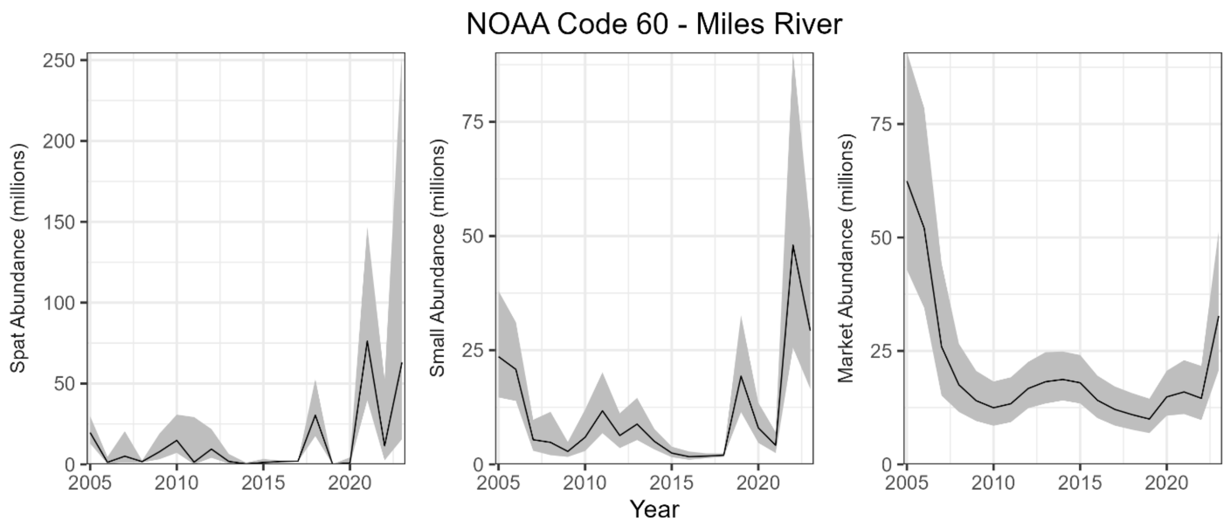

Figure 129. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Miles River. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

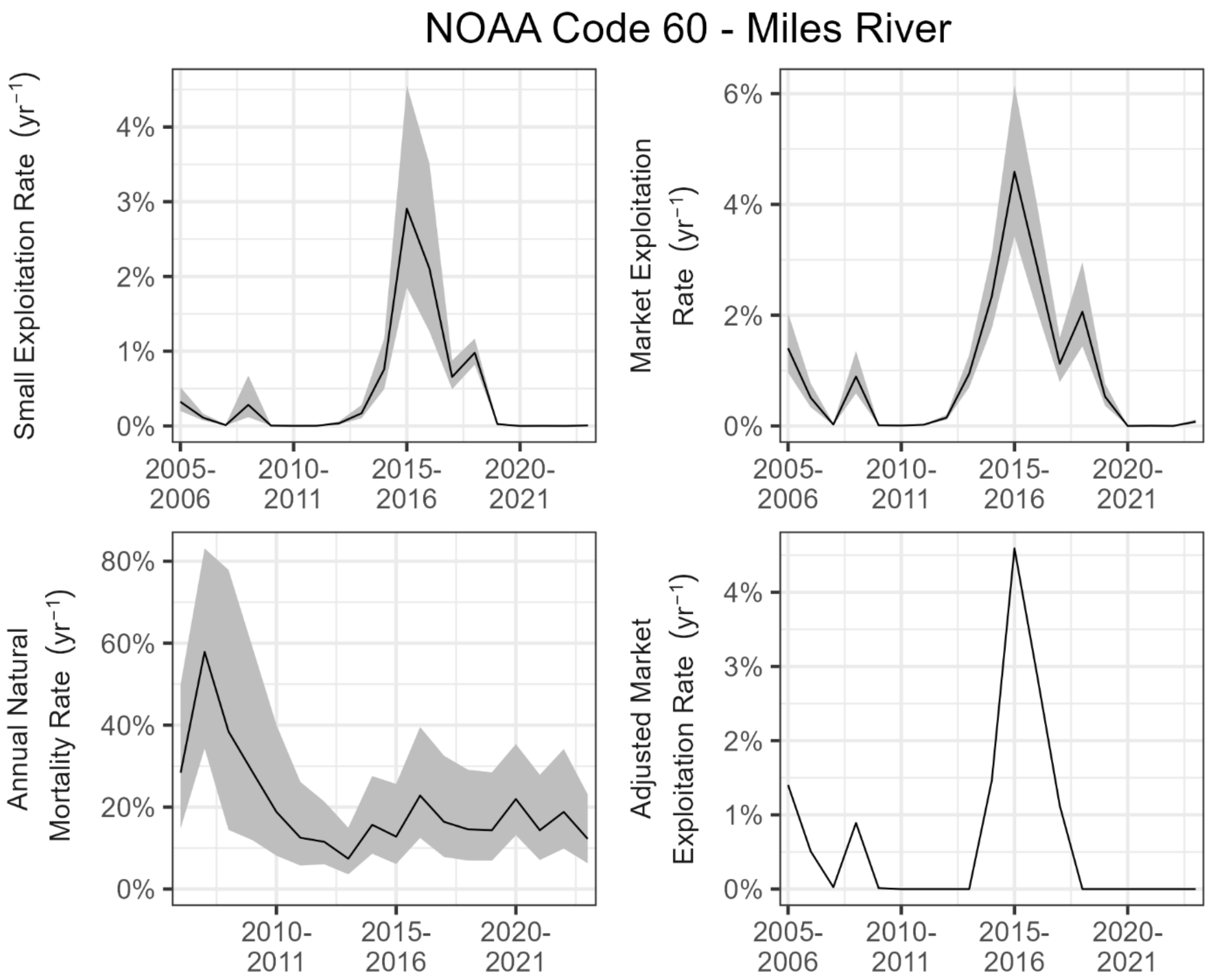

Figure 130. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Miles River. The shaded areas indicate approximate 95% confidence intervals.

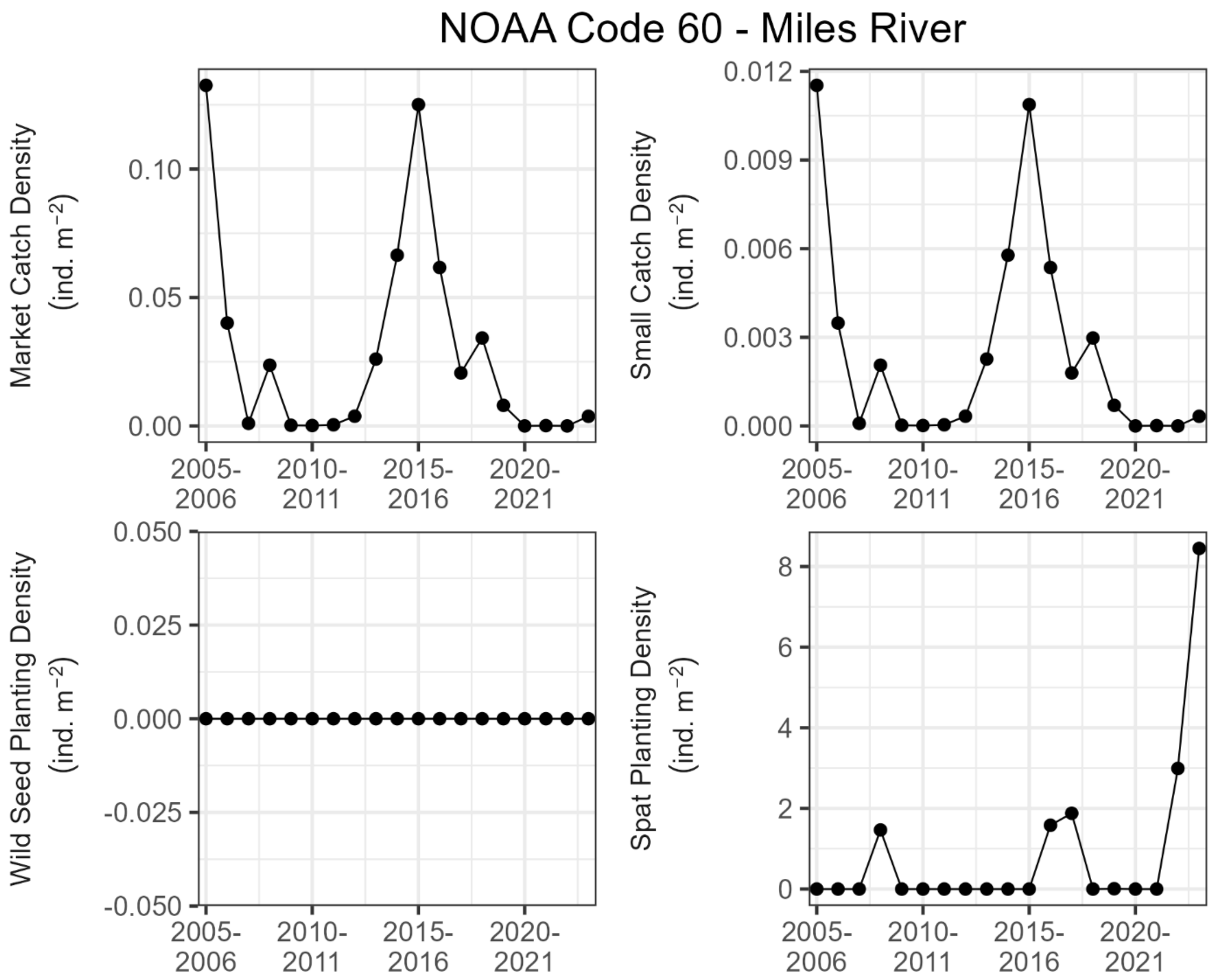

Figure 131. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Miles River. Density was calculated as the number of individuals divided by habitat area for each data source.

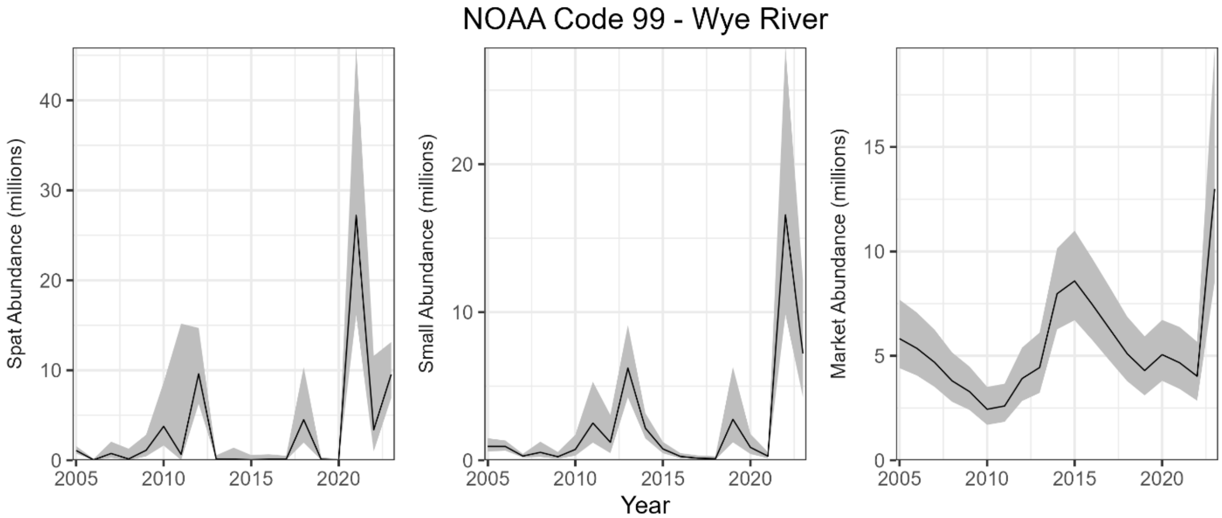

Figure 132. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Wye River. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

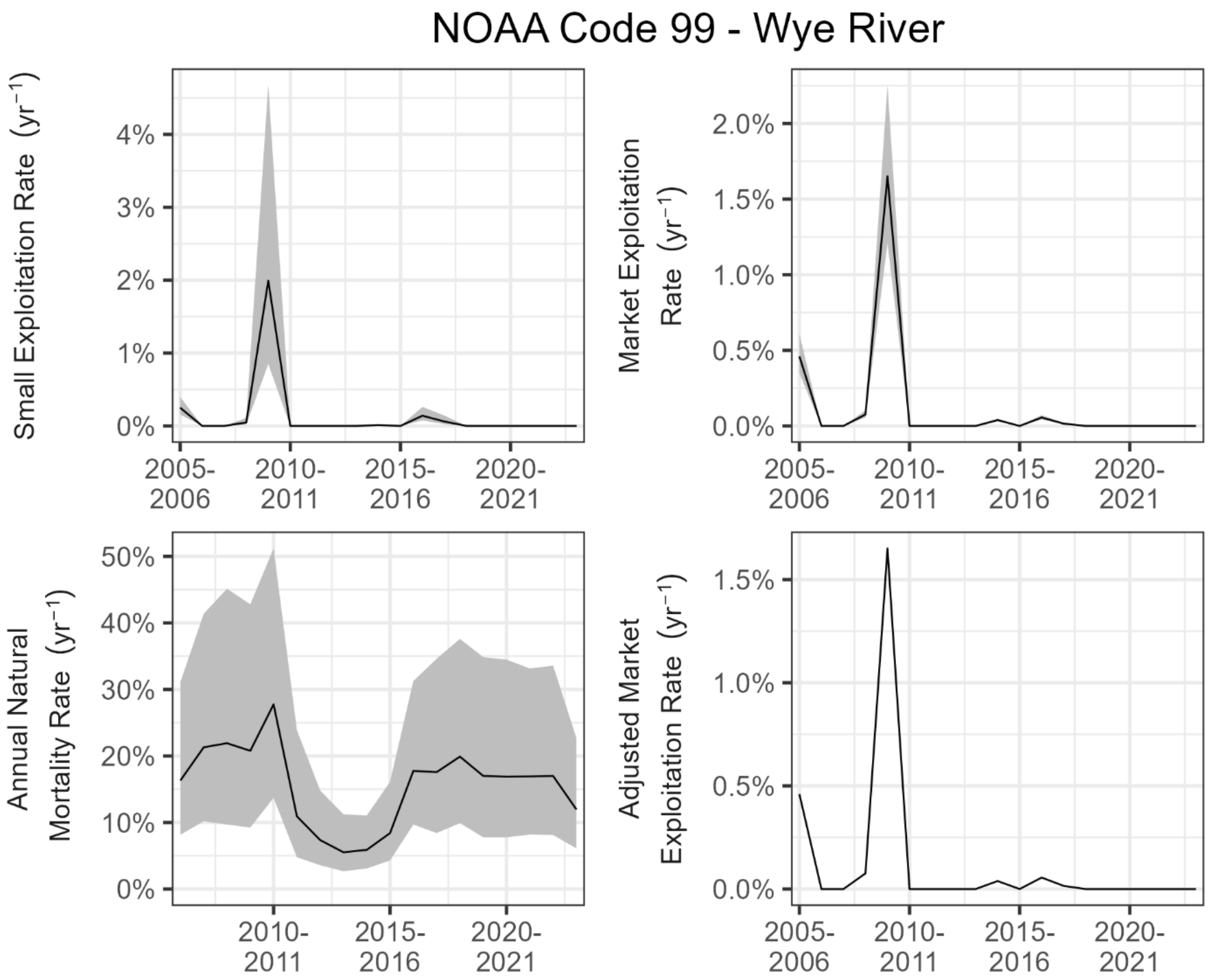

Figure 133. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Wye River. The shaded areas indicate approximate 95% confidence intervals.

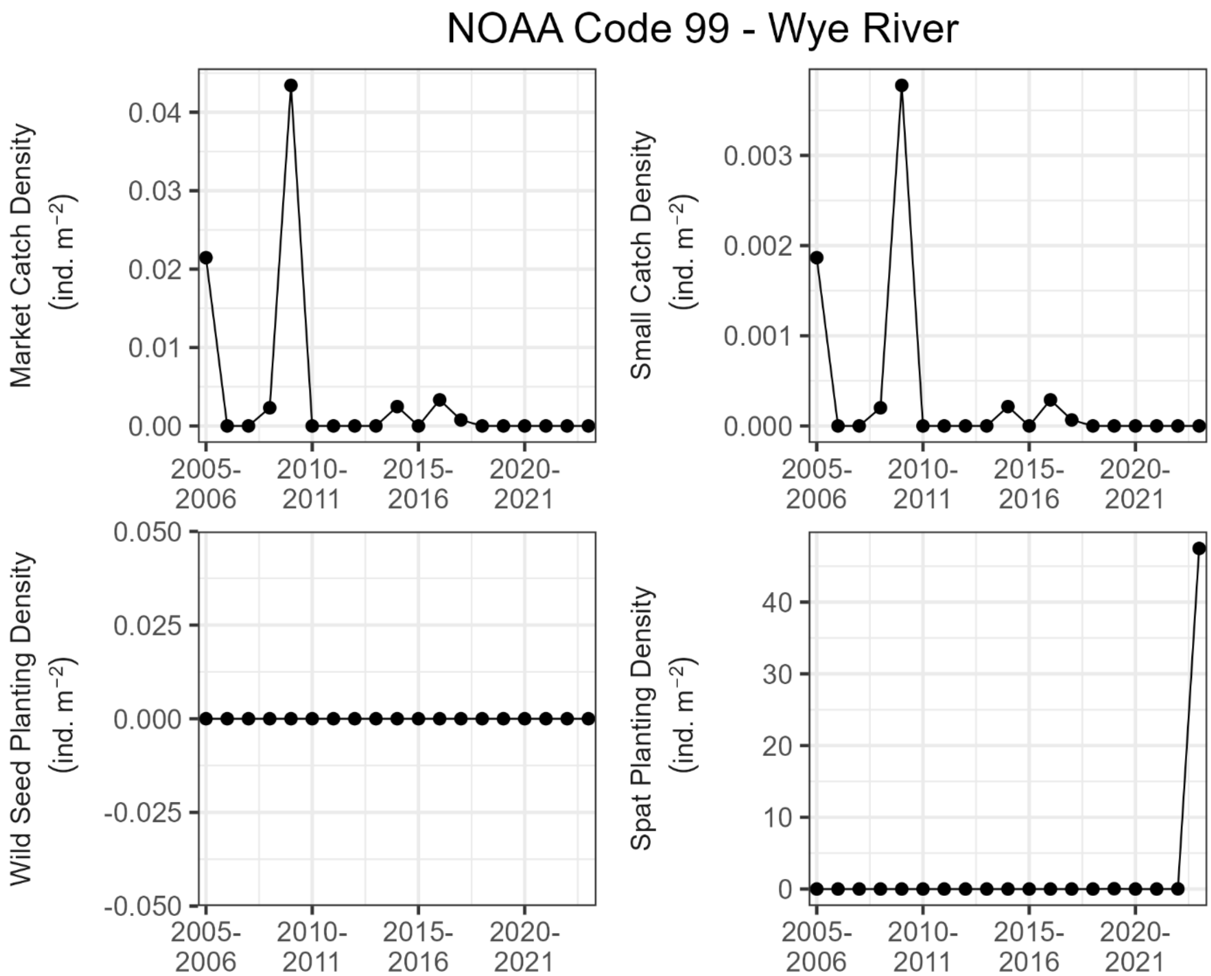

Figure 134. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Wye River. Density was calculated as the number of individuals divided by habitat area for each data source.

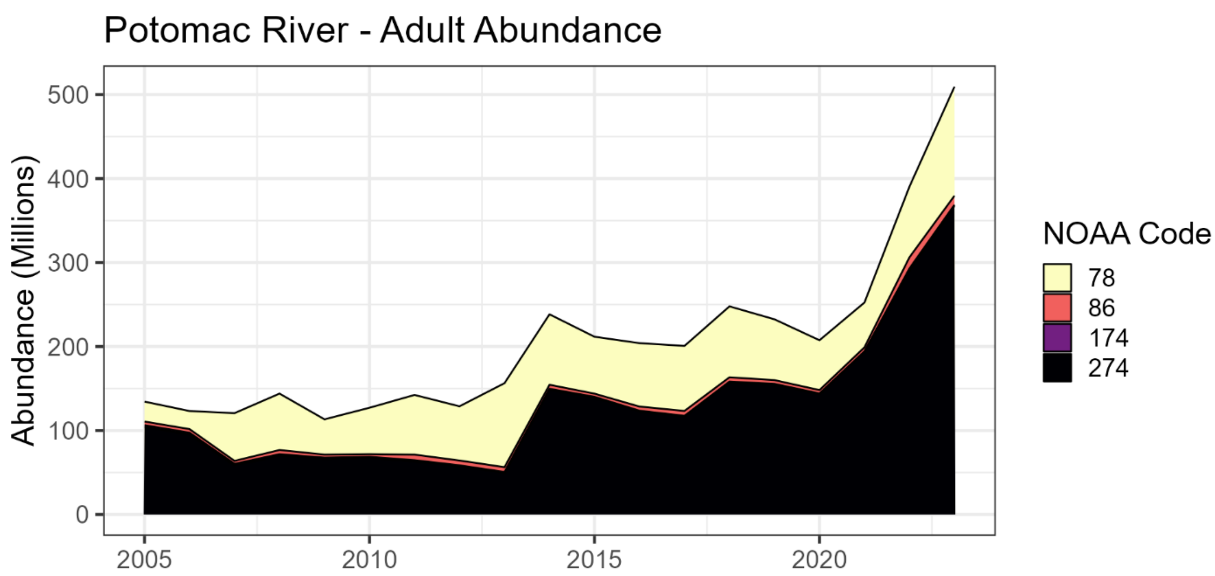

Figure 135. Estimated adult oyster abundance among modeled NOAA codes in the Potomac River Region under Maryland management during 2005-2023.

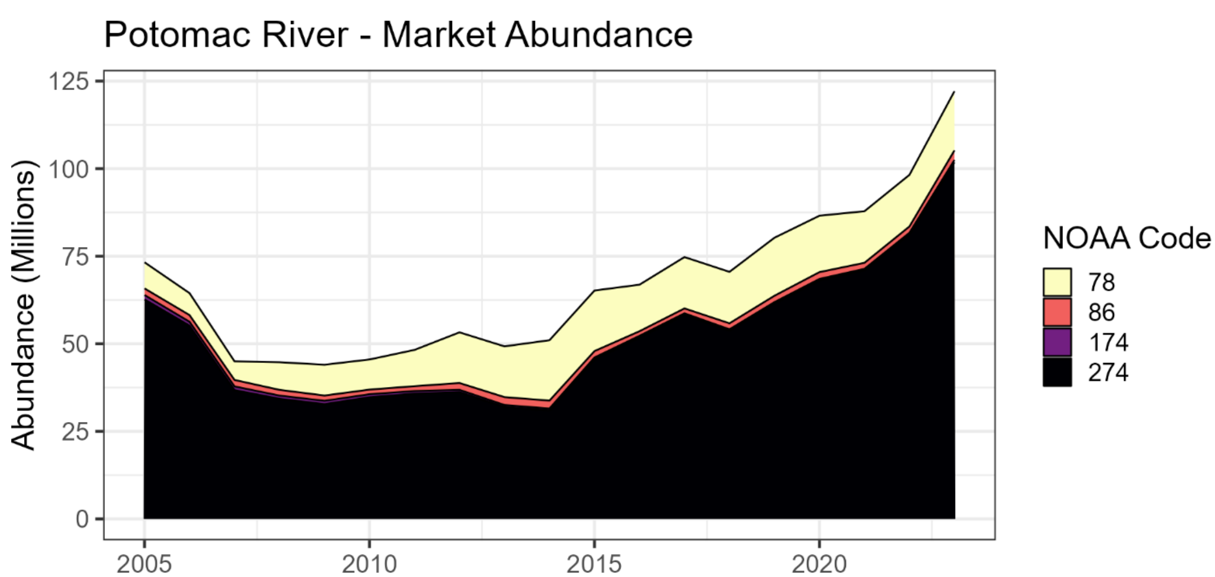

Figure 136. Estimated market oyster abundance among modeled NOAA codes in the Potomac River Region under Maryland management during 2005-2023.

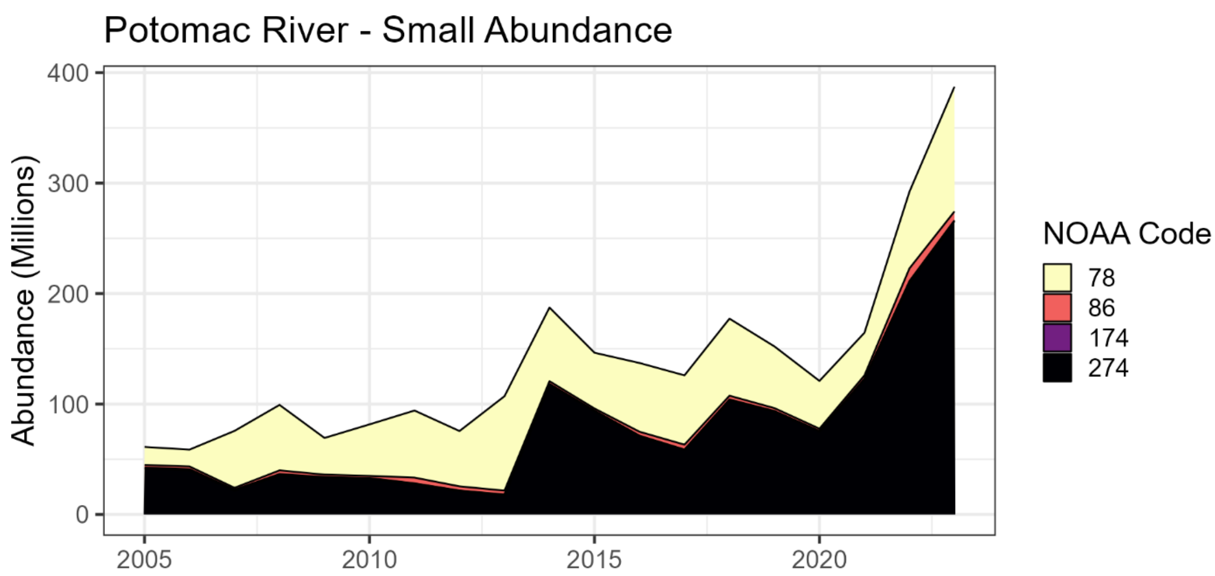

Figure 137. Estimated small oyster abundance among modeled NOAA codes in the Potomac River Region under Maryland management during 2005-2023.

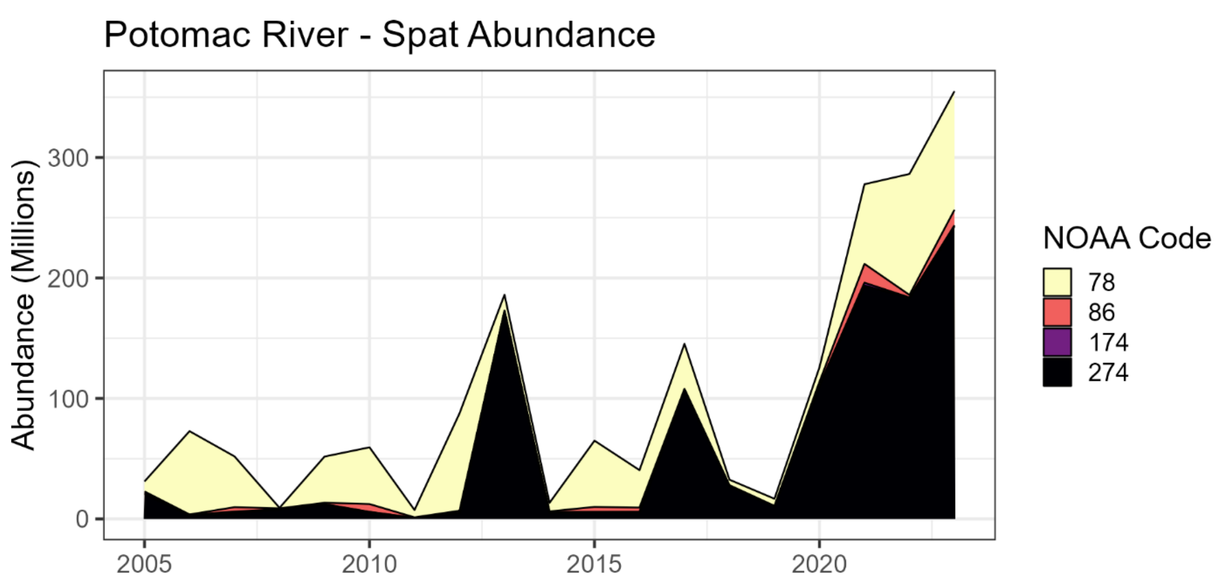

Figure 138. Estimated spat oyster abundance among modeled NOAA codes in the Potomac River Region under Maryland management during 2005-2023.

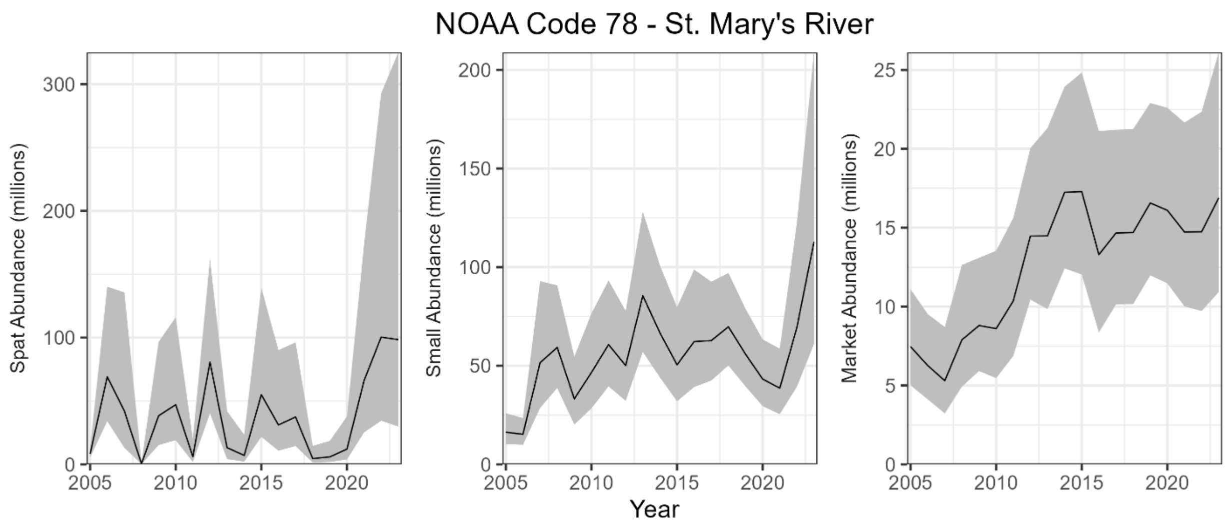

Figure 139. Estimated abundance of spat, small, and markets oysters during 2005-2023 in St. Mary's River. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

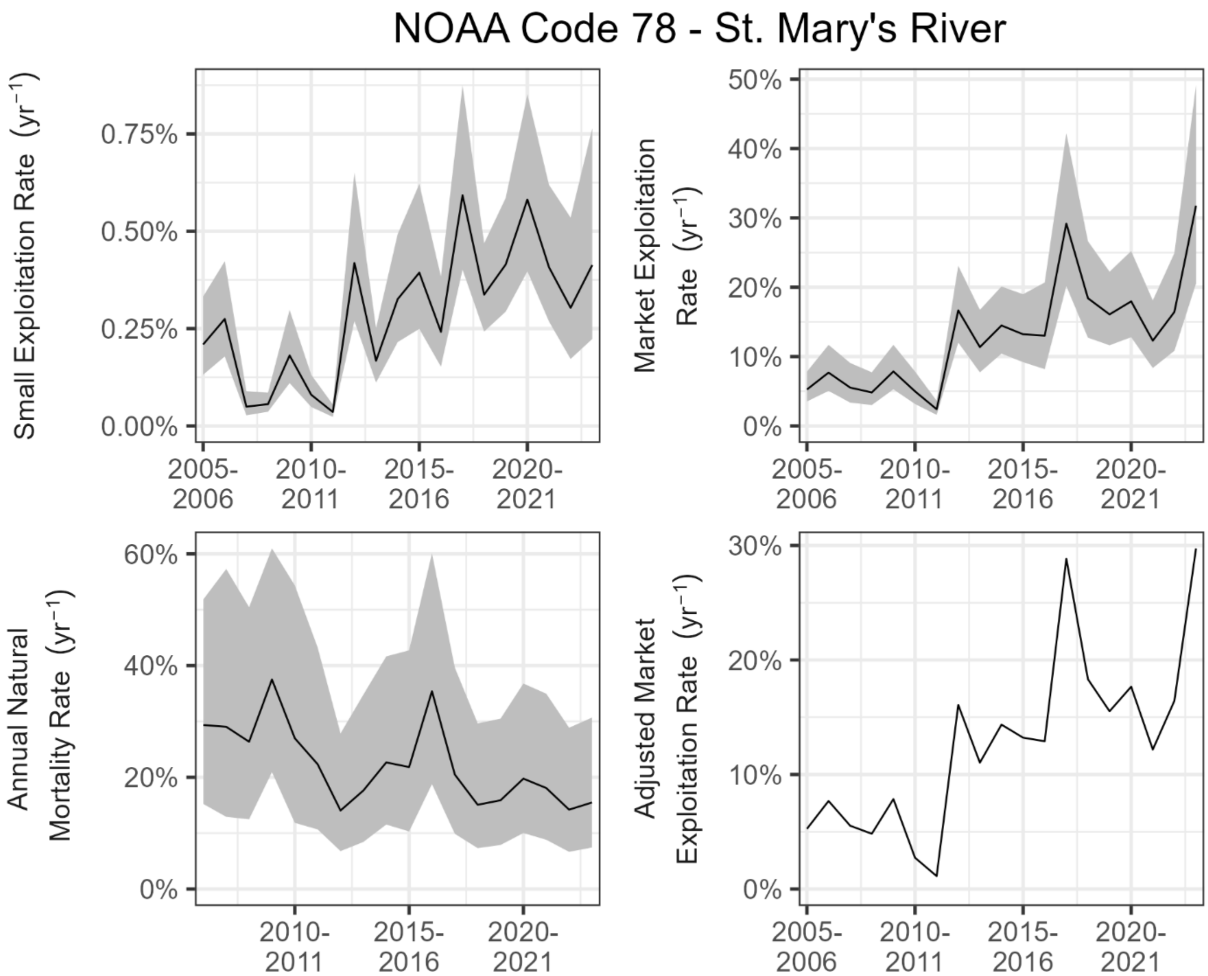

Figure 140. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in St. Mary's River. The shaded areas indicate approximate 95% confidence intervals.

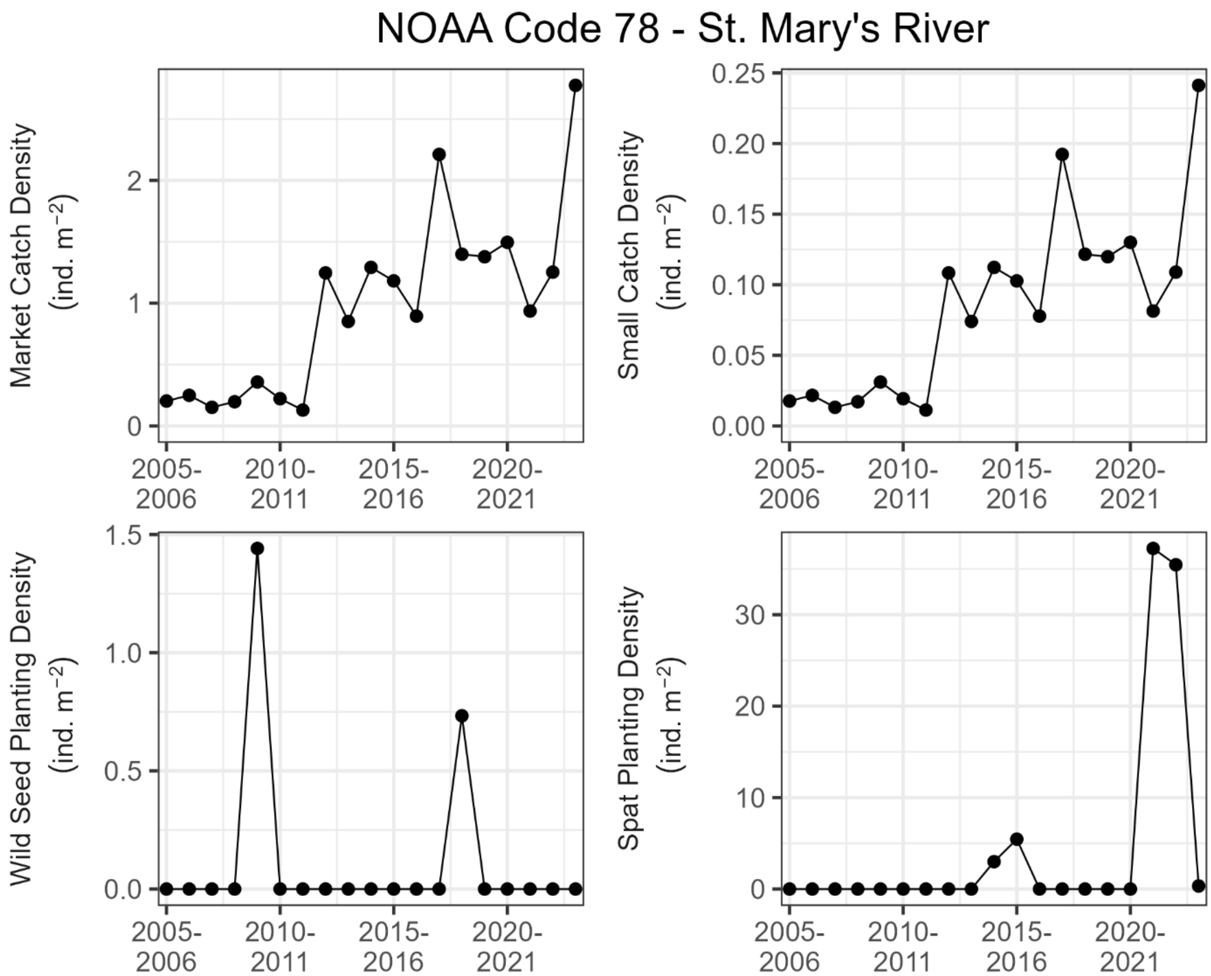

Figure 141. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in St. Mary's River. Density was calculated as the number of individuals divided by habitat area for each data source.

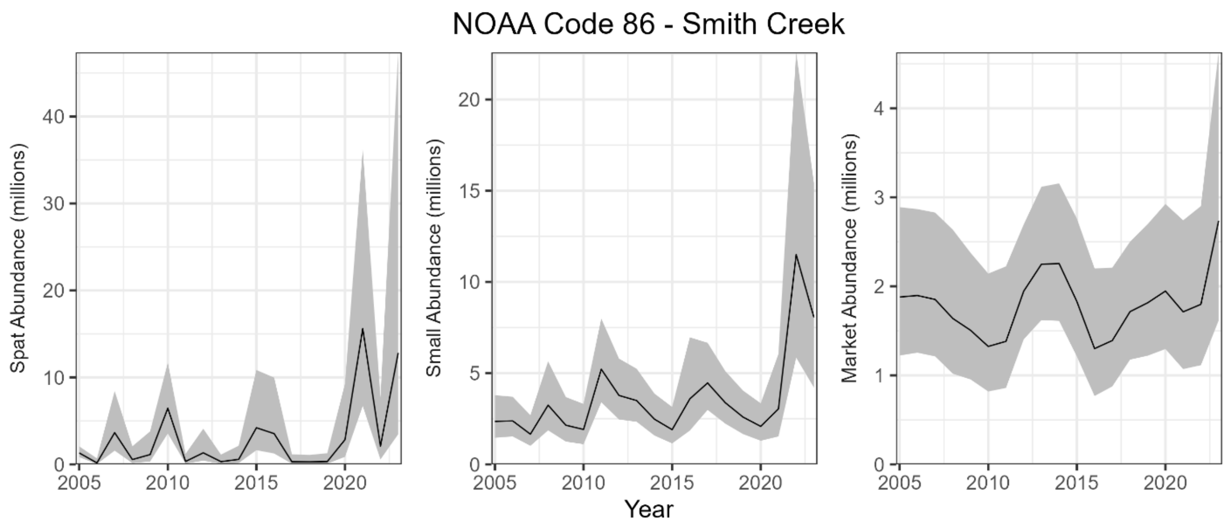

Figure 142. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Smith Creek. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

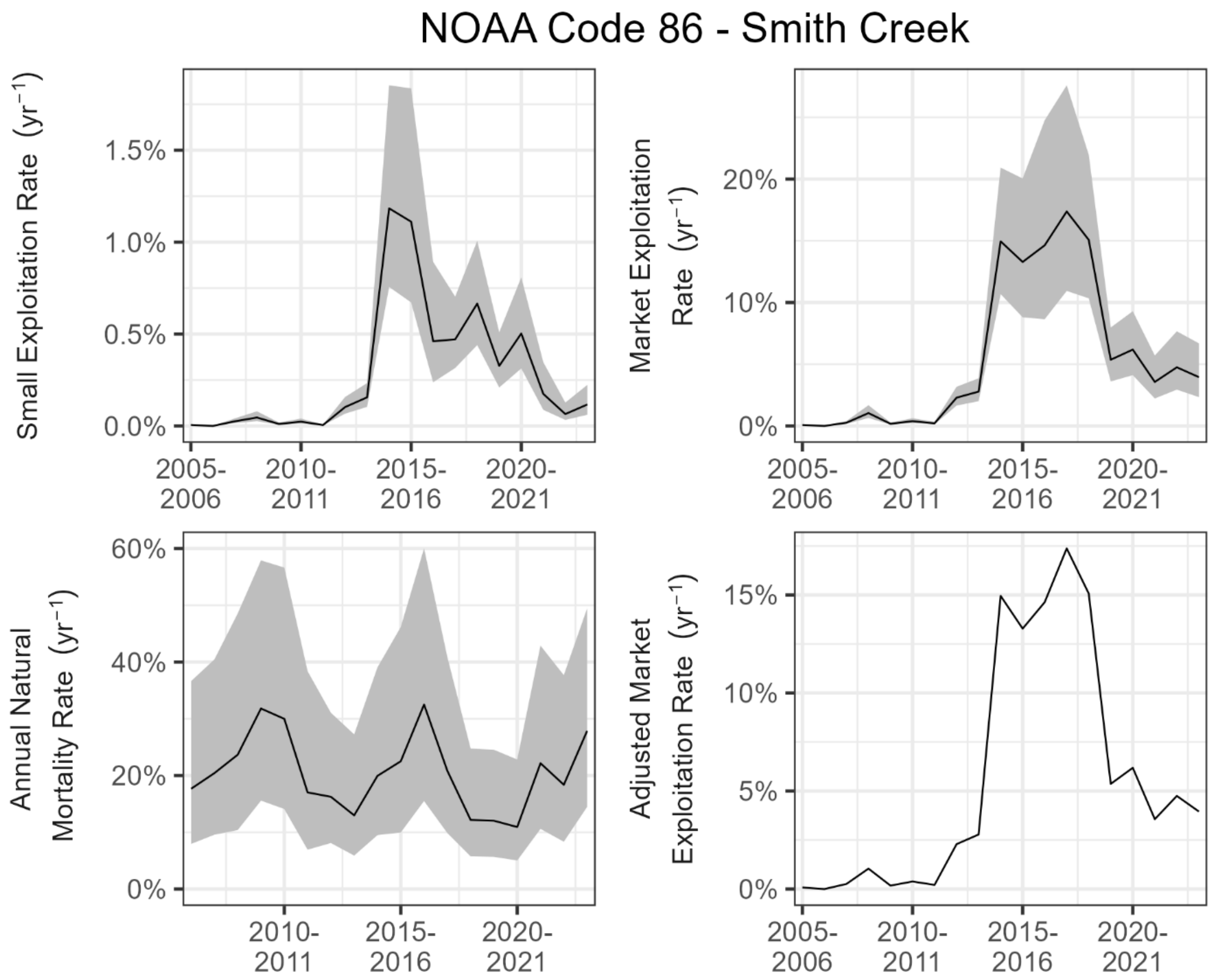

Figure 143. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Smith Creek. The shaded areas indicate approximate 95% confidence intervals.

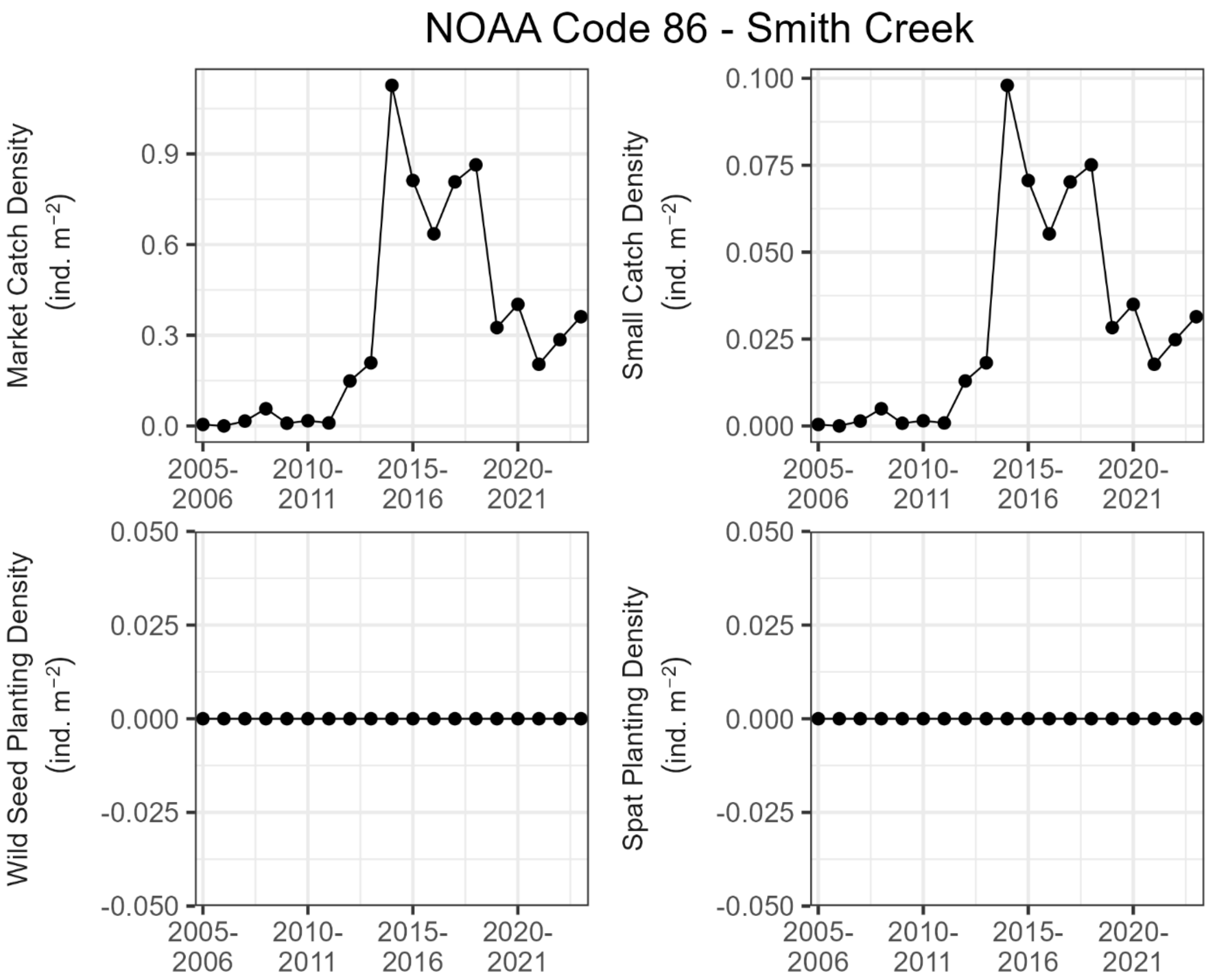

Figure 144. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Smith Creek. Density was calculated as the number of individuals divided by habitat area for each data source.

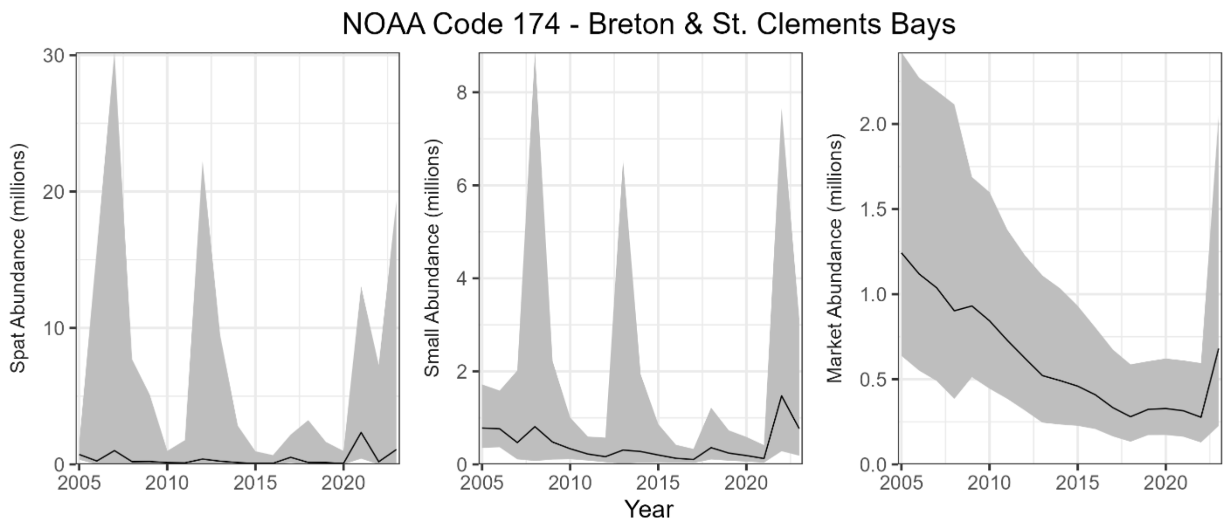

Figure 145. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Breton & St. Clements Bay. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

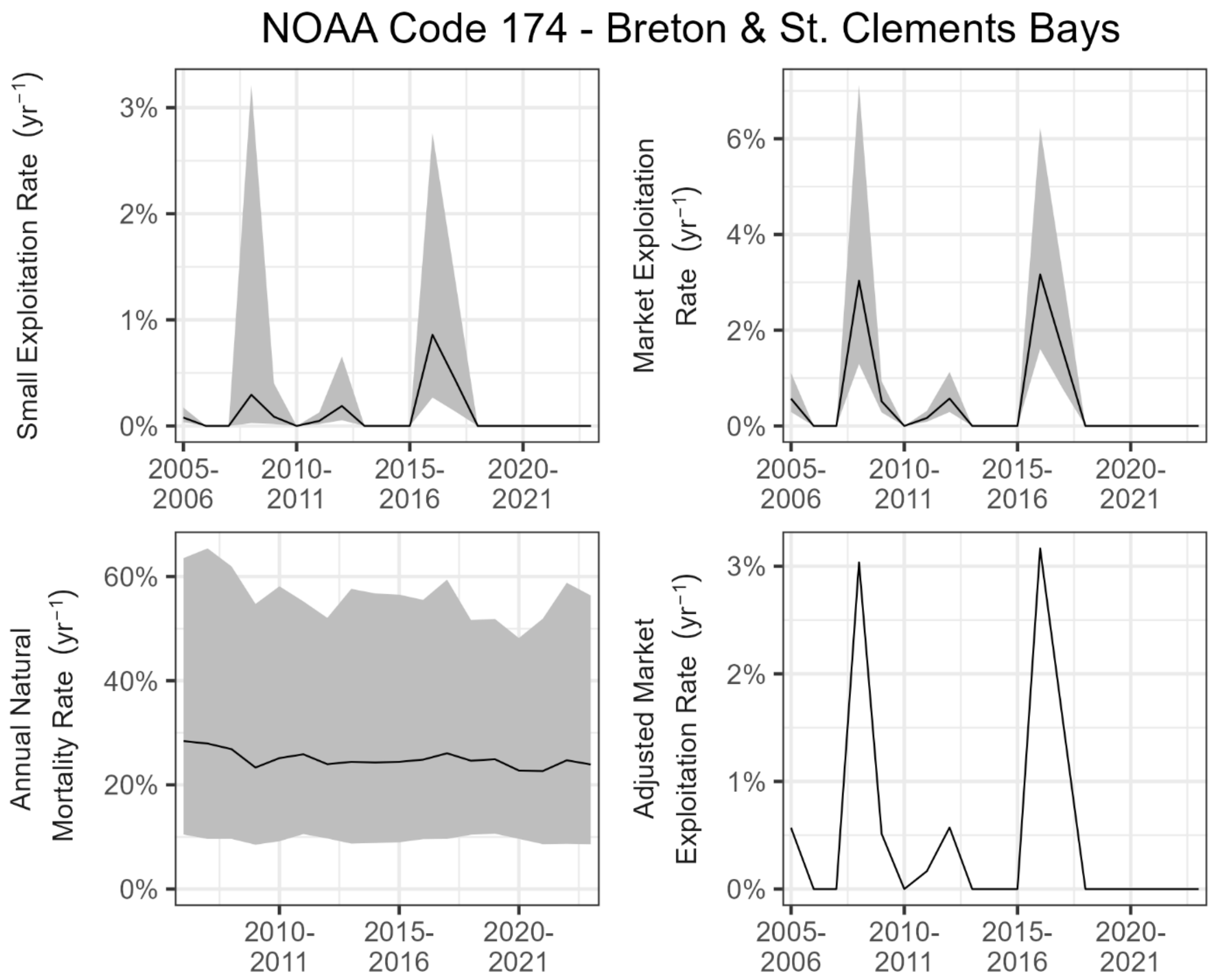

Figure 146. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Breton & St. Clements Bay. The shaded areas indicate approximate 95% confidence intervals.

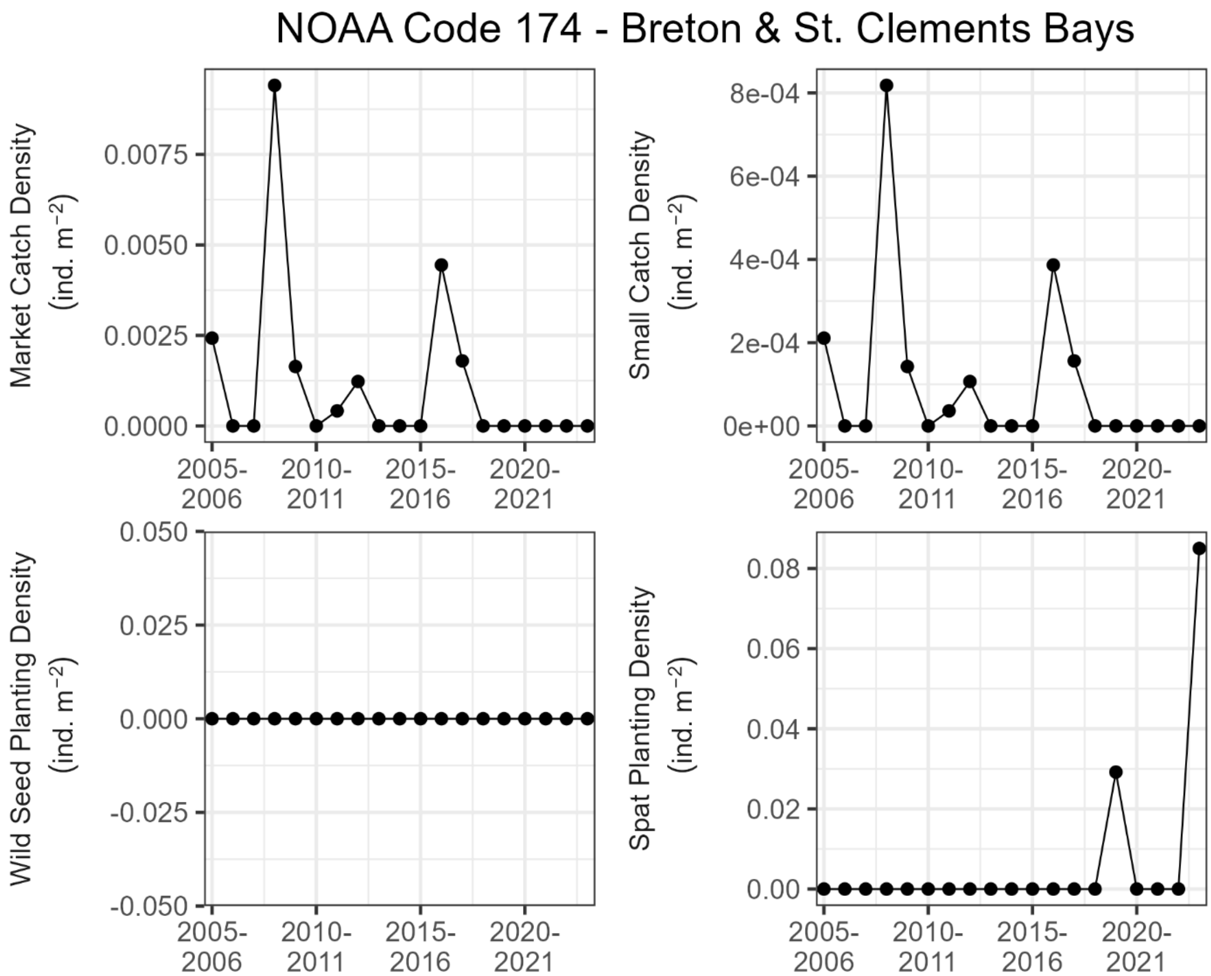

Figure 147. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Breton & St. Clements Bay. Density was calculated as the number of individuals divided by habitat area for each data source.

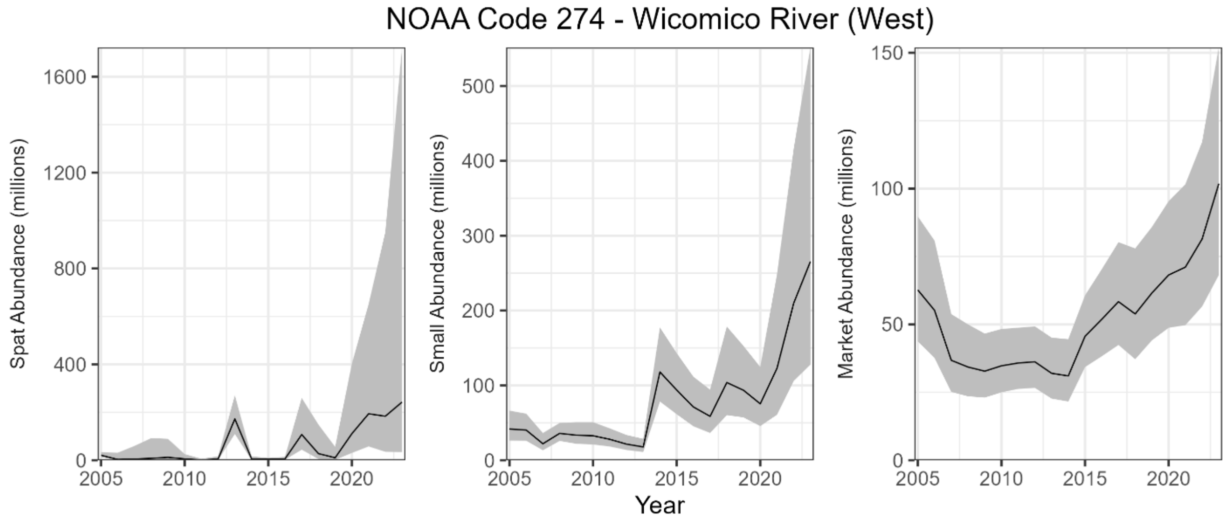

Figure 148. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Wicomico River (West). The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

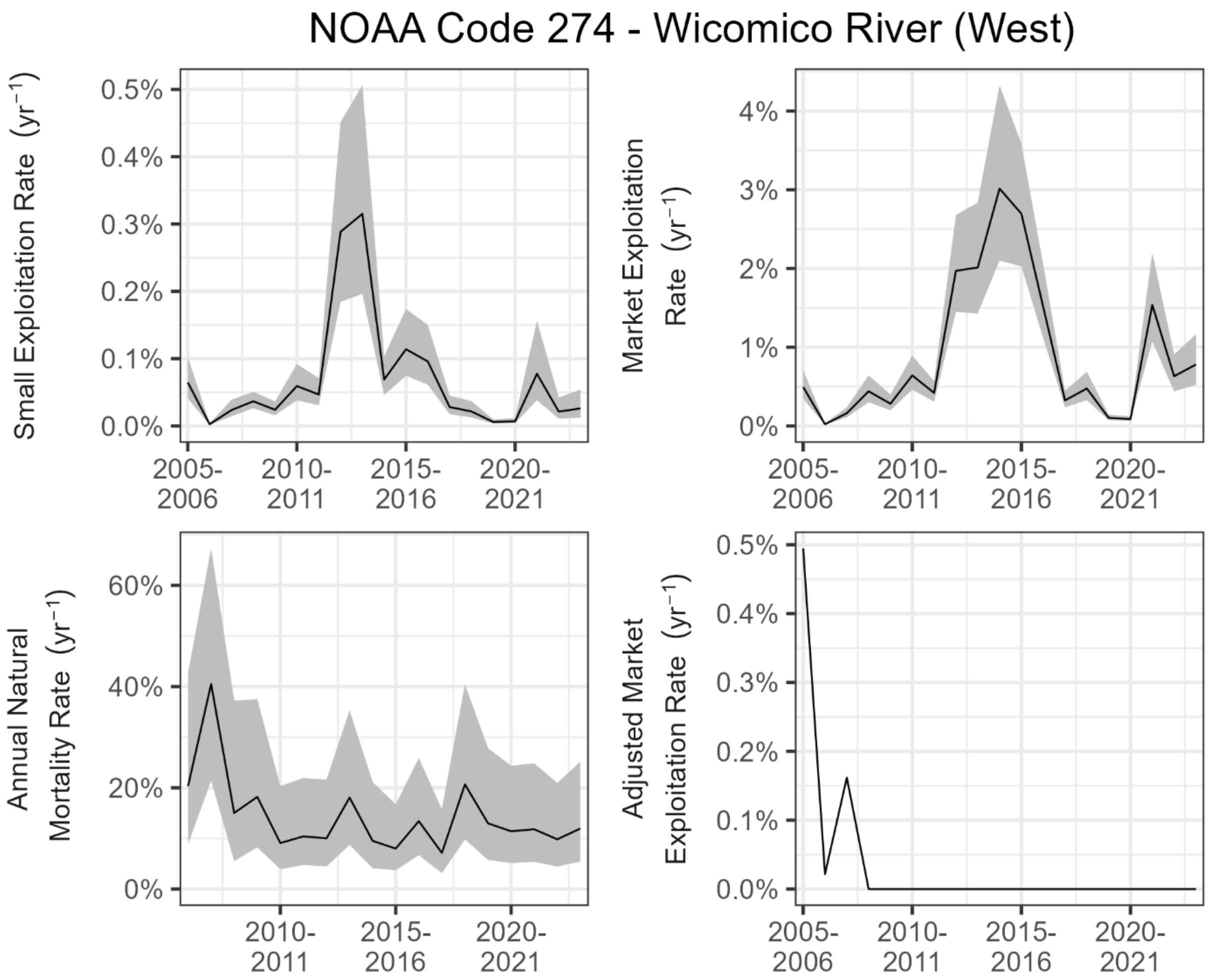

Figure 149. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Wicomico River (West). The shaded areas indicate approximate 95% confidence intervals.

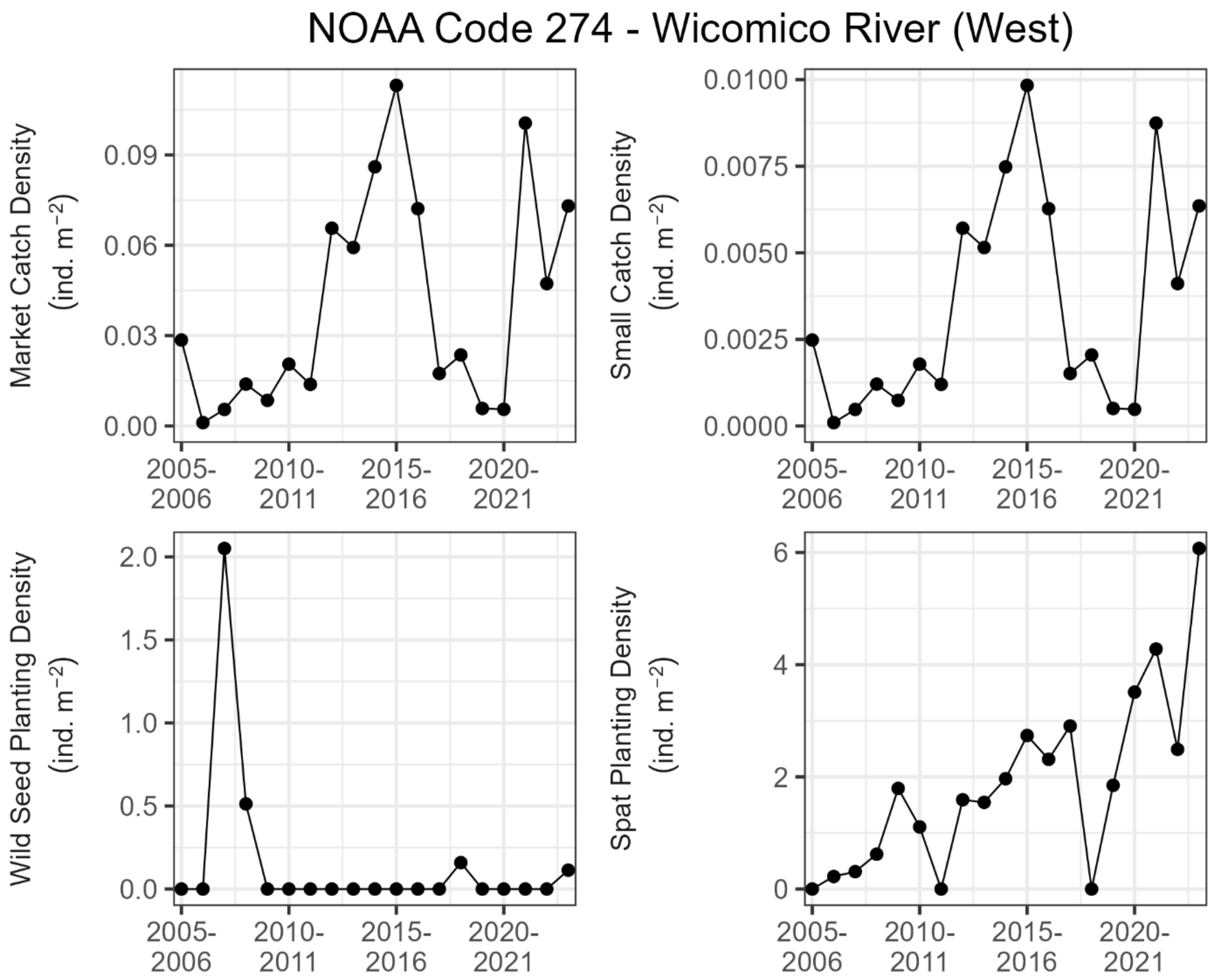

Figure 150. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Wicomico River (West). Density was calculated as the number of individuals divided by habitat area for each data source.

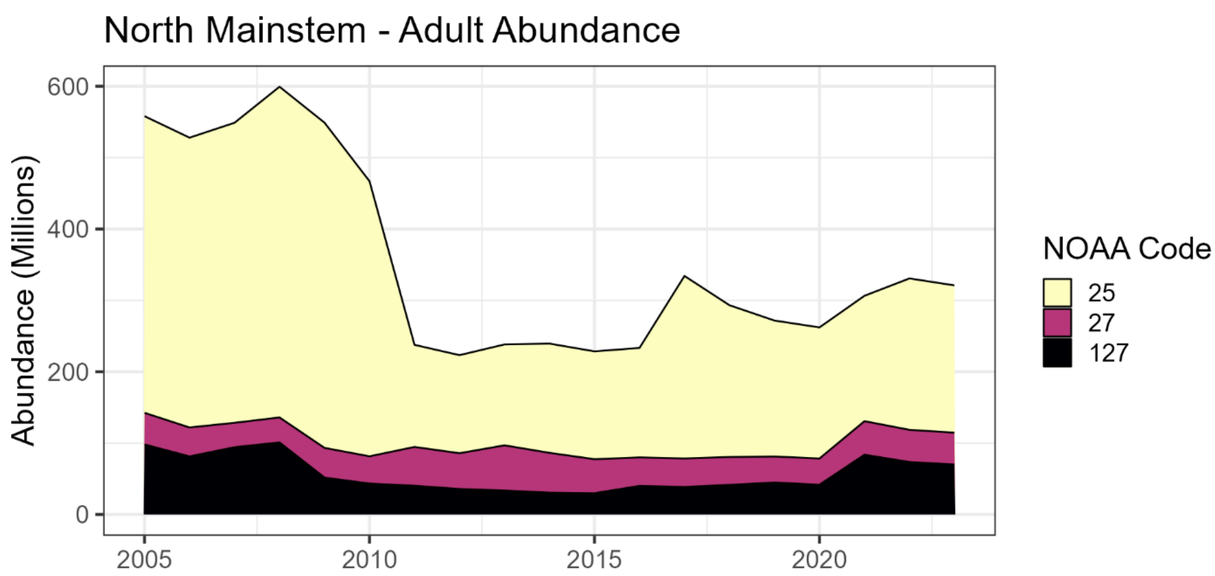

Figure 151. Estimated adult oyster abundance among modeled NOAA codes in the North Mainstem Region under Maryland management during 2005-2023.

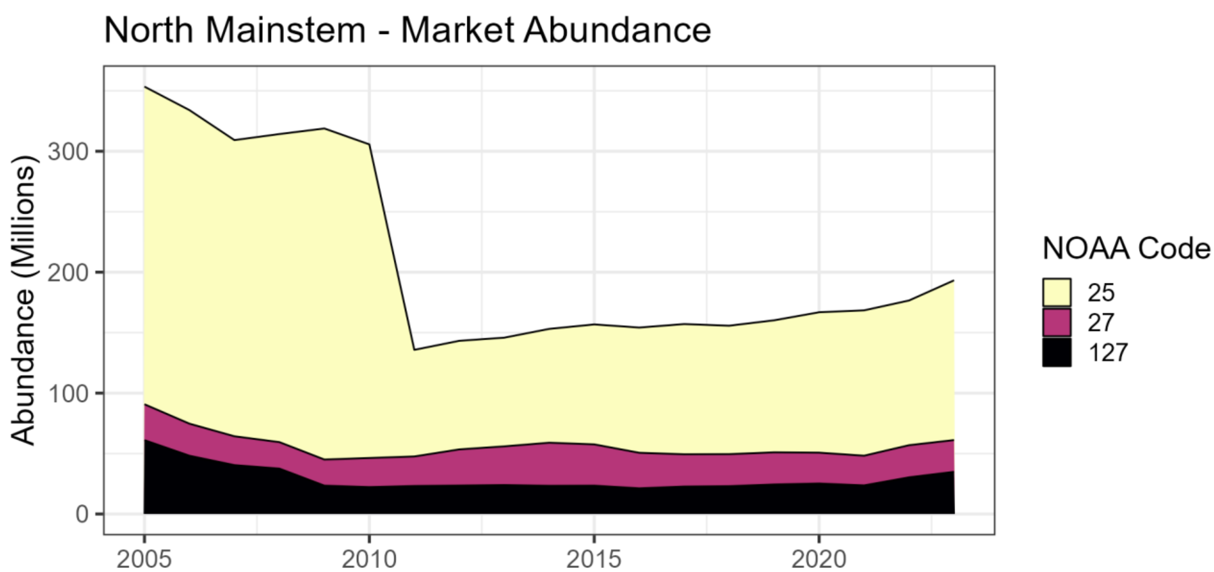

Figure 152. Estimated market oyster abundance among modeled NOAA codes in the North Mainstem Region under Maryland management during 2005-2023.

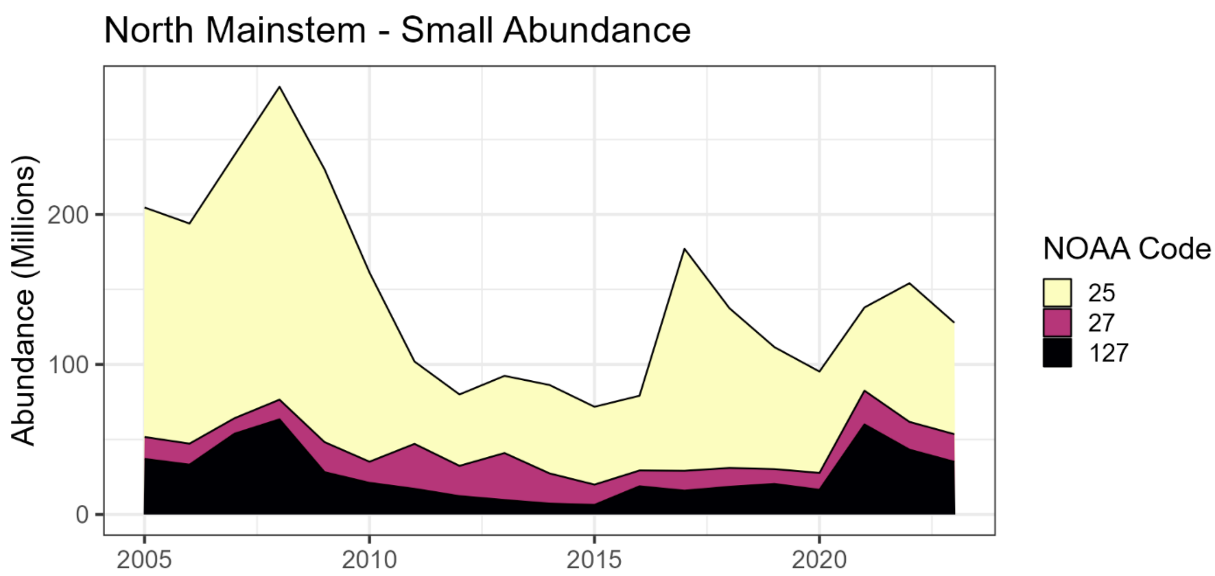

Figure 153. Estimated small oyster abundance among modeled NOAA codes in the North Mainstem Region under Maryland management during 2005-2023.

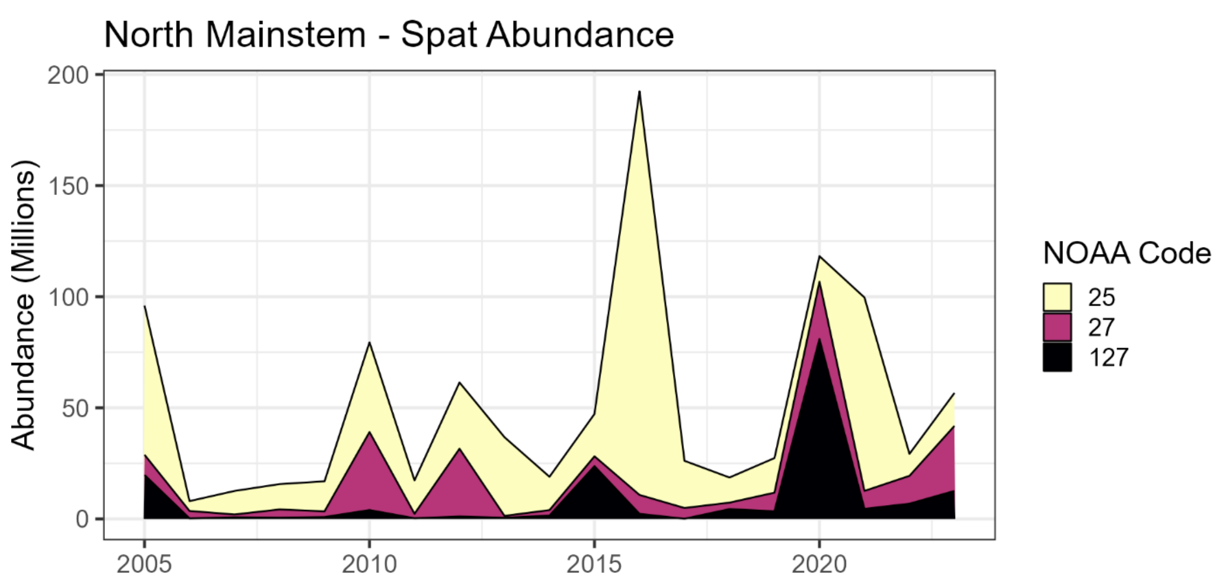

Figure 154. Estimated spat oyster abundance among modeled NOAA codes in the North Mainstem Region under Maryland management during 2005-2023.

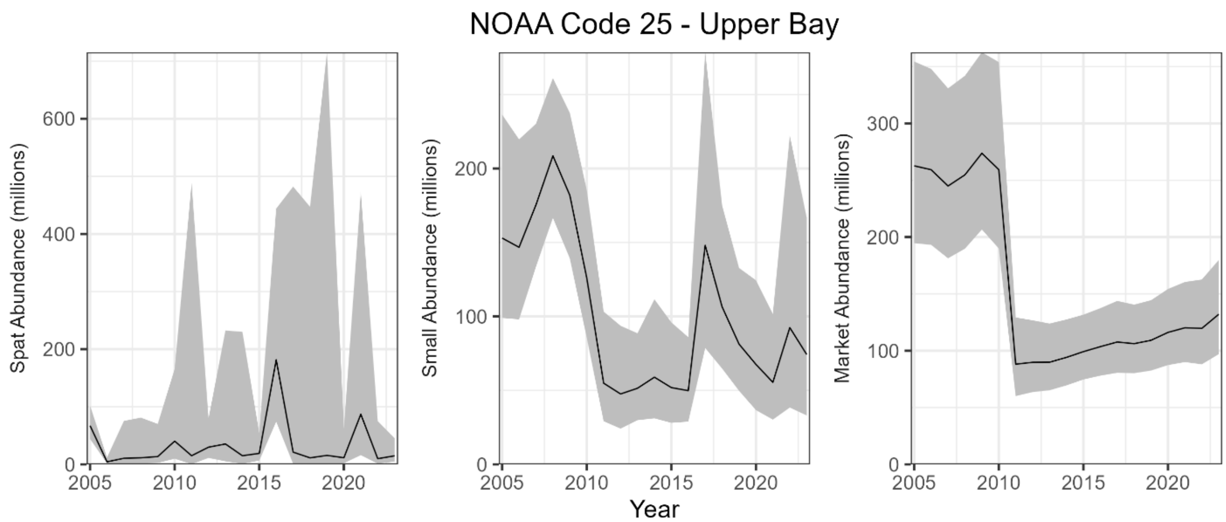

Figure 155. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Upper Bay. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

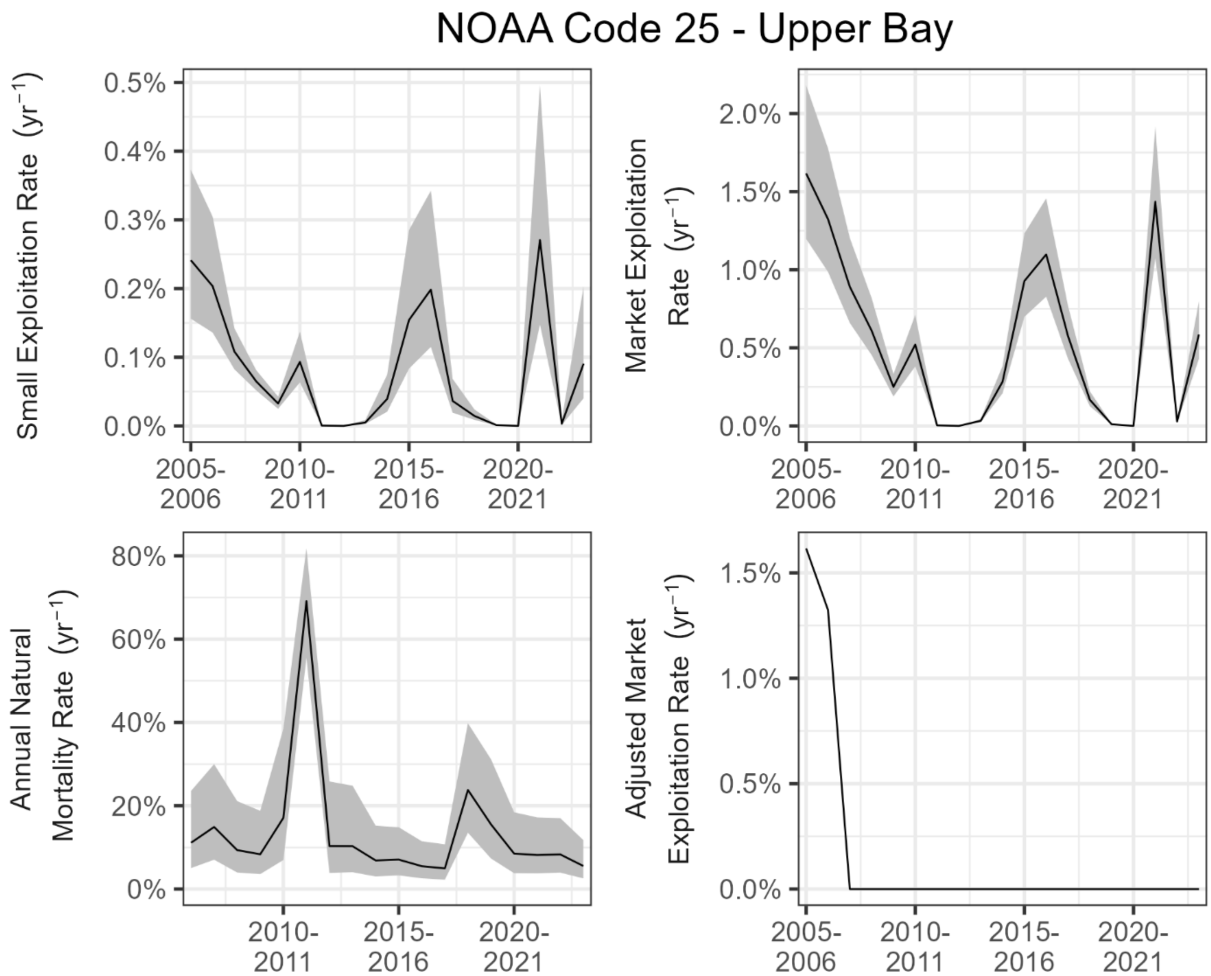

Figure 156. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Upper Bay. The shaded areas indicate approximate 95% confidence intervals.

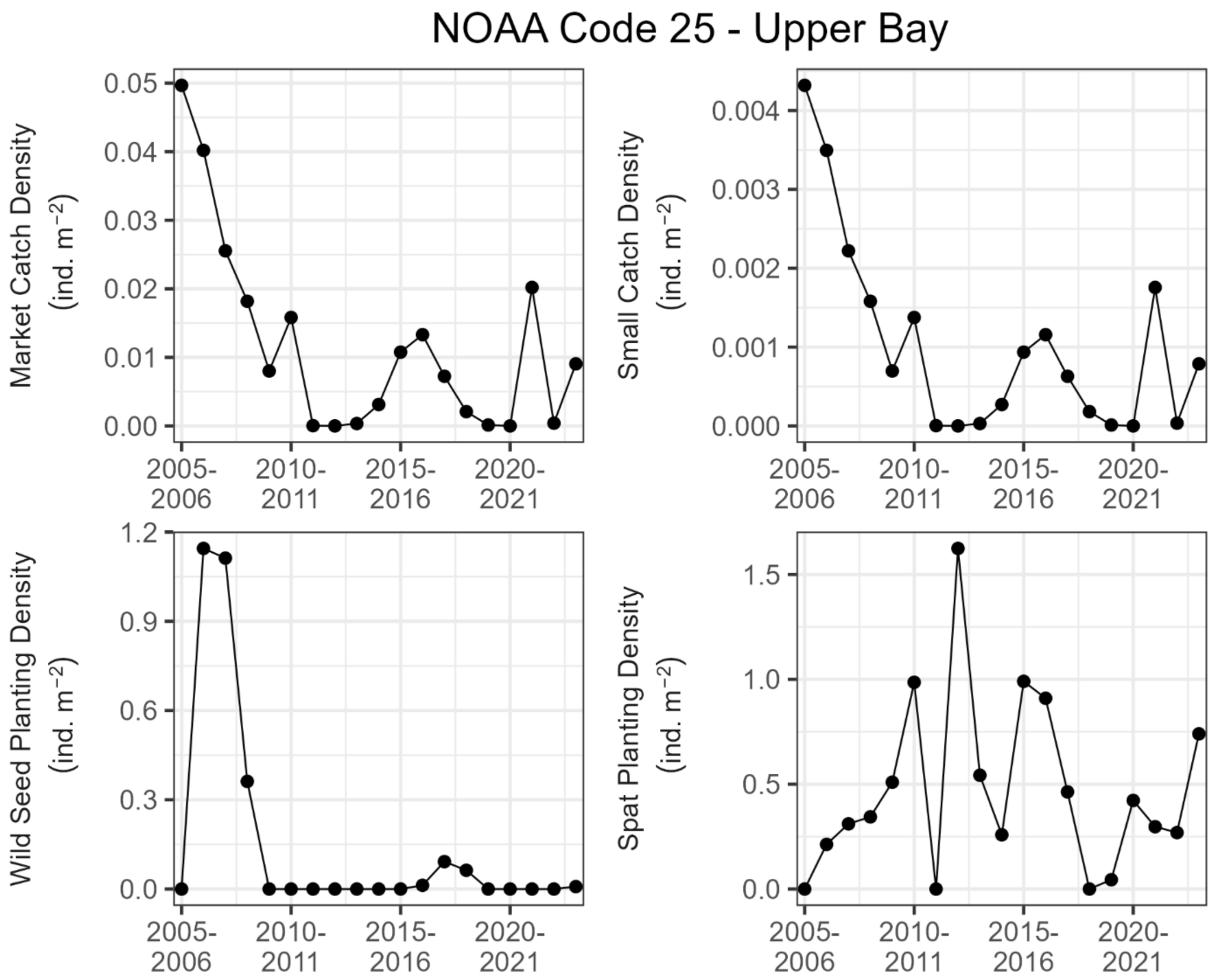

Figure 157. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Upper Bay. Density was calculated as the number of individuals divided by habitat area for each data source.

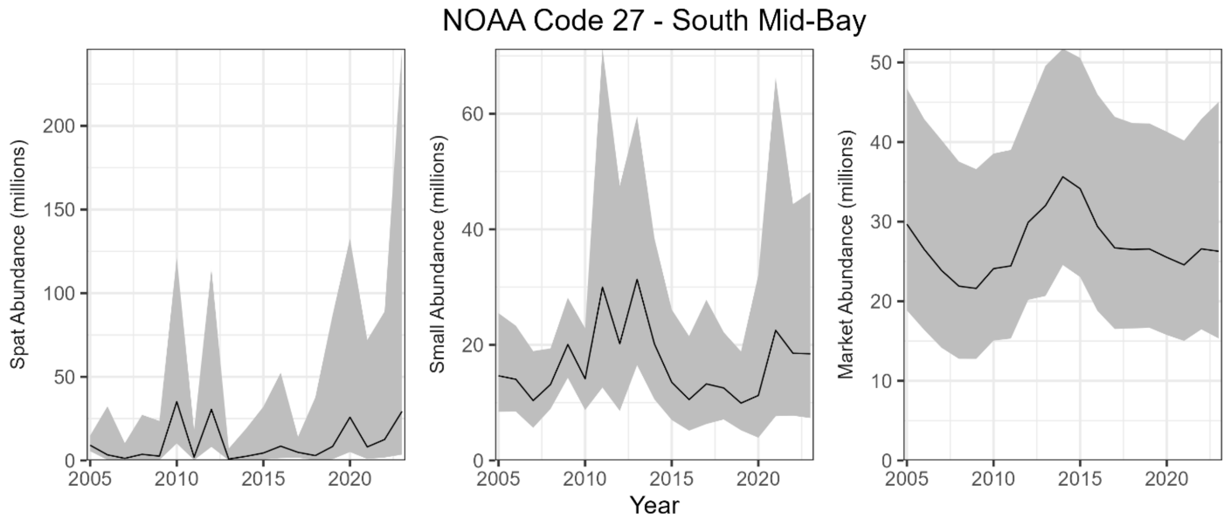

Figure 158. Estimated abundance of spat, small, and markets oysters during 2005-2023 in South Mid-Bay. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

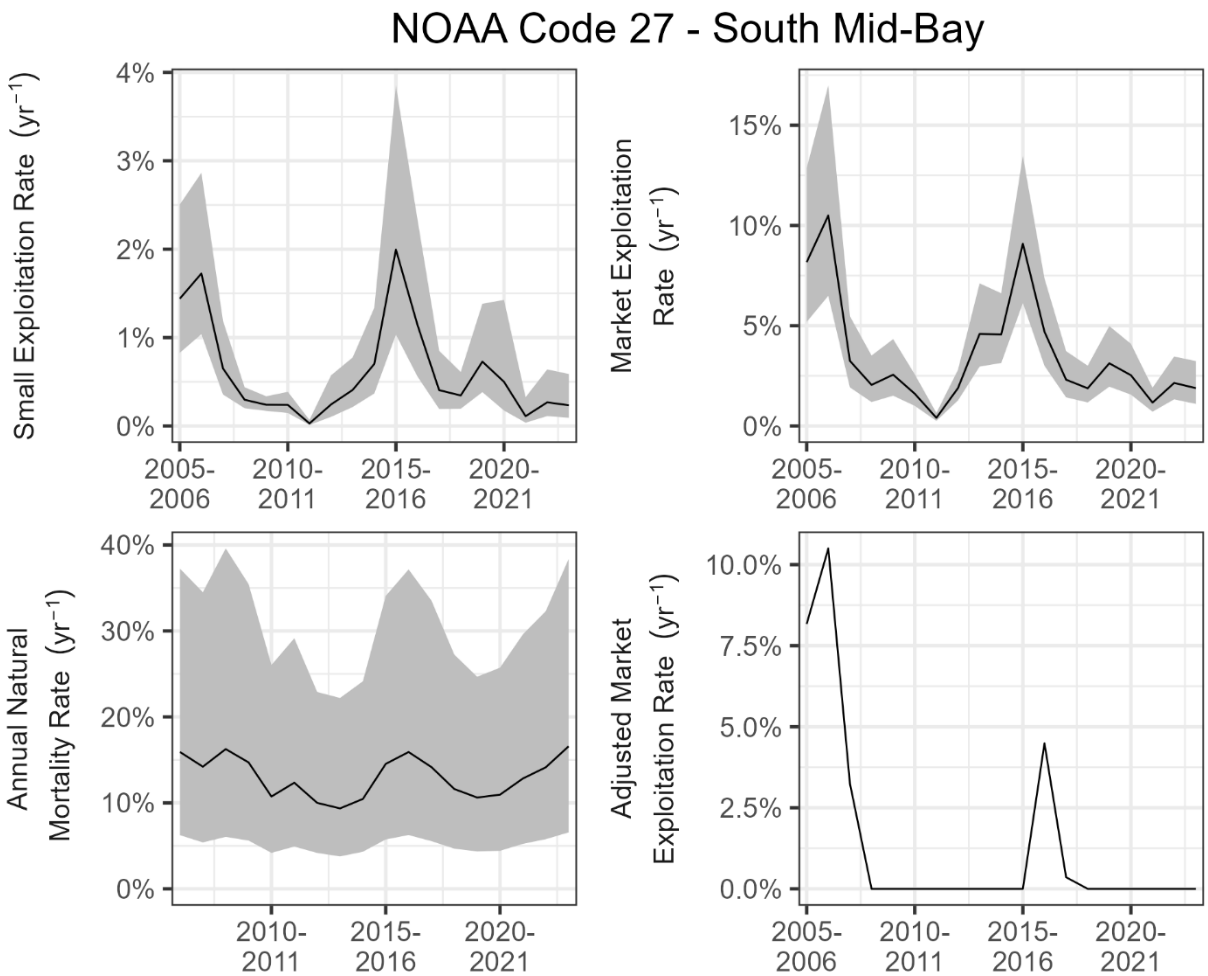

Figure 159. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in South Mid-Bay. The shaded areas indicate approximate 95% confidence intervals.

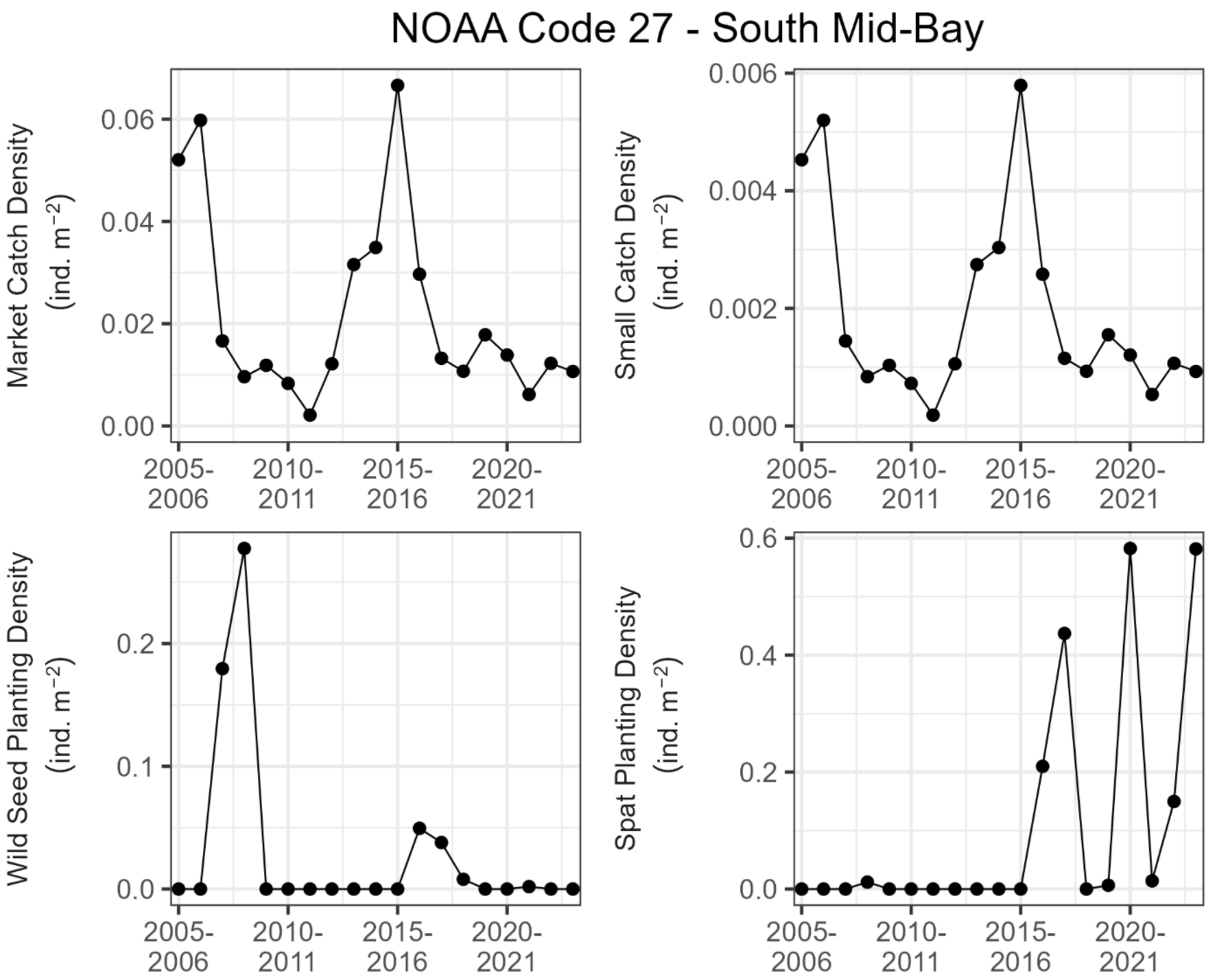

Figure 160. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in South Mid-Bay. Density was calculated as the number of individuals divided by habitat area for each data source.

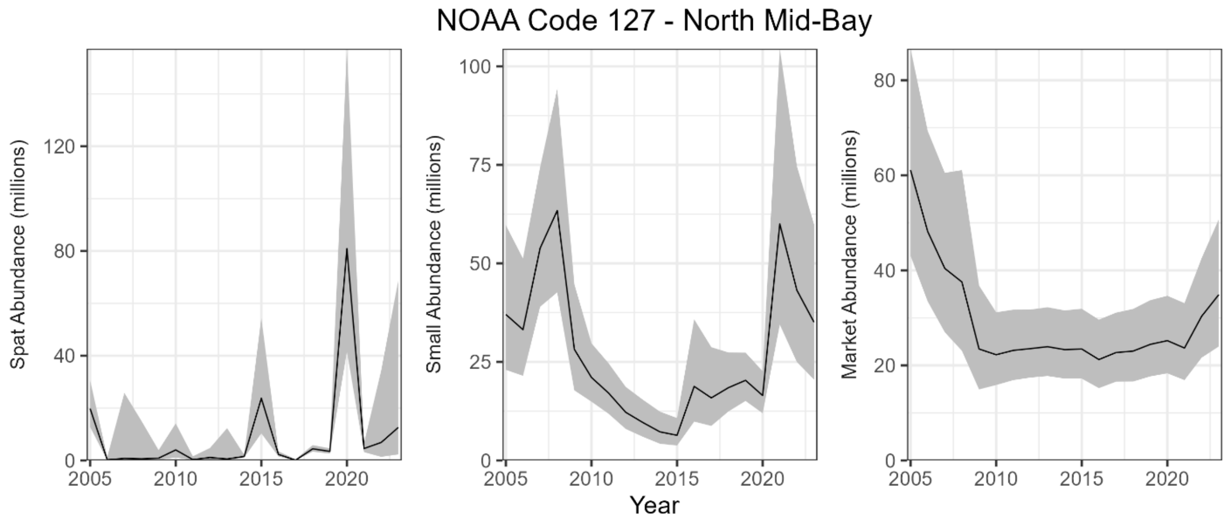

Figure 161. Estimated abundance of spat, small, and markets oysters during 2005-2023 in North Mid-Bay. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

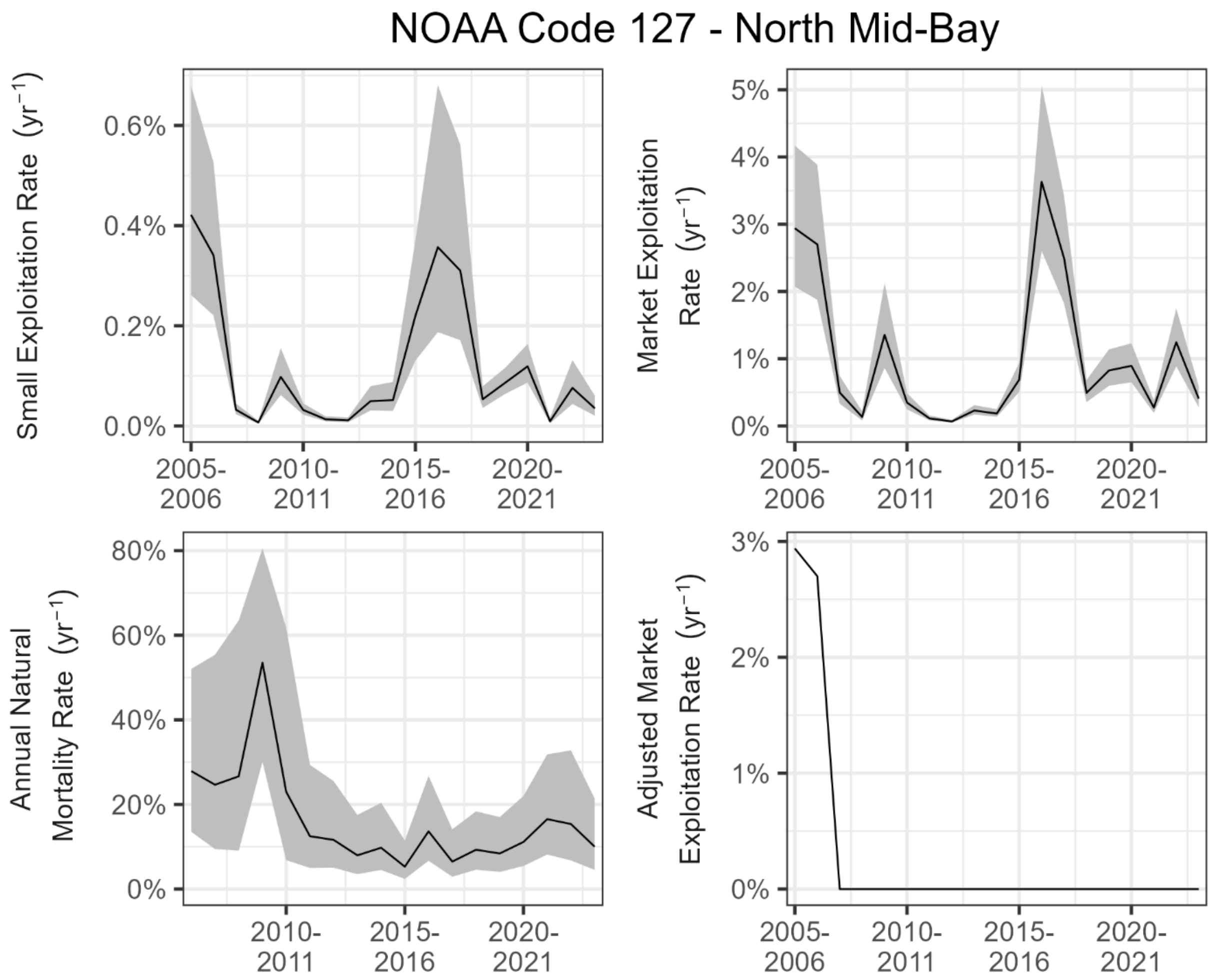

Figure 162. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in North Mid-Bay. The shaded areas indicate approximate 95% confidence intervals.

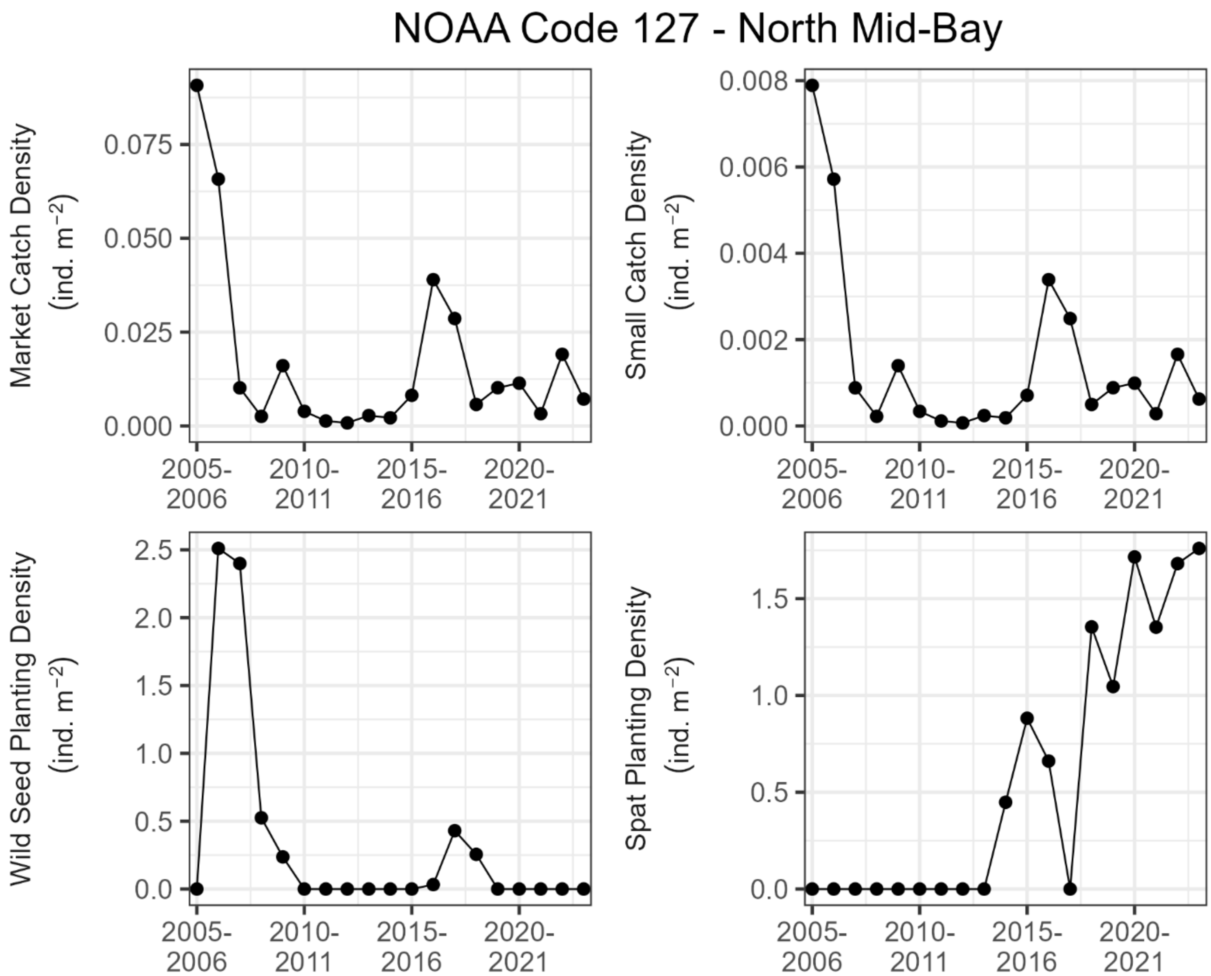

Figure 163. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in North Mid-Bay. Density was calculated as the number of individuals divided by habitat area for each data source.

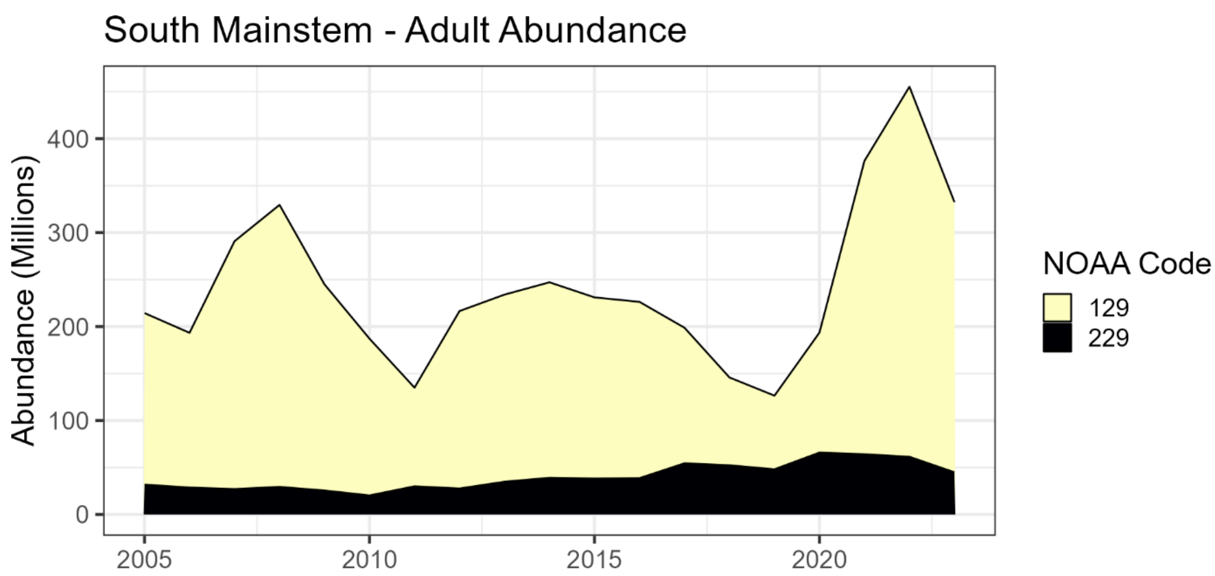

Figure 164. Estimated adult oyster abundance among modeled NOAA codes in the South Mainstem Region under Maryland management during 2005-2023.

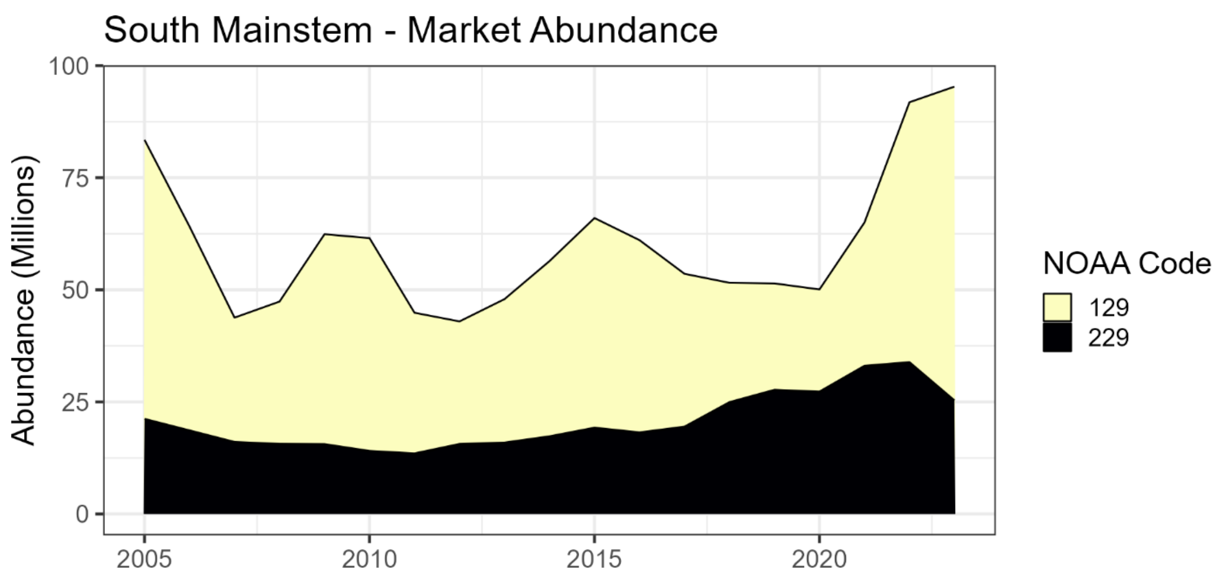

Figure 165. Estimated market oyster abundance among modeled NOAA codes in the South Mainstem Region under Maryland management during 2005-2023.

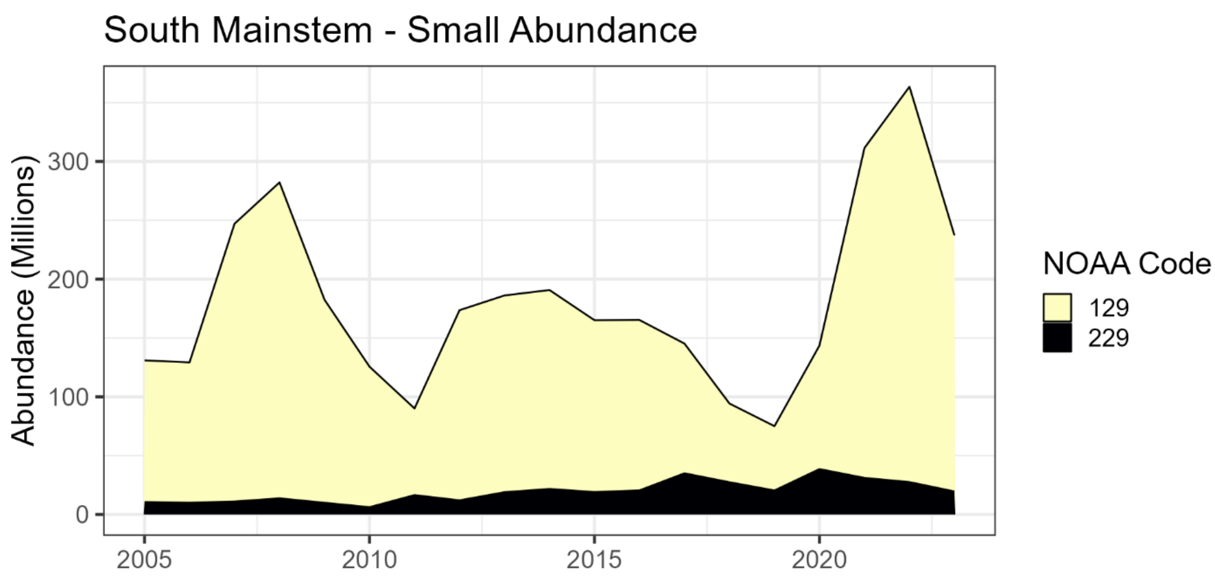

Figure 166. Estimated small oyster abundance among modeled NOAA codes in the South Mainstem Region under Maryland management during 2005-2023.

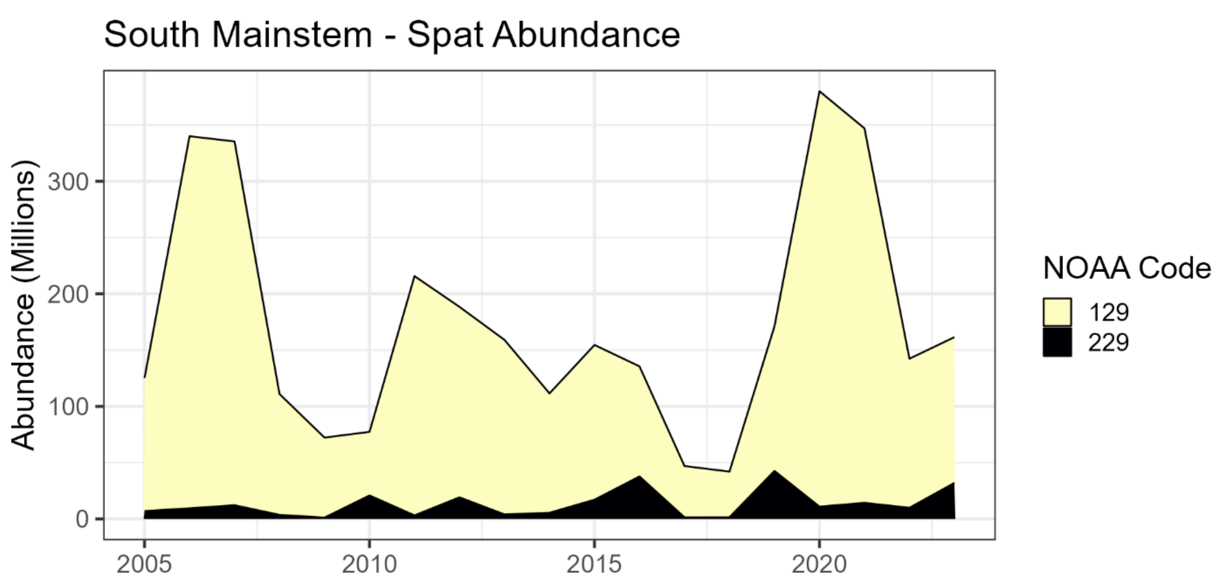

Figure 167. Estimated spat oyster abundance among modeled NOAA codes in the South Mainstem Region under Maryland management during 2005-2023.

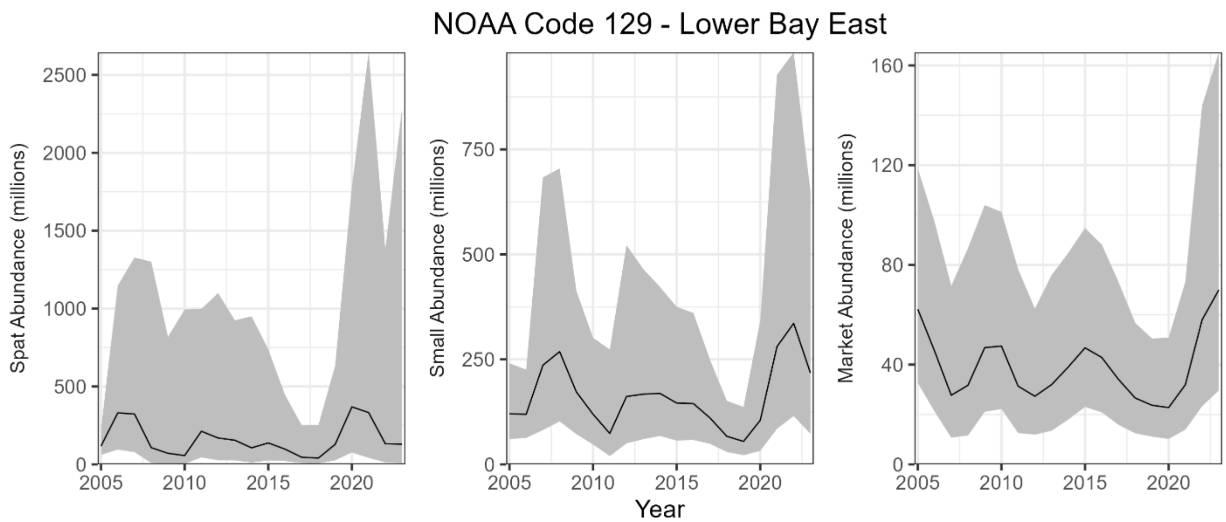

Figure 168. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Lower Bay East. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

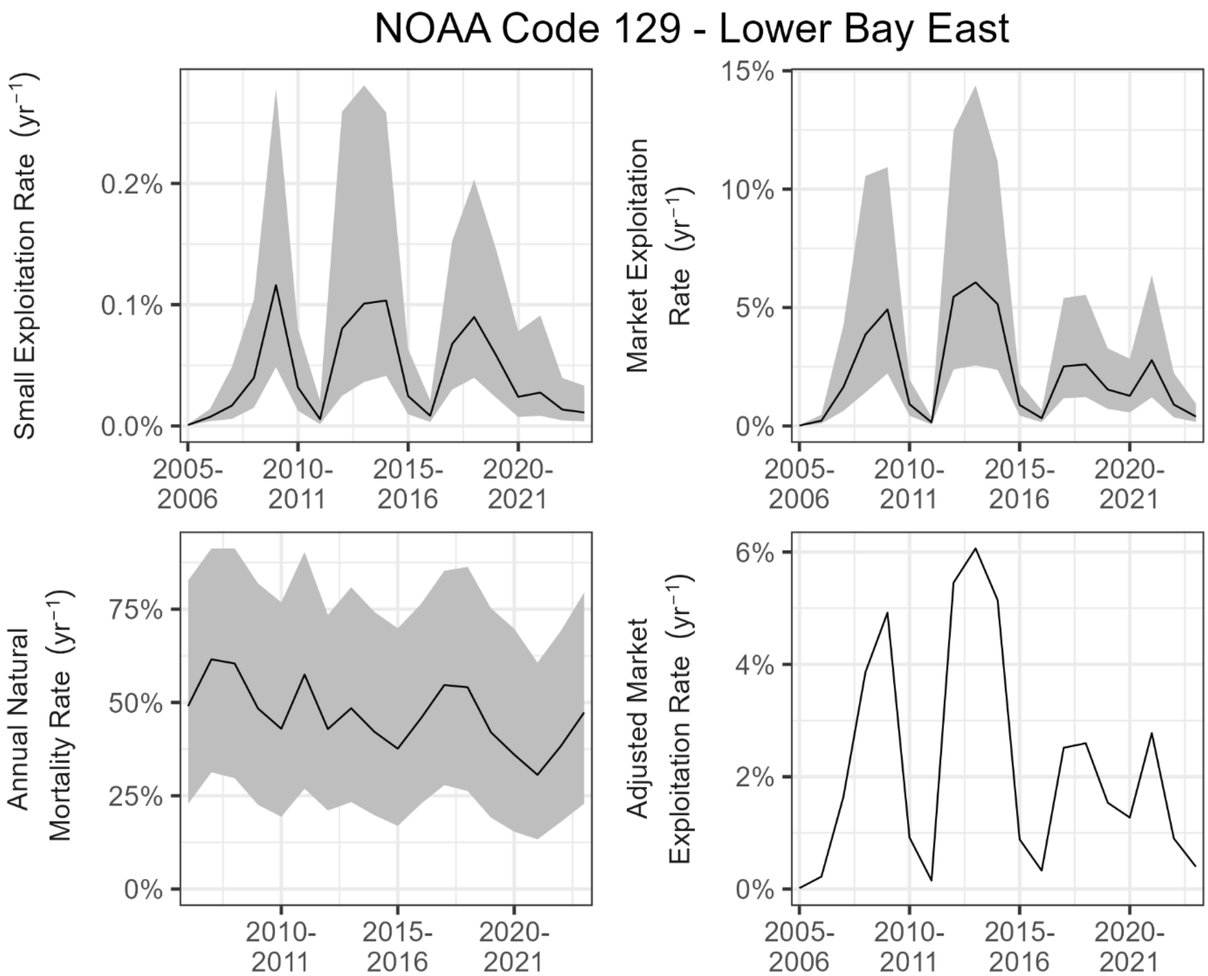

Figure 169. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Lower Bay East. The shaded areas indicate approximate 95% confidence intervals.

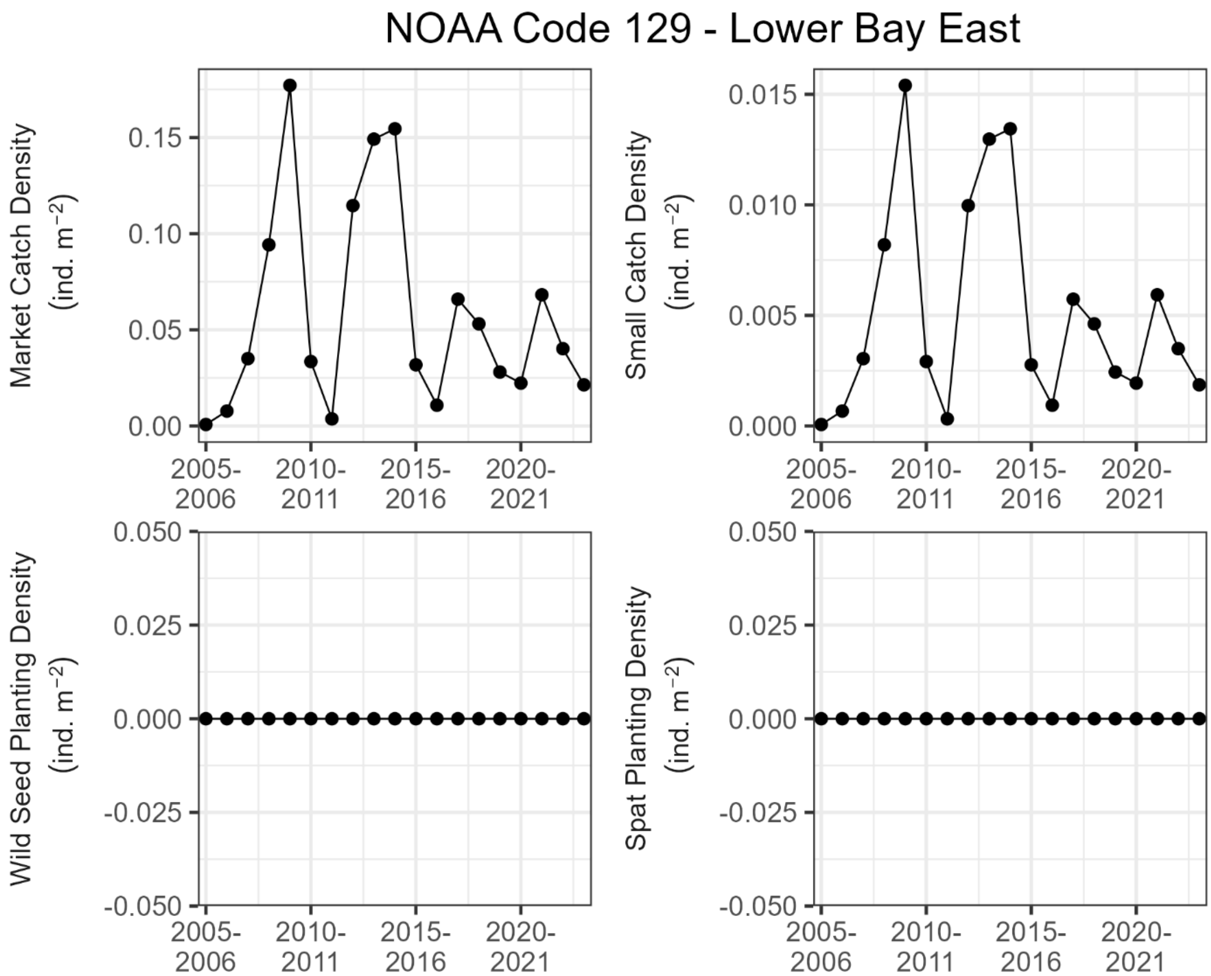

Figure 170. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Lower Bay East. Density was calculated as the number of individuals divided by habitat area for each data source.

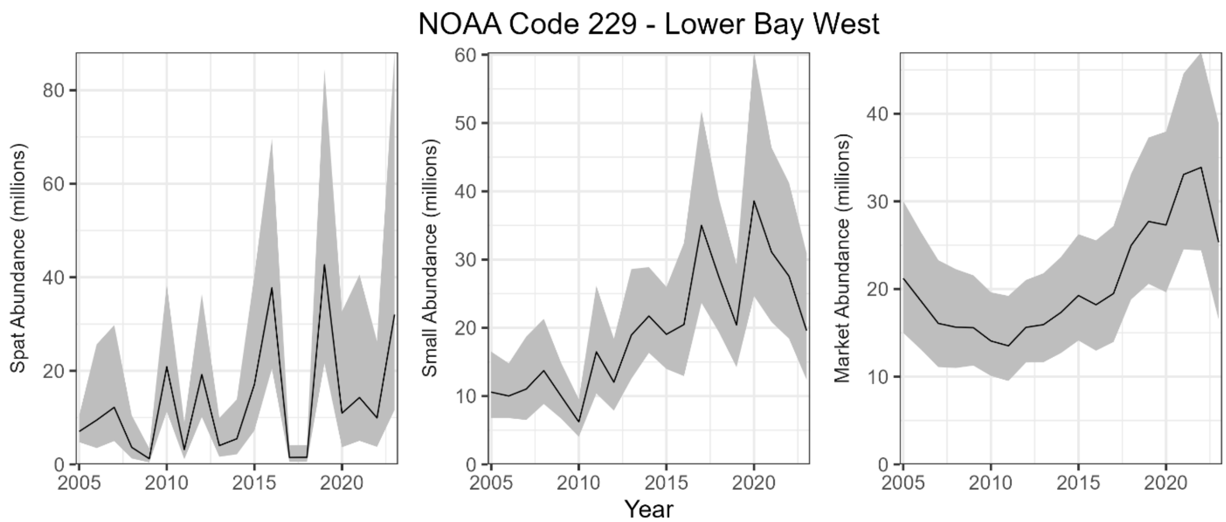

Figure 171. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Lower Bay West. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

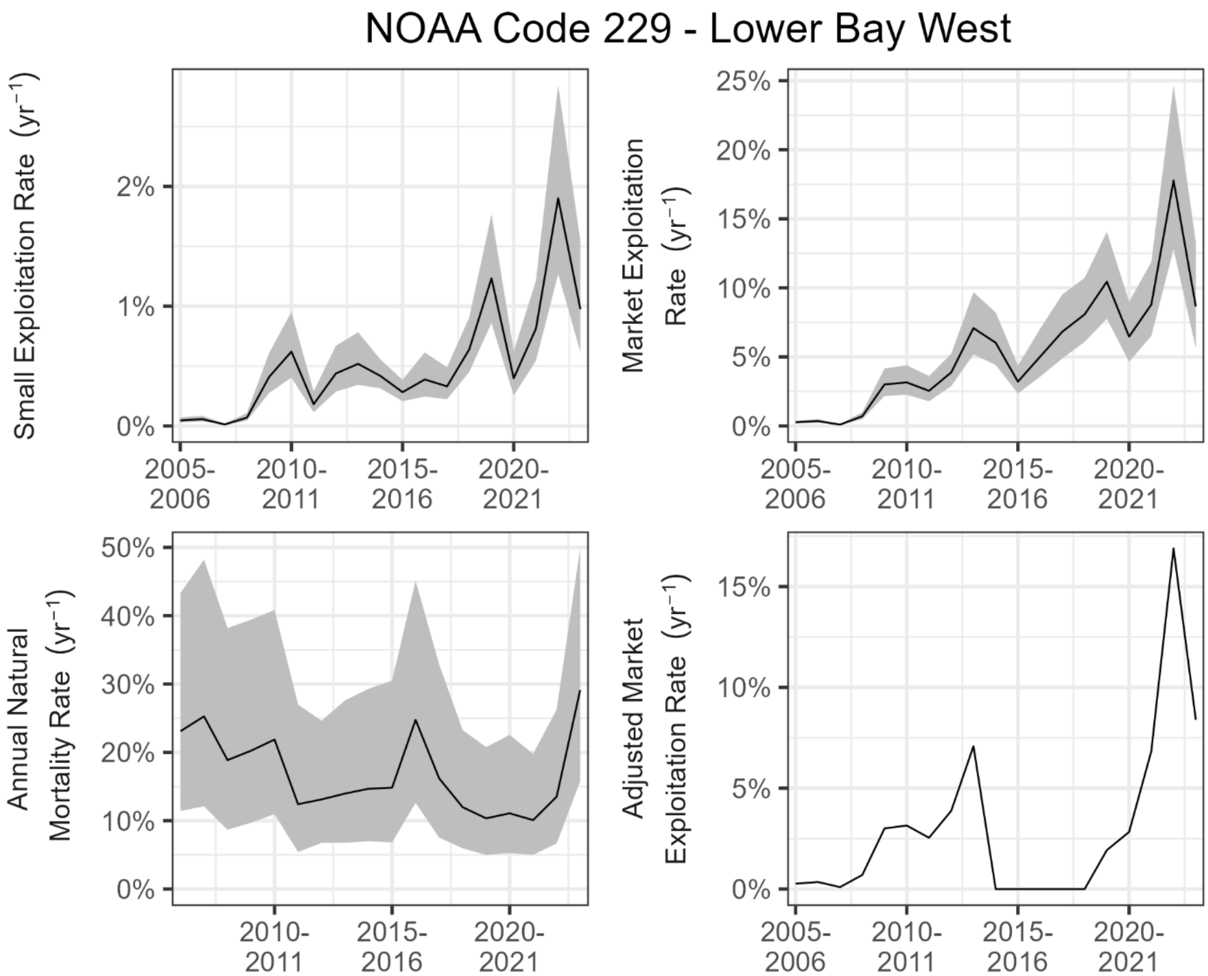

Figure 172. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Lower Bay West. The shaded areas indicate approximate 95% confidence intervals.

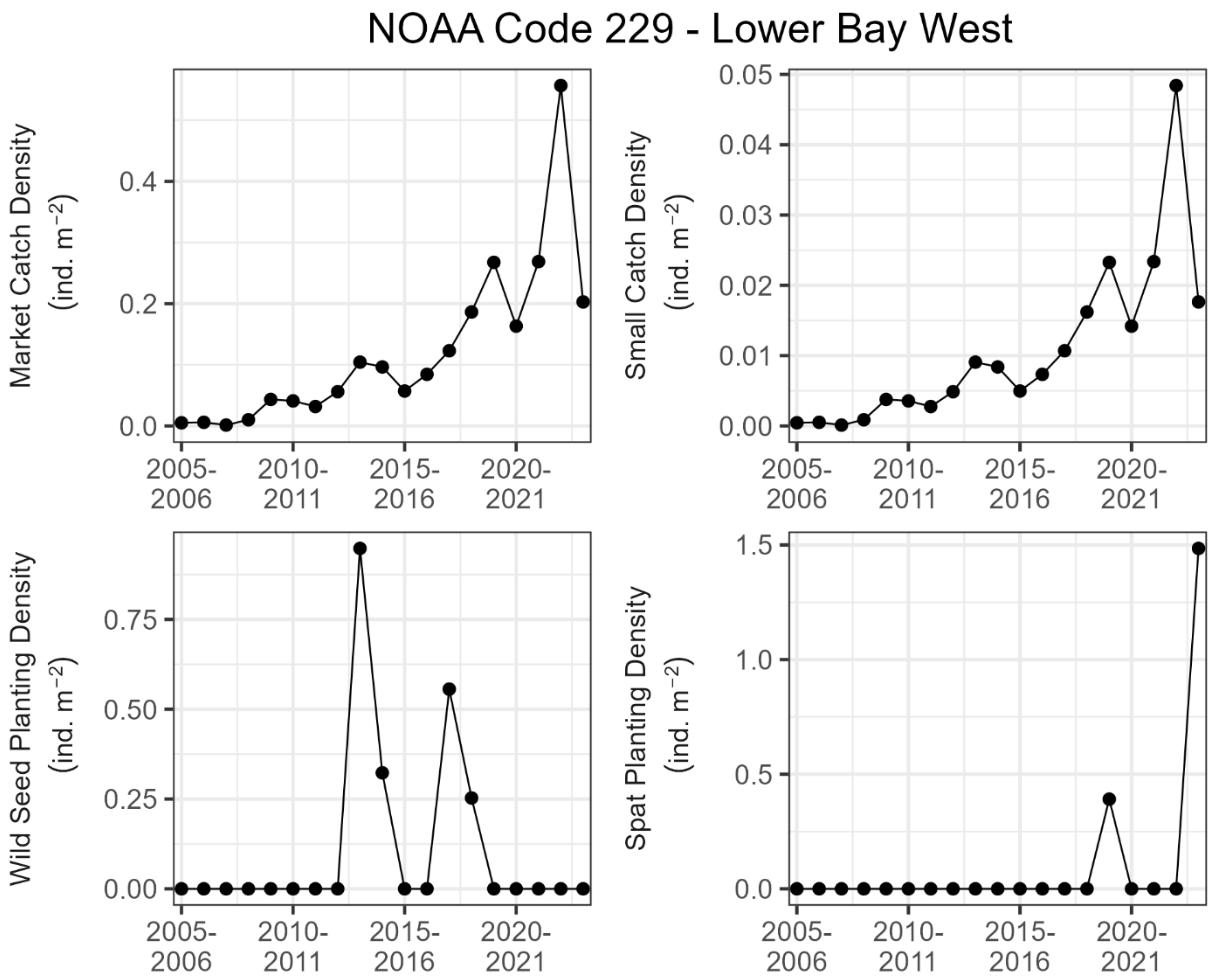

Figure 173. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Lower Bay West. Density was calculated as the number of individuals divided by habitat area for each data source.

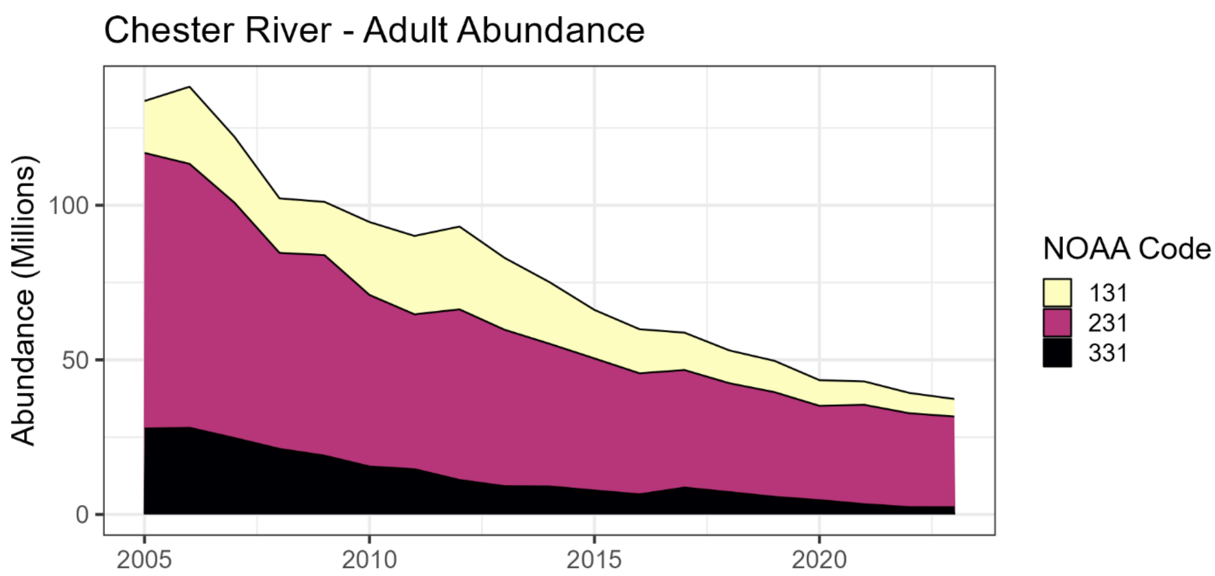

Figure 174. Estimated adult oyster abundance among modeled NOAA codes in the Chester River Region under Maryland management during 2005-2023.

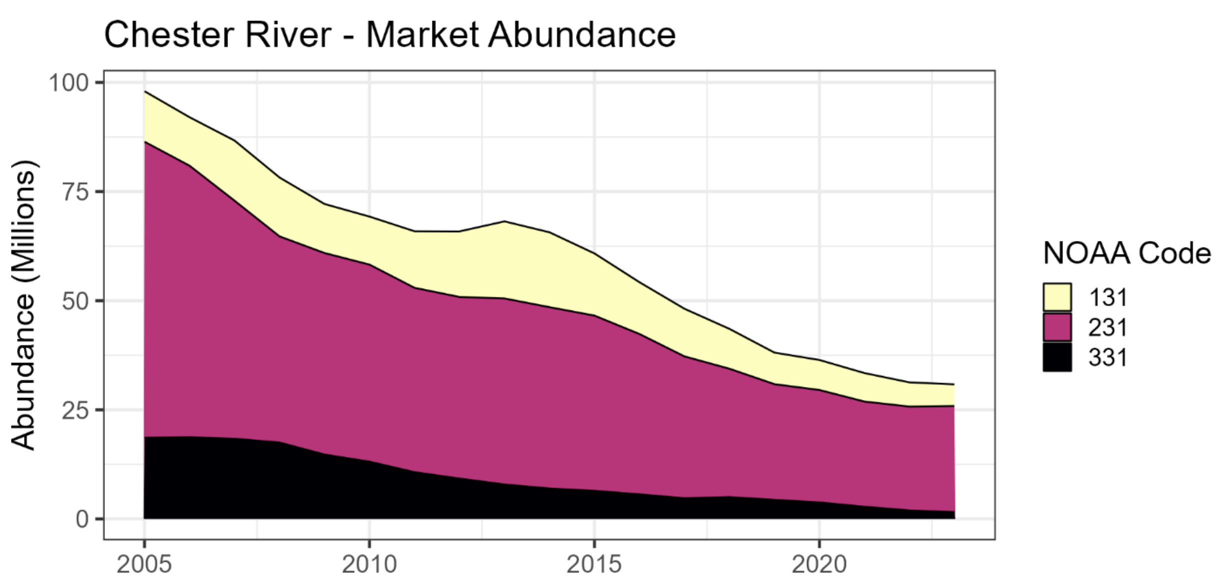

Figure 175. Estimated market oyster abundance among modeled NOAA codes in the Chester River Region under Maryland management during 2005-2023.

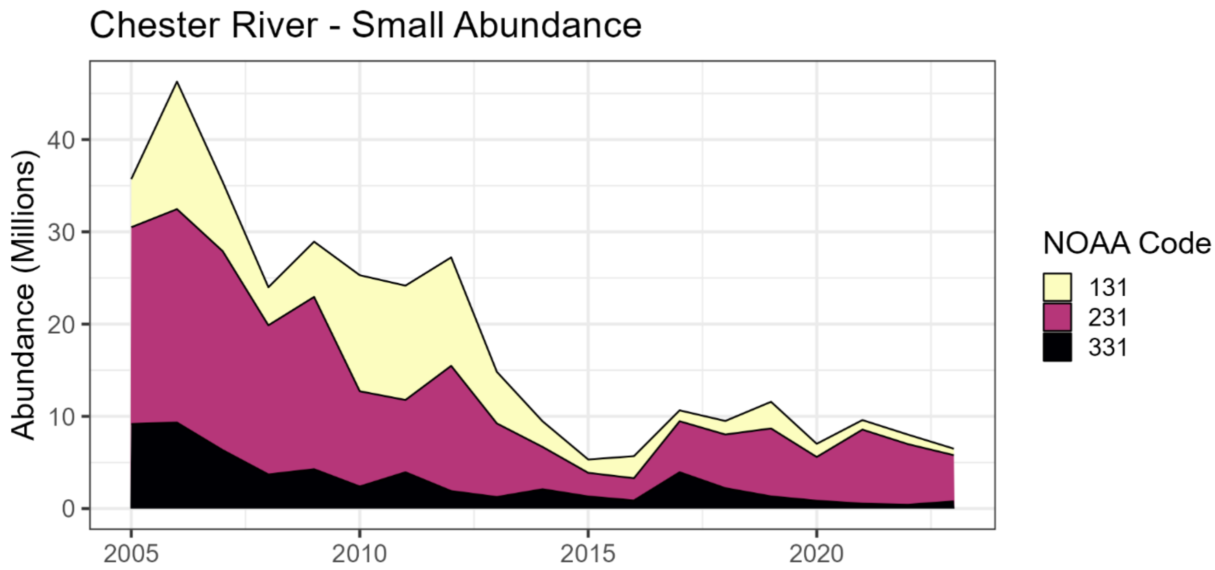

Figure 176. Estimated small oyster abundance among modeled NOAA codes in the Chester River Region under Maryland management during 2005-2023.

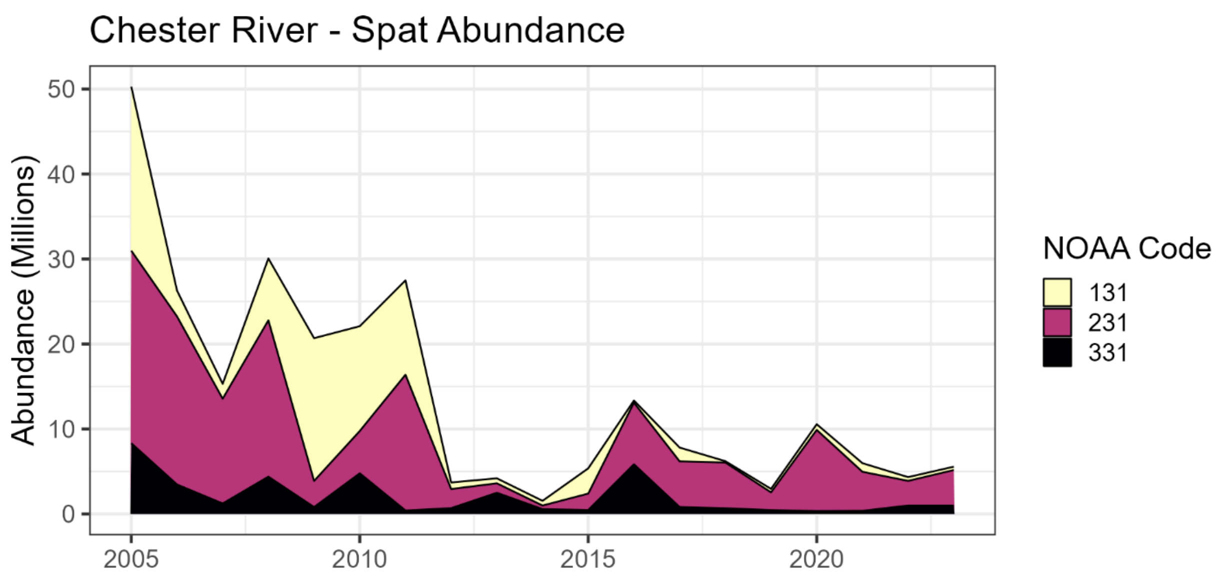

Figure 177. Estimated spat oyster abundance among modeled NOAA codes in the Chester River Region under Maryland management during 2005-2023.

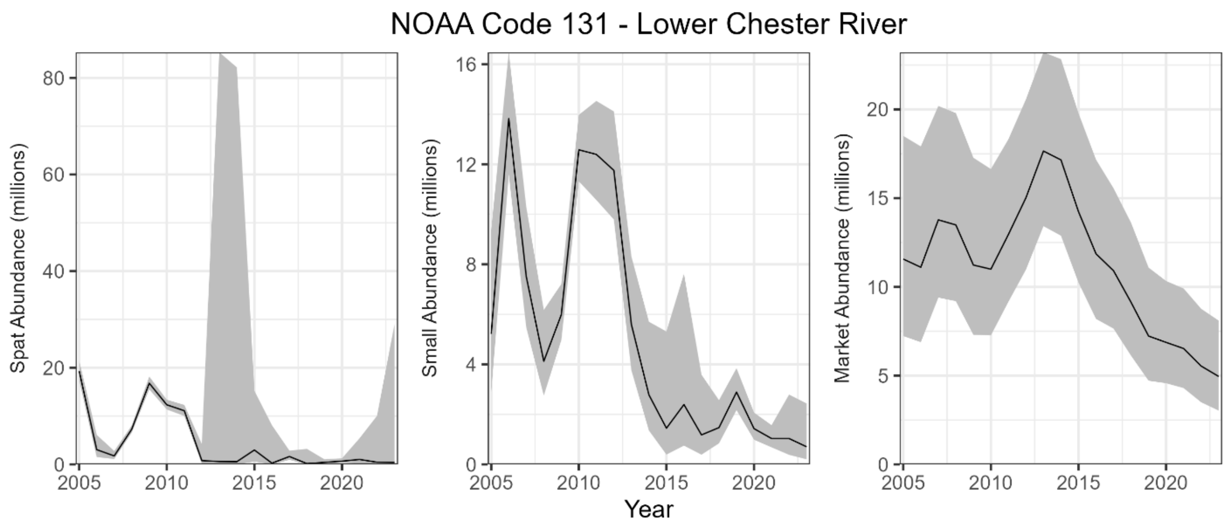

Figure 178. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Lower Chester River. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

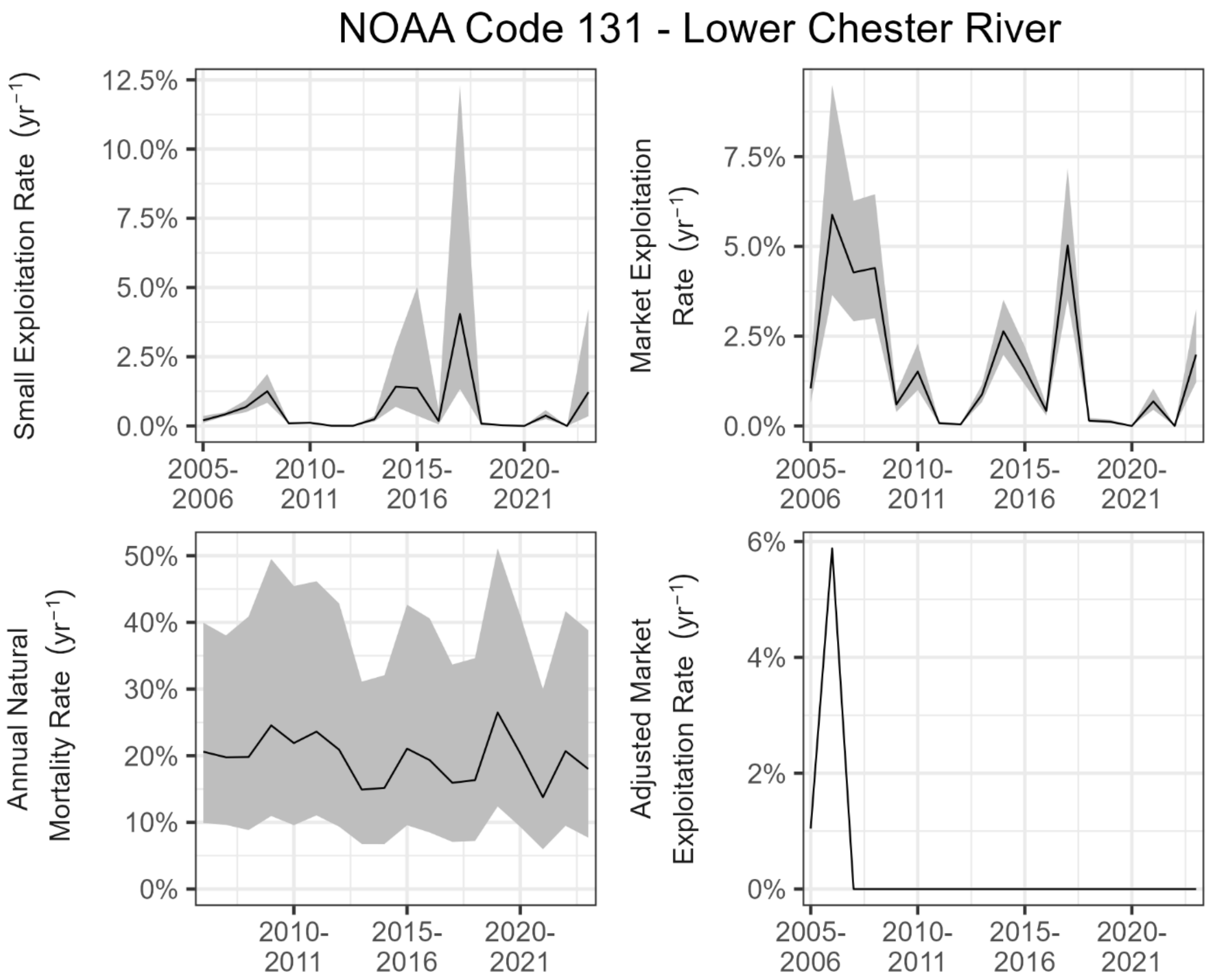

Figure 179. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Lower Chester River. The shaded areas indicate approximate 95% confidence intervals.

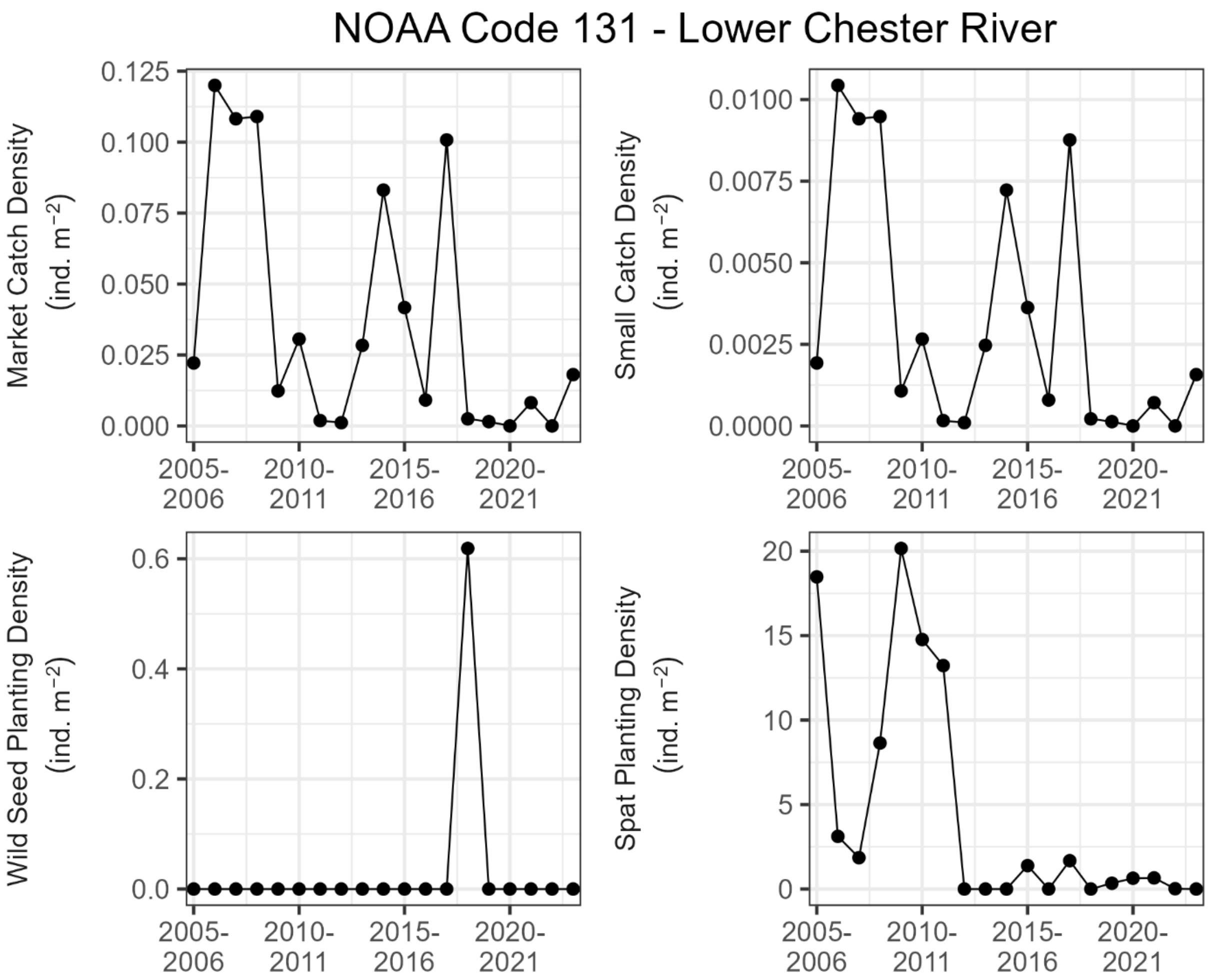

Figure 180. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Lower Chester River. Density was calculated as the number of individuals divided by habitat area for each data source.

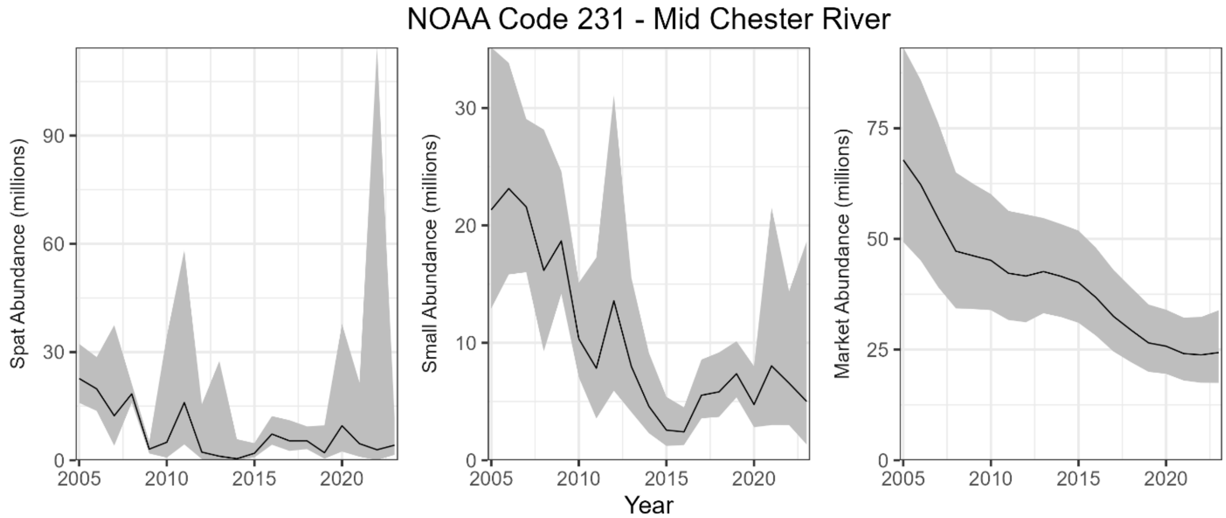

Figure 181. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Mid Chester River. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

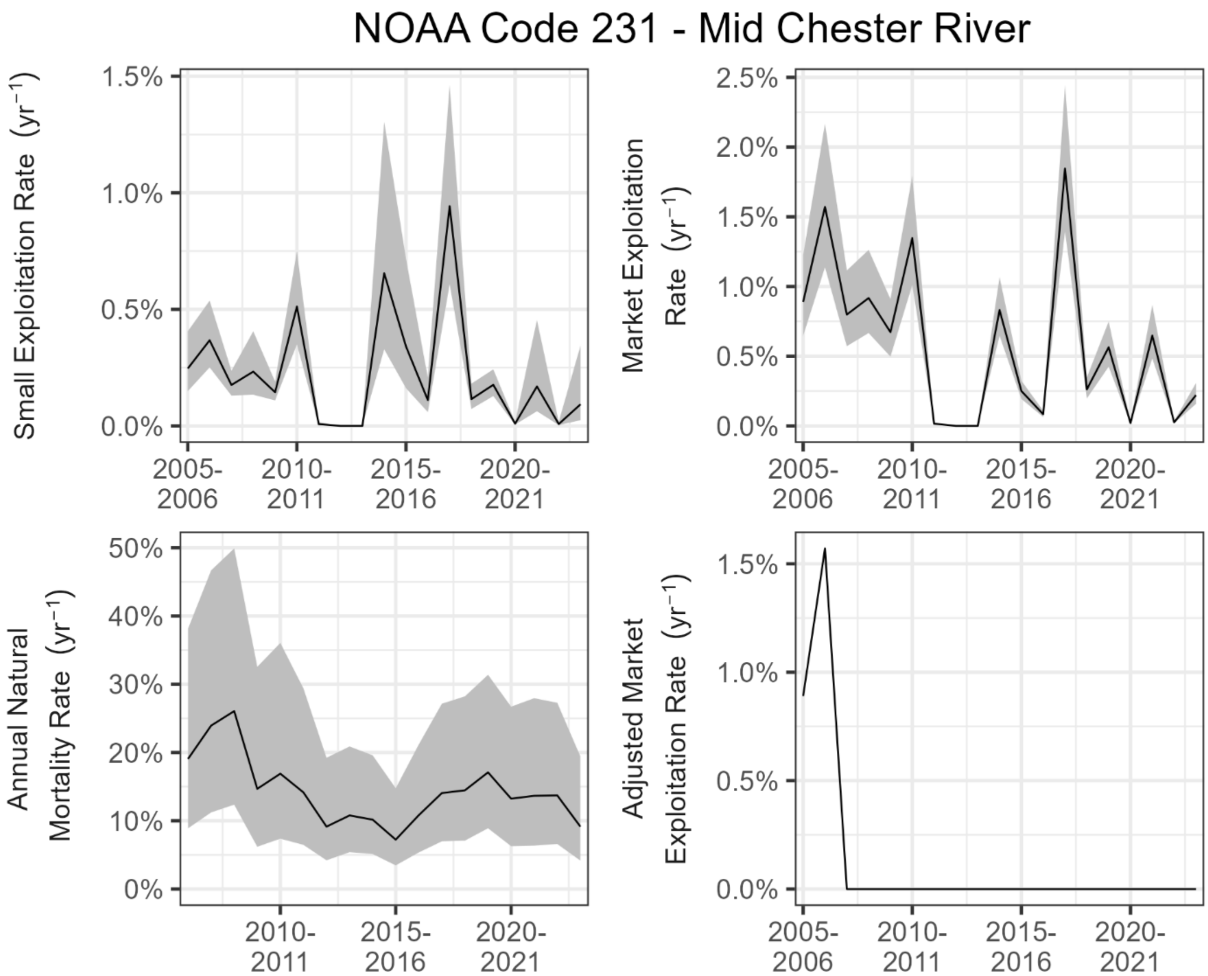

Figure 182. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Mid Chester River. The shaded areas indicate approximate 95% confidence intervals.

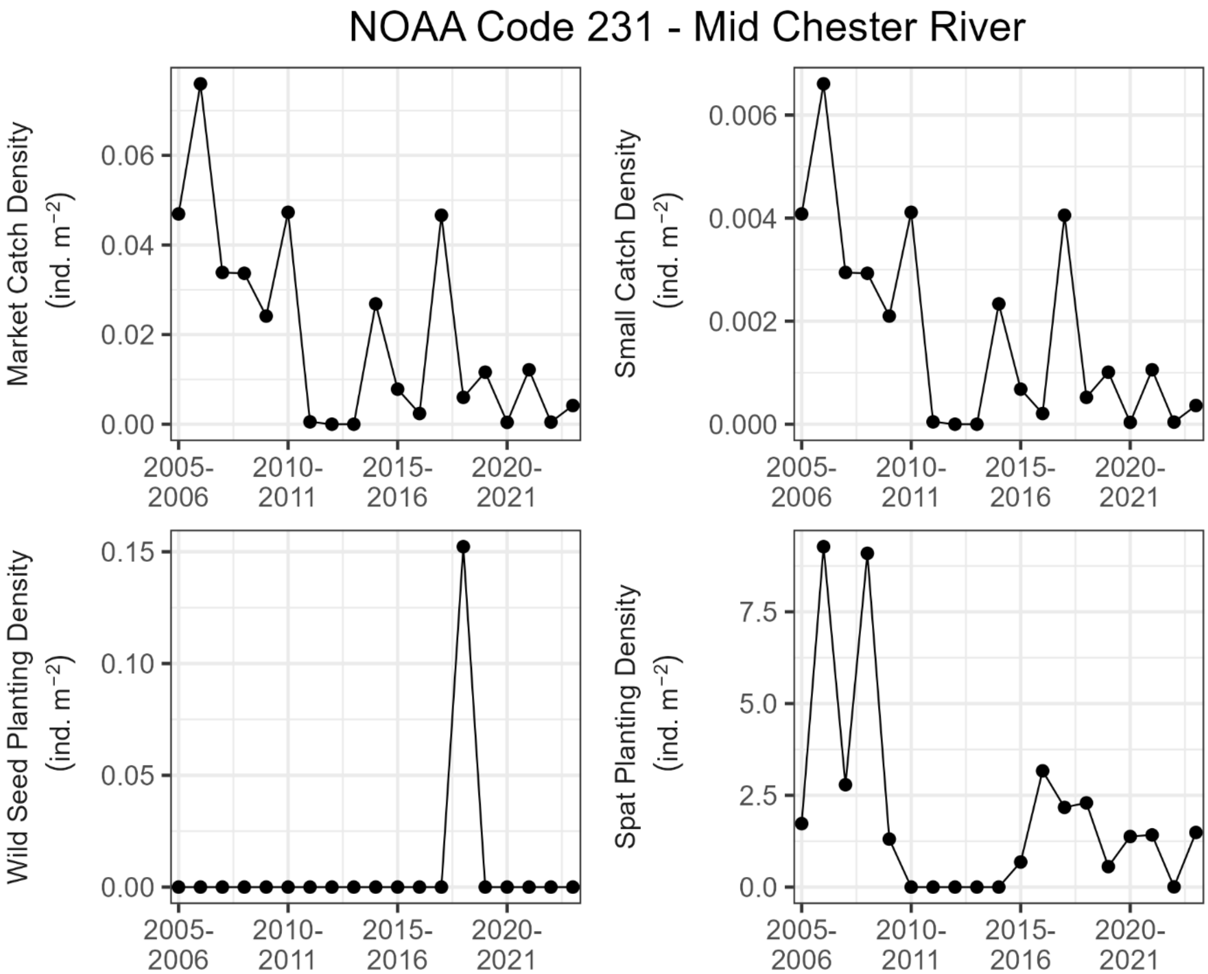

Figure 183. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Mid Chester River. Density was calculated as the number of individuals divided by habitat area for each data source.

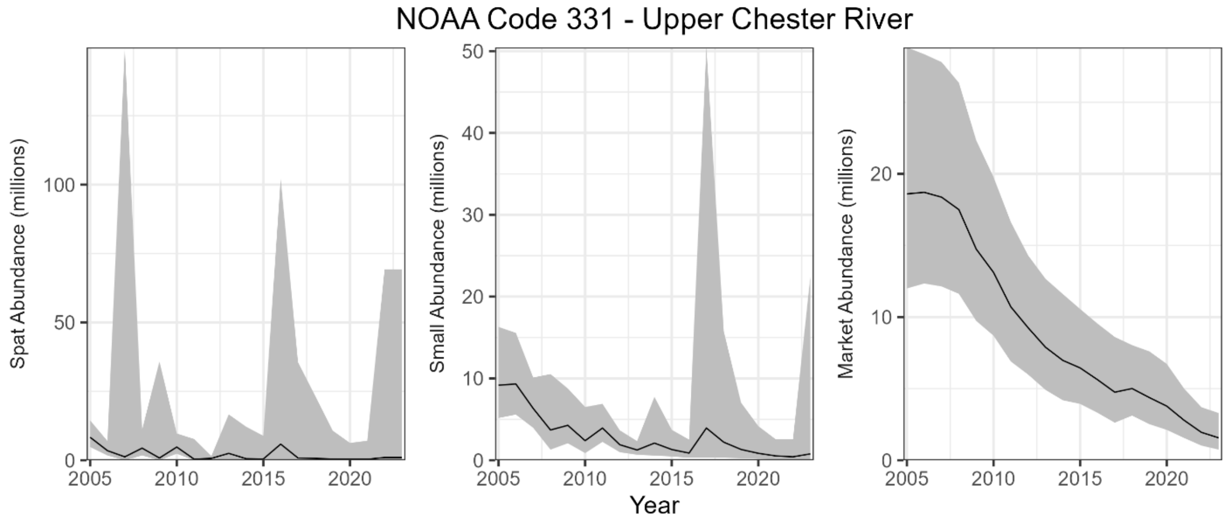

Figure 184. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Upper Chester River. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

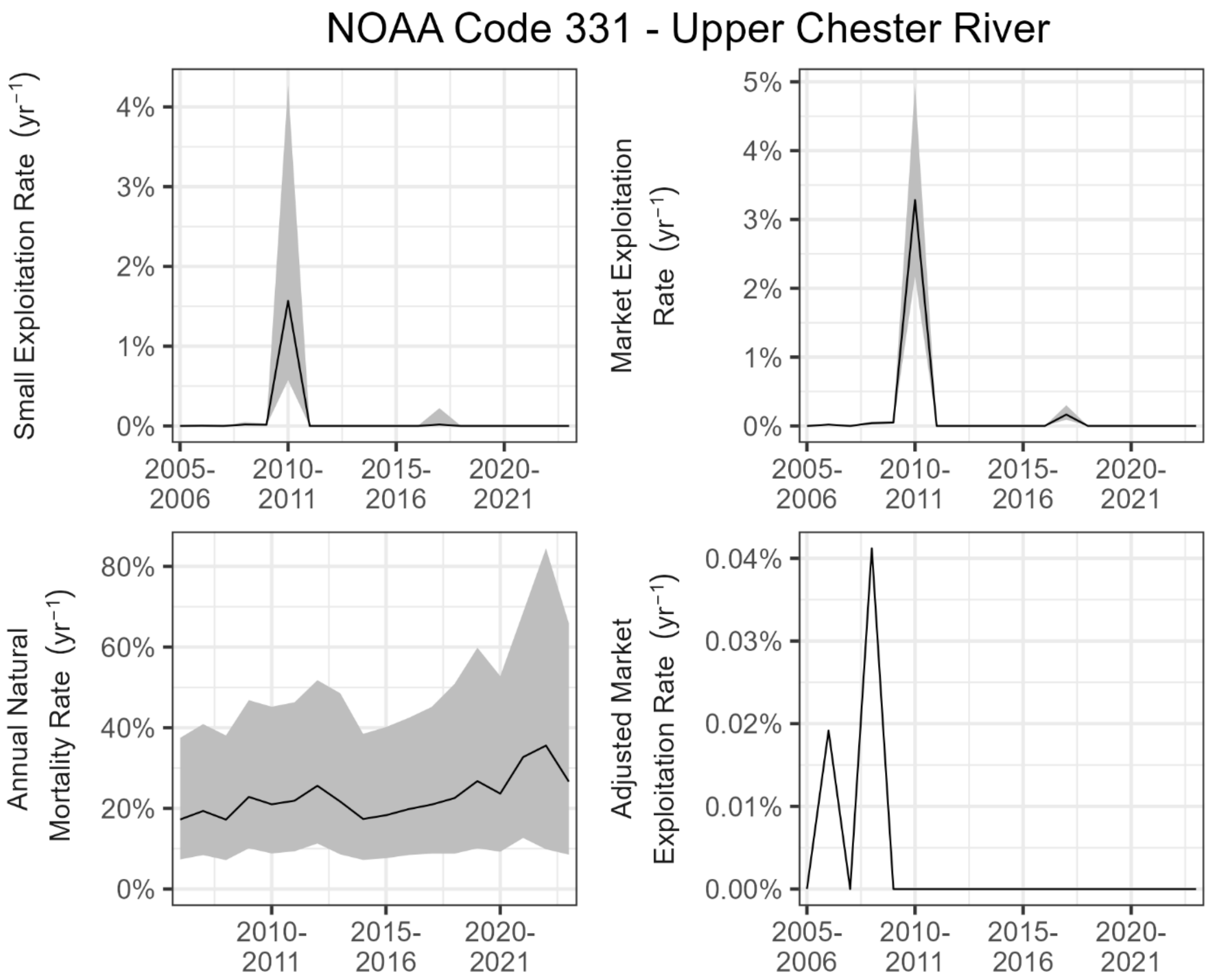

Figure 185. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Upper Chester River. The shaded areas indicate approximate 95% confidence intervals.

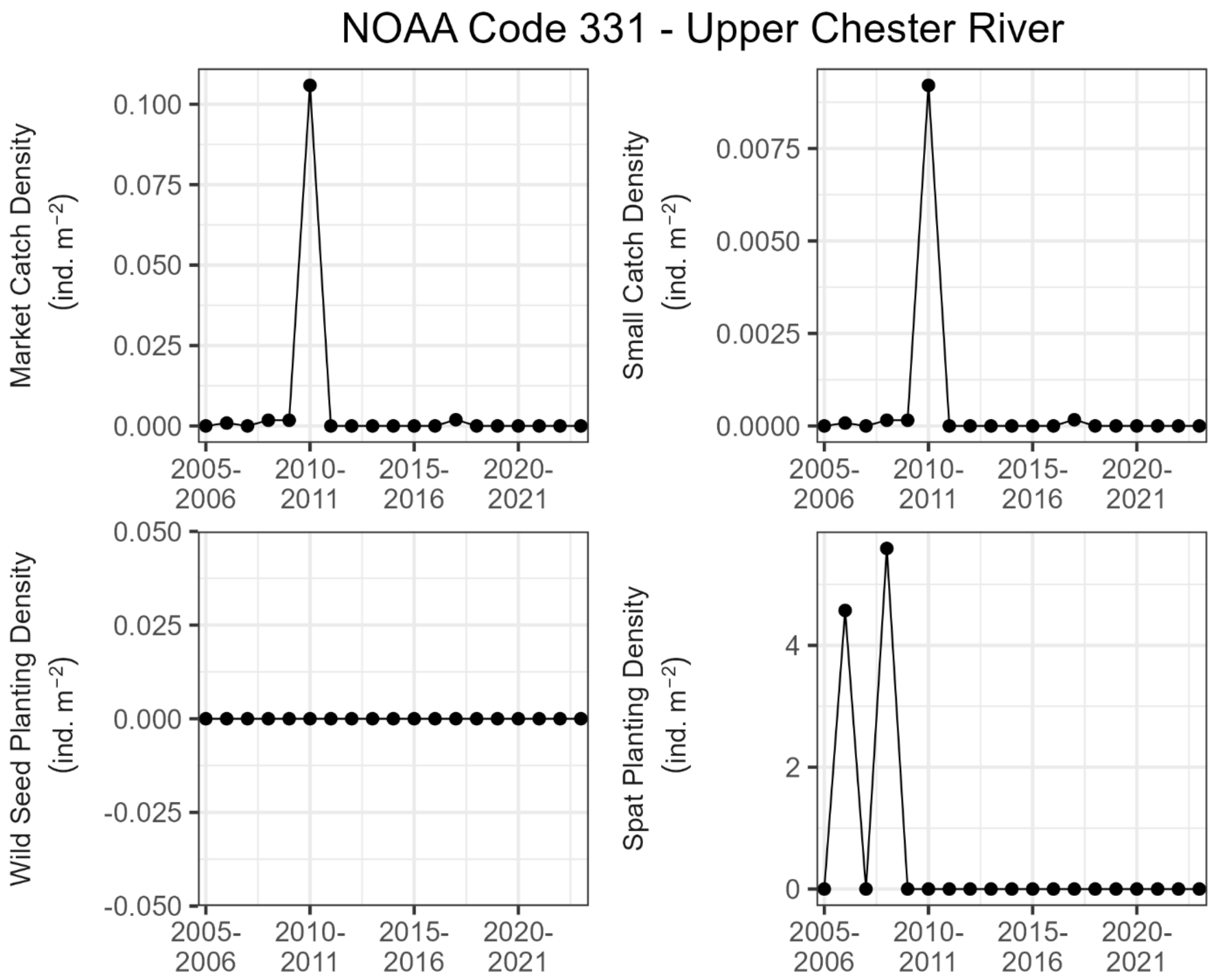

Figure 186. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Upper Chester River. Density was calculated as the number of individuals divided by habitat area for each data source.

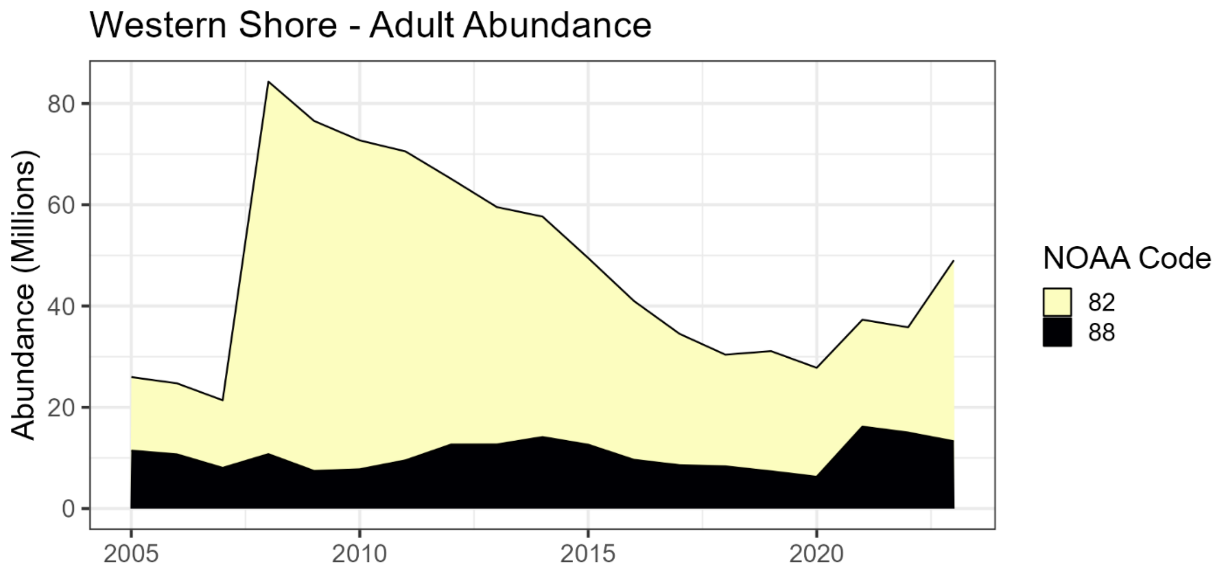

Figure 187. Estimated adult oyster abundance among modeled NOAA codes in the Western Shore Region under Maryland management during 2005-2023.

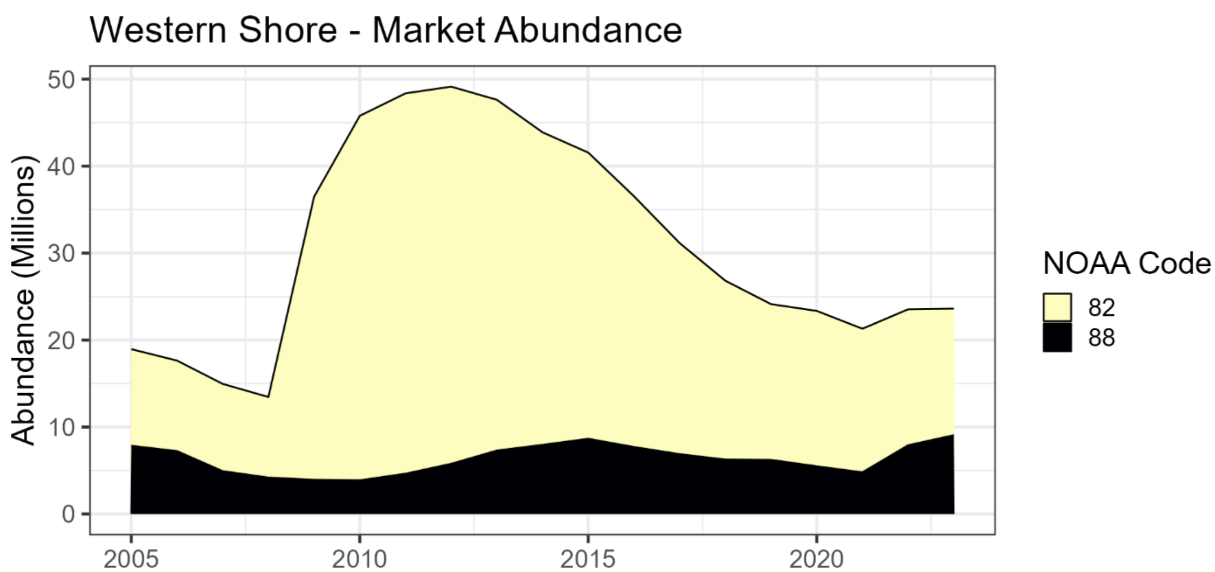

Figure 188. Estimated market oyster abundance among modeled NOAA codes in the Western Shore Region under Maryland management during 2005-2023.

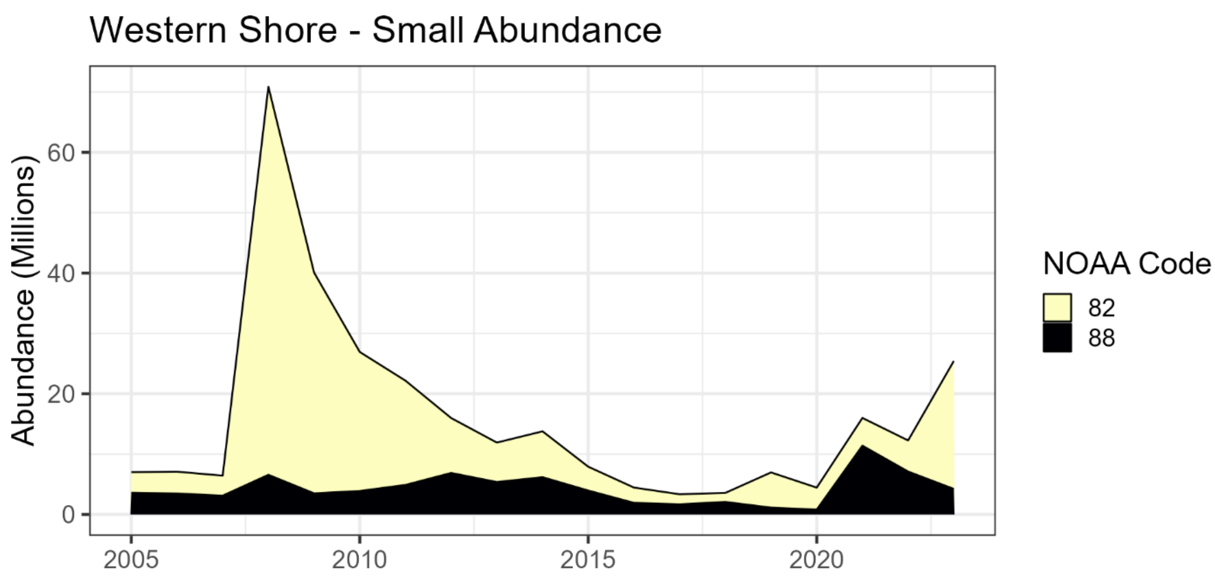

Figure 189. Estimated small oyster abundance among modeled NOAA codes in the Western Shore Region under Maryland management during 2005-2023.

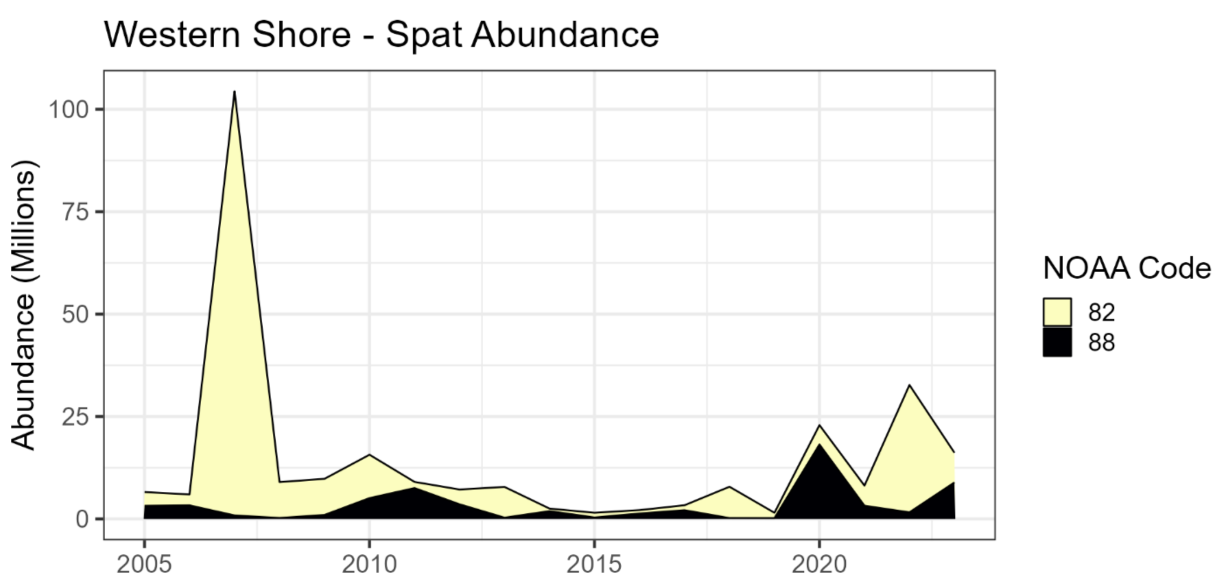

Figure 190. Estimated spat oyster abundance among modeled NOAA codes in the Western Shore Region under Maryland management during 2005-2023.

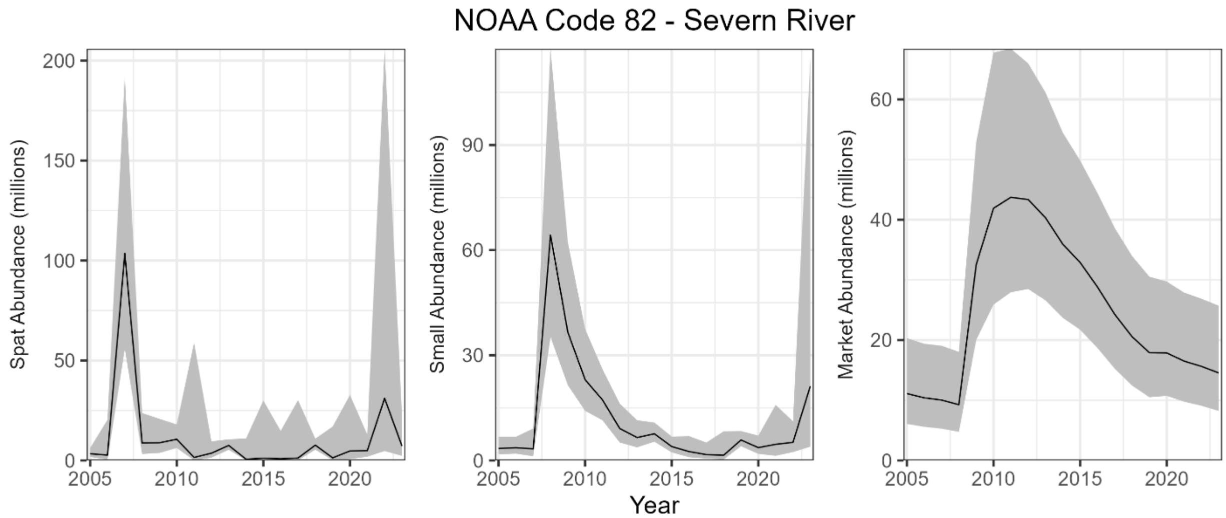

Figure 191. Estimated abundance of spat, small, and markets oysters during 2005-2023 in Severn River. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

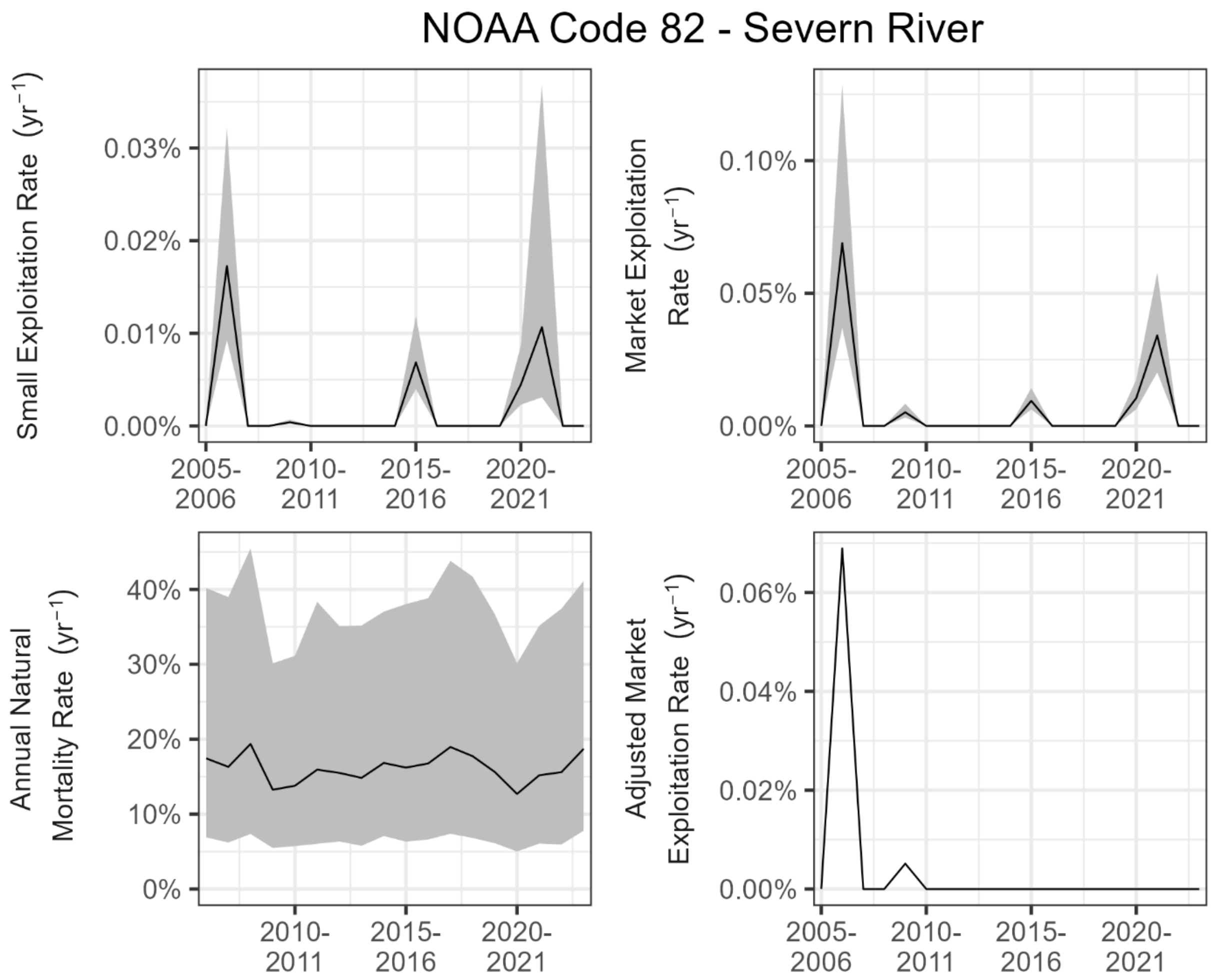

Figure 192. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in Severn River. The shaded areas indicate approximate 95% confidence intervals.

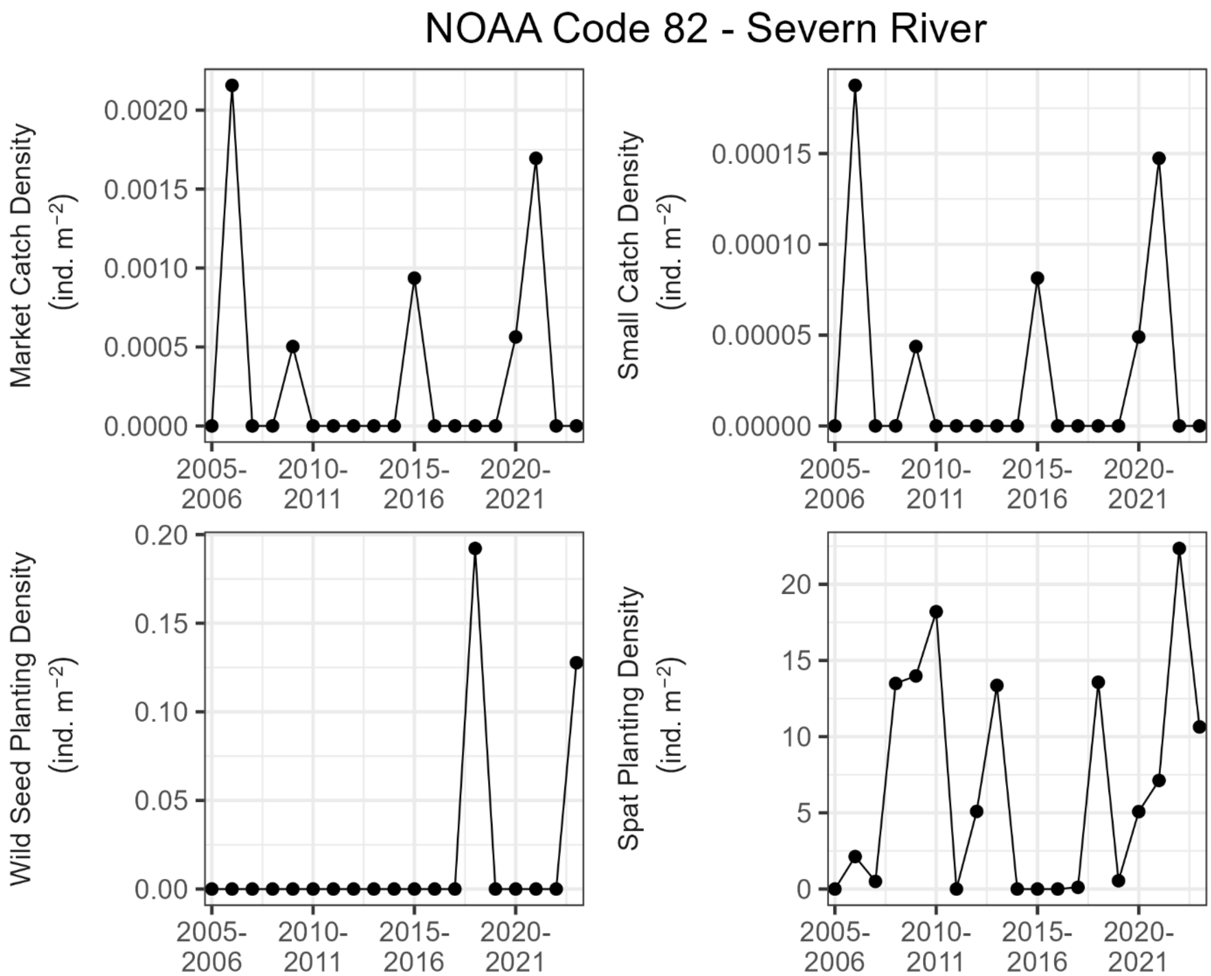

Figure 193. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in Severn River. Density was calculated as the number of individuals divided by habitat area for each data source.

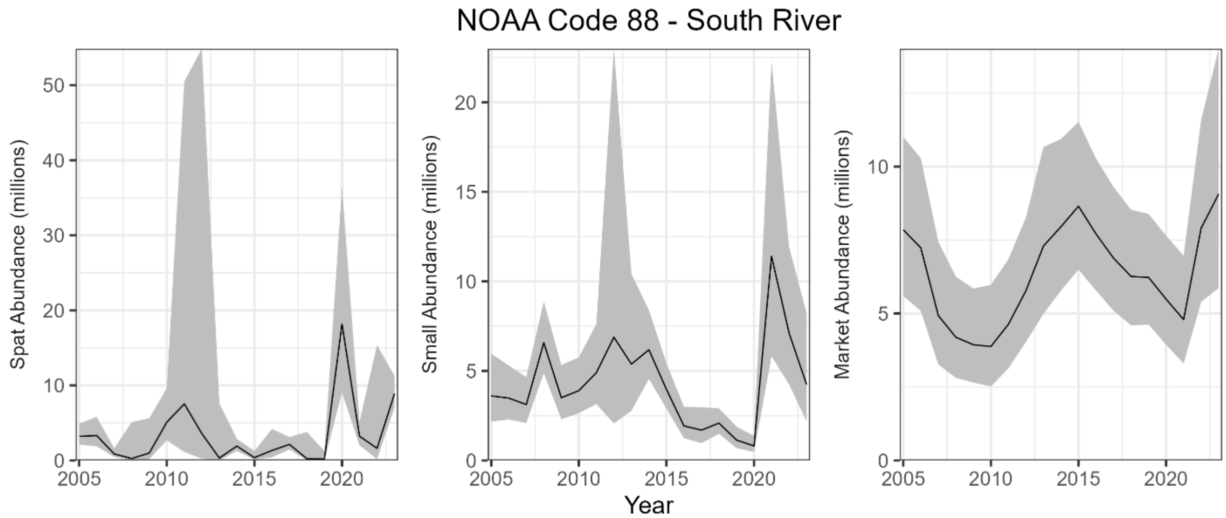

Figure 194. Estimated abundance of spat, small, and markets oysters during 2005-2023 in South River. The lines indicate the estimated abundances, and the shaded areas indicate approximate 95% confidence intervals.

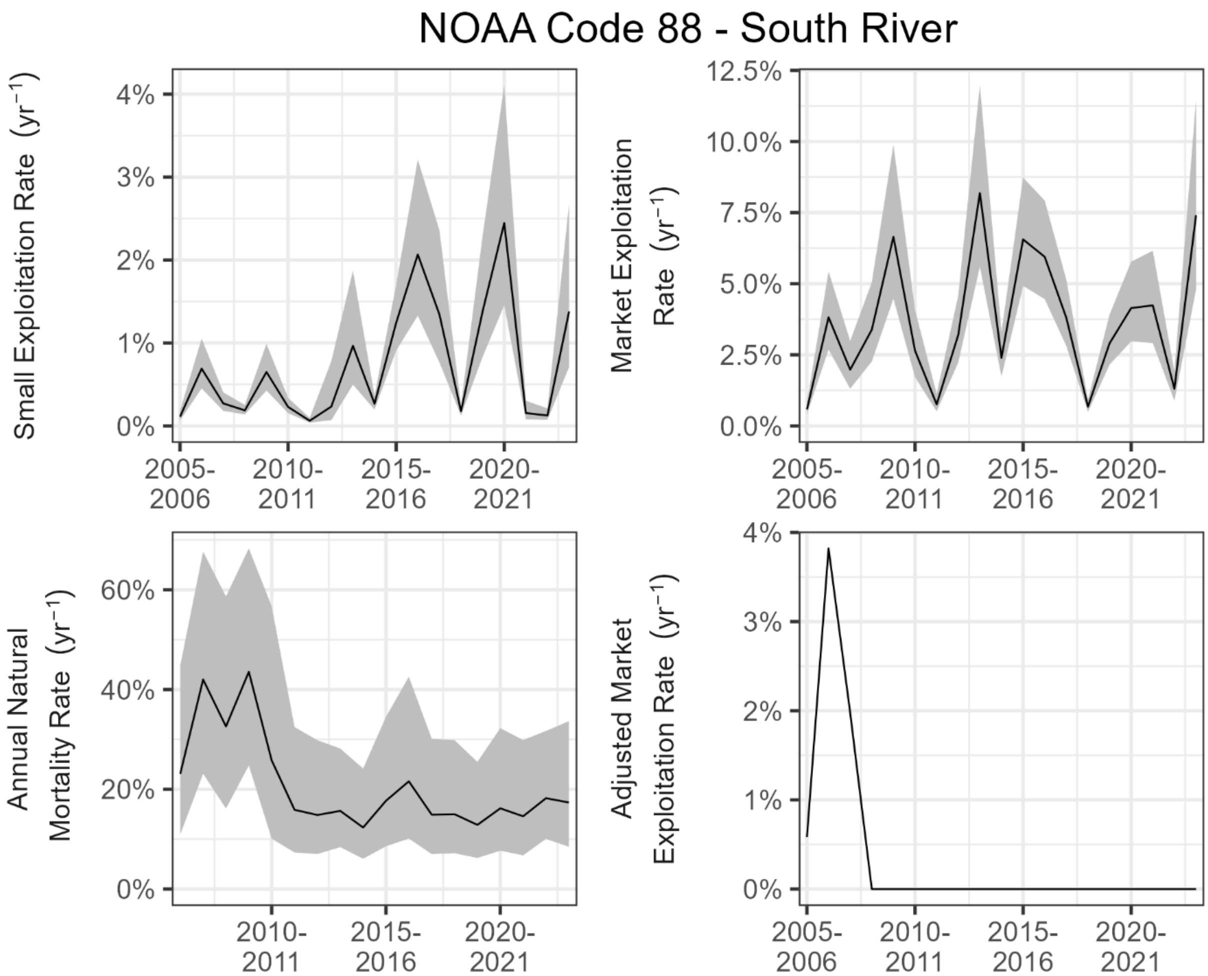

Figure 195. Estimated small exploitation rate, market exploitation rate, annual natural mortality rate, and adjusted market exploitation rate during 2005-2023 in South River. The shaded areas indicate approximate 95% confidence intervals.

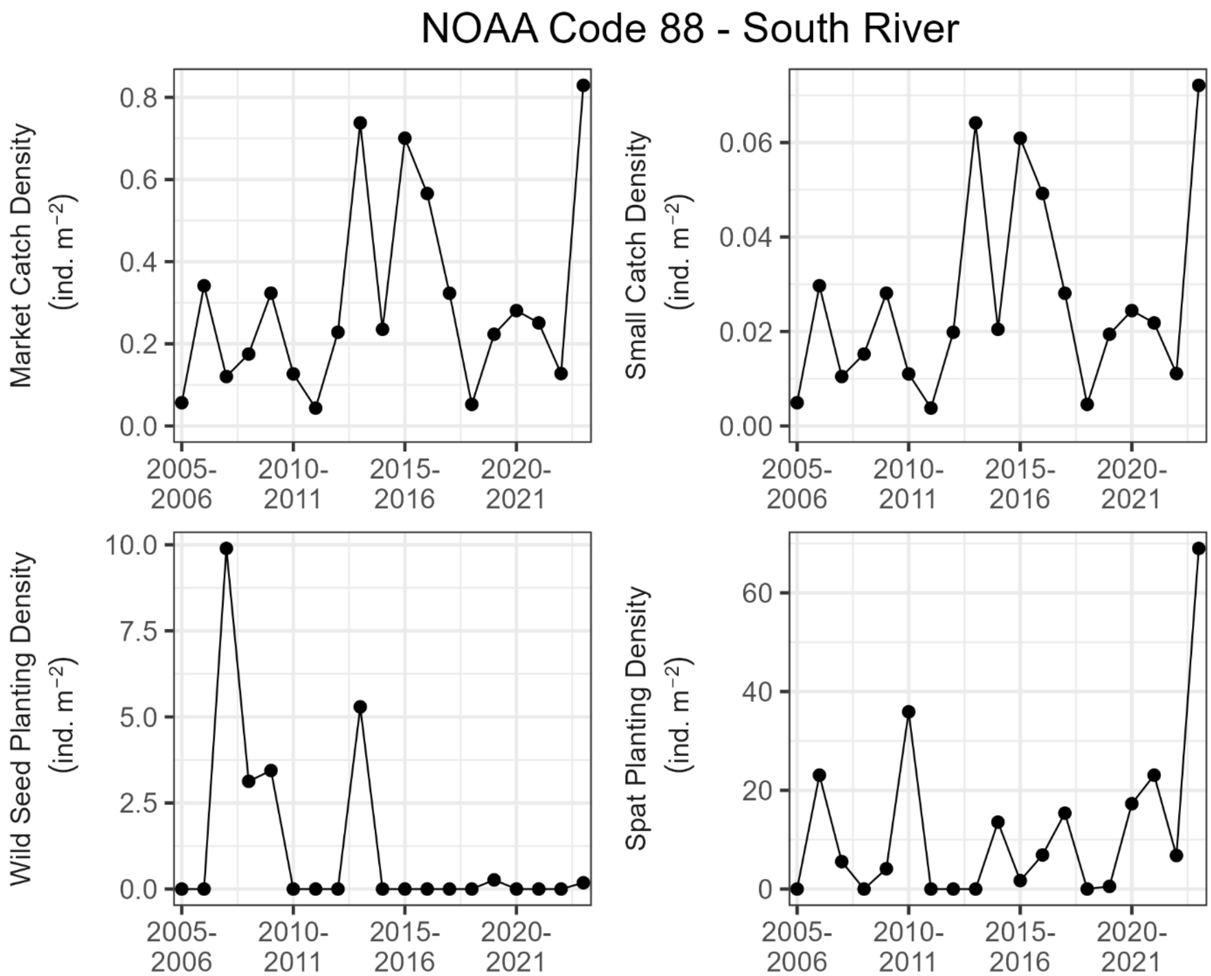

Figure 196. Catch density of market oysters, catch density of small oysters, wild seed planting density, and spat planting density during 2005-2023 in South River. Density was calculated as the number of individuals divided by habitat area for each data source.

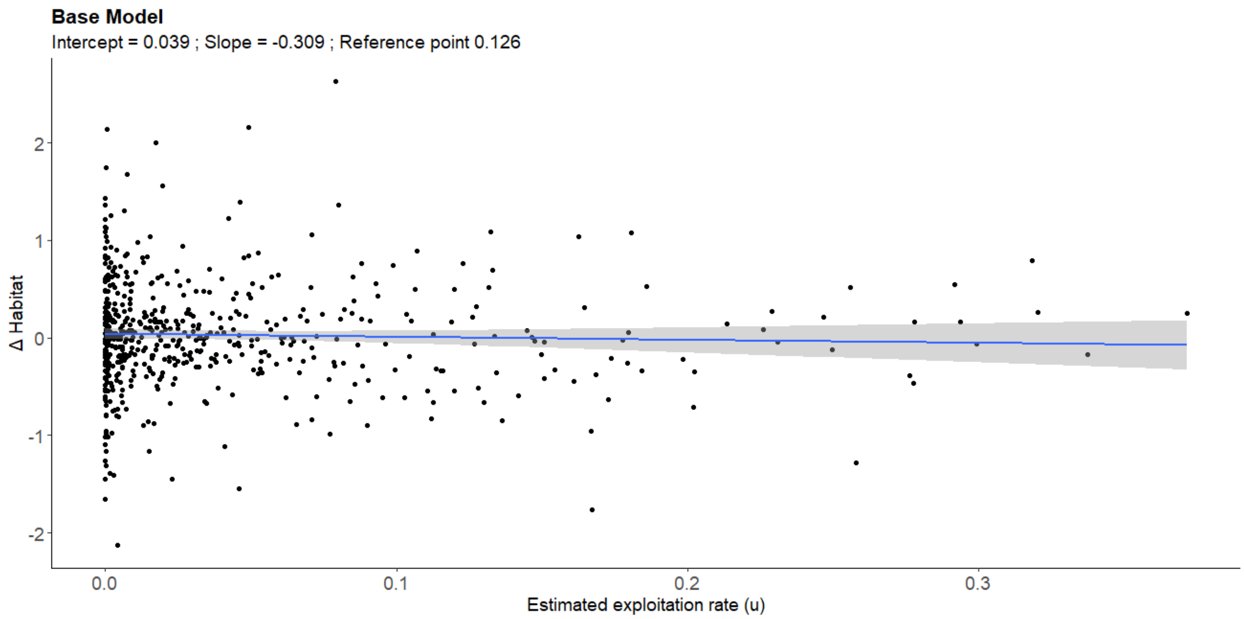

Figure 197. Linear regression of year-over-year changes in cultch per m^2 from the Fall Dredge Survey against estimated exploitation rate from the assessment model. The exploitation rate that achieved no net habitat loss (i.e., where the regression line intersected the line $\Delta\ Habitat\ =\ 0$) was used as the upper threshold exploitation rate reference point.

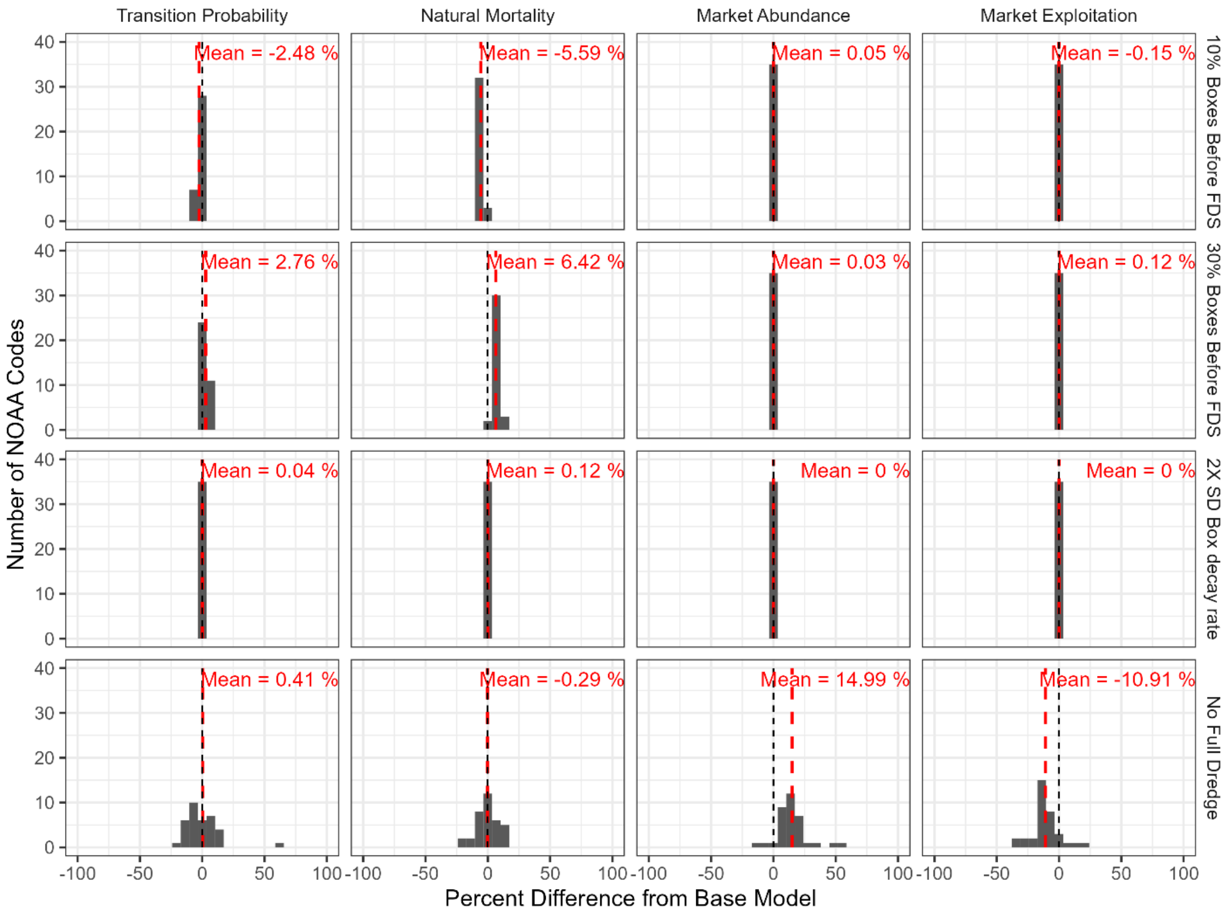

Figure 198. Results of sensitivity analyses for 10% of boxes not available to the Fall Dredge Survey (FDS; top row), 30% of boxes not available to the FDS (second row), doubling the prior standard deviation (SD) of the box decay rate (third row), and removing full dredge tows from Fall Survey data (bottom row). Bars indicate frequency histogram of relative errors between the base model and sensitivity analysis for all NOAA codes. The mean relative error (over NOAA codes) is indicated by the red dashed line and no difference between the base model and sensitivity analysis is indicated by the black dashed line.

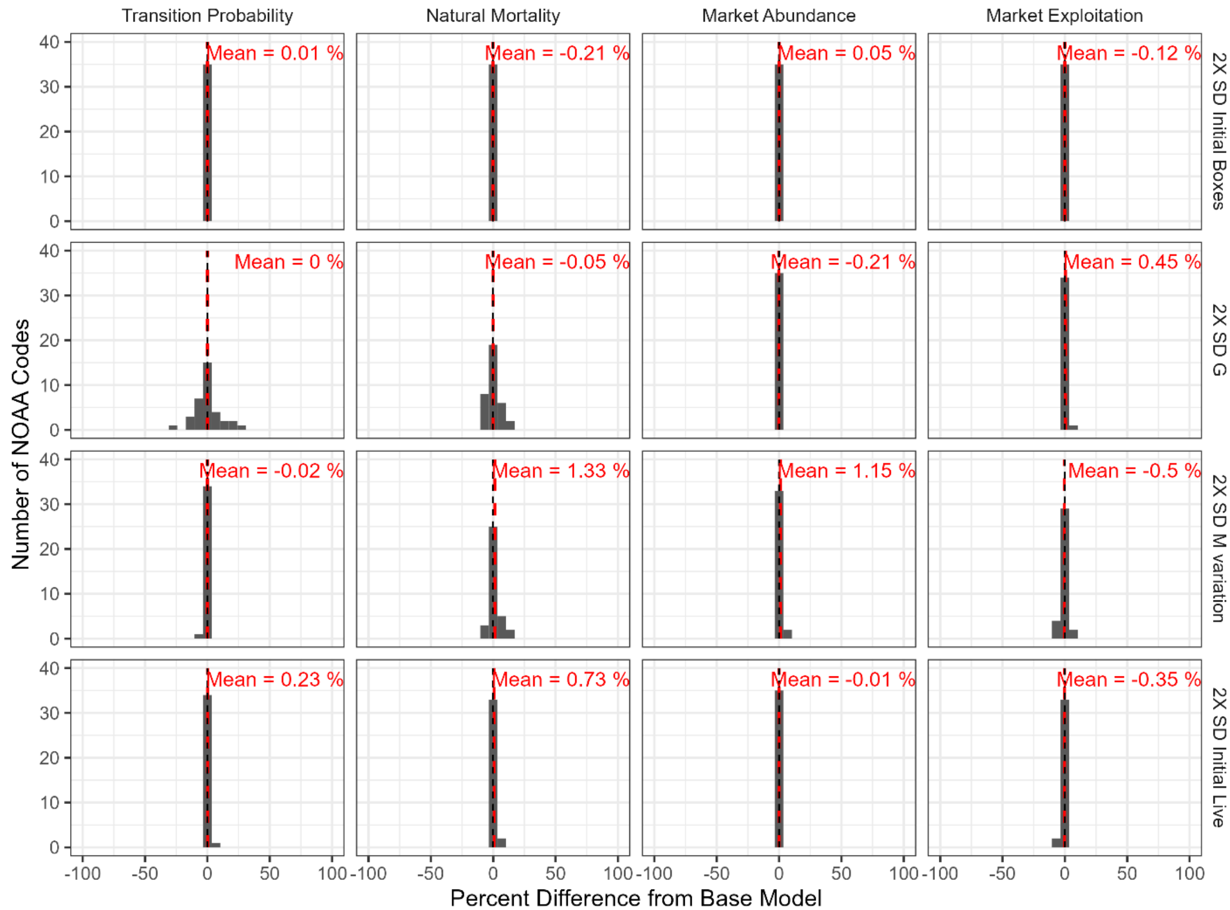

Figure 199. Results of sensitivity analyses for the mean of the standard deviation (SD) of the penalty for the initial abundance of boxes (top row), the standard deviation (SD) of the penalty on the transition probability (G) (second row), the standard deviation (SD) of the penalty for variation in natural mortality within NOAA codes over time (third row), the standard deviation (SD) of the penalty on initial abundance of live small and market oysters (bottom row). Bars indicate frequency histogram of relative errors between the base model and sensitivity analysis for all NOAA codes. The mean relative error (over NOAA codes) is indicated by the red dashed line and no difference between the base model and sensitivity analysis is indicated by the black dashed line.

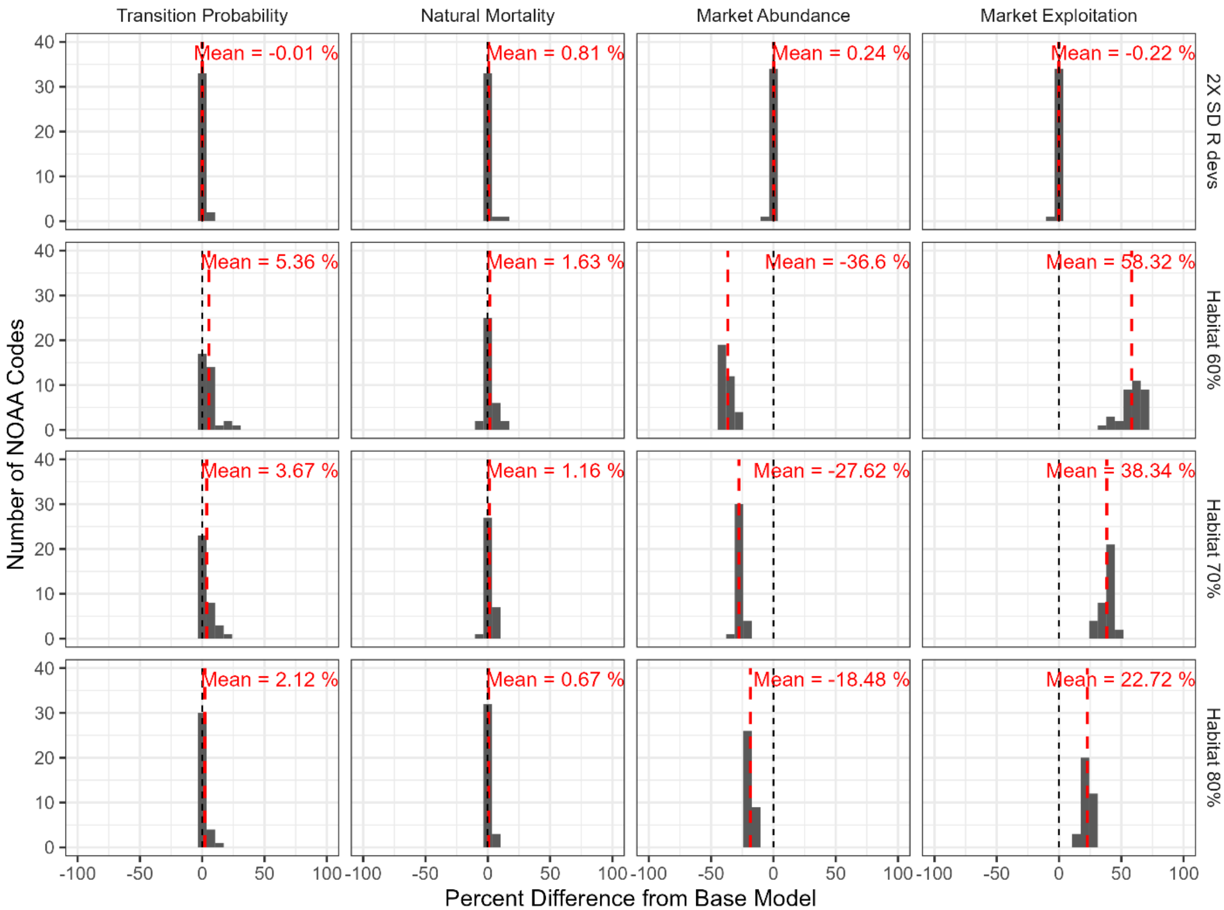

Figure 200. Results of sensitivity analyses for the mean of the standard deviation (SD) of the penalty for recruitment deviations (top row), habitat area at 60% of the base model in each NOAA code (second row), habitat area at 70% of the base model in each NOAA code (third row), and habitat area at 80% of the base model in each NOAA code (bottom row). Bars indicate frequency histogram of relative errors between the base model and sensitivity analysis for all NOAA codes. The mean relative error (over NOAA codes) is indicated by the red dashed line and no difference between the base model and sensitivity analysis is indicated by the black dashed line.

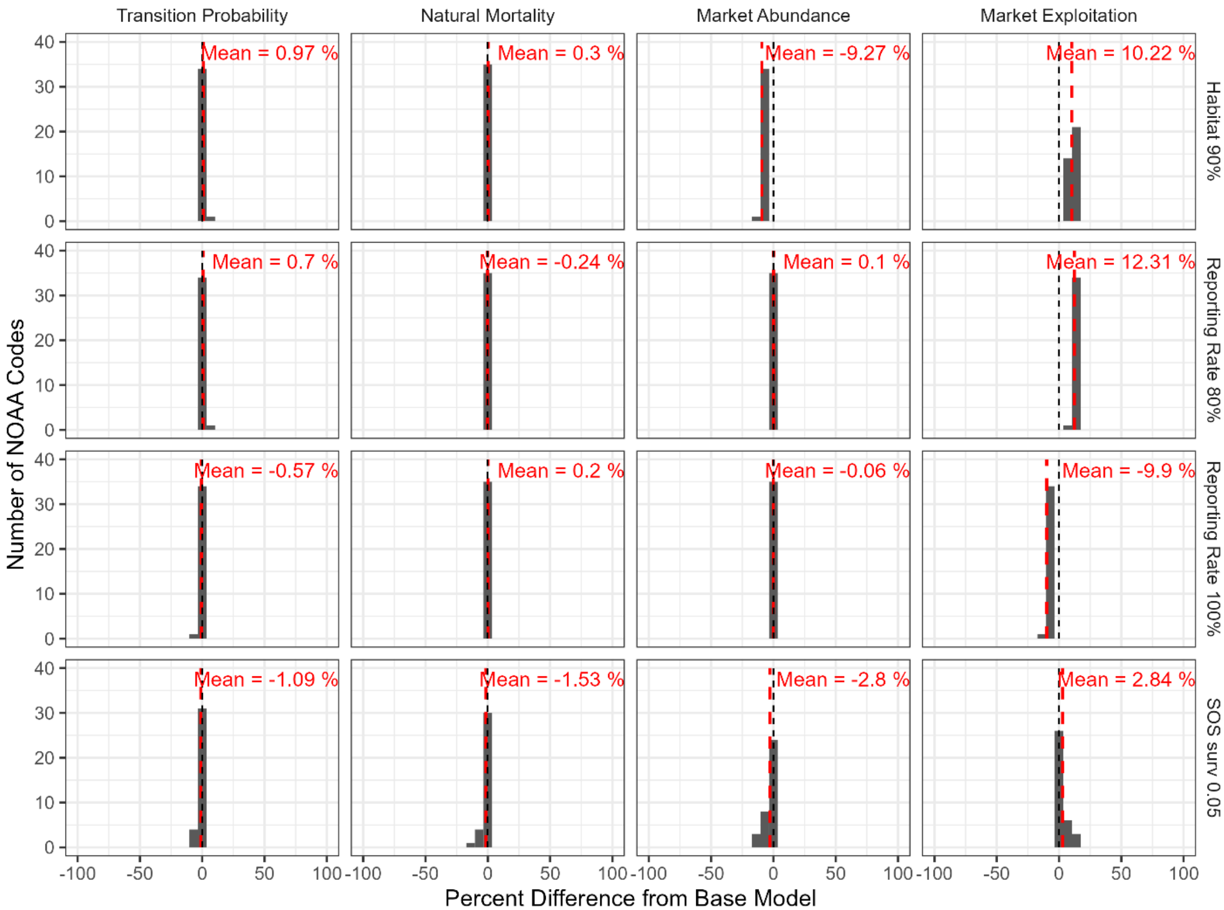

Figure 201. Results of sensitivity analyses for the habitat area at 90% of the base model in each NOAA code (top row), 80% reporting rate for harvest (second row), 100% reporting rate for harvest (third row), and 5% survival of hatchery spat (bottom row). Bars indicate frequency histogram of relative errors between the base model and sensitivity analysis for all NOAA codes. The mean relative error (over NOAA codes) is indicated by the red dashed line and no difference between the base model and sensitivity analysis is indicated by the black dashed line.

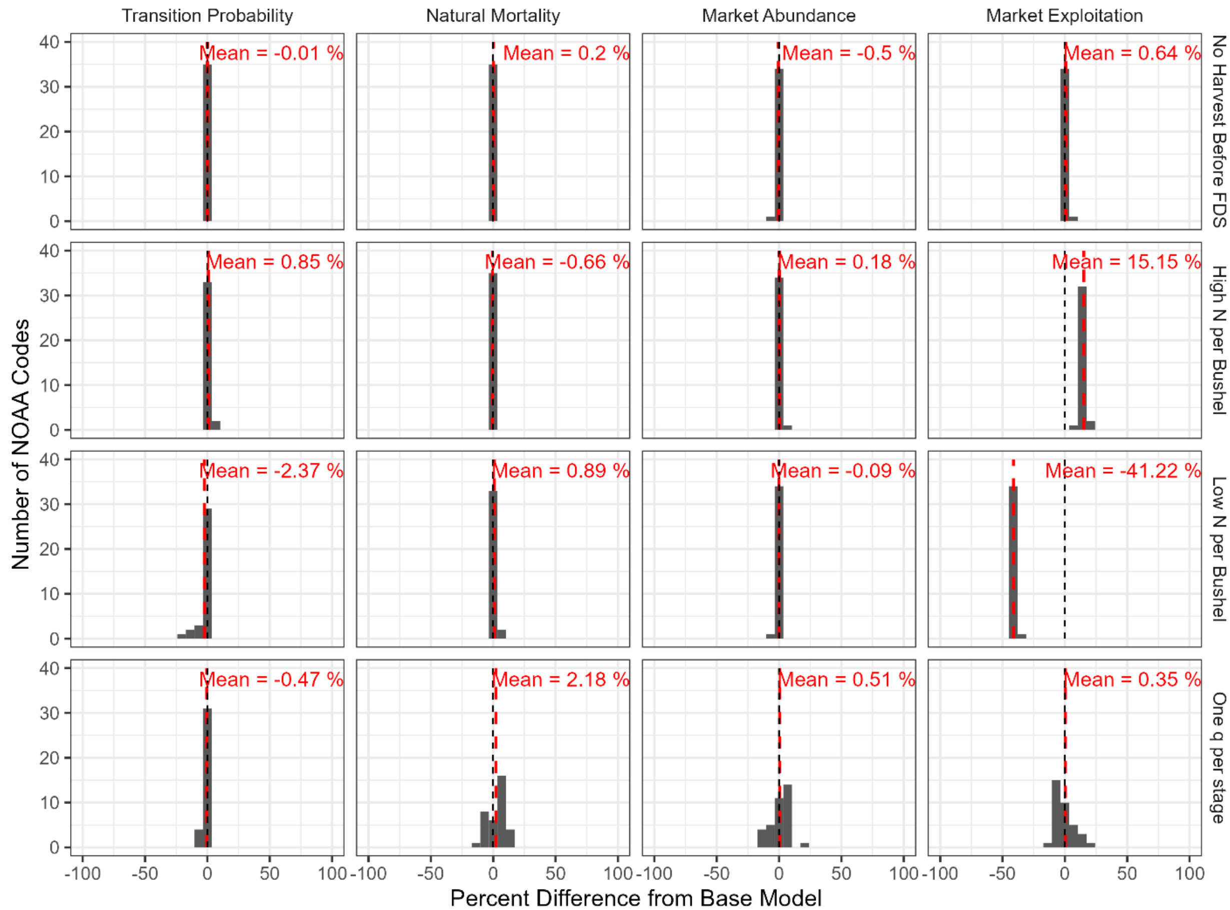

Figure 202. Results of sensitivity analyses for the assuming all harvest happens after the Fall Survey in each NOAA code (top row), 350 oysters per bushel and 25% small oysters per bushel for harvest (second row), 150 oysters per bushel and 5% small oysters per bushel for harvest (third row), and only one catchability parameter for each stage (live adults, spat, and boxes) across all NOAA codes (bottom row). Bars indicate frequency histogram of relative errors between the base model and sensitivity analysis for all NOAA codes. The mean relative error (over NOAA codes) is indicated by the red dashed line and no difference between the base model and sensitivity analysis is indicated by the black dashed line.

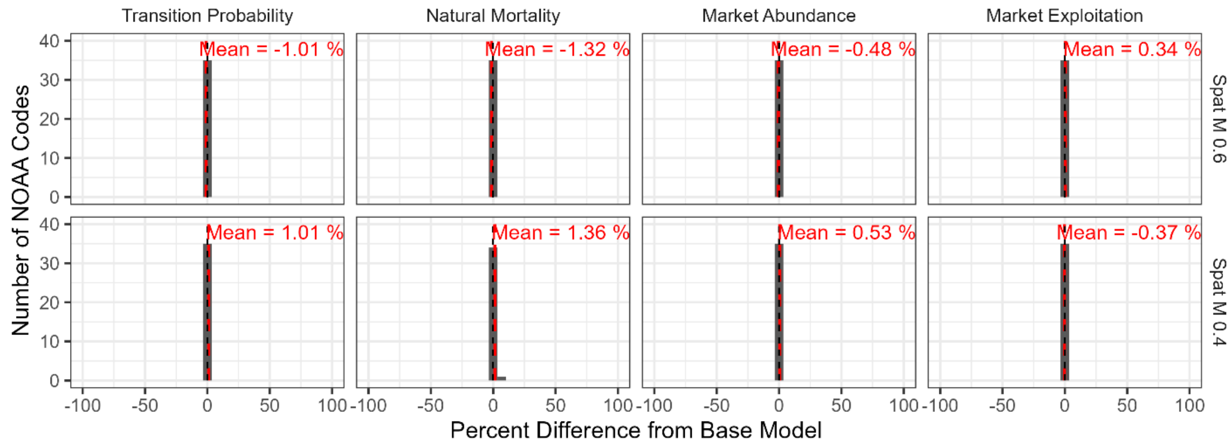

Figure 203. Results of sensitivity analyses for 0.6 instantaneous natural mortality rate for spat (top row), 0.4 instantaneous natural mortality rate for spat (bottom row). Bars indicate frequency histogram of relative errors between the base model and sensitivity analysis for all NOAA codes. The mean relative error (over NOAA codes) is indicated by the red dashed line and no difference between the base model and sensitivity analysis is indicated by the black dashed line.

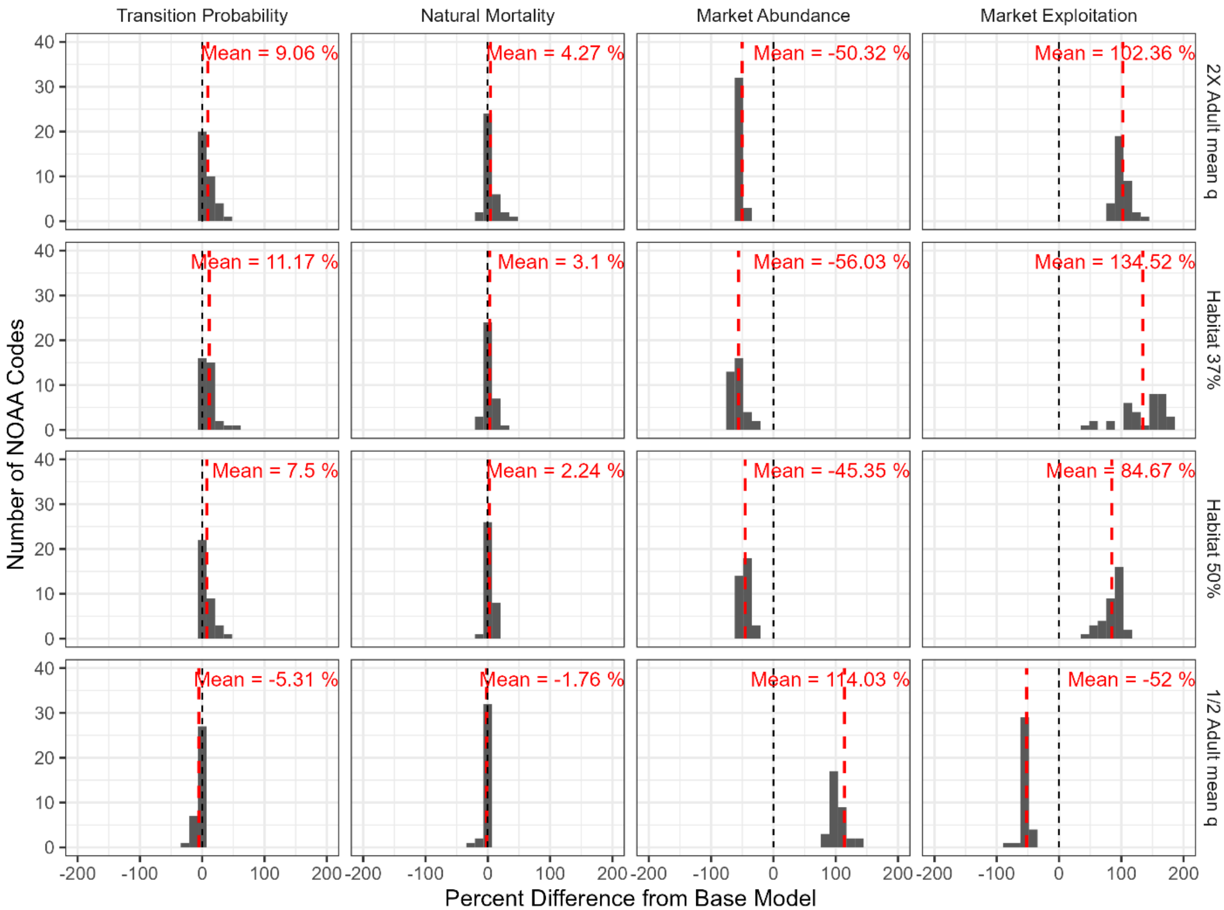

Figure 204. Results of sensitivity analyses for doubling standard deviation (SD) of the penalty for adult catchability (top row), habitat at 37% of base mode for each NOAA code (second row), habitat at 50% of base mode for each NOAA code (third row) and halving the mean of the adult catchability penalty (bottom row). Bars indicate frequency histogram of relative errors between the base model and sensitivity analysis for all NOAA codes. The mean relative error (over NOAA codes) is indicated by the red dashed line and no difference between the base model and sensitivity analysis is indicated by the black dashed line.

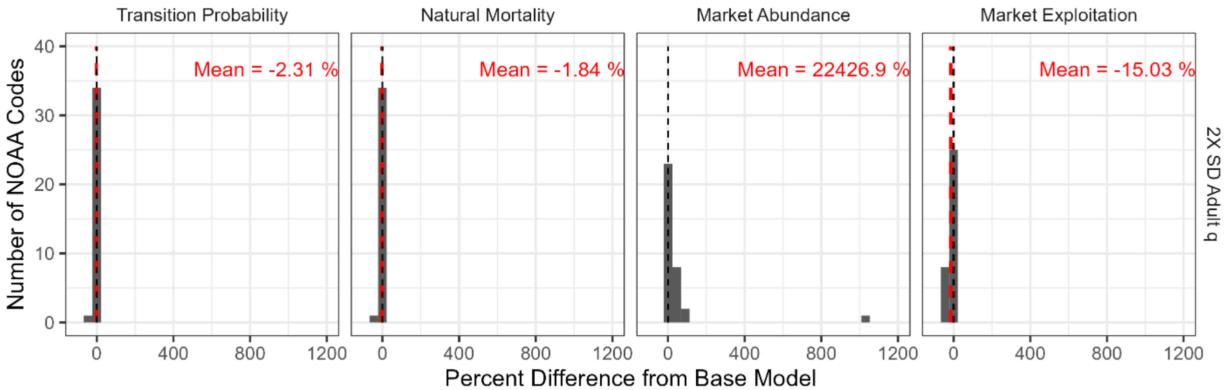

Figure 205. Results of sensitivity analyses for doubling the standard deviation (SD) of adult catchability penalty. Bars indicate frequency histogram of relative errors between the base model and sensitivity analysis for all NOAA codes. The mean relative error (over NOAA codes) is indicated by the red dashed line and no difference between the base model and sensitivity analysis is indicated by the black dashed line.

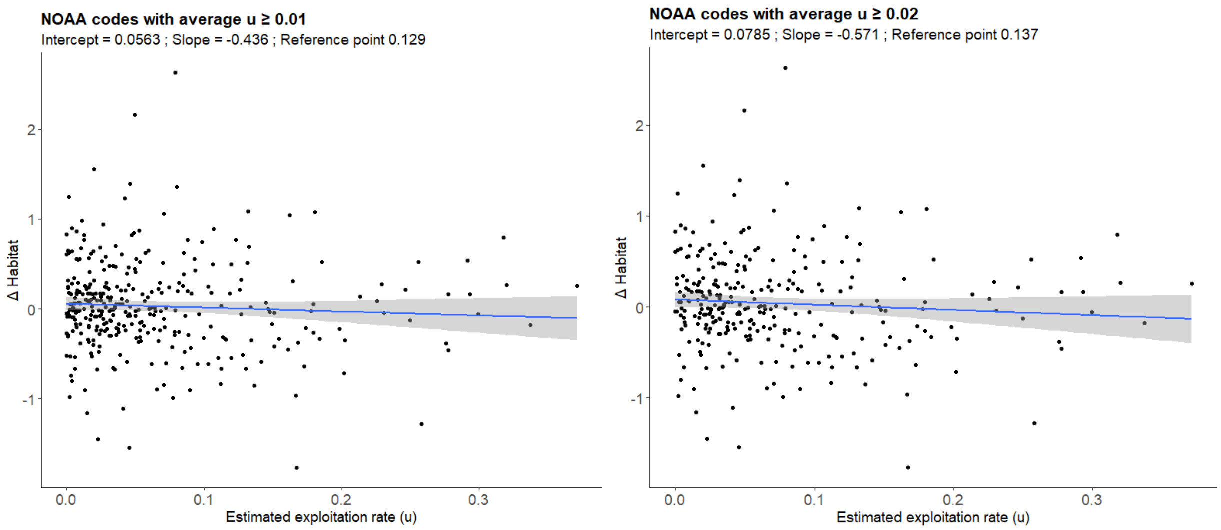

Figure 206. Results of sensitivity analysis for the exploitation rate reference point when excluding NOAA codes with an average exploitation rate < 0.01 and <0.02.

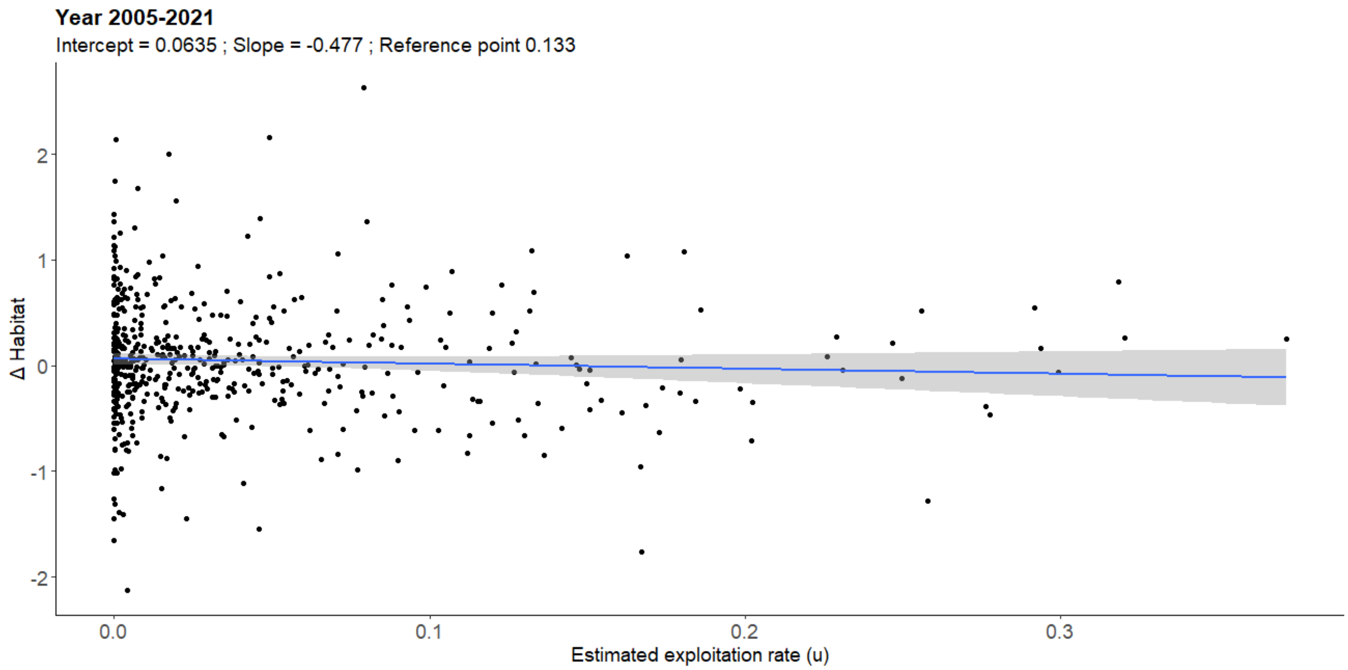

Figure 207 Results of sensitivity analysis for the exploitation rate reference point when using alternative ranges of years 2005-2021.

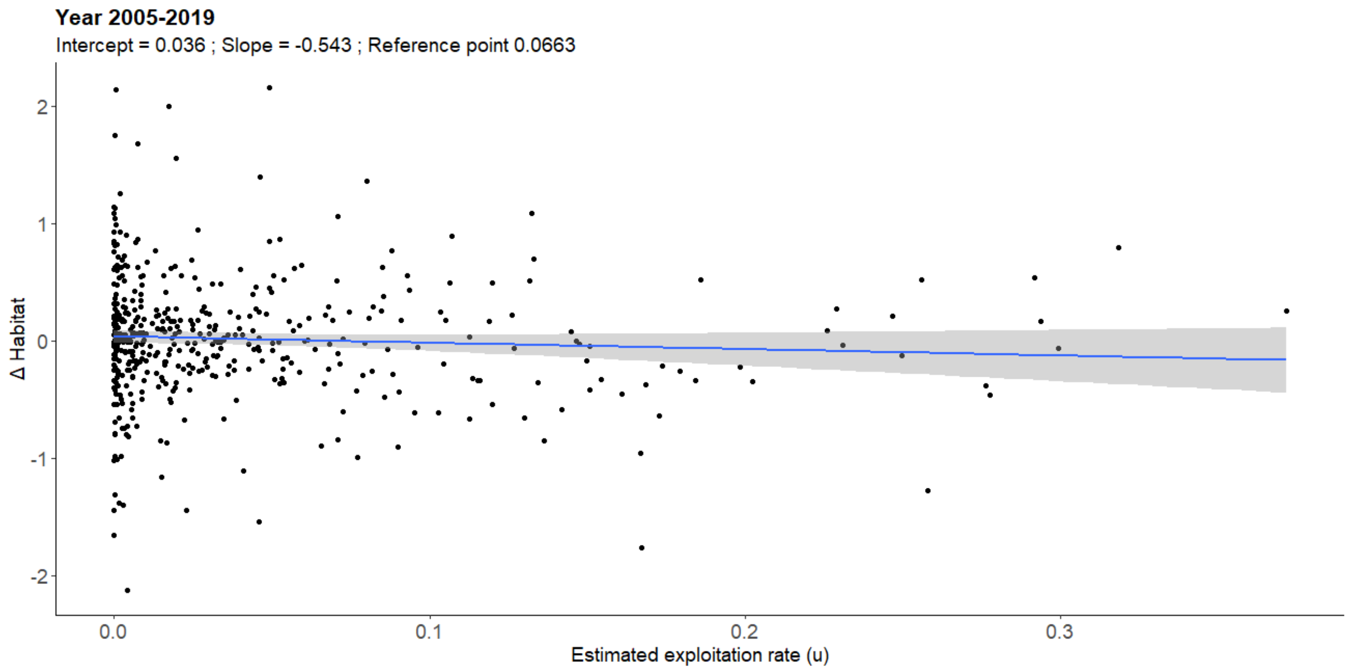

Figure 208 Results of sensitivity analysis for the exploitation rate reference point when using alternative ranges of years 2005-2020.

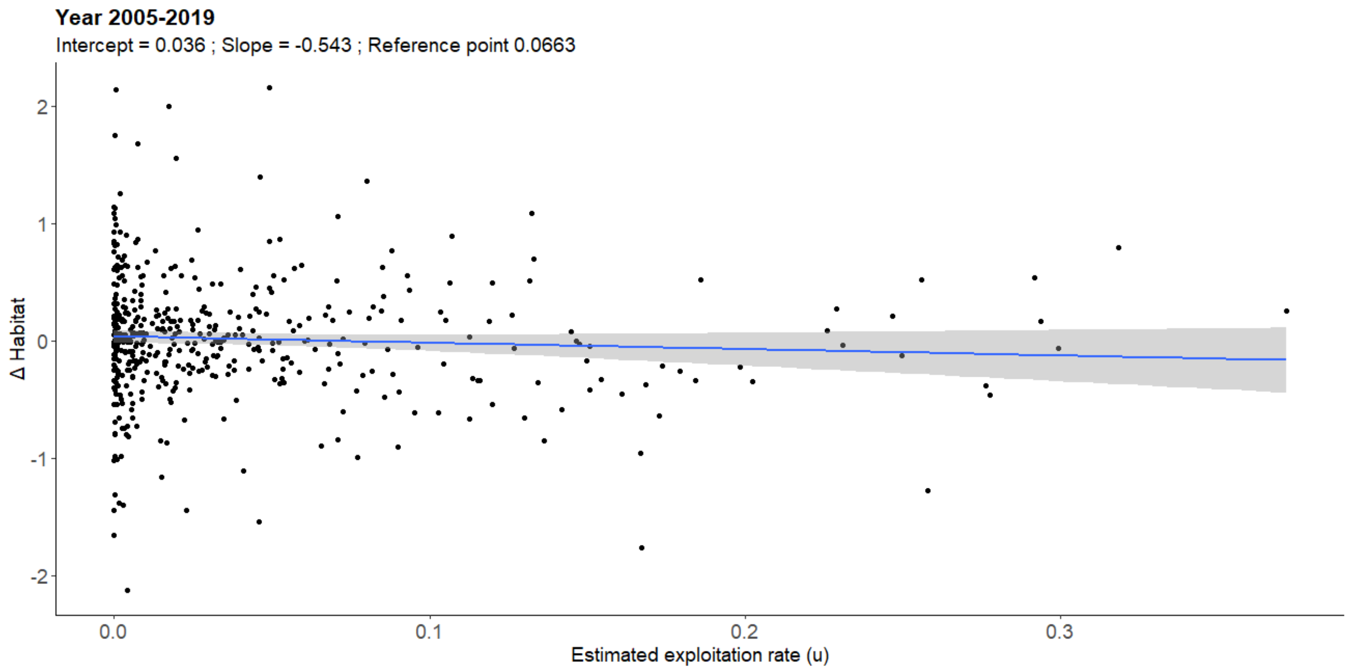

Figure 209 Results of sensitivity analysis for the exploitation rate reference point when using alternative ranges of years 2005-2019.

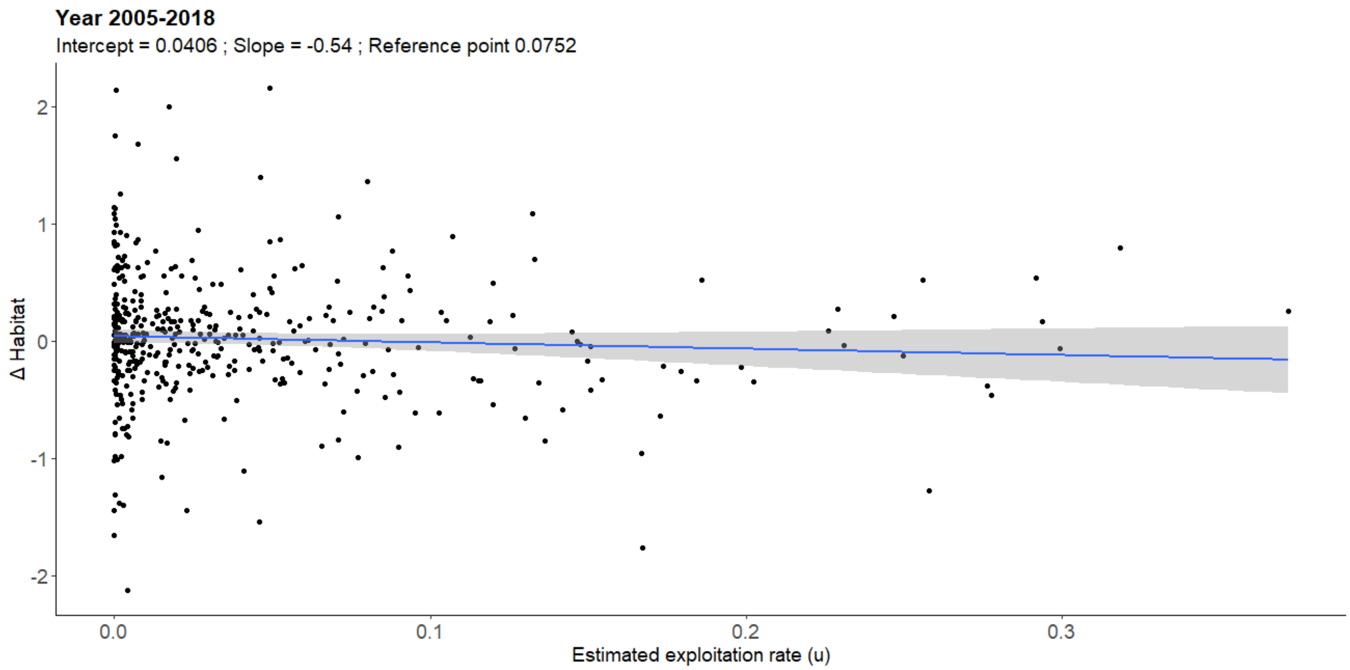

Figure 210. Results of sensitivity analysis for the exploitation rate reference point when using alternative ranges of years 2005-2018.

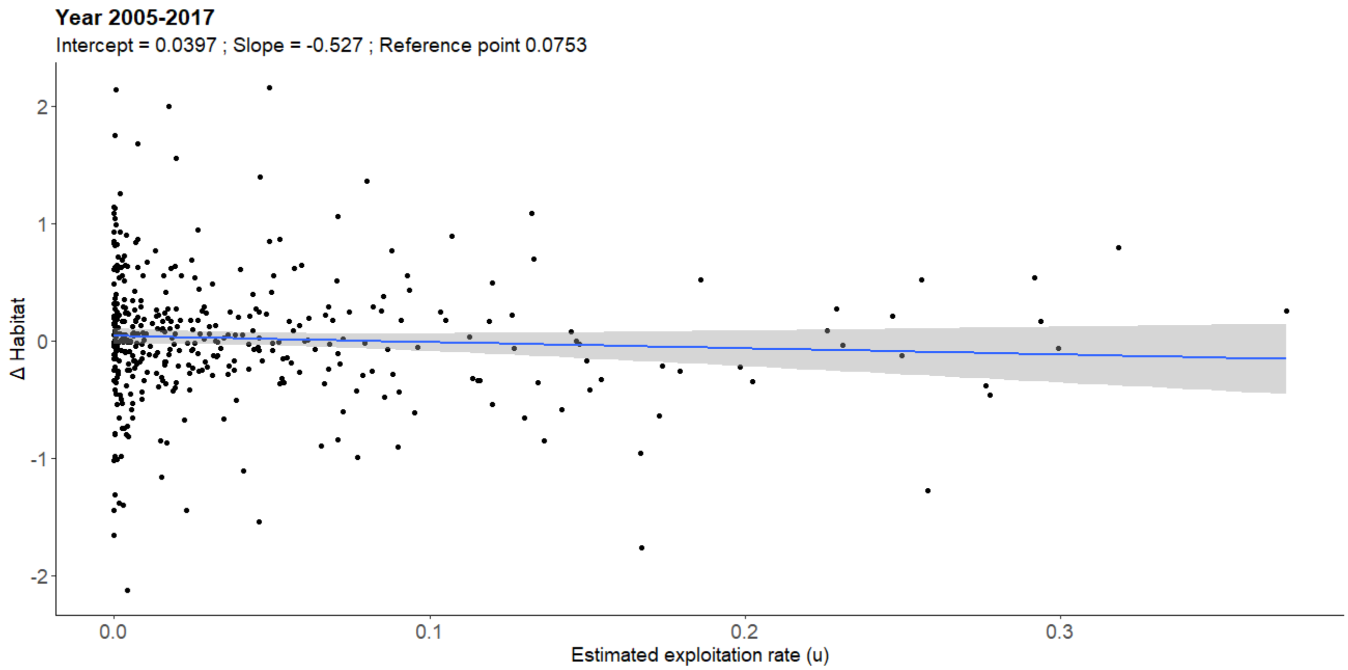

Figure 211. Results of sensitivity analysis for the exploitation rate reference point when using alternative ranges of years 2005-2017.

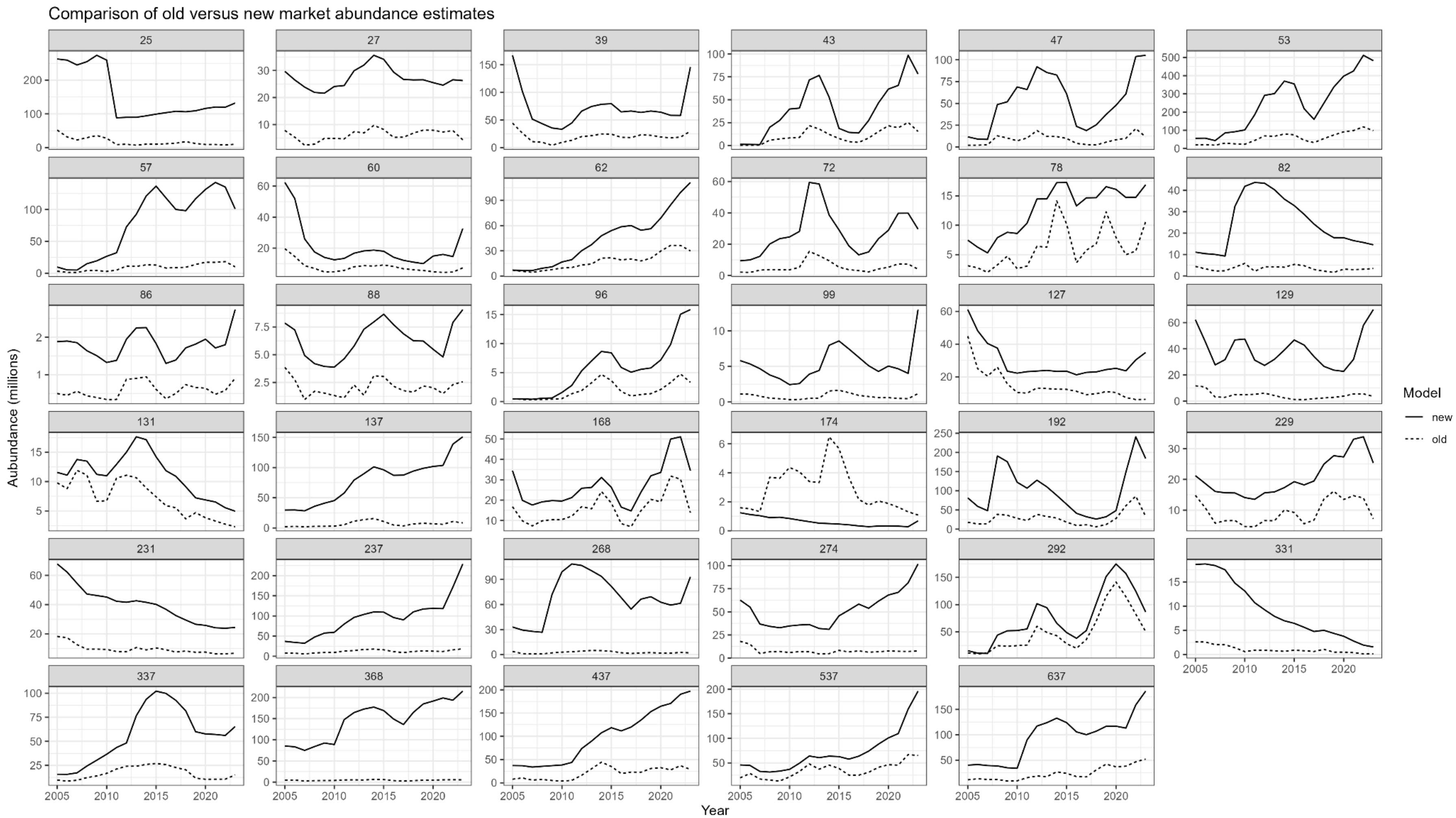

Figure 212. Comparison of market abundance estimates for each NOAA Code from the new assessment model presented in this document (solid line) compared to the previous Maryland Oyster Stock Assessment model (dashed line).

7 Appendix A

7.1 Effects of fishing on bottom habitat for oysters in the Chesapeake Bay, Maryland

1. Introduction

Oysters are important commercially and for the other ecosystem services they provide. In Maryland, the eastern oyster (*Crassostrea virginica*) has been commercially harvested since the 1820s (Kennedy & Breisch, 1981) and had a total dockside value of $21.4 million in the 2021 – 2022 oyster harvest season (Tarnowski, 2023). The eastern oyster is also an ecosystem engineer that creates its own habitat and reef habitat for other organisms. Oyster reefs develop from oysters settling on one another to form vertical structures that allow live oysters to inhabit the mixed surface water of an estuary and avoid seasonal anoxic and hypoxic bottom waters (Lenihan & Peterson, 1998). Oyster reefs also provide habitat for a myriad of species including several commercially important fish and crustacean species that inhabit oyster reefs or forage on them (Dame & Patten, 1981; Zimmerman et al., 1989; Coen et al., 1999, 2007; Peterson et al., 2003; Grabowski & Peterson, 2007). Other valuable ecosystem services provided by oysters include enhancing nutrient cycling, filtering water (Dame & Patten, 1981; Newell, 1988; Dame & Libes, 1993; Coen et al., 2007; Grabowski & Peterson, 2007; Fulford et al., 2010), and reducing the effects of anthropogenic eutrophication (Cerco & Noel, 2007; Fulford et al., 2010).

Oyster populations and oyster reef habitats around the world have been greatly diminished with Beck et al. (2011) estimating the loss of 85% of naturally occurring oysters globally. In Maryland, oyster populations are reported to be at less than 1% of their original pre-commercial exploitation abundance (Newell, 1988; Jackson et al., 2001; National Research Council, 2002; Kirby, 2004; Wilberg et al., 2011). This decline of oysters in the Chesapeake Bay is due to overfishing (Rothschild et al., 1994; Jackson et al., 2001), diseases such as MSX caused by *Haplosporidium nelsoni* and Dermo caused by *Perkinsus marinus* (Andrews, 1988; Ford et al., 1999; Dittman et al., 2001; Ford & Smolowitz, 2007), and habitat loss from reduced water quality (Chesapeake Bay Program, 2014). However, overexploitation of oysters has been attributed to be the main cause or initial driver for the oyster population decline (Rothschild et al., 1994; Jackson et al., 2001; Wilberg et al., 2011).

The effect of fishing for oysters on their reef habitat is not well understood (Mercaldo-Allen & Goldberg, 2011), particularly the effect of modern harvest practices on reefs that have been fished for decades or centuries. Fishing for oysters has been shown to reduce the height of man-made oyster reefs composed of loose shell (Lenihan & Peterson, 2004) and natural oyster reefs (DeAlteris, 1988). Because oysters create their own habitat and are harvested with their shells, harvesting oysters removes some habitat regardless the gear type used. However, fishing gears may have differing effects on oyster reefs and the ecosystem they create. For example, the use of oyster dredges has been described as the most destructive fishing practice for oyster reef habitat (Stevenson, 1894; DeAlteris, 1988; Rothschild et al., 1994; Lenihan & Peterson, 2004).
In Maryland, two types of dredging are allowed for oyster harvest: power dredging and sail dredging. Power dredging consists of towing a steel frame with teeth and a bag to penetrate the substrate in order to capture oysters using a motorized vessel (National Research Council, 2002; Mercaldo-Allen & Goldberg, 2011; Maryland Department of Natural Resources, 2018). Sail dredging is similar to power dredging, but the dredge is operated under sail power with either a

sailboat or skipjack, although regulations in Maryland allow a sailboat to be pushed by another vessel (i.e., a yawl boat) several days per week, which likely makes it similar to power dredging (Maryland Department of Natural Resources, 2018). For the purposes of this report, dredging refers to mechanical dredging for oyster harvest and does not include clam dredging, dredging to maintain navigational channels, or other types of dredging.

Oyster harvest can also have secondary effects by causing sediments to become suspended, which may cause sedimentation on parts of oyster reefs, or if the sediment if transported elsewhere, may remove sediment from a reef. Oyster settlement can be inhibited by sedimentation (Galtsoff, 1964; MacKenzie, 1983; Wilber & Clarke, 2010). For example, Galtsoff (1964) observed that as little as 1 – 2 mm of loose sediment could prevent the settlement of oyster larvae. Alternatively, a common view in the oyster industry is that fishing practices such as dredging remove sediment from oyster cultch, thus "cleaning" it and making more habitat available for spat.
The effect of fishing on oyster reefs has been raised as an issue of concern due to the unknown effects it can have on the substrate, benthic community, and both targeted and not targeted species (National Research Council, 2002). Additionally, an effect of fishing on oyster habitat would affect shell budgets and models to estimate sustainable harvest rates (Wilberg et al. 2013). To our knowledge, no comprehensive studies have been published that evaluate the effects of fishing on oyster habitat, particularly the effects of dredging on natural oyster reefs within the Chesapeake Bay. Our objective was to estimate the effect of fishing on recruitment and the amount of bottom habitat for oysters in the Chesapeake Bay, Maryland using two sets of available harvest and survey data. We conducted an analysis of monitoring data from areas that were opened to power dredging during 2010 – 2015. Additionally, we analyzed data from the Maryland Department of Natural Resources (DNR) Fall Dredge Survey (FDS) sites during 2010 – 2019 to evaluate effects of fishing on cultch and spat.

2. Methods

2.1 Power Dredge Area Methods

In the Chesapeake Bay, portions of three oyster bars (Swan Point, Wild Ground, and Parsons Island) in two areas (Upper Bay and Eastern Bay) were opened to power dredging in 2010 and slated for increased monitoring to inform the effects of power dredging as an adaptive management experiment (Figure 1). The Maryland DNR selected comparison sites near each power dredge area in which power dredging was not allowed (Bodkin Shoals and Peach Orchard). The comparison sites allowed oyster fishing using diving and patent tonging. The comparison sites allowed fishing by other methods because the goal was to estimate the effect of power dredging relative to other gears. Oyster harvest in Maryland is reported at a spatial resolution of an oyster bar. Because each comparison site was only a portion of the bar, harvest for these sites could not be determined and, therefore, was not used in these analyses. A power dredge and comparison site on the Holland Straits oyster bar was also originally part of this study. In Holland Straits, 82.15 hectares were opened to power dredging, and the comparison area was only 1.21 hectares. We did not include Holland Straits in our analyses because the small comparison site made determining the effect of dredging highly uncertain. Harvest was also only reported in Holland Straits from power dredging in 2012 and 2013, which was likely insufficient for estimating an effect.

All sites were monitored by the Maryland DNR using hydraulic patent tongs. Sites were gridded and 100 random sample locations were selected. Sampling began in the fall of 2010 before power dredging occurred and the spring of 2011 in Bodkin Shoals, and sampling took place annually in the fall until 2015. Each study site was monitored for six years and had approximately 600 total samples collected by patent tong during 2010-2015 (Table 1). The volume of cultch, which includes live oysters and shell, and number of oysters in spat (i.e., young-of-the-year), small (age $\geq$ 1 yr, shell height <76 mm), and market (shell height $\geq$ 76 mm) categories per m^2 were recorded.

We used a before-after control-impact (BACI) ANOVA to estimate the effects of power dredging on cultch or spat (Underwood, 1992; Hewitt et al., 2001; National Research Council, 2002; Lenihan & Peterson, 2004). In the BACI ANOVAs, patent tong sampling that occurred in 2010 or in the spring of 2011, for Bodkin Shoals, was used as the before period, and sampling that occurred in 2015 was used as the after period ($year$). The ANOVAs also included the power dredge areas as the treatment and an interaction between the treatment and year (Eq. 1).

Eq. 1: $$\hat{Y} = treatment + year + treatment \times year$$

A significant interaction term of treatment by year, $treatment \times year$, would indicate a significant effect of dredging, and the sign of the term would indicate if the effect was positive or negative. Analyses were conducted separately for two dependent variables ($\hat{Y}$): the number of spat per m^2 and volume of cultch (L per m^2). Eastern Bay and the Upper Bay were analyzed separately to account for the possibility of different effects of power dredging on cultch and spat production in the two locations. The significance of the explanatory variables was determined based on an alpha level of 0.05, which resulted in a Bonferroni corrected critical p-value of 0.0125 after controlling for the number of tests (total of four tests).

2.2 Harvester Reports and Fall Dredge Survey Analysis Methods

We also estimated the effects of dredging and oyster harvest by other gears on habitat and recruitment. Data on commercial harvest of oysters in each fishing season (October – March) and the gear type used for harvest were obtained from daily harvester reports collected by Maryland DNR. Daily harvester reports were required to be filled out and submitted by oyster permit holders each month, even if no harvest took place. The reports included the date, number of bushels harvested, gear type, location, number of crew, hours spent harvesting, buyer license number, and buy ticket number. Data on catches were summarized from the harvester reports by bar, gear, and year. The gear types were grouped as dredging (power and sail dredging) and other (including patent tongs, hand tongs, and diving). Oyster harvest in Maryland is reported in bushels (~36 L). To standardize effects of fishing across bars of different sizes, we calculated bushels harvested per area of each bar (m^2).

Data on the number of spat and amount of cultch were collected by the Maryland DNR's FDS. The FDS is conducted annually at over 250 oyster reefs each year. The FDS was conducted using the R/V *Miss Kay,* and the average tow distance was approximately 66 m (Tarnowski, 2023). Catch per unit effort (CPUE) was calculated by dividing the volume of cultch and number of spat by the tow distance for each dredge sample. Data from the FDS were summarized for each bar and year for three metrics of habitat and spat set: the year-over-year change in the mean CPUE of cultch, the year-over-year change in the mean CPUE of spat, and the CPUE of spat. We included data from the 2010 – 2011 season to the 2018 – 2019 season because these were the seasons for which the harvester report data were available and considered complete.

We used linear mixed effects models to estimate the effects harvest by gear type on the change in the CPUE of cultch ($C_{y,b}$) (Eq. 2), the change in the CPUE of spat ($S_{y,b}$) (Eq. 3), and the spat per bushel of cultch ($R_{y,b}$) (Eq. 4). Some oyster bars were harvested using multiple gears, which was included as separate independent variables. The linear mixed effects models included an intercept (α), coefficient (β_d and β_o) for harvest per m^2 of bar area with a gear type of dredging ($X_{d,y,b}$) or other gears ($X_{o,y,b}$), a random year effect (γ_y), and a residual error term for each year and bar ($\varepsilon_{y,b}$). The spat per bushel of cultch model also includes a random bar effect (γ_b).

Eq. 2: $log\left(\frac{(C_{y+1,b}+0.1)}{(C_{y,b}+0.1)}\right) = \alpha + \beta_{d,y,b} \times X_{d,y,b} + \beta_{o,y,b} \times X_{o,y,b} + \gamma_y + \varepsilon_{y,b}$

Eq. 3: $log\left(\frac{(S_{y+1,b}+1)}{(S_{y,b}+1)}\right) = \alpha + \beta_{d,y,b} \times X_{d,y,b} + \beta_{o,y,b} \times X_{o,y,b} + \gamma_y + \varepsilon_{y,b}$

Eq. 4: $log(R_{y,b} + 1) = \alpha + \beta_{d,y,b} \times X_{d,y,b} + \beta \times X_{o,y,b} + \gamma_y + \gamma_b + \varepsilon_{y,b}$

The change in cultch and change in spat variables were log-transformed to center them at zero when no change occurred and to normalize the residuals. Small constants were added to avoid dividing by zero or taking the logarithm of zero for all dependent variables. A random bar effect was included in the spat CPUE model to account for differences in average recruitment on each bar. A bar effect was not included in the other models because the y-variable was the change over time, which reduces differences in the means among bars. The critical p-value (0.017) was determined using the Bonferroni correction adjusted for multiple comparisons using an alpha-level of 0.05 (three tests: change in cultch, change in spat, and the number of spat).

3. Results

3.1 Power Dredge Area BACI Results

The Upper Bay and Eastern Bay power dredge areas had different patterns in the number of spat and adult oysters during 2010 – 2015. Parsons Island, Wild Ground, and Bodkin Shoals in the Eastern Bay had variable patterns of spat density with peaks in 2010 and 2012 (Figure 3A). Adult density in Eastern Bay also varied over time among bars with the power dredge sites generally having a decreasing trend and the comparison site peaking in 2013 (Figure 3B). Swan Point and Peach Orchard bars in the Upper Bay had lower densities of spat and adult oysters compared to the Eastern Bay sites without any apparent trends during the study period (Figure 3A & B). The volume of cultch per m^2 varied among sites in the Upper Bay and Eastern Bay, but they all generally showed a decreasing trend over time (Figure 3C).

We did not find significant effects of power dredging on spat or cultch in Eastern Bay or the Upper Bay. Parameter estimates from the BACI ANOVAs included a negative interaction of treatment and year for the number of spat in the power dredge sites in the Upper Bay (p-value =

0.39) and Eastern Bay (p-value = 0.56; Table 2). Similarly, the BACI ANOVAs also estimated nonsignificant interactions between treatment and year for the amount of cultch in the Upper Bay (p-value = 0.12) and Eastern Bay (p-value = 0.02; Table 2).

3.2 Harvester Reports and Fall Dredge Survey Analysis Results

Harvest appeared to have different effects on the change in cultch compared to the change in spat or spat CPUE. Harvest from dredging had a significant negative effect on the year-over-year change in cultch (p=0.008), but the effect was not significant for other gear types (p=0.76; Table 3; Figure 4). The intercept was also not significantly different from zero, which implies no change in habitat, on average, in the absence of harvest (p-value=0.73; Table 3). The effect of harvest on the year-over-year change in spat was negative but not significant for both dredging (p-value=0.03), other gear types (p=0.11), and the intercept (p-value=0.89; Table 3; Figure 5). The harvest effect on spat CPUE was positive but also was not significant for either dredging (p-value=0.84) or other (p-value=0.68) gear types (Table 3; Figure 6).

4. Discussion

We investigated the effects of oyster harvest on cultch and recruitment and estimated whether dredging as a harvest method had different effects on cultch and recruitment than harvest using other gears. We found that dredging had a significant negative effect on cultch but neither gear type significantly affected recruitment. However, the effect of dredging was not significantly different from other harvest gears in the areas that were open to power dredging. The analyses of harvester reports and the FDS estimated no significant difference between dredging and other gear types for their effects on change in spat CPUE or spat CPUE. The main difference between our two studies is the power dredge study was substantially smaller and the effect of harvest was likely relatively low compared to the harvester reports and FDS data. The analysis of the harvester reports and FDS data had a longer time series and wider spatial coverage, which should result in higher power to detect differences than the power dredge study.

We found negative effects of oyster harvest on cultch, but the effects were smaller than what has previously been described in the literature (Stevenson, 1894; DeAlteris, 1988; Rothschild et al., 1994; Lenihan & Peterson, 2004). Our results were similar to other studies that found that oyster harvest negatively affected cultch and oyster reef habitat (DeAlteris, 1988; Lenihan & Peterson, 2004). Lenihan and Peterson (2004) found that dredging reduced reef height on man-made oyster reefs more than hand tonging and diving. The oyster reefs in Lenihan and Peterson (2004) were piles of loose shell about 1 m tall and 6 -7 m in diameter, whereas the reefs in our study were mostly natural bottom with some shell plantings in recent years. This difference in the structure of the oyster reefs likely explains the difference between our results and Lenihan and Peterson’s. DeAlteris (1988) also described a loss of elevation on the Wreck Shoal oyster reef in the James River, Virginia during the mid-1850s – 1985 that was large enough to change the tidal flow in the area. The fishing practices during the period when Wreck Shoal was most affected by harvest were likely quite different from modern fishing practices for oysters. In particular, it was common in the 1800s to separate oysters from the shell on shore, which caused more shell to be removed from oyster reefs. In Maryland, regulations required return of shell to the oyster reef starting in the early 1900s (Kennedy & Breisch, 1983). Effects of harvest on cultch were approximately the same as the volume of oysters harvested in our study, which suggests that additional effects of dredging on oyster habitat may be relatively small if shell and undersized oysters are required to be returned to the bar as they currently are in Maryland (Kennedy & Breisch, 1983).

None of our analyses indicated an effect of oyster harvest on spat production (i.e., recruitment). The hypothesized effects of harvest on an oyster bar, removing cultch or removing sediment from existing cultch, may have competing effects on spat settlement. A loss of cultch would be expected to reduce larvae settlement, whereas removing sediment from cultch should improve conditions for settlement (Galtsoff, 1964; MacKenzie, 1983; Wilber & Clarke, 2010). We found no benefit of harvest on spat settlement in the next year. This may be because either harvest of oysters does not remove sediment from an oyster bar as a whole (i.e., sediment that is removed is redeposited on other parts of the bar), or that any cleaning effect is short-lived and does not persist until the timing of spat settlement in the summer (Kennedy, 1996). One study that analyzed long-term trends of sediment in the nontidal Chesapeake Bay watershed found that the amount of suspended sediment peaks in the winter and spring (Zhang et al., 2015). Therefore, any "cleaning" that could occur from harvest in the fall through the winter would likely not benefit oyster larval settlement in the summer and fall months. The studies that have suggested that dredging can increase recruitment did not focus solely on oyster harvest, but they mainly focused on clam harvest or removing cultch to uncover buried fossil shell (Mercaldo-Allen & Goldberg, 2011). It is important to note that the main driver causing an increase of sedimentation that prevents oyster larvae settlement and burying reefs have not directly been identified to one source, and potential effects are influenced by several factors including location (Wilber & Clarke, 2010).

Two other studies have reported significant oyster habitat declines in the Maryland portion of the Chesapeake Bay (Rothschild et al., 1994; Smith et al., 2005). Both of these studies estimated habitat loss by comparing several estimates of the area of oyster habitat over time. Rothschild et al. (1994) compared oyster habitat during 1907 – 1990 using three oyster bottom habitat surveys: the Yates survey during 1907 – 1912, the Maryland Bay Bottom Survey during 1974 – 1982, and patent tong sampling during 1989 – 1990. Smith et al. (2005) compared an acoustic seabed classification survey during 1999 – 2001 with the Yates habitat survey and the Maryland Bay Bottom Survey. Importantly, the areas designated as oyster habitat were done using different methods in each survey. The goal of the Yates survey was to identify natural oyster reefs so that areas without oysters could be leased for aquaculture. It is unlikely that the large areas defined in the Yates survey were homogonous oyster reefs. Similarly, the goal of the Maryland Bay Bottom Survey was to describe the spatial extent of oyster bottom habitat for all of the Chesapeake Bay, Maryland. In contrast, the more recent estimates of Rothschild et al. (1994) and Smith et al. (2005) looked at finer scale oyster habitat in much smaller regions than the previous habitat surveys. Because oyster reefs are often patchy at small spatial scales, the scale of the study likely affected the estimates of change in area. These differences in methodology likely cause the inconsistencies in estimates of habitat loss between studies, but it is clear that oyster habitat has been degraded over the past century partly due to the effects of fishing (Kennedy & Breisch, 1981).

We used the results of a management experiment to estimate the effects of power dredging on oyster cultch and spat, but our study had a number of limitations. In particular, our power dredge BACI study only occurred during a relatively short period, 2010 – 2015, and focused on two relatively small regions in the Chesapeake Bay. The study design also assumes that the comparison sites are equivalent to the power dredged sites except for type of gear allowed to harvest oysters (National Research Council, 2002). The comparison sites also were open to harvest using non-power dredge gears. Therefore, the study design was to specifically estimate differential effects of power dredging relative to other gears. Given that this was a management experiment, effort was not controlled such that it would be similar in treatment and comparison sites. Harvest patterns were likely different in the treatment and comparison sites such that there was limited ability to separate effects of harvest from gear-specific effects.

5. Conclusions

We estimated the effects of oyster fishing on cultch and spat. We estimated a negative effect of power dredging on cultch, but none of the gears had a negative effect on spat. The loss of cultch associated with harvest was approximately similar to the amount of oysters removed through harvest. Given limitations in the data used for these analyses, the results had a substantial amount of uncertainty. Evidence from our study suggests that harvest does not increase oyster habitat, and harvest using current approaches and levels of exploitation also does not appear to be causing habitat degradation beyond the removal of the harvested oysters.

6. References

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7. Tables

Table 1. Area (ha) and sample sizes (N) of the reef areas by location, year, and site type. Treatment areas were areas open to power dredging, and comparison areas were ones where power dredging remained prohibited, but harvest by other gears was allowed.

Location	**Area Name**	**Site Type**	**Area**	**N**	**2010 N**	**2015 N**
Upper Bay	Swan Point	Treatment	234.7	600	100	100
	Peach Orchard	Comparison	532.6	600	100	100
Eastern Bay	Wild Ground	Treatment	115.3	601	101	100
	Parsons Island	Treatment	123.0	601	100	100
	Bodkin Shoal	Comparison	114.5	600	100	100

Table 2. Results from a Before-After-Control-Impact ANOVA for the number of spat and the amount of cultch in the Upper Bay and Eastern Bay areas of the Chesapeake Bay. The variables included the treatment as either a power dredge (treatment) or comparison area, the year before power dredging started (2010) and after the power dredge study ended (2015), and an interaction between the treatment and year (Treatment: 2015). The table includes the estimates, standard errors (SE), 95% lower confidence intervals (CI), 95% upper CI, and p-values for each parameter.

Parameter	Estimate	SE	Lower CI	Upper CI	P-value
Number of spat in the Upper Bay					
(Intercept)	0.12	0.05	0.03	0.21	0.01
Treatment	0.08	0.07	-0.05	0.21	0.23
2015	-0.12	0.07	-0.25	0.01	0.07
Treatment: 2015	-0.08	0.09	-0.26	0.10	0.39
Number of spat in Eastern Bay					
(Intercept)	0.48	0.14	0.20	0.76	0.001
Treatment	0.07	0.17	-0.27	0.42	0.67
2015	-0.36	0.20	-0.76	0.04	0.07
Treatment: 2015	-0.14	0.25	-0.63	0.34	0.56
Amount of cultch in the Upper Bay					
(Intercept)	0.62	0.22	0.18	1.06	0.006
Treatment	1.18	0.32	0.56	1.80	<0.001
2015	-0.11	0.32	-0.73	0.51	0.73
Treatment: 2015	-0.69	0.45	-1.57	0.19	0.12
Amount of cultch in Eastern Bay					
(Intercept)	1.16	0.49	0.20	2.12	0.02
Treatment	1.67	0.60	0.50	2.84	0.006
2015	-0.65	0.69	-2.01	0.71	0.35
Treatment: 2015	-1.96	0.84	-3.62	-0.30	0.02

Table 3. Results of linear mixed effects models for the change in the volume of cultch, the change in the mean number of spat, and the number of spat caught per unit effort (CPUE). The explanatory variables were bushels (36L) of harvest per m^2 for dredging and other gears. The models included a random effect for year, and the number of spat CPUE also had a random effect for bar. The gear types include dredging (power and sail dredging) and other gears (diving, hand tonging, and patent tonging). The number of spat CPUE model aslo includes a random effect of oyster bar. The parameter estimates, standard errors (SE), 95% lower confidence intervals (CI), 95% upper CIs, and p-values are provided for each parameter.

Parameter	**Estimate**	**SE**	**Lower CI**	**Upper CI**	**P-value**
Change in cultch					
(Intercept)	-0.01	0.02	-0.04	0.03	0.73
Dredge	-17.50	6.63	-30.62	-4.58	0.008
Other Gears	-1.14	3.67	-8.33	6.04	0.76
Change in spat					
(Intercept)	-0.01	0.11	-0.25	0.22	0.89
Dredge	-39.92	18.53	-76.27	-3.65	0.03
Other Gears	-16.59	10.25	-36.68	3.49	0.11
Number of spat CPUE					
(Intercept)	0.42	0.09	0.23	0.61	<0.001
Dredge	3.79	18.26	-32.83	40.34	0.84
Other Gear	4.54	11.12	-17.49	26.42	0.68

8. Figures

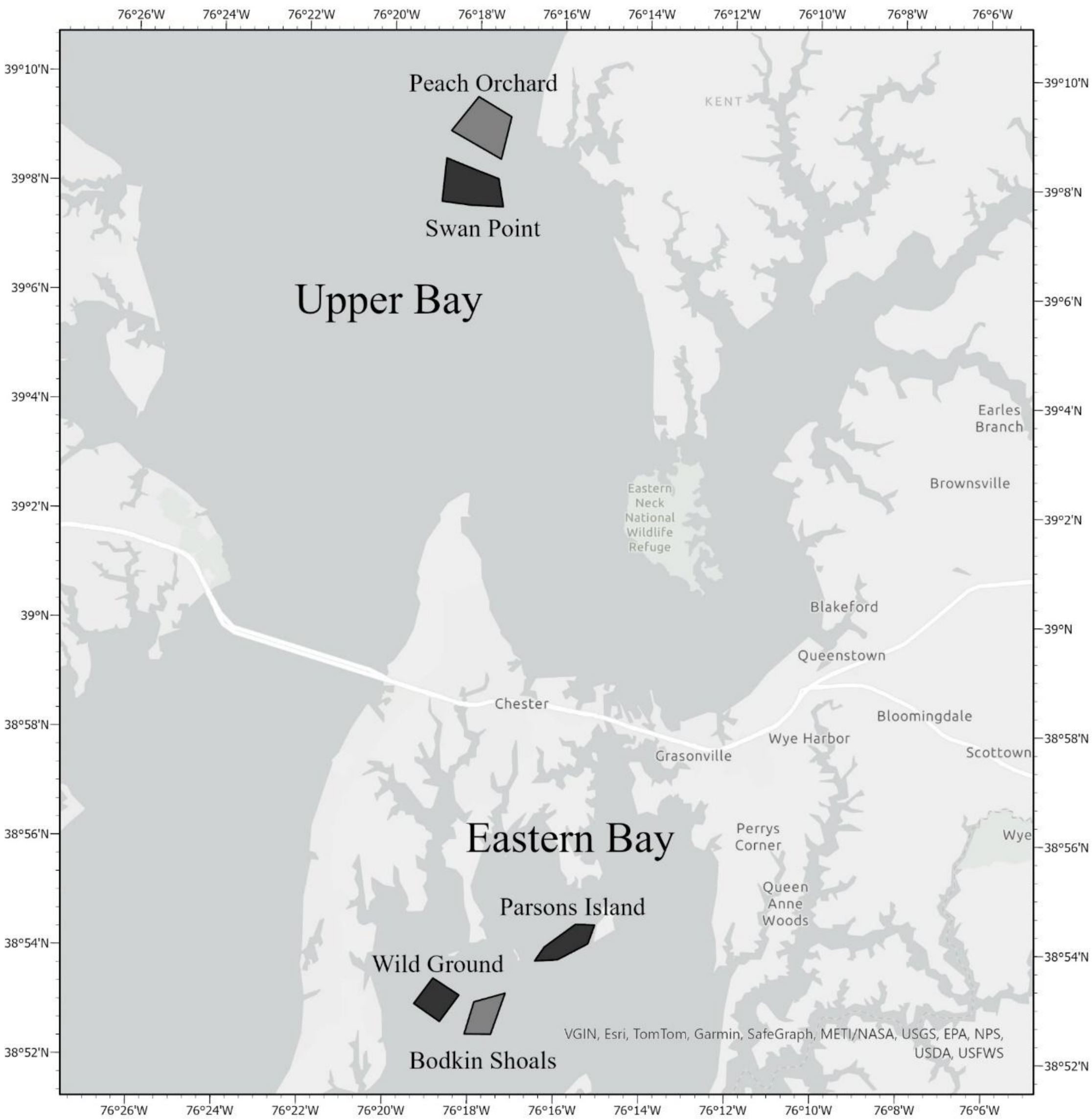

Figure 1. The study sites for the power dredge study in the Chesapeake Bay, Maryland. In the Upper Bay, Swan Point was the power dredge site and Peach Orchard was the comparison site. In Eastern Bay, Bodkin Shoals was the comparison site and Wild Ground and Parsons Island were the power dredge sites. The black polygons represent the treatment sites, and the gray polygons represent the comparison sites.

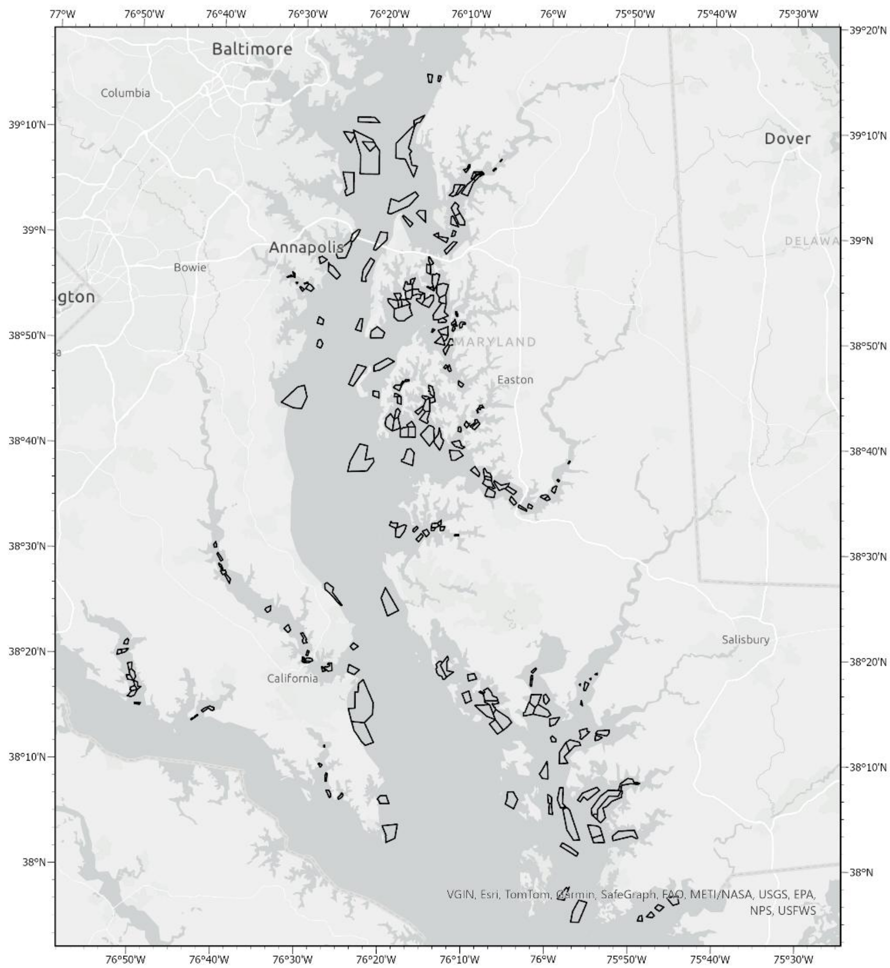

Figure 2. Locations with harvester report and fall dredge survey data to estimate effects of harvest on cultch and spat in the Chesapeake Bay, Maryland. Individual oyster bars are outlined in black.

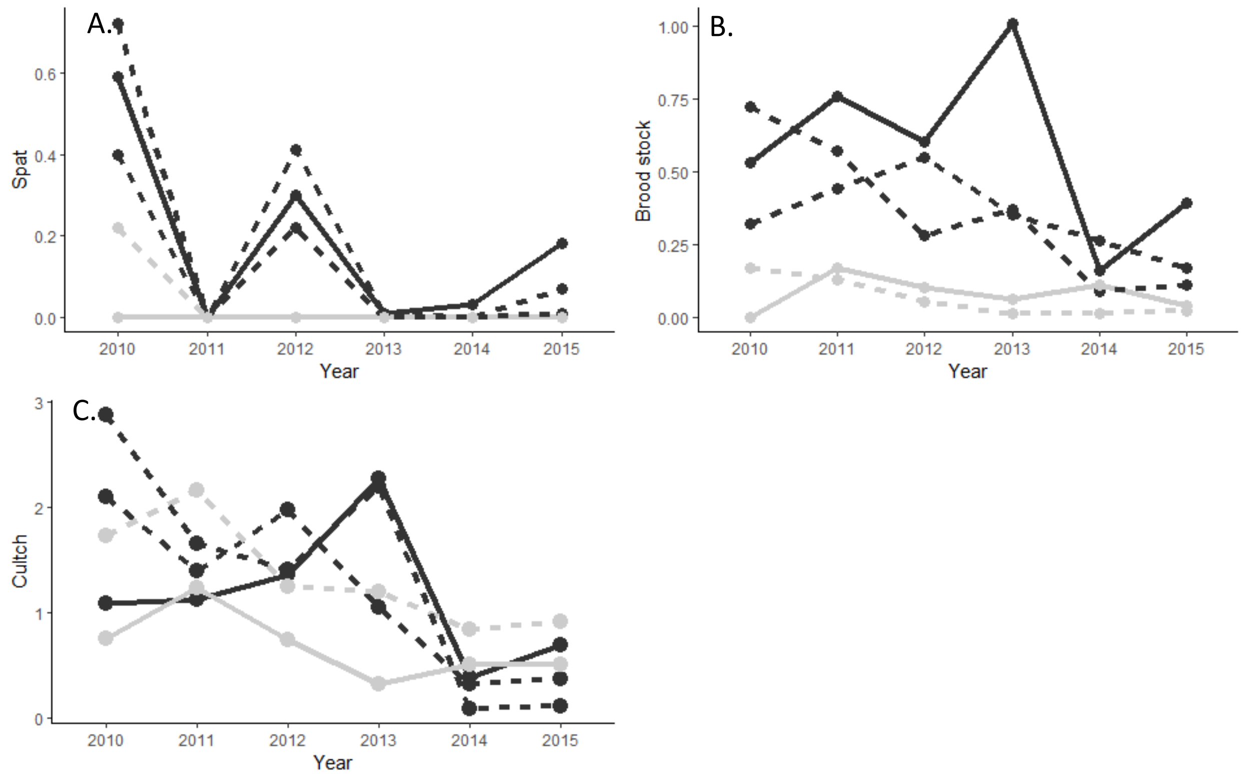

Figure 3. The A) number of spat per m^2, B) number of brood stock (i.e., adults) per m^2, and C) volume (L) of cultch per m^2 from hydraulic patent tong sampling during 2010 – 2015 on the comparison sites Bodkin Shoals and Peach Orchard and the power dredge sites Parsons Island, Peach Orchard, Swan Point, and Wild Ground in the Upper Bay and Eastern Bay of the Chesapeake Bay. Black represents the Eastern Bay, and light gray represents the Upper Bay. Solid lines represent comparison sites, and dotted lines represent power dredge sites.

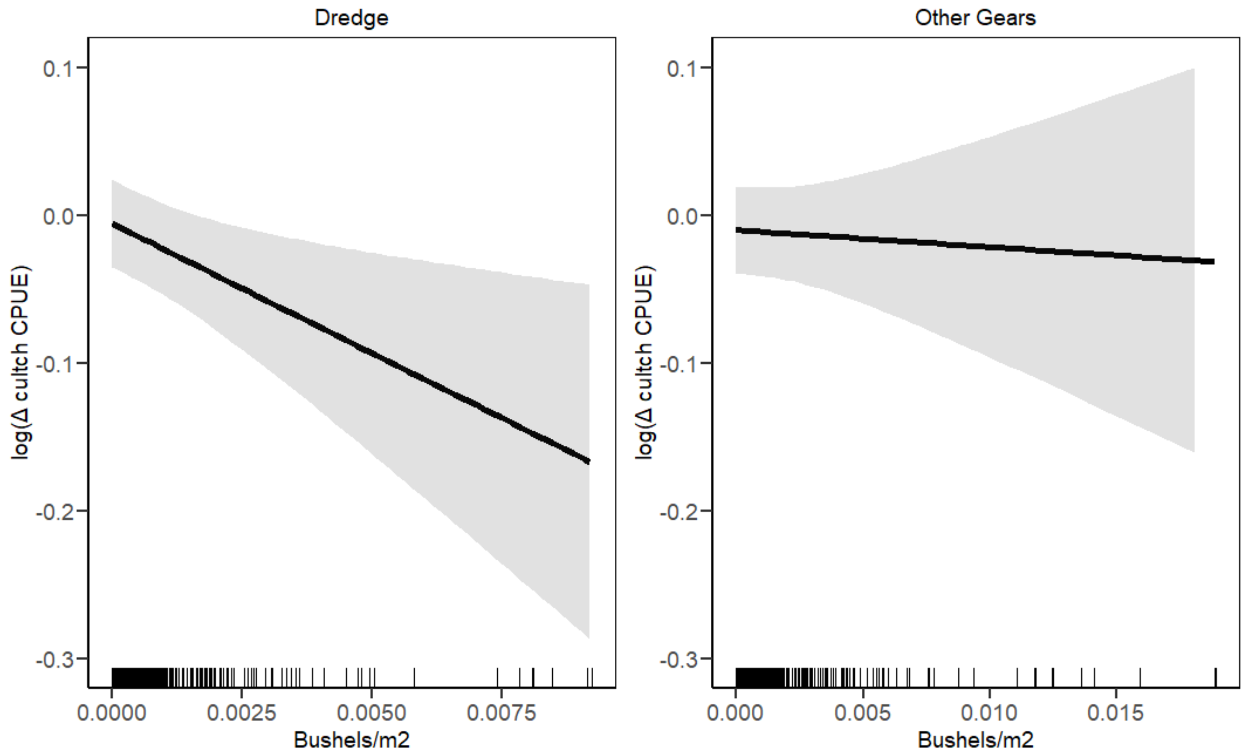

Figure 4. Estimated relationship (line) and 95% confidence intervals (gray shaded area) between the log(change in cultch catch per unit effort (Δ cultch CPUE)) and bushels (36 L) of oysters harvested per m^2 by gear types from a linear mixed effects model. The gear types included dredge (power or sail dredging) and other gears (diving, patent and hand tonging).

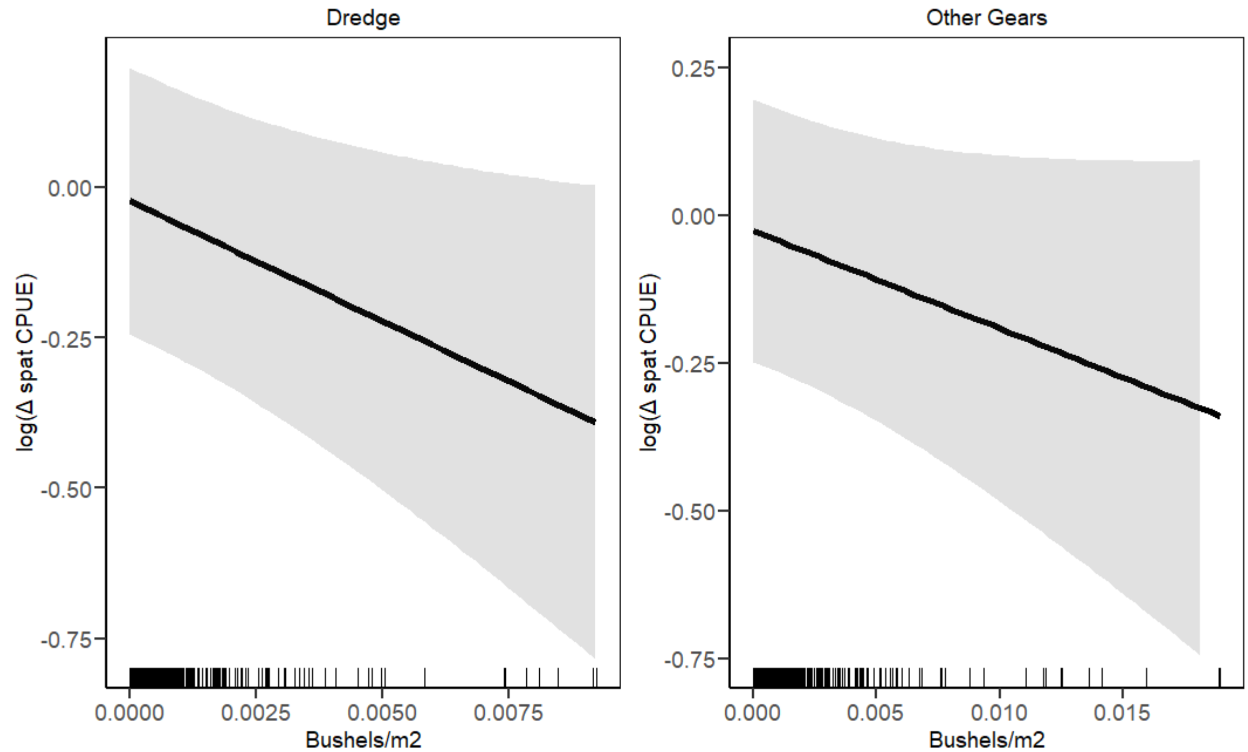

Figure 5. Estimated relationship (line) and 95% confidence intervals (gray shaded area) between the log(change in spat catch per unit effort (Δ spat CPUE)) and bushels (36 L) of oysters harvested per m^2 by gear types from a linear mixed effects model. The gear types included dredge (power or sail dredging) and other gears (diving, patent and hand tonging).

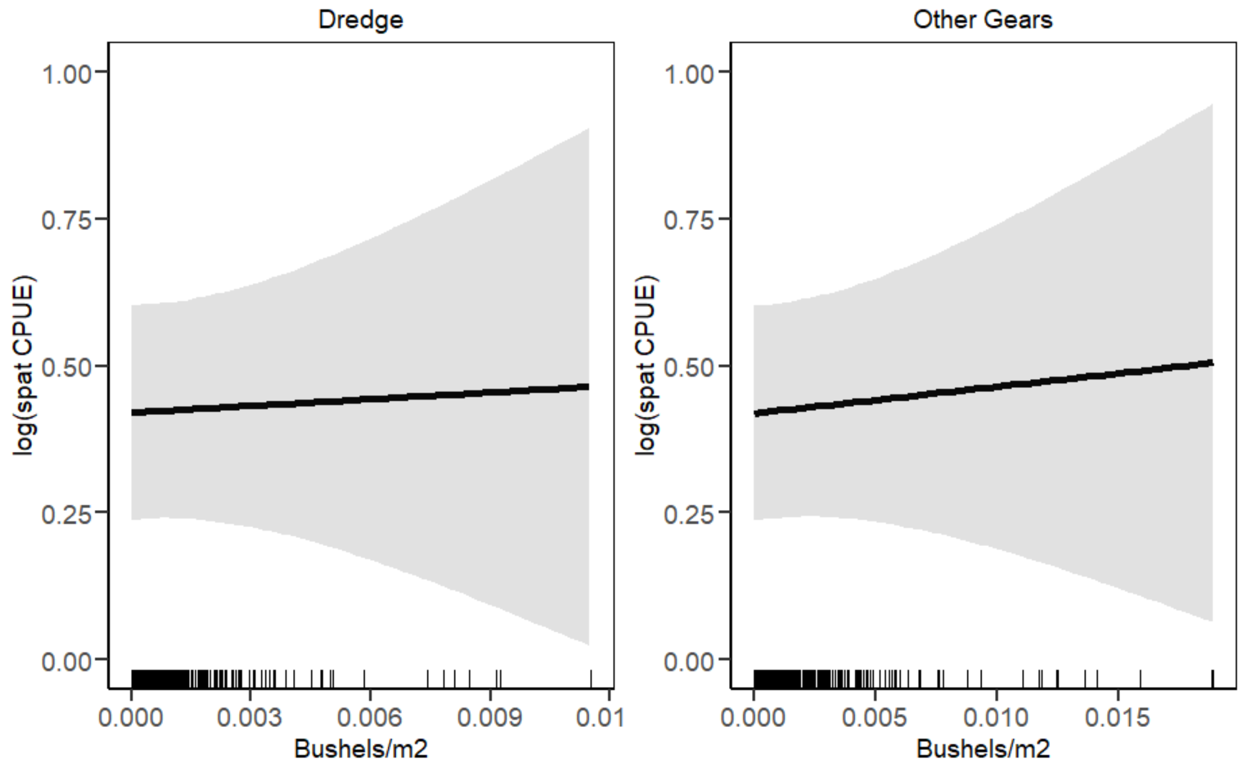

Figure 6. Estimated relationship (line) and 95% confidence intervals (gray shaded area) between the log(spat catch per unit effort (spat CPUE)) and bushels (36 L) of oysters harvested per m^2 by gear types from a linear mixed effects model. The gear types included dredge (power or sail dredging) and other gears (diving, patent and hand tonging).