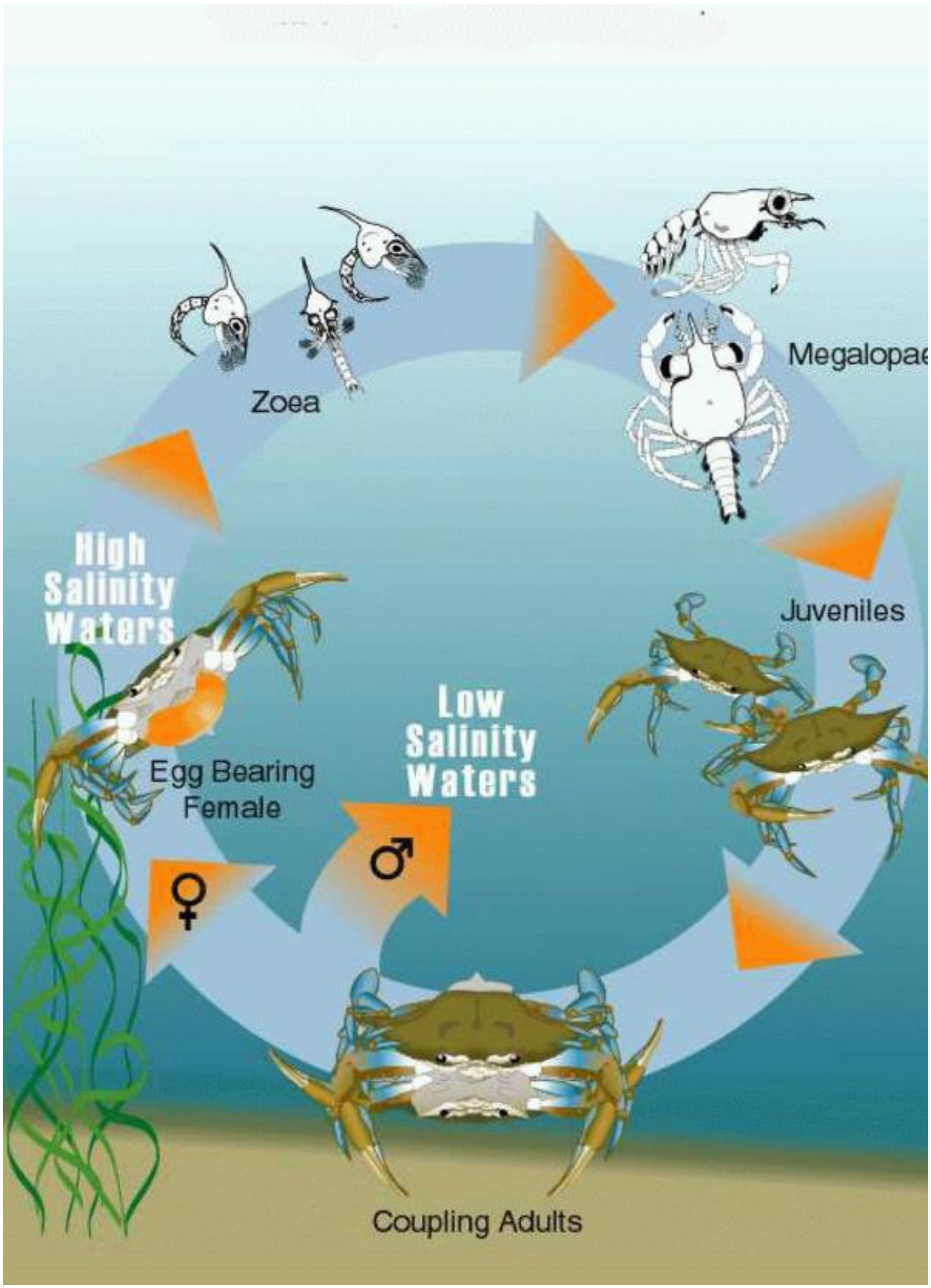
Stock Assessment of Blue Crab in Chesapeake Bay

2026



Stock Assessment of Blue Crab in Chesapeake Bay

2026

Stock Assessment Report

June 15, 2026

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Dedication

It is with deep sadness that we acknowledge the passing of Lonnie Moore this past year. Lonnie captained the *Loni Carol II* on the winter dredge survey 1992-1997. His experience and professionalism during the early years of the survey made a lasting contribution to our understanding and management of blue crabs in the Chesapeake Bay.

Acknowledgments

The stock assessment team would like to thank four independent peer reviewers for their thorough evaluation and contributions to the improvement of this work: Dr. Nick Caputi, Dr. Yong Chen, Dr. Daniel Hennen, and Dr. Simon de Lestang.

Executive Summary

The blue crab (*Callinectes sapidus*) is an icon for the Chesapeake Bay region and supports the most valuable commercial fishery in Chesapeake Bay. Ecologically, blue crab is an important component of the Chesapeake Bay ecosystem. Thus, the best scientific information available is needed to support sustainable use of this resource is critical. Since 2011, Chesapeake Bay blue crabs have been monitored annually using estimated abundance and exploitation rates from the Chesapeake Bay Blue Crab Winter Dredge Survey (WDS) along with target and threshold female abundance and exploitation rate reference points derived from updated runs of the 2011 assessment model. Initially, the population showed a strong recovery after the new management regime was implemented in 2008 to reduce fishing mortality rates on females. However, the post-2008 increase in abundance was short-lived, with abundance and catches declining through the 2010s and 2020s. Additionally, updates to the 2011 assessment model indicated declining stock productivity with associated changes to biological reference points. Further, additional work with the 2011 assessment model found instability in the estimation of the stock-recruitment parameters that are important components of reference point calculations. The decline in abundance and fishery catch were the primary impetus for conducting this new stock assessment. This report describes the results of the 2026 Chesapeake Bay Blue Crab Stock Assessment and is organized by the Terms of Reference (TORs) that were developed by the management agencies and approved by the Chesapeake Bay Stock Assessment Committee (CBSAC).

TOR 1: *Critically review and estimate life history parameters and vital rates of blue crab in the Chesapeake Bay that are relevant to the stock assessment. In particular, the assessment should evaluate the extent and scale of interannual variation in life history parameters and vital rates of blue crab in the Chesapeake Bay.*

The team reviewed the literature on blue crab biology and life history in Chesapeake Bay and throughout its range. Substantial work has been done exploring reproductive dynamics and habitat usage since the 2011 assessment. In the current assessment, we conducted new analyses to estimate length-weight relationships, natural mortality, overwinter mortality, size at recruitment, and female maturity and growth. These new relationships were subsequently used in the sex- and length-based stock assessment model (SLAM) that uses fishery-dependent and fishery-independent data from 1994-2023.

TOR 2: *Describe and quantify patterns in fishery-independent surveys to develop indices of abundance and characterize the size composition of the population. Analyses should include: (1) A comprehensive evaluation of the utility of fishery-independent surveys to inform the stock assessment; (2) Consideration of index standardization which may* *include effects of environmental and abiotic factors on survey catches; and (3) Characterization of uncertainty in indices of abundance.*

We considered eight surveys and developed new, model-based indices for surveys with sufficient length- and sex-specific data. For surveys with designs that used random sampling (WDS, Virginia Institute of Marine Science (VIMS) Trawl Survey, Chesapeake Bay Multispecies Monitoring and Assessment Program [ChesMMAP]), we used spatio-temporal models to estimate the indices, and for those with fixed site designs (Maryland Trawl Survey including the SERC Trawl Survey, and PEARL Pot Survey), we used generalized additive models. The indices were used to represent the population in specific months because the sampling frames of the surveys were generally monthly. Additionally, the length and sex composition of crabs in each survey was quantified. To avoid having recruitment occur over an extended period from summer-winter, we chose to represent recruitment as a pulse in the winter for modeling purposes. To facilitate this representation of recruitment, we censored the size distributions of the surveys for August-January to remove the new recruits. The uncertainty of the indices of abundance was estimated.

The estimated indices were largely concordant and showed initial declines between the early 1990s and early 2000s. After management changes to conserve females in 2008, survey indices initially increased. However, since 2010, most surveys have shown a declining trend in abundance. Indices of abundance were somewhat different across surveys and across months within a survey.

TOR 3: *Describe and quantify patterns in catch, effort, and CPUE. Analyses should include: (1) Estimation of catch and effort for each jurisdiction; (2) Evaluation of the utility of a commercial CPUE index in the assessment; (3) Examination of the impacts of reporting changes and trends in CPUE; (4) Evaluation and quantification of bycatch and/or discard mortality, and recreational harvest using available data from the jurisdictions; and (5) Characterization of uncertainty in the data.*

We characterized monthly catch, effort, and catch per unit effort (CPUE) for each management jurisdiction (Maryland, Virginia, and the Potomac River) for 1994-2023. Time series in our analysis began in 1994 because mandatory commercial landings[1] reporting was available for all jurisdictions since that year. Catches were separated into six fleets: Maryland Pot, Maryland Trotline, Virginia Pot, Virginia Dredge, Potomac River, and peeler (aggregated across gears and jurisdictions). The fleets represent fishing modes with different selectivity and monthly patterns of harvest. To estimate total

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[1] Throughout this report, landings will refer to commercial fishery removals that are landed. Catch will refer to landings that are expanded for dead discards and recreational harvest.

catches, reported commercial landings were increased to account for recreational harvest and dead discards of blue crabs in the commercial fisheries using new approaches. The sex ratios and size compositions of the catch for each fleet were estimated using several data sources including cooperative commercial monitoring, dealer monitoring, and concomitant survey data. Blue crab commercial effort and CPUE were not considered sufficiently reliable to carry forward in analyses for this assessment.

Catches showed different patterns over time across fleets and sexes within a fleet. The differences in trends in the catch mainly occurred before 2010. Since 2010 catches have declined across all fleets. Characterizing uncertainty of the catch is difficult because reporting of commercial landings is considered to be a census. However, the catch has uncertainty due to known reporting anomalies and expansions for both dead discards and recreational harvest. Estimates of this uncertainty were used in subsequent analyses.

TOR 4: *Evaluate the feasibility of, and if possible, implement blue crab stock assessment models that operate on sub-annual time steps and/or at spatial resolutions lower than that of the entire Chesapeake Bay to better represent population dynamics.*

We developed a new sex- and length-structured stock assessment model (SLAM) for Chesapeake Bay blue crabs that includes recruitment, growth, and fishing and natural mortality. The model was spatially-aggregated and represented the whole Chesapeake Bay. The model operates on a monthly time step with recruitment happening each winter in February to coincide with the timing of the WDS and included the years 1994-2023. Natural mortality was length-specific, and we used the WDS and an index of abundance rather than estimates of absolute abundance as was done in previous assessments. Growth followed a Gompertz growth model with a modification for female maturation growth. Fishery selectivity was based on minimum size limit regulations, which differed over years and months across fleets. The model was implemented in RTMB.

The SLAM model was fitted to sex-specific fishery catch, sex-specific fishery proportions at length, sex-aggregated survey indices of abundance, and survey proportions at sex and length. The model included survey indices from the WDS, VIMS Trawl Survey, Maryland Trawl Survey, ChesMMAP, and the PEARL Pot Survey. We prioritized fitting the WDS because it is thought to best reflect Chesapeake Bay-wide blue crab abundance because it was specifically designed as a blue crab survey and it covers the largest spatial extent.

The SLAM model was able to converge and had diagnostics that did not indicate any substantial issues. The SLAM model fit the catch time series better than the 2011 assessment model, but it still had some sex-specific residual patterns. The model was able to fit the survey indices and sex- and length-composition data relatively well without substantial sex-specific residual patterns.

Estimated fishing mortality rates differed by sex with female fishing mortality rates declining over time but those for males staying relatively high. In the early 1990s, female fishing mortality rates were about equal to those for males, but by the mid-2000s female fishing mortality rates were lower than those for males concomitantly with regulations to conserve more females around that time. Estimated recruitment showed a declining pattern over time with substantial interannual variability. Two periods of low recruitment were estimated: 1998-2007 and 2017-2023. Estimated male and female abundance of harvestable-sized blue crabs differed in their patterns over time with females increasing and males decreasing since 1994. Mature female abundance approximately doubled between 1994 and 2010, whereas male abundance did not increase. After 2010, estimated abundance of both sexes declined by about 50%.

TOR 5: *Characterize uncertainty in assessment estimates (mortality and abundance).*

We characterized uncertainty in assessment using asymptotic standard errors, 95% confidence intervals, and through sensitivity analyses of key growth, natural mortality, and WDS selectivity parameters. Most parameters and model quantities were estimated with relatively high precision (coefficient of variation < 30%). Sensitivity analyses indicated that trends in estimated fishing mortality rates and abundance were not sensitive to alternative values for fixed parameters. Estimated abundance and fishing mortality rates were relatively insensitive to alternative values of natural mortality and WDS selectivity parameters but were highly sensitive to alternative growth parameters. The alternative growth parameters, however, resulted in substantially worse fits to the data than the base model.

TOR 6: *Update the sex-specific catch survey models used in the 2011 benchmark stock assessment with relevant new data. Characterize major changes in assumptions between the 2011 assessment model and the 2023 model.*

We updated the 2011 stock assessment model and compared the results to the 2023 model. In addition to changes in model structure, the new assessment approach calculated catch and indices of abundance differently than was done in 2011.

Trends in the input data were generally similar between the two assessment frameworks. Similarly, trends in estimated abundance were similar. However, estimated abundance was higher in the new model, with much of the difference due to alternative assumptions of WDS selectivity of recruits that influenced the fraction of age-0 blue crabs that are observed in the WDS.

TOR 7: *Based on assessment model results recommend appropriate biological reference points for management. To extent possible, evaluate the appropriateness and utility of (1) Aggregate bay-wide reference points; (2) Sex specific reference points; and (3) Recruitment reference points.*

We adopted a spawning potential ratio approach (SPR) for calculating Chesapeake Bay-wide biological reference points. We developed threshold and target reference points for male and mature female abundance and fishing mortality rates. We chose $F_{40\%}$ as the basis for the threshold reference points, where $F_{40\%}$ represents the fishing mortality rate that would be expected to reduce the lifetime reproductive potential to 40% of the unfished level. Abundance threshold reference points represent the expected equilibrium abundance under median recruitment and the threshold fishing mortality rate reference points. Sex-specific target fishing mortality rates were calculated as 75% of the threshold values, and target abundances were calculated assuming median recruitment and the target fishing mortality rates.

We also developed Chesapeake Bay-wide recruitment reference points to indicate extended periods of low recruitment that would be of sufficient concern that management action may be warranted. The lower threshold recruitment reference point was defined as the 3-yr running average recruitment compared to the 25th percentile of estimated recruitment during 1994-2023.

TOR 8: *Evaluate stock status relative to recommended reference points.*

Male and female fishing mortality rates in the most recent year were below the threshold fishing mortality rate reference point indicating that overfishing was not occurring relative to the recommended threshold. However, overfishing was estimated to have occurred in some previous years. Fishing mortality rates were also less than the target levels in recent years.

Mature female abundance was estimated to be slightly above the recommended target in 2023, but it was near the recommended threshold in 2022. In contrast, male abundance has been below the target and threshold since 2020.

Three-year average recruitment was below the recommended threshold for 2022 and 2023, but it was above the threshold for all previous years.

TOR 9: *Identify relevant ecosystem and climate influences (such as habitat, environmental drivers, prey availability, and predation/cannibalism) on the population dynamics and fisheries and, to the extent possible, explore other analyses that support the assessment.*

We conducted analyses and investigations to identify potential ecosystem and climate effects on Chesapeake Bay blue crabs. We considered effects of blue catfish (*Ictalurus* *furcatus*), effects of temperature on blue crab growth and overwinter mortality, and effects of hypoxia. Additionally, we characterized spatial temperature patterns in Chesapeake Bay. Survey CPUE for blue crabs was lower when blue catfish abundance was high in regions where blue crab and blue catfish overlap.

The estimated effect of blue catfish on blue crab recruitment increased over time and may have caused recruitment to be about 8% lower than it would have been in the absence of blue catfish. However, across most of the time series, the effect of blue catfish was estimated to be < 5%.

Overwinter mortality was estimated by length and sex for Maryland and Virginia separately using data on dead crabs observed in the WDS. Estimates were combined to produce Chesapeake Bay-wide estimates. Overwinter mortality was higher for larger blue crabs and varied substantially over time (1-13% Chesapeake Bay-wide). Overwinter mortality rates were higher in years with severe winters.

Substantial efforts were made to develop a temperature-dependent growth model. However, apparent periods of high growth in the spring and late summer that were evident in the Maryland and VIMS trawl surveys could not be described by our temperature-dependent growth models.

We evaluated whether survey indices were related to hypoxic volume using data from ChesMMAP and the WDS. We did not find clear relationships between survey CPUE and hypoxic volume either of the surveys evaluated.

TOR 10: *Identify existing data sources and gaps, and, to the extent possible, characterize the uncertainty in the relevant sources of data.*

We described the main data gaps that were identified in the 2026 stock assessment process. The data gaps that were considered most influential included blue crab growth, drivers of recruitment, recreational harvest and bycatch mortality, spatial differences in survey trends and size distributions, natural mortality, and the WDS catchability and selectivity.

TOR 11: *Report on the status of research recommendations from the most recent benchmark assessment. Identify and prioritize research recommendations for future work.*

We described the work that has been done to address the research recommendations from the 2011 benchmark assessment and the 2017 update of that model. Additionally, we provide recommendations for future research to address knowledge gaps that were identified in this assessment.

Conclusions

We addressed all of the TORs for the Chesapeake Bay blue crab stock assessment and developed new approaches for estimating catch and survey indices and a new model for estimating blue crab abundance and fishing mortality rates. Estimates from the new stock assessment indicate that female abundance remained above the levels of concern observed in the early 2000s, but it has been declining since 2010. Male abundance has been relatively low relative to the recommended reference points during the last five years. Fishing mortality rates were above the new reference points in many years before 2010, but after 2010, fishing mortality rates were below the target for females and below the limit for males. The most concerning pattern is the long-term decline in recruitment. While we explored several potential causes of declining recruitment, we did not identify a likely cause. The new reference points and stock assessment approach have improved our understanding of blue crab dynamics in Chesapeake Bay and provide useful information for guiding sustainable management.

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Terms of Reference

The 2026 Chesapeake Bay blue crab stock assessment was funded by grants from the Maryland Department of Natural Resources and the Virginia Marine Resources Commission through the Atlantic States Marine Fisheries Commission and by support from the NOAA Chesapeake Bay Office and the Potomac River Fisheries Commission. The three management agencies jointly developed the following 11 specific terms of reference (TORs) that were approved by the Chesapeake Bay Stock Assessment Committee (CBSAC), and this report is organized according to the TORs.

TOR 1: *Critically review and estimate life history parameters and vital rates of blue crab in the Chesapeake Bay that are relevant to the stock assessment. In particular, the assessment should evaluate the extent and scale of interannual variation in life history parameters and vital rates of blue crab in the Chesapeake Bay.*

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TOR 5: *Characterize uncertainty in assessment estimates (mortality and abundance).*

TOR 6: *Update the sex-specific catch survey models used in the 2011 benchmark stock assessment with relevant new data. Characterize major changes in assumptions between the 2011 assessment model and the 2023 model.*

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TOR 8: *Evaluate stock status relative to recommended reference points.*

TOR 9: *Identify relevant ecosystem and climate influences (such as habitat, environmental drivers, prey availability, and predation/cannibalism) on the population dynamics and fisheries and, to the extent possible, explore other analyses that support the assessment.*

TOR 10: *Identify existing data sources and gaps, and, to the extent possible, characterize the uncertainty in the relevant sources of data.*

TOR 11: *Report on the status of research recommendations from the most recent benchmark assessment. Identify and prioritize research recommendations for future work.*

Introduction

The blue crab (*Callinectes sapidus*) supports important commercial and recreational fisheries throughout Chesapeake Bay. Maryland, Virginia and the Potomac River Fisheries Commission are the management jurisdictions for blue crab in Chesapeake Bay. The management actions of the three jurisdictions are coordinated because they are signatories to the Chesapeake Bay Blue Crab Fishery Management Plan (FMP; Chesapeake Bay Program 1997). The FMP provides recommendations for the management of commercial and recreational fishing of blue crab in the Bay. The FMP goal is "to manage blue crabs in the Chesapeake Bay to conserve the bay wide stock, protect its ecological value, and optimize the long-term utilization of the resource." The blue crab FMP adheres to the principles proposed for Chesapeake Bay FMPs that were developed by the Chesapeake Bay Program in 1998, in which precautionary management and protection of critical habitats are highlighted. Regulations and management actions are complementary across the jurisdictions but recognize age-specific and sex-specific differences in habitat use and historical fishing patterns.

Assessment History

Studies of the dynamics of blue crab in Chesapeake Bay began as early as the late 19th Century. Considerable efforts were made in subsequent years to understand blue crab population dynamics in Chesapeake Bay. These initial studies documented growth, spawning periodicity, and population variability. However, the first comprehensive stock assessment of blue crab in Chesapeake Bay was conducted in 1997 (Rugolo et al. 1997). Rugolo et al. (1997) used index-based approaches and a simple production model in their assessment. They indicated that stock abundance had been high in the 1980s and had declined to more average abundances over the subsequent decade. The stock was characterized as moderately to fully-utilized at the exploitation levels then occurring. Rugolo et al. (1997) recommended establishing and maintaining a fishing mortality rate reference point that ensured escapement of at least 10% of the unfished spawning potential. Although finding no cause for alarm, Rugolo et al. (1997) recommended no further increases in fishing effort or fishing mortality.

Following the Rugolo et al. (1997) assessment, Miller and Houde (1999) revisited the assessment of the blue crab fishery to develop threshold and target reference points. Miller and Houde (1999) recommended a hierarchy of target levels to address sustainability, efficiency, and recovery scenarios. Targets were derived from 1) reported catches and effort in the commercial fishery, 2) statistics from fishery-independent surveys, and 3) knowledge of the biology of blue crab. Miller and Houde (1999) recommended a long-term potential yield of ~36,000 metric tons (MT; about 80 million lbs) and fishing mortality rates (F) < 0.9 yr^{-1}. A second target level equivalent to F=0.6 yr^{-1} was recommended to ensure that the maximum reproductive potential per crab would be obtained over the long term. A recovery target was also recommended of F <0.5 yr^{-1} to help build the stock in the case of recruitment overfishing.

In 1996, the Governors and Legislatures of Maryland and Virginia established the “Bi-State Blue Crab Advisory Committee” (BBCAC) to provide them with independent advice on the status and future trends of the blue crab fisheries. In 1998, BBCAC endorsed the findings of its technical work group that indicated that there were signs that the crab population was not in a healthy condition. Specifically, BBCAC identified the following indicators of concern:

- Overall abundance for all age groups was down,
- Fishing mortality was increasing,
- Fishing effort was at near record levels,
- Spawning stock biomass was below the long-term average,
- The average size of crabs was decreasing,
- Fishery-independent surveys showed a decreasing percentage of legal-size crabs,
- The reproductive potential of the population was of concern because of the reduced size of males and lack of mature females.

This consensus view motivated the development of a new management framework for the Chesapeake Bay blue crab fisheries (Miller 2001b). The framework recognized the need to distinguish between threshold and target reference points. Specifically, the framework identified biomass- and exploitation-based threshold reference points that bounded a zone of sustainable exploitation. Within this zone of sustainable exploitation, researchers recommended a target exploitation rate that sought to double the current spawning potential of the blue crab population. In making these control rules functional, empirical evidence and elementary per recruit analyses were combined to determine values for the threshold and target reference points.

Miller et al. (2005) produced the next full assessment of the blue crab stock and its fisheries in Chesapeake Bay. These authors reviewed key life history parameters for blue crab including direct and indirect estimates of the rate of natural mortality (Hewitt et al. 2007). Miller et al. (2005) recommended abandoning the $M = 0.375\ yr^{-1}$ value used by Rugolo et al. (1997) in favor of a revised $M=0.9\ yr^{-1}$ estimate. This increased level of M was used in the 2005 assessment, although assessment results retaining the former lower estimate were presented for comparison purposes. The 2005 assessment used an individual-based yield per recruit model to estimate fishery reference points (Bunnell and Miller 2005). The changes in M and in the methodological approach yielded new values for the target and threshold reference points, although the definitions of the reference points (i.e., 20% and 10% virgin spawning potential) were maintained. However, Miller et al. (2005) expressed these reference-points not in terms of instantaneous rates (e.g., F) but in terms of the target and threshold exploitation fractions (U) equivalent to the 20% and 10% spawning potential ratios. Specifically, Miller et al. (2005) calculated values of $U_{target}=0.46$ and $U_{threshold}=0.53$. Miller et al. (2005) maintained the definition of the overfished threshold as the abundance equivalent to the lowest abundance observed in the Chesapeake Bay winter dredge survey but expressed this value in terms of absolute abundance rather than as a standardized value. To assess the status of the blue crab stock against these reference points, Miller et al. (2005) used a catch-survey model (Collie and Sissenwine 1983), modified to include multiple fishery-independent surveys. Based on this new framework, Miller et al. (2005) concluded that the blue crab stock in 2005 was not overfished nor was it experiencing overfishing.

Several modifications to the management framework were made by the Chesapeake Bay Stock Assessment Committee (CBSAC) between 2005 and 2011. Perhaps most significantly, stock status was determined annually using a purely empirical approach. The abundance of crabs was estimated using the winter dredge survey and the exploitation fraction is calculated as the harvest during the year divided by the observed winter dredge survey abundance at the beginning of the year. The 2005 catch-survey model was not used in the annual determination of stock status. In 2008 an interim abundance target was established, equal to 200 million crabs (CBSAC 2008). This figure was based on analyses of the relationship between winter dredge survey-based estimates of abundance and harvest, and abundance and recruitment. Moreover, in 2008 CBSAC noted that management actions had yet to achieve the target exploitation rate and recommended adoption of management policies that focused on conserving female crabs.

Concerns over declining abundances in the mid-2000s, particularly related to adult female blue crabs, together with advances in assessment methodologies led to the next blue crab stock assessment (Miller et al. 2011). This assessment considered life history parameters in more depth (Hewit et al. 2007), developed index standardization approaches for the fishery independent surveys and applied time series methods to adjust for historical changes in how catches were reported (Fogarty and Miller 2004). Most importantly, the 2011 assessment brought forward a new sex-specific catch-multiple survey analysis assessment model (SSCMSA) to address management concerns and interests in protecting the spawning stock (Miller et al. 2011). An important advance in this assessment was the integration of the assessment model and the determination of biological reference points, so that each became inherently compatible, overcoming a concern with the 2005 assessment that analyzed these two important elements separately. The biological reference points were also estimated using a maximum sustainable yield approach. The 2011 assessment went through independent peer-review by the Center for Independent Experts (CIE) which determined it represented the best scientific information available for management. Subsequently, the 2011 assessment transitioned to an operational assessment that was regularly updated starting in 2017 by Maryland DNR and VIMS scientists and reviewed by CBSAC annually until 2024. The reference points served as the basis of management of blue crab in Chesapeake Bay since 2011.

Since 2011, Chesapeake Bay blue crabs have been monitored annually using estimated abundance and exploitation rates from the Winter Dredge Survey and target and threshold female abundance and exploitation rates from the 2011 assessment model. Initially, the population showed a strong recovery after the new management regime that was implemented in 2008 to reduce fishing mortality rates on females. However, the post-2008 increase in abundance was short-lived, and abundance and catches have declined through the 2010s and 2020s. Additionally, subsequent updates to the 2011 assessment model indicated declining stock productivity with associated changes to biological reference points. Further, additional work with the 2011 assessment model found instability in the estimation of the stock-recruitment parameters that are important components of reference point calculations. The declines in abundance and fishery catch were the primary impetus for conducting this new stock assessment.

TOR 1. Biology and Life History

1.1. Stock Structure

Recent studies suggest that blue crab consists of one genetically panmictic population extending from Chesapeake Bay (the northern-most site used in the analysis) to the US Gulf of Mexico. Macedo et al. (2019) found very low levels of genetic differentiation from 16 microsatellite loci along with high genetic diversity among ten estuaries that were studied from Chesapeake Bay to Lower Laguna Madre, TX (Macedo et al. 2019). A similar microsatellite study of blue crab in South Brazil used nine markers and found low levels of genetic differentiation among the four blue crab populations examined along 740 km of the Brazilian coast (Lacerda et al. 2016) demonstrating high gene flow across broad geographic regions for blue crab. High similarity of *Callinectes sapidus* Reovirus 1 (CsRV1) between the U.S. Atlantic coast and Gulf of Mexico also supports high levels of genetic connectivity (Zhao et al. 2023), although those authors suggested human-mediated movement as a potential cause of their results. Previously, McMillen-Jackson et al. (1994) used a protein electrophoretic approach to quantify the genetic variability in samples collected from Texas to New York. That research indicated moderate genetic structuring, with spatial patchiness of several loci evident throughout the range. However, the findings also indicated that a high level of regional gene flow acted to diminish population structure. These researchers revisited the question of population structure within the blue crab using multiple genetic markers and restriction length fragment polymorphism analysis of mitochondrial DNA (McMillen-Jackson and Bert 2004). The genetic results indicated no clear split between Gulf of Mexico stocks and Atlantic coast stocks, similar to the findings of Macedo et al. (2019). However, there was a cline of genetic diversity within the Atlantic coast with the New York samples exhibiting significantly lower diversity than more southerly stocks (McMillen-Jackson and Bert 2004). Whether this pattern is also present in microsatellite markers used by Macedo et al. (2019) is unknown as estuaries north of Chesapeake Bay were not included in the Macedo et al. (2019) analysis. Thus, at the genetic level, blue crab populations cannot be differentiated into distinct stocks.

Studies of larval distributions provide evidence for the presence of a largely discrete Chesapeake Bay stock. After being hatched near the Bay mouth, larvae are advected to the continental shelf, where they develop and enter the estuary as megalopae (Epifanio 2007). While the precise details of the physical context and behavioral mechanisms employed by larvae to return to estuaries are not fully understood, what is known suggests that large scale exchanges of larvae between estuaries are likely not typical. The prevailing oceanography of the regions suggests that only the Chesapeake Bay and more northerly populations (i.e., coastal bays and Delaware Bay) are sources of potential recruits to Chesapeake Bay. This suggests that population interchange is restricted. However, Colton et al. (2014) found evidence of recruitment synchrony over time from New York to Florida, which could be caused by interchange of larvae or a common response to large-scale environmental drivers.

Aspects of the physical environment and behavior of zoea suggest that the exchange is likely not a persistent feature of the dynamics of the different populations. Female crabs release zoea near the mouth of coastal Atlantic estuaries. Natunewicz and Epifanio (2001) found that zoea occur in distinct patches 0.5 – 2.5 km diameter in the vicinity of the mouth of Delaware Bay. Modeling by Garvine et al. (1997) indicated that some larvae return to Delaware Bay using upwelling-favorable wind events. However, these modeling studies also indicated that a portion of zoea are advected southward in a buoyancy driven coastal current. These larvae may represent potential recruits to the Chesapeake Bay population. Studies of recruitment in the Chesapeake Bay stock indicate a similar picture to that found for Delaware. Roman and Boicourt (1999) found patches of zoea associated with the Chesapeake Bay plume front. In a later study Biermann et al. (2016) found evidence for diel vertical migration of zoea, suggesting this as a mechanism for local retention. In a numerical analysis Johnson and Hess (1990) estimated that only 13% of released zoea remained in the Chesapeake Bay and that the remaining zoea (87%) are advected out to sea. Johnson and Hess (op. cit.) calculated that 29% of the zoeal production returns to the Chesapeake Bay. It is important to note that these figures do not include zoeal mortality, which is likely to be substantial, and thus represent an upper bound.

From this review, we conclude that there is sufficient evidence to support the assumption that the blue crab population in Chesapeake Bay comprises a unit stock, at least for assessment purposes. This does not imply that there is no exchange with or subsidy from neighboring populations; rather it assumes that the dynamics of the Chesapeake Bay population are determined internally , and not from subsidies or exchanges with other populations. Populations can be genetically well-mixed while also having demographic independence. For example, very few juvenile and adult blue crabs tagged in Chesapeake Bay have been recaptured outside of Chesapeake Bay (<<1% from tens of thousands of tagged blue crabs). Subsidies and exchanges do likely occur with genetic and evolutionary implications – we are simply assuming that they are not significant enough to affect population dynamics. However, we note that such subsidies and exchanges are likely to be more important when the size of the Chesapeake Bay population is small.

1.2. Growth

Information on blue crab growth expanded substantially prior to the 2011 assessment (Miller et al. 2011). Publications on lipofuscin-based aging (Ju et al. 2001), molt-process modeling (Brylawski and Miller 2006) and stock enhancement efforts (Zohar et al. 2008) all contributed new information available for that assessment. Additional research through 2026 has further refined the established dynamics and the possible influences of prey availability on growth (Seitz et al. 2005), habitat use (Ralph et al. 2013), and environmental conditions (Glandon and Miller 2017; Glandon et al. 2018; Glandon et al. 2019b).

The physiology and energetics of growth in blue crab were summarized by Smith and Chang (2007). However, documenting the growth dynamics of blue crab and other crustaceans in the field is difficult because of the lack of structures for aging. Lipofuscin, a complex lipo-protein builds up in post-mitotic tissues of all organisms as a result of intracellular reactions to protect cells from oxidative stresses. Ju et al. (1999) developed a biochemical assay to quantify the level of lipofuscin in blue crab eye stalks. By measuring the lipofuscin level in non-dividing tissues, such as nervous tissue, Ju et al. (1999) were able to estimate physiological age. Validation studies have been conducted that permit the absolute level of lipofuscin to be correlated with chronological age based on crabs raised in both the laboratory and in artificial ponds (Ju et al. 1999). Crabs raised in artificial ponds were held at ambient conditions, allowed to forage on naturally abundant prey and sampled on several occasions over 18 months. Information on the sizes of known age crabs from the ponds were fit to a von Bertalanffy growth function. Puckett et al. (2008) used the lipofuscin assay to age free-living crabs in the Chesapeake Bay. These authors concluded that the peeler-soft crab and the hard crab fisheries generally harvest blue crabs less than 18 months of age. Lipofuscin-based aging has remained a research method and has not been adopted for routine monitoring of the Chesapeake Bay blue crab population due to high variability in the relationship between lipofuscin levels and age.

Smith (1997) developed a discrete molt-process model for blue crab in Chesapeake Bay. He used empirical relationships developed for crustaceans to develop a specific parameterization for blue crab. Using this approach, Smith (1997) estimated von Bertalanffy parameters that best described the growth trajectory. These model parameters yielded estimates of sizes at the onset of overwintering in the first, second and third years of crabs measuring 32.5, 107.5 and 147.6 mm carapace width (CW). Brylawski and Miller (2006) conducted laboratory experiments to directly estimate the parameters of the Smith (1997) molt process model. These authors incorporated their parameter estimates into a simulation model demonstrating that variation in winter temperatures could alter the timing of recruitment to the fishery by up to 10%. Further discussion of molt dynamics and post-maturity growth is presented in section 1.3.

Research efforts to assess the feasibility of stock enhancement for blue crabs in Chesapeake Bay generated additional information on growth. Growth data are available from two components of this project: (1) growth of early life stages during the development of aquaculture technologies and (2) growth of larger juveniles and adults from experimental field releases of hatchery-reared animals. Zmora et al. (2005) cultured juvenile crabs in a hatchery from captive spawning adults; zoea grew to 1st stage juveniles (C1) in approximately one month, and from C1 to C6-7 stage (~20 mm CW) in the subsequent month. Although no quantitative estimates are given, Zmora et al. (2005) noted striking variability in growth rates among individuals in a single brood. Releases of hatchery-reared blue crab juveniles (6-30 mm CW) into shallow water habitats of the upper and lower Chesapeake Bay provided an opportunity to estimate growth rates of free-ranging animals under natural conditions (Davis et al. 2005; Hines et al. 2008). Similar to previous studies, growth was temperature-dependent with peak growth rates of 1.2 mm CW d^{-1} observed in July. A deterministic growth model based on field data predicted that juveniles recruiting in fall will enter the hard crab fishery during late summer to early fall of the following year. Growth rates of hatchery-reared animals appear to be representative of wild crabs; paired experimental releases of hatchery-reared and wild cohorts showed no difference in observed growth rates (Johnson et al. 2011).

Field studies indicate that blue crab growth rates can vary spatially and temporally within the Chesapeake Bay. Seitz et al. (2005) quantified juvenile (25-52 mm CW) blue crab growth across upriver and downriver areas and between vegetated and unvegetated habitats within a Chesapeake Bay subestuary. Growth rates were highest in upriver unvegetated habitats, whereas in downriver areas juveniles exhibited higher growth in vegetated (seagrass) habitats (Seitz et al. 2005). Growth was positively associated with prey availability, specifically clam density (*Macoma balthica* and *Mya arenaria*), and exhibited strong seasonal variation, with maximum growth during spring-summer months and minimal growth during fall-winter months (Seitz et al. 2005). Ralph et al. (2013) examined the relationship between juvenile blue crab density and seagrass bed percent cover between the western and eastern shores of the Chesapeake Bay. Ralph et al. (2013) reported regional differences in juvenile size structure, with fewer but larger juveniles on the Chesapeake Bay eastern shore and higher densities of smaller juveniles on the western shore. These patterns were hypothesized to reflect differences in growth rates and habitat residence time, whereby faster-growing juveniles may transition more rapidly out of vegetated habitats, resulting in lower densities but larger sizes in some regions. However, Ralph et al. (2013) emphasizes that additional research is needed to more fully resolve the effects of habitat complexity on growth rates and population structure.

More recent work has quantified the effects of environmental shifts, including warming water temperatures and increasing $p\text{CO}_2$, on blue crab growth and related processes such as food consumption, shell properties, and growing season length. Glandon and Miller (2017) demonstrated that juvenile blue crabs exposed to warmer water (32°C relative to an ambient 28°C treatment) exhibited significantly higher food consumption and faster growth via shorter inter-molt periods. In a subsequent study, Glandon et al. (2018) found that elevated temperature was also associated with an 8.5% reduction in carapace thickness and decreased shell mineral content, particularly the percent weight of high-magnesium calcite (HMC). In contrast, increased pCO_2 led to higher shell magnesium content and increased HMC, indicating that temperature and acidification may exert opposing influences on shell mineralization. Together, these findings suggest a potential tradeoff between enhanced growth and shell integrity (thickness and mineral composition) under warmer conditions. However, these effects were observed in juvenile crabs, and responses may differ for adult life stages (Glandon et al. 2019b).

Warming water temperatures may promote more rapid growth and an extended growing season for Blue Crab (Glandon et al. 2019b). Using projections from downscaled climate models in combination with estimates of overwintering duration and overwinter survival probability, Glandon et al. (2019b) estimated that future winters could be up to 50% shorter and Blue Crab overwinter survival could increase by approximately 20%. These changes would reduce seasonal mortality and extend the period of favorable growth conditions. However, Glandon et al. (2019b) also noted that the extent to which such increases in productivity are realized will likely depend on interacting ecological conditions and fishery management policy.

As part of this assessment, we also investigated length-weight relationships of blue crab (Liang et al. 2026). Data from the ChesMMAP trawl survey and the PEARL pot survey were used to estimate sex-specific length-weight relationships and to evaluate potential changes over time. The results indicated that males tend to weigh more than females for CWs greater than about 9 cm (Figure 1.1), but that the length-weight relationship has not changed over time.

1.3. Reproduction

1.3.1. Molt to maturity

Blue crabs reproduce sexually, and males and females are sexually dimorphic and exhibit different growth forms. The reproductive physiology and anatomy are reviewed by Jivoff et al. (2007). Circumstantial evidence strongly suggests the presence of a terminal molt in female blue crab (Van Engel 1958; Abbe 1974). Limited physiological evidence suggests that the Y-organ does not degenerate as it does in other crabs that exhibit determinate growth. Rather, Zmora et al. (2009) found that molt-inhibiting hormone produced by the X-organ also stimulates vitellogenesis, thus enforcing the terminal molt while coordinating reproduction. Evidence for a terminal molt in males is less definitive than in females. There is some evidence for continued growth in males, particularly as most of the largest crabs collected are males. However, similar to large females, large males form limb buds when they lose an appendage, and such males are often collected in the field suggesting that males molt infrequently at large sizes.

Growth of females associated with their maturation molt was investigated as part of this assessment (Ogburn et al. 2026). Based on size distribution data of pre-pubertal and mature females in the SERC Trawl Survey, growth during the maturation molt appeared to be larger than for juvenile molts (mean increase in CW of approximately 40%) with the percentage change in CW well described by a decreasing linear function of pre-pubertal CW (Figure 1.2). This increase in CW for the female maturation molt was somewhat higher than the 32% increase in CW observed by Tagatz (1968). Tagatz (1968) noted that the growth increment at the molt to maturity was the largest increment and that the maximum observed increment was 50%. Similarly, Haefner and Shuster (1964) observed molt increments of up to 32% (N=56 crabs) at the molt to maturity for pre-pubertal females held in field cages in Chesapeake Bay.

Lipcius and Seebo (2026) investigated changes in spine width for immature female, mature female, and male blue crabs in Chesapeake Bay using measurements of CW from tip to tip of the spines and from the base of each spine (NW). The CW relative to the NW increased significantly after maturation for females with immature females having CWs about 28% larger than NWs and mature females having CWs about 38% larger than NWs, which supports the hypothesis that females grow disproportionately longer spines at the molt to maturity. Similar to females, males also showed a change in morphology associated with maturity, with CW being about 25% larger than NW for immature males and about 39% larger for mature males[2].

1.3.2. Age and size at maturity

Our limited ability to age blue crabs has precluded empirical development of maturity ogives for blue crab. However, evidence from attempts to develop large scale aquaculture of blue crabs at the Institute for Marine and Environmental Technology indicates that females can mature within their first year under ideal conditions (Johnson et al. 2008). In the field, given the Chesapeake Bay annual temperature cycle and typical megalopal settlement dates in August and September, it is unlikely that crabs could mature within their first year. It is more likely that they mature in the autumn of the following year when they are 12-18 months of age. Those that do not mature in autumn likely delay maturity until the following spring and mature when they are 24-30 months old.

Hester et al. (1982) reviewed information on age at maturity in Chesapeake Bay. Their review suggested two production schedules: those females originally hatched in May reach maturity in 15 months (August) and spawn at 24 –27 months of age (May - August), and those crabs originally hatched in August reach maturity in 21 months (May) and spawn at 24 months (August). Hines et al. (2003) suggest that although females in different parts of Chesapeake Bay may mature at the same time, they differ in the timing of larval release (see Section 1.3.3). Importantly, the time at which a female molts to maturity may affect her terminal size; females that molt to maturity in summer,

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[2] This analysis was done very late in the assessment process such that modifications to the growth models could not be made for males. Potentially modifying the male growth model was added as a research recommendation.

when temperatures are higher, are smaller than crabs that molt to maturity in cooler seasons (Darnell et al. 2009).

We investigated size at maturation for female and male blue crabs as part of this assessment. Ogburn et al. (2026) estimated relationships for the probability of maturation for female blue crabs using data on immature and pre-pubertal females in the SERC Trawl survey. The probability of maturation increased with increasing CW, and large immature females had higher probabilities of being pre-pubertal in May-June and in September-October than in July-August (Figure 1.3). Ralph et al. (2026b) estimated the probability that a male blue crab was mature as a function of CW using data from the ChesMMAP trawl survey. The slope of the maturation curve versus CW differed depending on the complexity of the model, and models that included a random effect for station had a higher slope than those without a station effect (Figure 1.4). The size at 50% maturity was estimated to be 105.5 mm CW, with very low probabilities of being mature below about 80 mm and > 95% probability of being mature once an individual reaches 123 mm. Male maturity patterns based on specimens collected primarily in the York River in the 1950s suggested that very few crabs were mature before 82 mm CW, with 50% maturity at 107 mm CW, and more than 80% were mature by 117 mm CW (Van Engel 1990; Jivoff et al. 2007).

In lieu of age data, research on the nemertean worm, *Carcinonemertes carcinophila*, has identified the species as a suitable biomarker for relative spawning age and spawning history for female blue crabs (Hopkins 1947; Graham et al. 2012; Schneider et al. 2023a; Pomroy et al. 2025). With this method, Schneider et al. (2023b) found that, in the Chesapeake Bay, 81 to 92% of mature females on the spawning grounds in winter have not spawned and will be entering their first spawning season. Moreover, by the start of the spawning season, females with eggs are mostly primiparous, producing their first egg mass (Schneider et al. 2024a; see 1.3.4). Overall, these findings support a reliance on one annual cohort of female blue crabs for reproduction each year.

1.3.3. Mating and spawning periods and locations

Mating typically occurs from May – October (Hines et al. 2003). Mating pairs have been reported widely throughout the Chesapeake Bay system. Mating success is high in Chesapeake Bay, ranging from 98 to 100% (Hines et al. 2003; Wolcott et al. 2005; Rains et al. 2016, Schneider et al. 2024a). Following mating, females migrate toward the lower Bay to high salinities that are conducive for egg development (Tankersley et al. 1998; Figure 1.5).

Female blue crabs are only able to mate during the period immediately following the post molt stage after their terminal molt to maturity (see Section 1.3.1). Thus, all subsequent larval production is thought to result from sperm transferred by males during this single receptive period. Sperm transfer is independent of male size (Wolcott et al. 2005), however, males that mate frequently transfer less sperm which could impact the number of zoea subsequently released by mated females (Hines et al. 2003, Kendall et al. 2002; Wolcott et al. 2005). Therefore, if male exploitation is high, the resulting sex ratio may cause males to mate more frequently and pass fewer sperm cells to females (Ogburn et al. 2019). This phenomenon has been a concern in Chesapeake Bay; the amount of stored sperm in recently mated females was positively related to the operational sex ratio (reproductively active males to prepubertal females) in the Rhode River (Ogburn et al. 2014). However, in a simulation study, Rains et al. (2018) found that fishing mortality rates had to be much higher than has been estimated in Chesapeake Bay to cause sperm limitation because once males mature, they can mate many times, whereas females are only receptive for a relatively short window.

Stored sperm quantity varies substantially between individuals, seasonally, regionally, and annually (Hines et al. 2003; Wolcott et al. 2005; Ogburn et al. 2014; Ogburn et al. 2019; Rains et al. 2016; Schneider et al. 2024a). Female stored sperm quantity decreases with brood production (Ogburn et al. 2014; Schneider et al. 2024a), however, under current stored sperm quantities and production estimates on the spawning grounds, sperm limitation is unlikely to decrease population level production in Chesapeake Bay (Schneider et al. 2024a).

The behavior and migration timing of inseminated females can differ depending on their mating location (Hines et al. 2003, Aguilar et al. 2005). Females that mate in the lower Bay migrate continuously to the spawning grounds during the reproductive season (Lambert et al. 2006b). Females inseminated in the upper Bay will migrate southward towards the lower Bay in late fall, regardless of when they mated. Current evidence suggests that females inseminated in upper Bay sub-estuaries produce their first broods the year following mating, while females inseminated in the lower Bay may reproduce the same year as they mated or the following year (Turner et al. 2003). After insemination, the female ovary has to mature and the sperm plug dissolve, therefore spawning occurs at least 14 weeks after mating (Wolcott et al. 2005).

Once on the spawning grounds, females remain in higher salinity areas of the Bay (Lambert et al. 2006b). Females are capable of producing multiple broods per season (see 1.3.4). The length of the spawning season is temperature dependent and occurs from May to September in Chesapeake Bay (Schneider et al. 2024b). Ralph et al. (2026a) estimated the fraction of ovigerous mature females by month using data from the VIMS Trawl Survey, the Maryland Trawl Survey, and ChesMMAP. Although females were observed with egg masses in almost all months, the proportion peaked at about 50% in June and July before decreasing to nearly zero by October (Figure 1.6). Hatching occurs around nocturnal high tide, larvae swim towards the surface, and zoea are carried seaward on the ensuing ebb current (Epifanio 2007).

1.3.4. Fecundity

Blue crab batch fecundity was re-assessed in 2023 for Chesapeake Bay, including models of fecundity that considered predictors beyond CW (Schneider et al. 2024a). The average fecundity in 2023, 2.17 million eggs per female, differed substantially from the previous estimate averaged from 1986 and 1987, 3.2 million eggs per female, which was used in the 2011 Chesapeake Bay Blue Crab Stock Assessment (Prager et al. 1990; Miller et al. 2011). The difference between the estimates is likely related to the methods used in Prager et al. (1990). In 1986, fecundity was estimated using a dry weight method, producing an average fecundity of 2.6 million eggs per female; however, in 1987 fecundity was estimated using a volumetric approach, producing an average fecundity of 4.0 million eggs per female (Prager et al. 1990). The 1987 estimate was likely biased high due to assumptions of the volumetric method; the 2023 estimate was produced using the dry weight method and generated similar results to those found in 1986 (Schneider et al. 2024a).

Fecundity in Chesapeake Bay is logarithmically related to CW, given by Fecundity = $268{,}337 \times e^{0.015 \times CW}$, with a 1.038 bias correction (Schneider et al. 2024a). Models of fecundity with additional parameters (i.e., month, egg stage, and spawning history) explained 54% of the variation in the data and provided quantitative evidence for a decline in fecundity with brood production. Moreover, fecundity in Chesapeake Bay has a seasonal component, with lower values in the early season (Prager et al. 1990; Schneider et al. 2024a). The positive relationship between fecundity and size between the 1980s and 2020s, years when abundance was high and variable, respectively, quells concerns about density dependent changes in fecundity posited by Wells (2009).

Two important studies experimentally quantified the number of broods per season in blue crab. Dickinson et al. (2006) quantified brood production of mature female blue crab in estuarine waters in North Carolina. Dickinson et al. (2006) held individual females in minnow traps in the field, feeding them daily. For each crab, Dickinson et al. (2006) measured brood production and volume over 18 weeks. Their data indicated that an average sized crab (127 mm CW) that is mature at the beginning of the spawning season could produce eight clutches within a full spawning season spanning 25 weeks. Additionally, Dickinson et al. (2006) reported that although larger crabs produced larger clutches, they did so less frequently than smaller crabs such that the total reproductive output was almost invariant with crab size. Other authors have reported similar results for the North Carolina blue crab population (Darnell et al. 2009). Importantly, these authors evaluated the effective larval production as a function of the brood number. They reported a consistent decline in effective reproductive output such that the percentage of embryos that developed normally declined by up to 40% from the first to the fourth brood. Darnell et al. (2009) concluded that the majority of the reproductive output of individual females derives from a few initial broods.

The number of broods produced per season or over a lifetime has not been experimentally tested in Chesapeake Bay. However, Schneider et al. (2024b) applied the relationship between brood production and temperature, derived by Darnell et al. (2009), to the Chesapeake Bay, which indicated that blue crabs in the Bay can produce up to four broods per year. This method also indicated the blue crabs in North Carolina can produce eight broods, which is one brood greater than the maximum brood production experimentally estimated in the early 2000s (Dickinson et al. 2006; Darnell et al. 2009). Schneider et al. (2024a) derived lifetime potential brood production from estimated fecundity and stored sperm quantity and found that under the most probable sperm to egg ratios (4:1 and 10:1; based on Ogburn et al. 2019), blue crabs could produce 6 to 24 broods over a lifetime. Given the low annual survival rate and reliance of a single cohort of females for spawning (Schneider et al. 2023b), females most likely produce 1 to 4 broods in Chesapeake Bay.

1.4. Larvae

Epifanio (2007) reviewed the biology and ecology of larvae. Briefly, larvae are transported out of the Chesapeake Bay and onto the coastal shelf (Roman and Boicourt 1999). Miller (2001a) used a size-based approach to estimate the mortality rate of this life history stage. Miller (2001a) estimated that the probability that an individual survives the entire zoeal and megalopal period was 1.19×10^{-6}. During their time at sea, zoea molt several times before molting to the last larval stage, the megalopa, which re-enter the Chesapeake Bay. Time series of abundances of zoea and megalopae are available from the Chesapeake Bay Program's monthly zooplankton monitoring program from 1979 – 1998. These data were analyzed by Lipcius and Stockhausen (2002). These authors report a decline in larval abundance by approximately an order of magnitude over the period of sampling.

1.5. Juveniles

The juvenile period is a critical life history stage for blue crabs and juvenile blue crab production is supported by a variety of structured nursery habitats such as marsh and seagrass (Orth and van Montfrans 1990; 2002; Lipcius et al. 2007). For example, Ralph et al. (2013) found that percent seagrass cover in Chesapeake Bay had a positive exponential relationship with juvenile blue crab densities and the magnitude of the relationship varied spatially and temporally. Marsh habitats, including both native marsh grasses and invasive *Phragmites*, are important nurseries for juvenile blue crabs, but the value of shoreline habitats was reduced when hardened (e.g., rip-rap or bulkhead shorelines; Long et al. 2011; Kornis et al. 2017). Shallow shorelines also represent critical refuge habitat for juveniles against cannibalism by adult blue crabs (Hines et al. 2026). Other studies have examined the importance of structured habitats and the relationship between habitat and blue crab size and found that forage efficiency and predator avoidance were trade-offs that helped determine when habitat shifts may occur for juvenile blue crabs and not necessarily blue crab size as once thought (Bromilow and Lipcius 2017; Hyman et al. 2024). These studies also demonstrate the importance of habitat mosaics that can be utilized as blue crab grow and that seagrass, salt marsh, and even a non-native red alga, *Gracilaria vermiculophylla* (Wood and Lipcius 2022) function to support blue crab production. In addition to structured habitats, turbidity also was a determinant of high juvenile crab abundance though whether high turbidity provided more prey or offered refuge from predation or a combination of the two is unknown (Hyman et al. 2022).

The distribution of CWs for recruits in the winter in Chesapeake Bay was investigated in Wilberg and Drzewicki (2026) using data and estimates from Ralph and Lipcius (2014). The WDS does not sample all habitats where age-0 blue crabs can be found in the winter because it has a minimum sampling depth of 1.5 m, and shallower habitats have smaller blue crabs, on average (Ralph and Lipcius 2014; Hines et al. 2026). A lognormal distribution with a median of about 1.6 cm described the distribution of blue crab CWs in winter well (Figure 1.7).

1.6. Adults

A considerable amount is known about the feeding ecology (Mansour and Lipcius 1991; Hines 2007) and the response to environmental and ecological conditions (Bell et al. 2003a, b; Liang et al., 2021; Ralph et al. 2024) of adult blue crabs. Research has also focused on assessing their role in structuring estuarine ecosystems (Hines et al. 1990; Hines 2007).

Size is a key characteristic of the adult population and is directly relevant to the fishery, which targets adult crabs and puts a higher value on the largest crabs. Analysis of 50+ years of data from the PEARL Pot Survey (section 2.1.5) suggests a significant decline in average size for both males and females within the survey area with much of the decline in male CW occurring prior to 1990 (Abbe 2002; Bevans, unpublished). The updated analysis by Bevans (unpublished) suggests different trends in size between males and females. Changes in mean size could be due to growth, mortality, or both. Selective harvest of larger males has the potential to impose evolutionary pressures that may counter selection for larger body size, with potential consequences for reproductive output and long-term population dynamics (Ogburn et al. 2014; Ogburn 2019). Due to time constraints, we were unable to evaluate whether similar trends were observed in the Maryland and VIMS trawl surveys, which also extend back to the 1960s and 1970s. However, archaeological evidence suggests that large crabs were more common prior to the development of modern fisheries (Rick et al. 2015). Average sizes of male crabs encountered in the PEARL Pot Survey have been at or below minimum legal size (127 mm) in the majority of years over the last three decades. In the mainstem spawning grounds, size of mature females was positively correlated with abundance (Lipcius and Stockhausen 2002). Using data from the VIMS trawl survey, Lipcius and Stockhausen (2002) demonstrated that mature female size and abundance in the spawning grounds concurrently dropped sharply in the early 1990s, suggesting an amplified reduction in reproductive output. Abundance and size increased after major management actions in 2008.

1.7. Natural Mortality

Estimates of natural mortality (M) changed over the course of conducting blue crab assessments. The Rugolo assessment used a value of M=0.375 yr^{-1} (Rugolo et al. 1997). In the 2005 assessment, direct and indirect approaches were combined to estimate the most likely value of M for blue crab in the Chesapeake Bay with details provided in Hewitt et al. (2007). Indirect estimates were developed using empirical estimates involving estimates of von Bertalanffy K and CW_{∞} parameters, ages at maturity and longevity as well as temperatures at different times during the season. Estimates of M based on these indirect measures ranged from 0.3 – 2.35 yr^{-1}. However, the distribution of values was centered around M=1.1 yr^{-1}. Hewitt et al. (2007) combined these indirect estimates with direct estimates application of Brownie tag return models to data for 2002-2004 (Lambert et al. 2006a). Tag-return based estimates of M required assumptions about exploitation rates and varied from 0.42-0.87 yr^{-1}. Based on both the direct and indirect approaches, a value of M=0.9 yr^{-1} was adopted as the most likely value for the rate of natural mortality for the 2005 assessment. All values used in previous Chesapeake Bay blue crab stock assessments were considered to be age-and sex-independent and constant over time.

Since November 2001, Lipcius et al. (2026a,b) have continued their tag-recapture studies of mature, female blue crabs in lower Chesapeake Bay. Lipcius et al. (2026a,b) updated these data to provide revised estimates of survival and M. During 2001-2017, a total of 5,542 blue crabs were tagged and released. Between 219 and 802 blue crabs were tagged annually. Of these, 917 (20.8%) were returned and 805 were used in analyses. All but two were returned by commercial fishers. Information-theoretic model comparisons indicated that a model with constant survival over time and tag-recovery rates that varied between 2002-2008 and 2009-2017 best explained the data. The mean annual survival rate of mature female crabs was 0.10 ± 0.01 (yr^{-1}; mean ± SE), and the mean recovery rates were 0.22±0.01 during 2002-2008 and 0.08 ± 0.004 during 2009-2017 (Lipcius et al. 2026a). The estimated survival includes natural and fishing mortality, so M cannot be estimated from this approach without knowledge of the fishing mortality rate.

Lipcius et al. (2026b) used tagging data of mature females to estimate longevity and applied the maximum age M estimator from Hamel and Cope (2022). Assuming that mature females were 1.5 years old when they were tagged, the time between tagging and recovery can provide an estimate of age. The longest time at large was 3.31 years for 2009-2017, whereas for 2002-2008, 11 crabs were at large longer than 3.31 years, ranging from 3.35 to 4.69 years. The three oldest and most reliable tags provide ages of 6.07, 6.05 and 5.88 years old, which result in M estimates ranging 0.74-0.89 yr^{-1} (Lipcius et al. 2026b). Natural mortality is likely size-based and is higher for smaller blue crabs than for larger blue crabs (Bromilow and Lipcius 2017). Bromilow and Lipcius (2017) quantified relative survival by size in a tethering study of blue crabs in the lower Chesapeake Bay.

Overwinter mortality of Chesapeake Bay blue crabs (OWM) has been observed to vary over time, associated with winter severity (Rome et al. 2005; Bauer and Miller 2010a,b). As part of the assessment, we conducted new analyses to quantify length- and sex-specific OWM rates during 1994-2023 in Chesapeake Bay (Liang et al. 2026b). Data on dead and live crabs from the WDS were used to estimate natural mortality during the winter. OWM was estimated to be higher for larger crabs, but patterns differed among immature females, mature females, and males. Mortality rates observed in the field varied between 1% and 13% over the years, and they were higher for years with lower cumulative water temperatures (Liang et al. 2026b).

TOR 2: Fishery-independent Data

2.1. Surveys

For this assessment, we evaluated the utility of 8 long-term fishery-independent surveys that have operated in the Bay for at least 10 years. These surveys differed in gear, survey design (random- vs. fixed-site), temporal resolution, and length of the available time-series (Table 2.1). The surveys also have variable spatial coverage and resolution that affects which statistical approaches might be appropriate (Figure 2.1).

2.1.1. Winter Dredge Survey

The Chesapeake Bay Winter Dredge Survey (WDS) has occurred in Maryland and Virginia since the winter of 1989/1990. Historically, the survey is cooperatively conducted by Chesapeake Biological Laboratory (CBL), Maryland Department of Natural Resources (MD DNR), and Virginia Institute of Marine Science (VIMS); since 1997, the survey has been conducted by MD DNR and VIMS (Vølstad et al. 2000; Sharov et al. 2003). This survey takes advantage of the torpid state that blue crabs enter at low water temperatures, typically < 10^{o}C (Van Engel 1958; Brylawski and Miller 2006; Smith and Chang 2007), when growth, movement, and feeding stop, and individuals typically bury into the sediments (Bauer and Miller 2010a). This period of inactivity provides a unique opportunity to conduct a Chesapeake Bay-wide synoptic survey, and sampling typically occurs between December and March.

WDS was designed as a stratified random survey. Survey design evolved over the first few years, including various geographic stratifications and an exploration of sediment-based substratification (Rothschild et al. 1992). Since the 1991/1992 winter, the survey has been conducted with three consistent, regional strata: the upper Bay & tributaries, the mid-Bay, and the lower Bay (Figure 2.1). Stations are allocated each year in proportion to stratum area; 1500 stations are sampled annually, with approximately 51.5, 33.0, and 15.5% of the sites allocated to the three strata, respectively. Further substratification occurred independently within strata sampled by MD DNR and VIMS to ensure consistent representation of smaller regions. Sampling in the lower Bay stratum occurs monthly. Historically (through 2015), sampling occurred from November-February to account for potential impacts of the winter dredge fishery; from 2016 to present, monthly sampling occurred December-March. Sampling is restricted to waters > 1.5 m depth.

The WDS uses a modified commercial Virginia crab dredge, consisting of a single 1.83-m wide dredge with 15.2-cm long teeth separated by 7.6 cm, lined with a 1.27 cm mesh liner and without the diver modification often used by commercial watermen. A single tow is taken at each station. The dredge is towed along the bottom, with the current, at a fixed speed (3 knots) for one minute, and the beginning and ending coordinates are recorded with a differential GPS. All blue crabs collected during a tow are measured for CW and sexed; maturity is recorded for all females and for males in Virginia.

Temperature, salinity, and water depth are recorded. Site-specific area sampled was estimated as the product of tow distance and dredge width (1.83 m).

Efforts to estimate vessel- and year-specific catchability coefficients have been conducted in a variety of ways. Depletion experiments were conducted near-annually by MD DNR and VIMS, though the specific design and logistics varied between the two vessels and over time (Vølstad et al. 2000; Sharov et al. 2003). Additionally, in 1998, 2009, 2013, 2014, 2016, and 2020, paired tows were completed by MD DNR and VIMS, where a series of sites in the Potomac River or Pocomoke Sound were sampled by both crews at the same time, side-by-side (9-52 additional sites per year were sampled by each vessel). Beginning in 2021 and occurring annually to present, an alternate approach was taken: each vessel crew returned to a subset of sites (20-27 additional sites per year) already sampled by the other vessel. Traditionally, the estimated catchability coefficients from depletion experiments have been used, together with estimates of tow-specific area dredged, to estimate the absolute density of crabs caught at each station (e.g., as part of the annual CBSAC advisory report; Sharov et al. 2003).

We developed standardized WDS indices using the spatiotemporal approach described below (section 2.2). We used data from 1993/1994 onwards in these analyses to match the time-series of the assessment model. The standard survey sites, as well as sites sampled during the paired tow experiments, were included in the analysis. A grid was generated over the sites included in the analysis, encompassing a total of 9,167 km^2. This is smaller than the area typically used for the WDS (9,812 km^2; Sharov et al. 2003), but likely represents, at least in part, differences between the idealized survey domain and that which can actually be sampled effectively by the survey vessels.

Six vessels have been used over the entirety of the survey, with most of the vessel changes occurring in the 1990s; VIMS has operated on the *R/V Bay Eagle* continuously since 1998 and MD DNR has used the *F/V Mydra Ann* since 2004. As the longest continuously used platform, the *R/V Bay Eagle* was the base vessel for model comparisons; the base vessel was switched to the *F/V Mydra Ann* to estimate relative catchabilities between the two vessels.

2.1.2. VIMS Juvenile Finfish & Blue Crab Trawl Survey

Since 1955, VIMS has conducted a trawl survey to monitor abundance trends in selected finfish and invertebrate species in the southern portion of Chesapeake Bay (Fabrizio and Tuckey 2016). Originally, the survey sampled only the York River, but it has expanded steadily; currently, the survey sampling frame includes the mouth of the Bay to just north of the Rappahannock River, and to the freshwater interfaces of the York, James and Rappahannock rivers (Figure 2.1). The survey employs a combination of fixed- and random-site designs. Fixed sites in the three rivers (8 each in the James and Rappahannock, and 9 in the York) are incorporated into a stratified random survey design with four main strata (mainstem Bay, and the three rivers) with substrata based on depth and river zone in the rivers and based on geographic region and depth in the mainstem Bay.

The survey design is implemented monthly, with some seasonal changes in the strata sampled. The 66 river stations are sampled every month. Up to 45 mainstem Bay stations are sampled monthly: 45 stations from May to November; 39 stations in December, February, and April; and no mainstem Bay stations are sampled in January and March.

A single tow is taken at each station. The trawl is towed along the bottom at approximately 2.5 knots for 5 minutes, and the beginning and ending coordinates are recorded. The catch is sorted by species and blue crabs were further categorized as male, immature female, or mature female. Large catches were sub-sampled with at least 30 individuals from each sex and maturity state (male, immature female, mature female – including egg stage) measured to the nearest mm using an electronic measuring board. The remaining catch was counted and the size distribution of the sub-sampled catch was expanded proportionally to the total number captured. Temperature, salinity, and water depth are recorded. As site-specific net geometry is not recorded, we applied a fixed average net width based on head-line length. The net width was estimated as 0.652 m head-line length (9.1 m and 5.8 m for the *R/V Fish Hawk* and *R/V Tidewater*, respectively), and the site-specific area sampled was estimated as the product of tow distance and the fixed net width.

The trawl used in the survey changed over time, including the addition of a tickler chain in 1973 and a net liner in 1979. In 2015, the vessel used as the sampling platform for this survey was retired; survey personnel used this opportunity to review and update the survey gear (Fabrizio and Tuckey 2016). From January 1996 to May 2015, the survey operated aboard the 8.5-m *R/V Fish Hawk*, using a 9.1-m head-line, 4-seam, semi-balloon otter trawl with 38.1 mm stretch-mesh body and a 6.4-mm mesh cod-end liner. Survey operations moved to the 13.1-m *R/V Tidewater*, outfitted with a 5.8-m head-line trawl with 40 mm stretch-mesh body and a 6.4-mm liner. This net is a scaled version of the gear used for several other surveys operating along the U.S. East Coast, including the NOAA Northeast Fisheries Science Center Bottom Trawl Survey, Northeast Area Monitoring and Assessment program (NEAMAP), and Chesapeake Bay Multispecies Monitoring and Assessment Program (ChesMMAP). Paired tows (typically < 40 m apart) were completed monthly between April 2014 and May 2015 to calculate conversion factors and ensure continuity of the time-series.

Previous assessments have used annual population indices based on fall surveys (Rugolo et al. 1997; Miller and Houde 1999; Miller 2001b; Miller et al. 2005) or spring surveys (Miller et al. 2011). For this assessment, we developed standardized monthly indices of total abundance using the spatiotemporal approach described below (section 2.2). We used data beginning in January 1994 to match the time-series of the assessment model. The standard survey sites, as well as site-paired tows conducted during the calibration cruises in 2014-2015, were included in the analysis. We used the survey sampling grid (2,990 km^2) as provided to generate the indices.

The *R/V Fish Hawk* was the base vessel for model comparisons; the base vessel was switched to the *R/V Tidewater* to estimate relative catchabilities between the two vessels. To improve index estimation during months when the full survey region was not sampled, the VAST spatiotemporal model used a monthly timestep for the spatiotemporal component, essentially allowing abundance to be smoothed across months.

2.1.3. Chesapeake Bay Multispecies Monitoring and Assessment Program (ChesMMAP)

Beginning in 2002, VIMS has conducted a bottom trawl survey that samples late-juvenile and adult fishes and several invertebrate species throughout the mainstem of Chesapeake Bay (Figure 2.1; Latour et al. 2003). ChesMMAP underwent a comprehensive review and redesign, resulting in changes to the stratification, survey timing, vessel, and gear beginning in 2019 (Latour et al. 2023). The survey employs a stratified random sampling design, with four latitudinal and two depth strata (previously five latitudinal and three depth strata, respectively). Sampling occurs four times annually, in March, June, September, and November (previously five, bimonthly cruises between March and November), with up to 80 sites sampled during each cruise.

A single trawl tow is taken at each station. The trawl is towed along the bottom at approximately 3 knots for 20 minutes, and the beginning and ending coordinates are recorded. The catch was sorted by species and blue crabs were further categorized as male, immature female, or mature female. The first 25 individuals were measured to the nearest 5 mm using an electronic measuring board and further processed for individual weight (kg), maturity (males), and egg stage. Typically, the remainder of the catch (male, immature female, and mature female) was weighed in aggregate and individuals were measured; very large catches were sub-sampled, and the size distribution of the sub-sampled catch was expanded proportionally to the total number captured. Temperature, salinity, and water depth are recorded. Site-specific net geometry is recorded, so the site-specific area sampled was estimated as the product of tow distance and average net width.

From March 2002 through April 2019, the 19.8-m *R/V Bay Eagle* was the sampling platform, using a 4-seam bottom trawl, with 13.7-m headline, 15.2-cm stretch body mesh, and 7.6-cm stretch cod-end mesh. During each of the five bimonthly cruises, up to 80 stations were sampled. Beginning in June 2019, the survey moved to a larger, more stable sampling platform, the 28.3-m *R/V Virginia*, outfitted with a three-bridle, four-seam bottom trawl, with a 23.3-m head-line, 6- and 4-cm stretch-mesh polyethylene webbing, 2.54-cm knotless nylon-lined cod-end, and a sweep made of 40.6 cm rubber disks; as indicated above, this is a scaled version of the net used by several other surveys operating along the U.S. East Coast. To account for the increased costs associated with the new vessel, survey timing was adjusted to reduce sampling intensity while minimizing impacts on the data streams routinely provided for stock assessments. It was determined that the spring (March) and fall (November) cruises could be shortened to focus solely on the Maryland and Virginia strata, respectively. Furthermore, the May and July cruises were replaced with a single June cruise. A series of 15 calibration cruises were conducted from June 2019 to November 2022, approximately 5-7 days after the completion of the respective month’s survey cruise to minimize disturbance effects. Species-specific and length-based intercalibration analyses of the two vessel-trawl combinations were conducted to ensure continuity of the survey time series (Latour et al. 2023). The new vessel-trawl combination is more efficient and catches a wider size range of individuals; as a result, the intercalibration coefficients were applied to the older, *R/V Bay Eagle* catches to account for the change in catchability.

This survey had not been incorporated into blue crab stock assessments because the length of the time series was too short during the last assessment (< 10 years). For this assessment, we developed standardized indices of total abundance using the spatiotemporal approach described below (section 2.2). Given the seasonal changes in blue crab distribution patterns and the temporal gaps between cruises, each month for which survey data were available was treated independently. As a result, the length of the monthly time-series varied: 2002-2023 for March, September, and November; 2002-2018 for May and July; and 2019-2023 for June. The standard survey sites, with the *R/V Bay Eagle* catches expanded to account for the increased catchability of the new vessel-trawl combination, were included in the analysis. The survey domain encompassed 5,019 km^2.

2.1.4. Maryland Trawl Survey and SERC Trawl Survey

For this analysis, the Maryland Trawl Surveys combines two independently conducted, but similar, surveys. In 1977, Maryland DNR initiated a trawl survey of Eastern Shore sites and tributaries (Maryland Trawl Survey). The survey was expanded in 1984 to include the Patuxent and Chester rivers, and again in 2003 to include the Nanticoke River, Little Choptank River, and Fishing Bay (Figure 2.1). Sites within each river system are fixed and were selected based on patterns of commercial activity and habitat. The survey is conducted monthly from May to November, but coverage is inconsistent temporally and spatially from year to year, particularly in the early part of the time-series.

At each site, the trawl is towed for 6 minutes at a fixed speed (3 knots). Blue Crabs are sorted and enumerated. Historically (1977-1988), crabs caught in a tow were counted and binned into predetermined size categories representing age-0, age-1, and age-2+ crabs; no size measurements were taken. Since 1989, each crab is measured to the nearest mm and weighed to the nearest g; sex, maturity (females), molt stage, and missing limbs are noted. Temperature, salinity, and water depth are also recorded.

The gear has been consistent throughout the time-series: a 4.9-m semi-balloon otter trawl with 3.2-cm stretch mesh body, 2.8-cm stretch mesh cod-end, and a 1.3-cm stretch mesh liner. The trawl is outfitted with a 0.5-cm foot-rope and a 0.5-cm tickler chain. No information on site-specific tow distance or net geometry is recorded. An average tow distance was estimated as duration (6 minutes) x speed (3 knots) and an average net width was based on head-line length (0.652 x 4.9 m). Thus, the fixed area sampled was estimated as tow distance x net width.

The Smithsonian Environmental Research Center (SERC) initiated a bottom trawl survey (SERC Trawl) of the Rhode River and adjacent upper Chesapeake Bay in 1981 (Figure 2.1; Hines et al. 1990). Four fixed sites are sampled, typically three times per month from April through December; the Chesapeake Bay station was added in 1992 and its location was moved several times prior to 2004.

At each site, the trawl is towed at a fixed speed (3 knots), aiming for 10 minutes; trawl duration is recorded. Blue crabs are sorted and enumerated. Each crab is measured to the nearest mm; sex, maturity (females), molt stage, and missing limbs are noted. Temperature, salinity, and water depth are also recorded. Data for the period 1981-2000 were not included because crab measurements were not available in a digital format.

SERC acquired a new trawling vessel in 2004. The gear has been consistent throughout the time-series: a 4.9-m semi-balloon otter trawl with 5-cm square mesh body, 7-mm stretch mesh, and a 0.5-cm tickler chain. No information on site-specific net geometry is recorded. Tow distance was estimated as tow duration (4-11 minutes) x speed (3 knots) and an average net width was based on head-line length (0.652 x 4.9 m); site-specific area sampled was estimated as the product of tow distance and net width.

The SERC Trawl Survey was not included in previous assessments because the length of the consistent time series (following the vessel change) was too short during the last assessment (< 10 years). Here, given the similarity in design and operation, the survey was included with the Maryland Trawl Survey as an additional river system. For this assessment, we developed standardized indices of total abundance using the gamlss (Rigby et al. 2019)framework described below (section 2.2). Given the seasonal changes in Blue Crab distribution patterns, each month for which sufficient survey data were available (May-October) was treated independently to avoid estimation of spatiotemporal interactions. River system was included as a random effect with 10 levels and the area sampled was included as the effort offset. A truncated dataset (2004-2023) was used to maximize coherence in river systems sampled each year. The final index was generated using a fixed-area tow of 1,500 m^2.

2.1.5. PEARL Pot Survey

Since 1968, crab pots have been used to monitor the crab population at three fixed sites near Calvert Cliffs, MD (Figure 2.1). Historically, this survey (sometimes referred to as the Calvert Cliffs Pot Survey, the Abbe Pot Survey, or the PEARL Pot Survey; this later name is used herein) was conducted by George Abbe at the Academy of Natural Sciences' Estuarine Research Center on the Patuxent River; however, the research center, now known as the Patuxent Environmental and Aquatic Research Laboratory (PEARL), and Abbe's survey, was transferred to Morgan State University in 2004. The survey was conducted annually until 2011; gaps in funding led to interruptions in the time-series in more recent years (2012-2013, 2020, and 2022-2023), but operations resumed in 2024.

Sampling occurs approximately biweekly from June through November; pots are fished for 24 hrs, typically twice each week (Abbe 1973; Abbe and Stagg 1996; Abbe 2002). At each site, 10 pots were deployed in a single, unattached string at about 4 m depth (1971-1981); beginning in 1982, 5 pots were deployed in two, unattached strings at about 2 and 4 m depth. Catches were aggregated by site and survey round; individuals were enumerated by sex and measured to the nearest mm.

The PEARL Pot uses commercial-style peeler crab pots with 2.5-cm wire mesh, two entrance funnels, and no cull rings. This design retains a wider range of crab sizes than would a standard hard crab pot, but still primarily targets larger juvenile and adult individuals. Survey effort was reported in pot-days per site per round of sampling, with a maximum of 20 pot-days per site per round.

This survey was not included in previous stock assessments due to its small regional footprint. For this assessment, we developed standardized indices of total abundance using the gamlss (Rigby et al. 2019) framework described above. Given the seasonal changes in blue crab distribution patterns, each month for which sufficient survey data were available (June-November) was treated independently to avoid estimation of spatiotemporal interactions. Site was included as a fixed effect with 3 levels, sampling day was included with a penalized smoothing function, and pot-days was included as the effort offset. The final index was generated to reflect 20 pot-days.

2.1.6. Maryland Juvenile Striped Bass Survey

Maryland DNR has operated a seine survey designed to monitor the status of young-of-the-year striped bass in Maryland tributaries of Chesapeake Bay since 1954 (Figure 2.1). Sampling occurred at 22 fixed sites in July, August, and September using a 30.5-m × 1.24-m bagless beach seine of untreated 6.4-mm bar mesh. Blue crabs, not a primary target of this survey, were enumerated but no data were retained on the sex or size compositions. This survey was excluded from further analysis due to a lack of sex and length observations.

2.1.7. VIMS Juvenile Striped Bass Seine Survey

VIMS has conducted a similar survey focused on young-of-the-year striped bass in Virginia tributaries of Chesapeake Bay (Figure 2.1) since 1967, with a gap from 1973-1979 due to lack of federal support. Sampling occurred at 18 index stations and 22 auxiliary stations approximately bi-weekly between June and September. Historically, a 30.5-m x 1.8-m bag-seine with 6.4-mm mesh was used; in 1986, the gear was changed to match that of the Maryland Juvenile Striped Bass Survey.

The VIMS Juvenile Striped Bass Seine Survey began enumerating blue crabs by sex and measuring individuals in 2015. It was determined that the length of the time series was too short to include this survey in this assessment, but this decision should be reconsidered during future assessments.

2.2. Index standardization

The previous assessment (Miller et al. 2011) developed standardized indices using a delta-generalized linear model framework with survey design and environmental variables as potential model covariates. Indices were developed for age-0 and age-1+ crabs for each year and survey included, as the assessment model was age-based with an annual time step.

As blue crabs, like most crustaceans, are difficult to age, there was interest in developing a length-based assessment model. Because many life history characteristics are highly dynamic and change among seasons in Chesapeake Bay, and abundant survey data are available year-round, a monthly time-step was deemed appropriate. Additionally, many of the surveys have a month-specific sampling frame. Thus, the current assessment model framework, sex- and length-based and with a monthly time-step, required data for each month and survey. For each survey, we developed an index of total abundance (across length bins and sexes) for each month and used survey- and month-specific sex and length distributions to apportion the index of total abundance to each 1-cm size and sex bin used in the assessment model.

Recruitment of megalopae into Chesapeake Bay occurs over a protracted season (typically approximately July to November: Lipcius et al. 2007); however, the current stock assessment model set recruitment in February to reflect the accumulation of recruits over the entire season and because the only Chesapeake Bay-wide survey occurs in winter. As a result, recruits needed to be excluded from the indices from surveys that occurred prior to the timing of recruitment in the model. Based on patterns in length-frequency distributions (Figure 2.2), we used a size cutoff of 35 mm in all August surveys and 65 mm in surveys occurring from September through January to censor the late summer through early winter recruits.

All indices were developed using model-based approaches. Two general approaches were used to standardize survey indices: surveys with random-site designs were analyzed using spatiotemporal delta-generalized linear mixed models, while those with fixed-site designs were analyzed using generalized additive models. Regardless of analytical approach, AIC, BIC, and model diagnostics were used to assess model performance. All analyses were run in R version 4.5.1 (R Core Team 2025) using RStudio version 2025.05.1 (Posit Team 2025).

Index standardization of surveys with a random-site design was conducted using a spatiotemporal framework. We applied a spatial delta-generalized linear mixed modelling approach using the vector-autoregressive spatio-temporal (VAST) package (version 4.0.0; Thorson and Barnett 2017). VAST is frequently applied for index standardization to account for latent spatial and spatiotemporal autocorrelation in survey data (e.g., Thorson et al. 2015; Thorson 2019).

The two linear predictors (p_1 and p_2) separately model encounter probability (p_1) and positive catches (p_2) as a function of temporal, spatial, & spatiotemporal effects, as well as vessel, density, and catchability covariates. For observation *i*, location s_i, and time t_i:

$$p_1(i) = \beta_1(t_i) + \omega_1(s_i) + \varepsilon_1(s_i, t_i) + \eta_1(v_i) + \nu_1(t_i) + \zeta_1(i) \quad \text{(Eq. 2.1)}$$

and

$$p_2(i) = \beta_2(t_i) + \omega_2(s_i) + \varepsilon_2(s_i, t_i) + \eta_2(v_i) + \nu_2(t_i) + \zeta_2(i) \quad \text{(Eq. 2.2)}$$

where β_1 and β_2 represent year intercepts as fixed effects, $\omega_1$and ω_2 represent spatial random fields (which can be interpreted as an overall average condition), $\varepsilon_1$and $\varepsilon_2$represent spatiotemporal random fields (which can be interpreted as annual deviations from the overall average spatial random fields), $\eta_1$and η_2 represent vessel effects, $\nu_1$and ν_2 represent density covariates (variables that are thought to affect the true, underlying abundance), and $\zeta_1$and $\zeta_2$represent catchability covariates (variables that are thought to affect gear performance).

The total number of blue crabs per site was the response variable, with a fixed year effect, vessel as a fixed catchability covariate (if necessary), and site-specific area sampled (in km^2) as an offset. A Poisson link function was used for the presence/absence portion of the delta-model; we considered lognormal, gamma, and generalized-gamma distributions for the count portion. Once an appropriate distribution was chosen based, we fit 11 models to determine which spatial and spatiotemporal random effects structures were supported, including whether the spatial correlations reflected isotropy or anisotropy (Table 2.2; Gartland and Latour 2024). The standardized index from these spatiotemporal models represents a minimum abundance within the survey domain, assuming a catchability of 1.

Index standardization for fixed-site surveys was conducted using the generalized additive models for location, scale, and shape (GAMLSS) regression framework, using the package gamlss (version 5.4-12: Stasinopoulos and Rigby 2023). This approach extends the GAM structure (Wood 2017) to encompass a wider range of distribution families for the response variable, including zero-inflated distributions, and to allow for distribution parameters beyond μ (i.e., σ, usually scale; ν, usually skewness, and τ, usually kurtosis) to be modeled as a function of covariates (Rigby and Stasinopoulos 2005; Stasinopoulos et al. 2017). The general form of the model was:

$$g(E[y]) = X\beta + \sum_{j=1}^{p} s_j(x_j) \quad \text{(Eq. 2.3)}$$

where g is the monotonic link function, $E[y]$ is the expected value of the response variable, X is the fixed effects matrix, β is the vector of fixed-effects, and s_j is the smoothing function for continuous covariate *j*. The total number of blue crabs per site was the response variable, with a fixed year effect, site (fixed or random), sampling day as a penalized smoothing function (if necessary), and effort as an offset variable. For each survey, a full model was fit using all count distributions available in the gamlss package. The preferred distribution was determined primarily based on AIC and diagnostic plots; in a few cases, when the preferred distribution was not stable and resulted in extreme standard errors, uncertainty in the predictions was quantified using 1,000 nonparametric bootstrapped samples (Efron and Tibshirani 1993), resampled with replacement. As compared to the minimum abundance indices provided by the spatiotemporal models, the standardized index generated by these gamlss models represents the average number of crabs for a given effort.

We used Kendall rank correlations to explore among- and within-survey consistency. Kendall τ is a non-parametric measure of correlation based on the rank-order of two variables. To evaluate among-survey coherence, we compared each pair of surveys that occurred within a given month. For example, in February, the WDS and VIMS Trawl surveys were compared for all years where both surveys occurred. No correlation was estimated for June ChesMMAP and PEARL Pot surveys, because only two years of overlap were available. For within-survey consistency, correlations were run depending on survey design. WDS, with only one monthly index per year, was compared across years. For the VIMS Trawl, with monthly indices year-round, comparisons were by month (e.g., January to February, February to March); if a survey did not occur for a given month, the comparison was excluded. The MD Trawls and PEARL Pot, with monthly indices in the summer and fall, were also compared by month, but months without a survey were excluded from comparisons.

We calculated the year-specific proportion of male recruits using data from the WDS. Recruits in the WDS were individuals less than 6.5 cm. Each tow was treated as a cluster, and a cluster sampling estimator was applied using the methods from Nelson (2014) to estimate the standard error of the proportion. We used a cluster sampling estimator because the number of male and female recruits was not independent within tows.

2.3. Results

2.3.1. Winter Dredge Survey

Overall, 50,024 standard stations (1518-1977 stations yr^{-1}) were included in this analysis; the inclusion of additional paired tows brought the total number of stations sampled to 50,364. The number of stations sampled annually was highest at the beginning of the time-series, settling to just over 1500 stations yr^{-1} by 2005. Catch ranged from 0-214 crabs tow^{-1}; 45.5% of tows had at least one crab. Across the standard and comparison stations, 109,750 crabs were collected, ranging from 1-230 mm CW.

The generalized gamma distribution was chosen for modeling the nonzero data. Evaluation of the random effects provided support for the inclusion of spatial and spatiotemporal random fields in both linear predictors, with anisotropy in the spatial correlation functions.

The WDS index of abundance, representing a minimum abundance in the Bay, ranged from 48 million (in 2001) to 180 million (in 2012) blue crabs, with a mean abundance of about 90 million (Table 2.3). The time-series exhibits distinct patterning, with a decline in late 1990s, an uptick in the mid- to late-2000s, followed by a more recent decline (Figure 2.3).

2.3.2. VIMS Juvenile Finfish & Blue Crab Trawl Survey

Overall, 34,648 standard stations (663-1237 stations yr^{-1}) were included in this analysis; including the additional tows completed during the calibration cruises (2014-2015) brought the total number of stations sampled to 35,789. The number of stations sampled annually was fairly consistent across most of the time-series, with < 1100 stations sampled in only 6 years (1994, 1995, 2001, 2002, 2018, and 2020). Catch ranged from 0-1205 crabs tow^{-1}; 63.0% of tows had at least one crab. Across the standard and comparison stations, 297,481 crabs were collected, ranging from 1-220 mm CW.

The gamma distribution was chosen for modeling the nonzero data. Evaluation of the random effects provided support for the inclusion of spatial and spatiotemporal random fields in both linear predictors, with anisotropy in the spatial correlation functions.

The VIMS Trawl index of abundance, representing a minimum abundance south of the Rappahannock River, was variable. Abundance estimates were generally quite low in colder months (January – March, December) and higher in warmer months, averaging 0.3 million (in January) to 7 million (in June) blue crabs (Table 2.4). This is due at least in part to a reduction in the availability of overwintering crabs to the trawl gear. Distinct seasonal patterning is evident in the monthly indices (Figure 2.4). Most months exhibited a decline in late 1990s, but patterns in more recent years diverged. In the spring and early summer, the indices primarily exhibited an uptick in the mid- to late-2000s, followed by a more recent decline; indices representing late summer months generally stabilized after a slight uptick in the mid-2000s; in the fall, indices primarily continued to gradually decline.

2.3.3. ChesMMAP

Overall, 7,686 standard stations (238-405 stations yr^{-1}) were included in this analysis. Sampling intensity was higher in the early part of the time series: between 2002 and 2018, 300-400 stations were typically sampled each year; since 2019, with the change in survey platform and design, ~ 240 stations have been consistently sampled each year. Catch ranged from 0-2,807 crabs tow^{-1}; 49.7% of tows had at least one crab. Across all standard stations, 37,094 crabs were measured, ranging from 9-220 mm CW.

Models with the Poisson link in the first linear predictor did not consistently converge, so a logit link was used for several months. The distribution that received the most support for modeling the nonzero data varied by month (Table 2.5). Evaluation of the random effects generally provided support for the inclusion of spatial and spatiotemporal random fields in both linear predictors (except in May), with anisotropy in the spatial correlation functions in most months (Table 2.5).

The ChesMMAP index of abundance, representing a minimum in the Bay's mainstem, was variable. Abundance estimates were generally quite low in March, with an increase in scale and variability in all other months, averaging 0.7 million (in January) to 5.5 million (in November) blue crabs (Table 2.6). This is due at least in part to a reduction in the availability of overwintering crabs to the trawl gear. The monthly indices were relatively consistent through time: generally increasing from 2002 to about 2010, declining to the lowest values in the mid-2010s (Figure 2.5). Since 2015, indices have been above the minima but generally lower than average and highly variable.

2.3.4. Maryland Trawl Surveys

Overall, 8,370 standard stations (318-434 stations yr^{-1}) were included in this analysis. Catch ranged from 0-597 crabs tow^{-1}; 74.1% of tows had at least one crab. Across all stations, 203,257 crabs were measured, ranging from 3-220 mm CW.

The distribution that received the most support for modeling the nonzero data varied by month. The beta negative binomial was chosen for May, June, September, and October, while the negative binomial type II was chosen for July and August.

The MD Trawl Surveys index of abundance, representing the average number of blue crabs per 1500 m^2 in Maryland's tributaries, was variable. Indices were generally higher in the summer and decreased in September and October; the average in October was 8.4 blue crabs per 1500 m^2 as compared to 33.6 in July (Table 2.7). Patterns in the monthly indices were generally consistent through time: generally increasing from 2004 to about 2010, declining to the lowest values in the mid-2010s, and increasing to a relatively stable, intermediate level to present (Figure 2.6).

2.3.5. PEARL Pot Survey

Overall, 810 stations (24-36 stations yr^{-1}) were included in this analysis. As the data were aggregated by round of sampling, these stations represented 382-713 pot-days fished; annual pot-days were consistently above 550 yr^{-1} until 2011; effort has generally declined in more recent years. Catch ranged from 1-333 crabs per sampling round (equivalent to 0.05 to 16.65 crabs pot-day^{-1}); at least one crab was taken each sampling round. Across these stations, 203,257 crabs were measured, ranging from 25-206 mm CW.

The negative binomial distribution was chosen for modeling the nonzero data for all months (type I in June and type II for the remaining months).

The PEARL Pot survey index of abundance, representing the average number of blue crabs per sampling round off Calvert Cliffs, MD, was variable. Indices were generally lower in June and November compared to the other methods during which the survey occurred; the average in November was 2.3 crabs per round as compared to 6.2 in August (Table 2.8). Patterns in the monthly indices were variable without clear trends (Figure 2.7).

2.3.6. Coherence among and within surveys

The number of surveys occurring in a given month was variable, ranging from just one (January, April, December) to a maximum of four (July, September). Kendall τ varied from a slight negative correlation (-0.04, VIMS Trawl and PEARL Pot in November) to a moderate positive correlation (0.46, ChesMMAP and MD Trawls in September), likely reflecting differences in the surveys' spatial extents, and therefore the proportions and demographics of blue crabs sampled by the various surveys (Figure 2.8). Coherence within a survey was generally higher than among the surveys (Table 2.9).

TOR 3: Fishery-dependent Data

There are a number of recreational and commercial blue crab fisheries in Chesapeake Bay. Here we review the development and current status of the principal fisheries. Because management regulations vary among the jurisdictions, we present each jurisdiction separately. While recreational fisheries data remain limited, some progress has been made in characterizing these fisheries which has been used to update the estimates used in the current assessment.

Kennedy et al. (2007) reviewed the history of commercial fisheries for blue crab along the Atlantic and Gulf coasts of the United States. The commercial crabbing industry dates to 1873 (Sette and Fiedler 1925). Van Engel (1999) suggested that the growth of the commercial fishery at this time resulted from the successful development of methods for shedding and shipping crabs out of the region. The decline of landings in New York and New Jersey created a demand for crab meat that further encouraged development and expansion of the fishery. In response to the developing fishery, the States of Maryland and Virginia mandated oversight of the fisheries by their respective state agencies (Van Engel 1999; Kennedy et al. 2007). Virginia vested authority over the blue crab fishery to the Virginia Board of Fisheries in 1898. The situation in Maryland was more fluid until 1939 when the Maryland Commission of Fisheries was created. Under the *Maryland and Virginia Potomac River Compact of 1958*, recreational and commercial fisheries in the Potomac River are managed by the Potomac River Fisheries Commission which is charged with the establishment and maintenance of a program to conserve and improve the fisheries resources in the river.

During the early development of the crab fishery, crabs were harvested principally by dipnet, trotlines, and scrapes (Van Engel 1999). Use of dredges to harvest overwintering crabs was limited to Virginia. Wire mesh crab pots were introduced in 1928 in Virginia, although they were not legalized in Maryland until 1941. Crab pots became the principal gear for hard crabs after World War II and remain so today.

The first regulations for the fisheries recognized gear, region, and season differences. The establishment of a closed winter season occurred early in the history of the fishery. Local winter closures occurred in individual counties in Maryland as early as 1902 (Van Engel 1999), but it was not until 1930 in Maryland and 1932 in Virginia that the winter closure of the fishery was broadly enforced. Minimum size limits on crabs were also established relatively early. The first successful implementation of minimum size limits occurred in 1916, which Van Engel (1999) credited to a lack of relevant biological information and a focus on the oyster fishery prior to this date. While effort controls were more common in the early years of the fishery, harvest controls in the form of daily bushel limits were instituted in the 2010s and are now in place throughout Chesapeake Bay.

3.1. Virginia

Commercial fishing for blue crabs in the Commonwealth of Virginia is regulated by the Virginia Marine Resources Commission (VMRC). There are a variety of gear types that can be legally used to harvest crabs within the Commonwealth, but crab pots, peeler pots, and (prior to 2008) crab dredges predominate. Crab pots, which represent 80-97% of annual harvest, can be fished in both the mainstem of Chesapeake Bay and in the tributaries. No person may place, set or fish more than a combined total of 425 hard crab pots (500 hard crab pots prior to 2008) in Virginia tidal waters. Peeler pots are fished on a more seasonal basis and can be “baited” with live adult male crabs or left empty for shedding crabs seeking shelter. Historically, crab dredges were restricted to the mainstem of the Chesapeake Bay during winter months (December – March), but the crab dredging season has been closed since 2008 as part of the female blue crab conservation strategy.

The main effort controls in Virginia’s commercial blue crab fishery are a limited entry fishery, pot limits for each crab pot license with lower pot limits in the tributaries, season limits, daily time limits, a Sunday prohibition on crabbing, spawning sanctuaries (654,246 acres of mainstem Chesapeake Bay and oceanfront), and cull rings in crab pots to allow escapement of small crabs. Output controls on the fishery include minimum size limits (5” (12.7 cm) for male and immature female crabs, varying for peeler and softshell crabs), prohibition on harvest of dark sponge crabs (having a brown or black egg mass) during spawning periods, and (since 2013) bushel limits on total daily harvest for each hard crab pot license category. For a complete listing of regulations, see the VMRC website (https://mrc.virginia.gov/regulations).

Regulatory changes in Virginia in the wake of the 2008 Blue Crab Fishery Disaster that have continued through 2023 include annual closure of the winter dredge fishery, reduced maximum pot limits, increased minimum size limits for peeler crabs (Table 3.1), a waiting list for latent licenses, and earlier closures of the spawning sanctuaries. In 2013, daily bushel limits were established for all hard crab pot licenses.

Virginia also has a recreational crab fishery, allowing crabbing with hand line, dip net, or two commercial-style crab pots without a license, and with crab traps/pounds, trotline, or up to five commercial-style crab pots with paid licenses. Recreational crabbers must follow most of the same rules as commercial crabbers.

3.2. Maryland

The state of Maryland recognizes both commercial and recreational fishery sectors. Currently, in the commercial fishery Maryland prescribes seven legal methods for harvesting blue crab: scrapes, dipnets, trotlines, handlines, seines, bank traps, and pots (https://dnr.maryland.gov/fisheries/pages/regulations/bay_regs.aspx). However, the fishery is dominated by the hard crab pot fishery and the trotline fishery. There are numerous temporal and spatial regulations that limit when, where and how these gear types can be used. The hard crab pot fishery is seasonal as a result of both regulation and the life history of the crab. Like the pot fishery in Maryland, the trotline fishery is also seasonal. The trotline fishery is limited principally to the tributaries in Maryland, where pot fishing is banned. The number of pots or length of trotline is regulated by the commercial license that each waterman holds. The limited crab catcher license allows for the commercial use up to 50 crab pots. The tidal fishing license and crab harvester license permit waterman to employ up to 300 crab pots. Two additional authorizations, the CB6 and CB9, increase the number of pots allowed to 600 and 900 respectively. All commercial licenses allow for use of scrapes and unlimited trotline length. As noted in the description of the Virginia fisheries, Maryland implemented a strategy to conserve female spawning stock. This has involved mid and late season bans on the harvest of female hard crabs in Maryland waters and bushel limits, which correspond to season and license type. Minimum size limits have changed over time and change during the year (Table 3.1). Maryland also has reduced harvest of mature females with daily bushel limits that depend on license type and time of year.

3.3. Potomac River Fisheries Commission (PRFC)

Under the Maryland and Virginia Potomac River Compact of 1958, recreational and commercial fisheries in the Potomac River are managed by the PRFC which is charged with the establishment and maintenance of a program to conserve and improve the fisheries resources in the river. Commercial gear types include crab trotlines, crab pots, and peeler traps. The dominant gear type in the Potomac River is crab pots; the PRFC has established regulations limiting the number of pots that can be used in the crab pot fishery and is regulated by the commercial license type of each commercial fisher. The highest pot license type allows for the use of up to 475 crab pots (500 hard crab pots prior to 2008). In addition to pot limitations, the license to fish crab pot gear is restricted by limited entry. The maximum number of licenses was set at 500 licenses in 1995 but was decreased to 400 licenses in 2005 as a method to decrease the number of crab pots.

Recreational crabbing in the mainstem of the Potomac River is managed by a sport crabbing license which allows a fisher the use of up to 5 crab pots, a 1,200' trot line, 20 collapsible crab traps, dip nets and handlines. Fishers are able to recreationally crab without a license with reduced gear limitations (up to 2 crab pots, a 600' trot line, up to 10 collapsible crab traps, dip nets, and handlines). Both licensed and unlicensed recreational fishers have daily bushel limits of no more than 5 dozen hard crabs, 2 dozen soft crabs and 2 dozen peeler crabs may be harvested per person per day. Recreational fishers must follow most of the same rules as the commercial sector such as size limits, seasons, time limits, and the use of cull rings.

As with other jurisdictions, since 2008 the PRFC has implemented commercial daily bushel limits (ranging from 8 to 24 bushels, varying by season, market category, and license type), late season bans on female harvest, reduced maximum crab pot limits, and increased minimum size limits. Many of the regulation changes have continued through 2023. Various minimum size limits (5.25” for males and immature female crabs, 3.5” for peeler crab) and prohibition on harvest of sponge crabs, spawn crabs, female blooming crab, or the female crab in which the egg pouch or bunion has been removed of any size apply to both the commercial and recreational fisheries. The Potomac River historically remains closed to crabbing from 1 December to 31 March each year. See the PRFC website for a full listing of regulations (https://prfc.us/).

3.4. Fishery-dependent Data

3.4.1. Commercial Harvest

Reported commercial landings adjusted for dead discards and recreational harvest are shown in Figure 3.2.

Virginia

In 1993, Virginia instituted a mandatory daily harvest and effort reporting program for commercial fishers. Data reported are consistent with the Atlantic Coastal Cooperative Statistics Program standards. Data are checked for quality control on a routine and consistent basis, and compliance and oversight procedures are in place to ensure accurate reporting. VMRC staff have low confidence in reported landings from 1993, the first year of the reporting program, but data quality is consistent from 1994/1995 onward. However, landings were not reported by sex until 1996; therefore, data are considered most reliable from 1997 onwards.

There is a portion of the catch in each jurisdiction that is reported without sex information from 1997 onwards. This was more common before reporting harvest by sex became mandatory in all jurisdictions. The unclassified market category was removed in 2022, requiring harvest of hard crabs to be reported by sex from that year forward. For the periods before and after 2008, we calculated monthly averages of the proportion of males and female crabs in the catch data and applied that ratio to the total harvest of unsexed crabs in each month and year. We chose to calculate pre- and post-2008 sex ratios to reflect any changes in availability or fishing patterns before and after the 2008 Fishery Disaster.

Commercial fishers report each day’s landings by species and market category, along with location of harvest, type and amount of gear fished, hours fished, and disposition of harvest. Reports are due by the fifth of the month following harvest. Reports were first submitted on standardized paper forms, then an online system was introduced in 2009 as an alternative. Since 2022, all crabbing reports must be submitted online to increase efficiency of data collection for management. If a fisher does not submit a report for a month, they receive follow-up emails and letters. Commercial fishers found out of compliance for non-reporting are not eligible to purchase their commercial licenses in the following year until they submit all missing reports.

Commercial fishers are able to report crab landings in various units – bushels, barrels (equivalent to three bushels), and pounds are most commonly used for hard crabs while bushels and number of crabs are most common for peeler and softshell crabs. VMRC uses standard conversions to convert all harvest data to pounds (0.475 lbs per crab and 40 lbs per bushel for hard crabs, 0.2083 lbs per crab and 37.5 lbs per bushel for peeler crabs, 0.2167 lbs per crab and 37.5 lbs per bushel for soft crabs; 1 lb = 0.454 kg). A buyer sampling program in 2016-2017 updated some conversions for hard crabs (0.3796 lbs per crab for male hard crabs (except No. 1 males), 0.307 lbs per crab for female hard crabs) from 2018 on, but all other conversions have been consistent since 1993.

Virginia's commercial landings data were provided in pounds of unclassified hard crabs (until 2022, when that market code was deprecated), hard female crabs, hard male crabs, and unclassified peeler and softshell crabs by month and year for three gear groups – crab dredge, peeler pot, and crab pot and all other gears. Number of trips per month and year were also provided. Any confidential data (fewer than three harvesters contributing per data point) were removed, but these make up less than 150,000 pounds (less than 0.07% of total harvest) across the time series.

Maryland

Commercial harvest data are collected by the Maryland Department of Natural Resources (MDNR) via logbook or electronic reporting. Logbooks are a daily record that are mailed to the department monthly, while electronic reports are submitted daily. Data collected from each harvester includes date, location, gear used, maximum amount of gear deployed, amount of gear used on the day of fishing, hours spent fishing, and landings. Landings can be reported in bushels, pounds, or number of individuals. Catch is further defined by market category – No. 1 males, No. 2 males, Females (mature), Culls/Mixed, soft crabs, and peeler crabs. The Culls/Mixed category is mostly lower quality male hard crabs. Prior to 2008, when female bushel limits were implemented, bushels in the Culls/Mixed category could be made up of both male and female hard crabs, but based on dealer sampling and the harvest location of most Culls/Mixed bushels, it was likely that Culls/Mixed were 90% male hard crabs. From 2008 onward, Culls/Mixed were all male hard crabs. The distinction between No. 1 (larger) male and No. 2 (smaller) male hard crabs is arbitrary and based on market conditions at the time and place of harvest.

Landings is converted to pounds using a conversion of 40 pounds/bushel for hard crabs and 2.5 pounds per dozen for soft and peeler crabs. To convert pounds to individual crabs, Maryland has used a conversion of 0.42 pounds/crab for No. 1 and No. 2 male hard crabs combined, 0.31 pounds/crab for female hard crabs, 0.31 pounds/crab for Culls/Mixed hard crabs, and 0.2083 pounds/crab for peelers and soft crabs. Conversion values for hard crabs come from the average size of legal crabs in the MDNR summer trawl survey and the MDNR Cooperative Commercial Blue Crab Data Collection Survey. While Cull crabs are male, there is no identifier in the data to select for what the market would consider a Cull. They are, however, recently shed and lighter than No. 1 and No. 2 hard crabs, so they were assigned the female weight conversion as a proxy.

Reporting is mandatory for license renewal in the following year, but there is still a small fraction of crabbing-eligible licenses who do not report. For summarized annual landings reported publicly by Maryland DNR, non-reporting licenses are assigned landings based on the reports of other crabbers with the same license type in the same month. However, the month-specific landings in this assessment were not adjusted.

Electronic reporting started in 2015, and its usage has increased since then, but overall reporting procedures and requirements have remained unchanged since 1994.

PRFC

Commercial crab harvest from the mainstem of the Potomac River is reported to the Potomac River Fisheries Commission. Data are reported by individual commercial fishers on a daily basis via paper reports submitted to the Commission each week. These reports collect information on daily landings including license type, gear, area fished, port, effort, and market category. Market categories include Male No. 1, Male No. 2, Females (mature), and Mixed bushel. Mixed bushels were allowed to be reported until 2010 when it became mandatory to separate bushels by sex. Mixed bushel hard crabs were assigned a sex based on recent sex-specific data, using the same methods explained for Virginia.

Landings can be reported in pounds, bushels, or number of crabs. All hard crab harvest is converted into pounds using a conversion of 40 pounds per bushel and 72 crabs per bushel. Soft and peeler crab harvest is converted into pounds using the Chesapeake Bay-wide average of 0.2083 pound per crab.

Any confidential data (fewer than three harvesters contributing per data point) were removed, but these make up less than 25,000 pounds (less than 0.0003% of total harvest) across the time series.

3.4.2. Catch Per Unit Effort

Time series of fishery CPUE can be considered as an index of abundance, when appropriately adjusted for factors other than abundance that can impact catch rates (Maunder and Punt 2004). Such indices can be useful, particularly in situations when independent surveys are unavailable, conflicting, or inconsistent with fishers' perception of the resource. Although removals and effort data are available from each jurisdiction, several considerations regarding effort gave pause to the consideration of CPUE series as additional abundance indices. First, determining an appropriate unit of effort in the blue crab fisheries is non-trivial. Number of trips is straight-forward to calculate, but the characteristics of a trip can vary widely. Other effort metrics could be person-hours, soak time, number of pots, dredge duration, length of trotline. Comparisons across gear types or combining infrequently used gear types into a single fleet can present challenges. Additionally, the effort data available for the Chesapeake Bay blue crab fisheries are generally considered less reliable than other data components. For example, "hours fished" may be interpreted differently by different users (e.g., time spent on the water, time spent actively working gear, soak time) and may not reflect what is intended by the analysts. Similarly, the number of pots fished appears to be inconsistently reported as either the number of pots that are checked during a particular trip, the total number of plots deployed, or the maximum number of pots allowed based on license type.

Given the uncertainties in the effort data and availability of multiple high-quality, large-scale fishery independent surveys, and early indications that the model would be able to reasonably reconcile the data and estimate stock dynamics with fishery-independent indices, we did not pursue standardized fishery CPUE series as additional indices of abundance for use in the assessment.

3.4.3. Biological Sampling of Commercial Harvest

Virginia

In 2016-17, the Virginia Marine Resources Commission conducted a seasonal study on biological information from the commercial blue crab fishery in Virginia waters. From late-summer 2016 through mid-summer 2017, technicians intercepted crabs at docks or local seafood buyers using a multi-stage random sampling design. Technicians recorded the total number of bushels harvested and total bushel weight, as well as individual blue crab widths, weights, sex, and maturity of a minimum of 30 crabs per bushels per market grade. Market grades, which were assigned by the dealer, included males, light males, females, and females with sponge. Widths were taken with fish measuring boards and weights taken with digital scales. A total of 226 commercial intercepts were conducted, sampling 10,088 crabs from eight water body systems.

Maryland

Since 2002, the Maryland DNR has recruited crabbers to be a part of the Commercial Blue Crab Data Collection Program (a.k.a., the Maryland Sentinel Fishery Program; Fegley et al., 2006). Watermen could work either independently, after going through a short training session, or carry a DNR observer aboard. Watermen who worked independently were asked to record the CW, sex, life stage (peeler, soft, egg-bearing), and maturity (females only) of each crab for a sample of 75 crabs and to do this one day per week throughout the season. They also recorded the total number of crabs caught per unit of gear until they reached their sample of 75 crabs. Observers collected the same data on all crabs caught but for their entire day aboard the fishing vessel, including data on crabs that are not allowed to be retained. Data have been collected from crab pots, peeler pots, trotlines, and scrapes. Sampling has taken place in the mainstem Chesapeake Bay from the Susquehanna Flats to the state line and in most major tributaries. Data are also available from limited dealer sampling in the early 2000s.

Potomac River

The PRFC does not collect biological data on the commercial harvest. However, some limited data for the Potomac River are available from the Maryland Sentinel program.

3.4.4. Calculation of fishery catch length and sex compositions

Virginia

To inform the length compositions for the Virginia pot fishery, we used data from a buyer sampling program that occurred in 2016-2017. The biological data were further aggregated by month sex, and length bin. Length bins ranged from 1- to 19+ cm where the first bin included all crabs less than 2 cm, and the 19+ bin included any blue crabs 19 cm and larger. Proportions at length and sex were calculated for each month and year.

There were no data from the Virginia winter dredge fishery to inform its length and sex composition, so we used data from the WDS from the same location as the winter dredge fishery (specifically the lower bay stratum) to inform the catch composition. Data from the Maryland portion of the WDS were removed. Data were aggregated across months for each year of the WDS; November and December from the previous year were combined with January through March of the following year. Proportions at length and sex were calculated for each year. Immature females were not included because they are not allowed to be retained.

Across all jurisdictions and fleets, mature females smaller than 7 cm were removed because they were extremely rare and unlikely to be retained.

Maryland and Potomac River Fisheries Commission

To inform proportions-at-length (i.e., CW) and -sex of the fishery catch in Maryland, the Potomac River, and the Bay-wide peeler/soft shell fishery, we used data from the Maryland Sentinel Fishery Monitoring Program. Through this program, biological data were collected from commercially caught blue crabs by state biologists and commercial fishers starting in 2002 (Fegley et al. 2006). We only used biological data collected by state biologists because they were thought to be more accurate and they sampled more crabs per trip. Blue crabs were identified to sex and maturity (for females) and measured for their CW as they were brought onboard the commercial vessels prior to culling. Shell condition (peeler, soft, and buckram) and presence of eggs was also recorded.

To represent the length and sex distribution of blue crabs harvested by the commercial fishery, we filtered the data to only retain blue crabs that meet the minimum size limit and other retention regulations from each jurisdiction and date (Table 3.1). This approach accounts for changes in size limits for hard, peeler, softshell, and sponge crabs within a year and throughout the entire time series. Any crabs not deemed legal were not included in the length composition data. Immature females were, therefore, removed from all fleets except the peeler fleet. Some blue crabs were classified as "buckram" to indicate crabs that have recently molted and have a shell that is not fully hardened. We treated buckram records the same as those for hard crabs. Additionally, we treated crabs classified as "soft" the same as peelers. Finally, any crabs recorded as dead or as mature females bearing eggs were removed. A very small fraction of the blue crabs (<0.04% of total catch) had an incorrect millimeter to inch conversion and were removed (CW in both units was present in the data base).

For Maryland, the biological data were aggregated by month, length bin, sex, and gear to represent different fleets (pot, trotlines, and peeler). Length bins ranged from 1- to 19+ cm where the first bin included all crabs less than 2 cm, and the 19+ bin included any blue crabs 19 cm and larger. We did not use length or sex composition data from PRFC or Virginia to inform the peeler length and sex compositions because these data were generally not available. This approach assumes that the length and sex compositions for the VA and Potomac River peeler fisheries are similar to those from Maryland. For the Potomac River, only length composition information from hard crab pots was used because the fraction of catch from other gears was very small.

3.4.5. Estimation of dead discards

Discard mortality estimates for Chesapeake Bay blue crab pot fisheries are limited and have not been used in previous assessments. The 2013 Florida blue crab stock assessment used 10% discard mortality for crab pots based on a 2000-2006 trapping study in Tampa Bay. Walters et al. (2025) used a reflex action mortality predictor method to predict discard mortality of blue crabs and found that mortality was highest (14%) in high salinity areas in the summer. Lower mortalities were predicted in low salinity areas in the summer (2%) and in both high and low salinity areas during the winter (4% and 6%, respectively). In this assessment, dead discards refer to crabs that were recorded dead, and we assume that dead crabs are discarded.

For dead discards in the Virginia dredge fishery, crab injury rates from Lipcius et al. (2013) were used. This study, which was conducted with commercial crab dredgers, estimated that the incidental mortality of a commercial crab dredge over one day was 13.1% under the conditions that most closely matched the pre-2008 dredge fishery (sandy habitat and with divers on the dredge).

To produce estimates of dead discards in the other fleets, we used reported dead crabs from the Maryland Sentinel Monitoring Program. For each year, sex (males and mature females), and gear (hard pots, peeler pots, or trotlines), we calculated the proportion of dead blue crabs in the observations. We assumed these dead crabs encountered in the gear would be discarded. The proportion of dead discards for each year, sex, and gear was multiplied by the year, sex, and gear-specific total catch to estimate the amount of dead discards in pounds. The same yearly proportion was used each month of a given year. The amount of dead discards in pounds was added to the total catch to calculate total catch with approximate dead discard included. There were no data to inform the proportion of dead discards for pots in Virginia waters or the Potomac River, so we used the estimates of proportion dead discards for males and mature females in the Maryland pot fleet.

3.4.6. Recreational Harvest

The 2011 benchmark assessment calculated recreational harvest, sexes combined, as being 8% of Chesapeake Bay-wide commercial harvest. This value was based on several studies conducted in 2001, 2002, 2005, and 2009 (Ashford et al. 2009; 2010a; 2010b; 2013a; and 2013b). Upon re-visiting these studies, the 8% value, which was not reported by Ashford et al., could not be replicated, and it ignored reported differences in harvest between jurisdictions and sex-specific regulations among jurisdictions. Ashford and Jones (2001; 2002) did not consider sex differences in recreational harvest, but the fishery takes place almost exclusively in tributaries where the harvest is skewed towards males relative to the overall fishery.

The studies were conducted in both Maryland and Virginia in 2001 and 2002, but only in Maryland in 2005 and 2009. The estimates from the 2002 study were regarded as being unusually low, especially for Virginia. The 2001, 2005, and 2009 studies provided similar results for Maryland, so the 2001 study was relied upon for the relative distribution of the recreational harvest between the states.

Since the last assessment, a tagging study by Semmler et al. (2021) estimated the recreational harvest of male blue crabs in Maryland.

The Ashford et al. (2001) study estimated that recreational harvest was 5.02 million crabs in Maryland and 2.1 million crabs in Virginia. From Maryland commercial landings data and MDNR Cooperative Blue Crab Commercial Survey data, harvest in tributaries where the recreational fishery takes place, is skewed 75:25 towards males. Splitting the Maryland estimate into males and females resulted in male recreational catch being 11% of commercial harvest of males, and female recreational catch being 3.7% of female commercial harvest. The Potomac River recreational fishery was considered similar to Maryland’s and the same fractions of recreational harvest relative to commercial were applied to that jurisdiction.

These estimates were considered representative of the 1994-2008 period, before the recreational harvest of female crabs was banned in Maryland and the Potomac River.

The Semmler et al. (2021) finding of Maryland’s male recreational harvest being 11.2% of male commercial harvest was almost identical to the Ashford et al. (2009; 2010a; 2010b; 2013a; and 2013b) studies and suggested that applying the estimate of 11% specific to male recreational harvest was reasonable for the period of 2009-present, after female-specific crabbing regulations were implemented.

The annual sex composition in the Virginia commercial harvest from tributaries has been 50:50 male:female, so that was applied to the recreational fishery, as well. Ashford and Jones (2001) estimated Virginia's 2001 recreational harvest at 2.1 million crabs in Virginia. An equal division of males and females resulted in male recreational harvest of 5.1% of commercial male harvest and female recreational harvest of 1.7% of commercial female harvest.

There are no other harvest estimates for Virginia's recreational fishery and no significant changes to Virginia's recreational crabbing regulations, so the Ashford and Jones (2001) estimates were used for the entire time series.

3.4.7. Characterizing Uncertainty

Virginia

Virginia audits harvest data by validating harvester reports against seafood dealer records, with staff confirming the correct information to resolve any inconsistencies found. Records are not kept of how many errors are found, so reporting error rates are not available.

Uncertainty was higher in 1994-1996, the first few years of mandatory harvester reporting, as harvesters adapted to the new requirements. In 1994-1995, harvest by sex was not collected. Staff believe records from 1997 forward to be the most reliable.

In 2008, blue crab licensees who had not reported harvest for several preceding years were placed on a license wait list until the population grew to exceed the target. It is believed that some commercial fishers reported harvest when they had none in order to maintain eligibility in case harvest history would be used as a license requirement again in the future. It is estimated that this practice ended by the time daily bushel limits were introduced in 2013, but 2008-2010 were the years this would have been more prevalent.

Maryland

While reporting is mandatory for license renewal, there are still licensees that do not report crab harvest. These licensees may report harvest in other fisheries and satisfy the reporting requirements. Non-reporting licensees that are assumed to be active in the blue crab fishery, are assigned harvest based on their license type and month.

In the fall of 2008, daily bushel limits for females were established based on harvest history. Some commercial fishers, wanting the highest possible bushel limits, began over-reporting their catch (CBSAC 2009). Despite bushel limits being based on license type starting in 2009, over-reporting persisted, and likely is still a bias in the data. This was mostly an issue for the reporting of female hard crabs and not for male hard crabs or peelers.

PRFC

The PRFC does not collect any seafood dealer reports, only harvest data from commercial fishers. Collection of only harvest data prevents the PRFC from auditing the data beyond staff confirming and/or correcting any outlier data.

Harvest data have been collected via paper reporting since 1964. Monthly harvest data were available beginning 1986. Monthly harvest data by market category were first available in 2000.

TOR 4: Stock Assessment Model and Uncertainty

4.1. Model structure

The Sex and Length Structured Assessment Model (SLAM) for Chesapeake Bay blue crab is length- and sex- specific. Hereafter, length indicates CW. The model includes a variety of potential selectivity and growth patterns. The model is implemented using a monthly time step. SLAM is fitted to data on sex-specific catch, sex-specific length composition of the catch, survey indices, and length and sex compositions of the survey indices. The model tracks the population abundance-at-length in three sex-maturity (x) categories: males (ma), immature females (if), and mature females (mf). The model estimates abundance, recruitment, fishing mortality rates, survey selectivity, and survey catchability. The model includes several potential selectivity functions and a stochastic increment-based Gompertz growth model modified for blue crab-specific female growth patterns. The model is implemented in RTMB (Kristensen 2025). Model variables are described in Table 4.1.

4.1.1. Recruitment

Recruitment of age-0 blue crabs occurred in February to coincide with the WDS. The model was specified to only estimate recruitment in February, but the specific month can be adjusted if needed. Recruitment in each year (R_y) was estimated as individual parameters that were constrained to be normally distributed on the $\log_e$ scale.

Recruitment in each year, sex, and length bin ($R_{y,l,x}$) was calculated as the product of the proportion at sex for recruits (κ_x), the estimated total recruitment ($R_{y,}$), and the proportions at length of recruits (p_l),

$$R_{y,l,x} = \kappa_x R_y p_l \, .$$

The proportion of male recruits was estimated on the logit scale, and the proportion female (κ_f) was calculated as $\kappa_{if} = 1 - \kappa_{ma}$. κ_{mf} was zero.

Size distribution of recruits

The proportions at length for recruits followed a lognormal distribution with mean and standard deviation (SD) parameters,

$$p_l = \begin{cases} \Phi\left(\log_e(l), \mu_p, \sigma_p\right) & if\ l\ is\ the\ first\ bin \\ \Phi\left(\log_e(l+b_w), \mu_p, \sigma_p\right) - \Phi\left(l, \mu_p, \sigma_p\right) & \\ 1 - \Phi\left(\log_e(l-b_w), \mu_p, \sigma_p\right) & if\ l\ is\ the\ last\ bin \end{cases},$$

where Φ was the normal cumulative distribution function, *l* was the upper limit of a length bin, b_w was the width of each length bin, μ_p was the $\log_e$-scale mean length of recruits, and σ_p was the $\log_e$-scale standard deviation (SD) of the length distribution of recruits. The first bin was a "minus" group that includes individuals up to the upper limit of the first length bin, and the last length bin was a "plus" group that includes all individuals greater than the lower limit of the largest size bin. The parameters of the initial size distribution of recruits were estimated outside of the model using data on the size distribution and estimated abundance of recruits in vegetated and unvegetated shallow and deep habitats during 2011 (Wilberg and Drzewicki 2026; Figure 1.7). The initial size distribution parameters were assumed to be constant over time.

4.1.2. Abundance at length

The abundance of males and immature females by length bin ($N_{t,l,x}$) was the sum of recruitment and the abundance of individuals that survive and grow to that size class,

$$N_{t+1,l,x} = R_{t+1,l,x} + \sum_{l'} G_{t,l',l,x}\left(N_{t,l',x}\left(1 - O_{t,l',x}\right)e^{-Z_{t,l',x}}\right),$$

where $G_{t,l',l,x}$ was the probability of transitioning from bin l' to bin *l* for time step *t* and sex *x*, $Z_{t,l',x}$ was the total instantaneous mortality rate for crabs in length bin l', sex *x*, and timestep t, $O_{t,l',x}$ was the overwinter mortality rate (as a proportion) for crabs in length bin *l,* sex *x*, and timestep t. The order of operations within a time step was overwinter mortality, total instantaneous mortality, growth, and then recruitment. This representation of the length-based population dynamics generally follows standard approaches in size-based population models (Punt et al. 2010; Punt et al. 2013; Cao et al. 2017) with the exception of including overwinter mortality. Overwinter mortality only occurred in February of each year and was calculated externally (Liang et al. 2026b).

For mature females, the model was similar to that of males and immature females, but it did not include recruitment or growth of mature females, and *G* included females that transition from immature to mature ($G_{t,l',l,mf}$),

$$N_{t+1,l,mf} = \sum_{l'} N_{t,l,mf}\left(1 - O_{t,l,mf}\right)e^{-Z_{t,l,mf}} + \sum_{l'} G_{t,l',l,mf}\left(N_{t,l',if}\left(1 - O_{t,l',if}\right)e^{-Z_{t,l',if}}\right)$$

For mature females, the molt to maturity serves as a functional terminal molt, after which they are thought to no longer grow (Smith and Chang 2007).

The initial abundance by sex and length ($\overline{N}_{0_{l,x}}$) was assumed to be in quasi-equilibrium with respect to recruitment, growth, overwinter mortality, and fishing mortality rates in the first year of the model. Specifically, abundance was calculated by applying the population dynamics over monthly time steps for a five-year period using the growth, fishing mortality, and overwinter mortality rates from the first year. The calculations started with mean recruitment in the second month of the first year,

$$\bar{N}_{0_{l,x}} = p_{l,x}\kappa_x R_{t=2}.$$

The quasi-equilibrium abundance was then calculated by projecting the population forward using the total mortality rates for each timestep.

4.1.3. Growth

We used a sex-specific stochastic Gompertz growth model that was modified for female maturation (Figure 4.1) because it better matched the pattern of slower growth at smaller sizes and more growth at intermediate sizes than a von Bertalanffy model. Blue crabs are likely not able to grow as fast as would be expected by a von Bertalanffy model when they are small because their growth is constrained by a relatively constant growth per molt and the need for an intermolt period between molts (Bunnell and Miller 2005; Brylawski and Miller 2006). The probability of growing from one length bin to another during a time step was based on the time-, length- and sex- specific mean growth increment and its distribution. The calculations assume that the starting size was the midpoint of a length bin. The growth increment was assumed to be normally distributed. For males, the growth increment was calculated as the difference between the cumulative distribution at the upper and lower bounds of a length bin,

$$G_{t,l',l,ma} = \Phi\left(l + b_w - l', \Delta_{t,l',ma}, \sigma_{\Delta_{t,l',ma}}\right) - \Phi\left(l - l', \Delta_{t,l',ma}, \sigma_{\Delta_{t,l',ma}}\right),$$

where $\Delta_{t,l}$ was the mean growth increment for an individual in a size bin with lower limit l'. Negative growth (i.e., individuals shrinking in their CW) was not allowed, and the proportion of crabs in a length bin that were expected to grow < 0.5 cm remained in that length bin,

$$G_{t,l',l,ma} = \Phi\left(\frac{b_w}{2}, \Delta_{t,l',ma}, \sigma_{\Delta_{t,l',ma}}\right).$$

The largest length (19 cm) bin was an aggregate length bin representing all individuals that length and larger,

$$G_{t,l',l,ma} = 1 - \Phi\left(l', \Delta_{t,l'}, \sigma_{\Delta_{t,l',ma}}\right).$$

The probability of an immature female crab transitioning from one size bin to another and remaining immature was similar to growth of males but also included transition due to maturation. The transition probability for immature females was the product of the probability of transitioning from length bin l' to length bin l and the probability of maturing during time step t at length bin l',

$$G_{t,l',l,if} = \left(\Phi\left(l + b_w - l', \Delta_{t,l',if}, \sigma_{\Delta_{t,l',if}}\right) - \Phi\left(l - l', \Delta_{t,l',if}, \sigma_{\Delta_{t,l',if}}\right)\right)(1 - \psi_{t,l'}),$$

where $\psi_{t,l'}$ was the probability of maturation (Figure 4.2). The probability of maturation was estimated externally (Ogburn et al. 2026) and was month and length-bin specific. The lower right diagonal element of $G_{t,l',l,if}$ was specified to be zero to indicate that immature females in the largest size bin would become mature that month, and $G_{t,l',l,mf}$ was specified to be one. During December-March, we assumed that blue crabs will not grow or mature, and *G* was represented by an identity matrix for males and immature females.

The mean growth increment was calculated using a discrete approximation of the differential equation version of the Gompertz growth model,

$$\Delta_{l',x} = \left(l' + \frac{b_w}{2}\right)\left(a_{t,x} - b_{t,x}\, log(\, l' + b_w/2)\right),$$

where $a_{t,x}$ and $b_{t,x}$ were the Gompertz growth model parameters. The mean increment was calculated by projecting the growth over a monthly timestep using 10 sub-timestep steps to reduce projection error. Each month was assigned $b_{t,x}$ parameters that were constant over time and the same for both sexes (Table 4.2). The values for $b_{t,x}$ were determined by iteratively adjusting the parameters until the model could match changes in the first mode of the length distribution in the WDS, the Maryland Trawl Survey, and the VIMS Trawl survey. The values of the other parameters of the Gompertz growth model are in Table 4.3. The $a_{t,x}$ parameters of the Gompertz model were calculated as a function of the asymptotic maximum size (L_{∞_x}) and the Gompertz $b_{t,x}$ parameters,

$$a_{t,x} = b_{t,x} log_e\left(L_{\infty_x}\right).$$

The variance of the growth increment was calculated at the midpoint of each length bin assuming that a_x and b_x were random variables,

$$\sigma^2_{\Delta,t,l,x} = \left(l + \frac{b_w}{2}\right)^2 \sigma^2_{a_{t,x}} + \left(l + \frac{b_w}{2}\right)^2 \sigma^2_{b_{t,x}} \left(\log\left(l + \frac{b_w}{2}\right)\right)^2 +$$

$$2\left(l + \frac{b_w}{2}\right)^2 \log\left(l + \frac{b_w}{2}\right) \sigma_{a_{t,x}} \sigma_{b_{t,x}} \rho_{a,b} + \sigma^2_G,$$

where the standard deviation for $a_{t,x}$, $\sigma_{a_{t,x}}$, was the product of $a_{t,x}$ and the coefficient of variation of $a_{t,x}$ (CV_{a_x}),

$$\sigma_{a_{t,x}} = a_x CV_{a_x},$$

and $\rho_{a,b}$ was the correlation between $a_{t,x}$ and $b_{t,x}$. Similarly, the standard deviation of $b_{t,x}$, $\sigma_{b_{t,x}}$, was the product of $b_{t,x}$ and its coefficient of variation,

$$\sigma_{b_{t,x}} = b_{t,x} CV_{b_x}.$$

σ^2_G represented additional variance that was needed to accurately describe the width of the length composition for smaller crabs.

The probability that an immature female at length l' becomes a mature female at length l was the product of the maturing and the probability of growing to length bin l,

$$G_{t,l',l,mf} = \Phi\left(l + b_w - l', \tilde{\Delta}_{l'}, \sigma_{\tilde{\Delta}_{t,l',mf}}\right) - \Phi\left(l - l', \tilde{\Delta}_{l'}, \sigma_{\tilde{\Delta}_{t,l',mf}}\right) \times \psi_{t,l'} \ ,$$

where $\tilde{\Delta}_{l'}$ was the mean amount of growth upon maturation for length bin l' and $\sigma_{\tilde{\Delta}_{t,l',mf}}$ was the SD of growth upon maturation for length bin l'. During December-March, we assumed that female blue crabs will not grow or mature, and $G_{t,l',l,mf}$ was represented by a matrix of zeros.

The $\tilde{\Delta}_{l'}$ was calculated as a decreasing linear function of starting length (Ogburn et al. 2026),

$$\tilde{\Delta}_{l'} = \left(l' + \frac{b_w}{2}\right)\left(\beta_0 + \beta_1\left(l' + \frac{b_w}{2}\right)\right),$$

where β_0 was the intercept and β_1 was the slope of the relationship of the proportional increase in CW upon maturation (Table 4.4). The values of the β_0 and β_1 parameters were chosen by slightly modifying those from Ogburn et al. (2026) until the length distribution of mature females in the WDS was approximately matched (Table 4). $\sigma_{\tilde{\Delta}_{t,l',mf}}$ was calculated using a constant CV of 2%. Larger values caused the length distribution of mature females to be wider than observed. Given the parameters of the growth model and female maturation, the model predicted that most females would mature during their first fall after recruitment (Figure 4.3).

4.1.4. Mortality

The total instantaneous mortality rate (*Z*) was the sum of natural mortality (*M*) and fishing mortality (*F*) summed over fleets (*ζ*),

$$Z_{t,l,x} = M_{mo(t),l,x} + \sum\nolimits_{\zeta} F_{t,l,x,\zeta},$$

where $mo(t)$ was the month associated with time step *t*.

There is evidence that natural mortality is higher for smaller blue crabs compared to larger blue crabs (Bromilow and Lipcius 2017). We developed length-based estimates of M using information from Bromilow and Lipcius (2017; Table 4.5), Lipcius et al. (2026b), and profiling over values within the model (section 4.2). Natural mortality was calculated as the product of a scaled decreasing function of relative natural mortality from the estimates in Bromilow and Lipcius (2017) and a reference level that was constant for larger sizes (Figure 4.4),

$$\begin{array}{c} M_l = (M_{rel_l} M_{Scale}) M_{ref} \ if \ l \leq 5 \ cm \\ M_l = M_{ref} \ if \ l > 5cm \end{array},$$

where M_{rel_l} was a decreasing function of length, M_{Scale} was 0.75, and M_{ref} was 0.65/9 mo^{-1} (Figure 4.4). These values were selected by doing a grid search over a range of values for M_{Scale} and M_{ref} and finding the ones that minimized the objective function for a previous version of the base model (Table 4.6). The decreasing portion of natural mortality was only applied to lengths ≤ 5 cm because 5 cm was the size of the largest crabs in Bromilow and Lipcius (2017). Estimates of length-based natural mortality were only applied in the months of April through December because overwinter mortality was described separately.

For February, we used length- and sex-specific estimates of overwinter mortality to represent combined natural mortality during January-March. Estimates of year-, sex-, and length-specific overwinter mortality $\left(\hat{O}_{y,l,x}\right)$ from Liang et al. (2026b) were smoothed using a GAM with 5 knots to provide estimates for missing size bins and to reduce variability caused by low sample sizes (L),

$$log\left(O_{y,x,l}\right) = f_{year_y,sex_x}(L_l),$$

where f_{year_y,sex_x} indicated separate smoothers over length bins for each combination of year and sex. Smoothing was done on the $\log_e$ scale to ensure positive values. In only a few estimates, mortality was estimated to be greater than 1. These cases were specified to be equal to 1, but they were for size-sex classes of crabs where the model estimated very few individuals (very large immature females and very small mature females).

We included six fleets in the model based on gears and crab condition: pots in Maryland (Maryland pot), trotlines and all other non-pot gears in Maryland (Maryland trotline), pot and all non-dredge gears in Virginia (Virginia pot), all gears in the Potomac River (PRFC), the winter dredge fishery in Virginia (Virginia dredge), and the peeler fishery (soft and peeler condition crabs) combined across all jurisdictions. We chose to separate peelers into a distinct fleet because they have different minimum size regulations that were represented with separate selectivity patterns. The fleets were disaggregated because regulations and blue crab availability differ among the jurisdictions and gears and data availability differs among these fleets. Fishing mortality was the product of length-, year-, and month-based selectivity for each fleet (ζ) and the fishing intensity ($F*$, i.e., the fully selected fishing mortality rate) during each time step for each fleet,

$$F_{y,t,l,x,\zeta} = s_{y,m,l,\zeta} F^*_{t,x,\zeta}.$$

The log-scale fishing intensities were estimated as free parameters for each month with a non-zero catch for a given sex and fleet. For months with zero reported catches, the fishing intensities were assumed to be 2×10^{-9} (i.e., e^{-20}).

Fishery selectivity followed an increasing logistic function for males and immature females,

$$s_{l,\zeta} = \frac{1}{1+e^{-p_{1,\zeta,y,m}\left(\frac{l+b_W}{2}-p_{2,\zeta,y,m}\right)}},$$

where p_1 was the slope parameter and p_2 was the inflection point parameter. We initially tried using dome-shaped selectivity functions for the peeler fleet, but they did not improve model fit.

We were unable to estimate fishery selectivity parameters simultaneously with the other parameters, so they were fixed based on minimum size regulations for each fleet and sex. Mature females do not have minimum size limits in the commercial fisheries, so selectivity was assumed to be 1.0 for all length bins. Fishery selectivity parameters for the peeler fleet were the same for males and immature females. Historical changes in size regulations are described in Table 3.1, and we adjusted the value of p_2 for a given month or year based on regulation changes (Table 4.7; Figures 4.5-4.10). To improve the selectivity curve for specific fleets, we iteratively added constants to p_2 and refit the model. The values for p_2 with the lowest objective function from an earlier version of the base model were chosen.

4.1.5. Catch at length

Catches ($C_{t,l,x,\varsigma}$) were calculated using the Baranov catch equation modified for overwinter mortality,

$$C_{t,l,x,\varsigma} = \frac{F_{t,l,x,\varsigma}}{Z_{t,l,x}}(1 - e^{-Z_{t,l,x}})\left[N_{t,l,x}\left(1 - O_{t,l,f,x}\right)\right].$$

We assumed that overwinter mortality occurred before fishing mortality. Overwinter mortality was only non-zero in March. Total catch in weight for each sex in each fleet and step ($T_{t,x,\varsigma}$) was the sum of the product of fleet- and sex-specific catch and mean weight for a length bin and sex ($w_{t,l,x}$),

$$T_{t,x,\varsigma} = \sum_l C_{t,l,x,\varsigma} w_{t,l,x}.$$

The estimated proportions at length for a time step and fleet ($P_{C_{t,l,x,\varsigma}}$) are calculated as the catch in a length bin and sex divided by the total catch in numbers for the fleet in that time step,

$$P_{C_{t,l,x,\varsigma}} = \frac{C_{t,l,x,\varsigma}}{T_{t,x,\varsigma}}.$$

4.1.6. Indices at length

Expected survey indices ($i_{t,l,v}$) at length and sex were calculated as the product of catchability ($q_{mo(t),x,v_m}$), survey selectivity ($s_{mo(t),x,v_{m,l}}$), and abundance,

$$i_{t,l,x,v} = q_{mo(t),x,v} s_{mo(t),l,x,v} N_{t,l,x},$$

where catchability can vary by month ($mo(t)$) and survey (v). Catchability varied across sexes except for the WDS where all sexes were assumed to have the same catchability and the PEARL pot survey where males and immature females were assumed to be equal. These assumptions were made because the WDS surveys almost all of Chesapeake Bay and female maturity data were not collected for the PEARL pot survey.

We assumed that the winter dredge survey occurred on the first day of February, before overwinter mortality occurred. ChesMMAP was split into two different indices: ChesMMAP 2002-2018 and ChesMMAP 2019-2023 (later referred to as ChesMMAP old and ChesMMAP new). This was done because the newer gear has higher selectivity of smaller crabs. This allowed us to estimate different selectivity curves for each period.

Survey selectivity functions differed across the surveys. Parameters were constant over months and sexes for ChesMMAP and the PEARL Pot Survey. Survey selectivity was modeled using an increasing logistic function with parameters that differed among surveys but were constant over months and sexes except for the MD trawl and the VIMS trawl surveys. Both of these surveys had somewhat different monthly length distributions in late spring-early summer (Maryland Trawl: May-July; VIMS Trawl: April-July), so we used B-splines with 4 knots to provide more flexibility. For the rest of the year for these two surveys, we fixed selectivity to be equal to 1 for all length bins. The basis matrix of the spline was generated using the "bs" function in the *splines* package (R Core Team 2025). A parameter was associated with each degree of freedom, but the first parameter was fixed to be zero so that selectivity and catchability would not be confounded. Selectivity was then calculated as the matrix product of the basis matrix and the parameters,

$$s_{v_{m,l}} = B\Theta_{m,v}/\max(B\Theta_{m,v}),$$

where $s_{v_{m,l}}$ was survey selectivity for a month and survey, *B* was the spline basis matrix, and $\Theta_{m,v}$ was the vector of spline parameters. The selectivity curve was scaled to its maximum so that it has a maximum of one. All survey selectivity parameters were estimated except those for the WDS and Maryland and VIMS trawl surveys after July. The increasing selectivity for the first length bin of the WDS was too steep to be stable when estimated in the model. Therefore, it was calculated using data from Ralph and Lipcius (2014) as described in Wilberg and Drzewicki (2026).

The total index value for a time step was the sum of the survey index over lengths and sexes,

$$I_{t,v} = \sum_x \sum_l i_{t,l,x,v}.$$

The index proportion by length and sex ($P_{I_{t,l,x,v}}$) were calculated as the survey index for a length and sex divided by the total index,

$$P_{I_{t,l,x,v}} = \frac{i_{t,l,x,v}}{I_{t,v}}.$$

4.1.7. Objective function

Model parameters were estimated by minimizing the objective function ($\mathcal{L}$), which was the sum of the negative log likelihood components for each data source and penalties on deviations from median recruitment,

$$\mathcal{L} = \sum_{\varsigma} nll_{C,\varsigma} + \sum_{\varsigma} nll_{C,l,x,\varsigma} + \sum_{v} nll_{I,v} + \sum_{v} nll_{I,l,x,v} + nll_{\kappa_x} + pen_{R,y},$$

where $nll_{C,\varsigma}$ was the negative log likelihood for the catch, $nll_{C,l,x,\varsigma}$ was the negative log likelihood for the proportions at length in the catch, $nll_{I,v}$ was the negative log likelihood for the survey indices, $nll_{I,l,x,v}$ was the negative log likelihood for the proportions at length and sex in the surveys, $nll_{\kappa_x}$was the negative log likelihood for the recruitment sex ratio, and $pen_{R,y}$ was the penalty on recruitment deviations.

A lognormal negative log likelihood function was used for the observed catch, total indices, and recruitment sex ratio. It was implemented using the *dnorm* function in RTMB with observations and estimates on the $\log_e$ scale,

$$nll = \sum_t \left(0.5\log_e(2\pi\sigma_t^2) + \frac{(\log_e(obs_t) - \log_e(est_t))^2}{2\sigma_t^2}\right),$$

where obs_t was the observed value at time t, est_t was the estimated value at time t, and σ_t was the assumed log-scale standard deviation. Missing values were coded as "-99", and the negative log likelihood was only calculated for time steps with positive observed values.   The penalties for recruitment deviations also were modeled as normal on the $\log_e$ scale. The assessment model was able to estimate the sex ratio of recruits (κ_x), but it typically estimated values that were well outside the range of observations from the WDS. Therefore, we also fitted the model to data on the sex ratio of recruits from the WDS.

Log-scale SDs were assumed known for the catch, total indices, and recruitment sex ratio likelihood functions. For the catch, log-scale SDs were assumed to be 0.1 for all time steps, sexes, and fleets. This value was chosen to primarily represent uncertainty from dead discards and recreational catch. For the total indices, the SDs were the same over time but differed among surveys to represent their ability to track Chesapeake Bay-wide trends in abundance. We prioritized fitting the WDS because it has the largest amount of overlap with the blue crab population and was designed to monitor the whole blue crab population in Chesapeake Bay. Therefore, it was given the lowest standard deviation of 0.25; lower values were tried because the precision of the WDS index is < 0.1, but these models resulted in extremely large standardized residuals. All other surveys had standard deviations fixed at 0.4. The SD for the proportion of male recruits was year-specific (Figure 4.11).

The negative log likelihood for the length compositions was modeled using a multinomial distribution. The implementation of the multinomial negative log likelihood function used the multinomial function in RTMB with "observed" numbers at length and sex and estimated proportions at length (or proportions at length and sex),

$$nll = -\sum_t \left(log_e\left(\Gamma\left(\sum_i d_{t,i} + 1\right)\right) + \sum_i log_e\left(\Gamma\left(d_{t,i} + 1\right)\right) - \sum_i d_{t,i}\, log_e\left(\hat{p}_{t,i}\right)\right),$$

where Γ was the gamma function, d_i was the "observed" numbers-at-length or numbers-at-length and sex (i.e., observed sample proportions multiplied by the assumed effective sample sizes in Table 4.8), and $\hat{p}_{t,i}$ was the estimated proportions-at-length or proportions at length and sex, and *i* was either length bin within a sex or length bin across lengths and sexes. We tested models that used a robust multinomial likelihood function (Fournier et al. 1990), but it had a poor fit to the sex compositions of some surveys with low observed proportions.

Calculation of the negative log likelihood functions for the proportions at length and sex for the catch and the surveys used externally calculated values of the effective sample sizes to weight the observed data. Effective sample size describes how informative the length composition data would be if it came from a truly random sample. The length and sex compositions from the catch and the surveys do not come from a truly random sampling. It has been suggested that using the number of trips is a better way to inform effective sample size for composition likelihood weighting (Crone and Sampson 1998; Truesdell et al. 2017). We calculated the number of trips for each gear and timestep to estimate effective sample size for catch length distributions from the Maryland pot, Maryland trotline, PRFC, and peeler fleets (Table 4.8). We used the number of trips sampled by month from the Maryland Sentinel Fishery Monitoring Program for these fleets. For the Virginia pot fleet, we did not have information on trips, so instead we used the total number of crabs sampled divided by 50 in each timestep where data were available from the Virginia biosampling program. For the Virginia dredge fishery, the effective sample size was fixed at 15 for each timestep. We used similar methods to estimate effective sample sizes for the surveys. For the WDS, the largest of all surveys, effective sample size was fixed at 250. We chose to weight the WDS length- and sex-composition data highest because it has the highest sample size, largest spatial coverage, and likely tracks the true population abundance better than any other survey. For the remaining surveys, we calculated the effective sample size as the number of stations that observed blue crabs for each timestep multiplied by a weighting term of 0.25 (Table 4.8). The weighting term was chosen such that there were few length and sex composition standardized residuals > 10, and the model was able to track the WDS index.

4.2. Model selection process

Three main criteria we used for determining a base model included: 1) the final parameter estimates had a relatively small maximum gradient component (≤0.05), 2) the model had an invertible hessian and could produce standard errors of parameter estimates, and 3) the correlations among the parameter estimates were not too high, $|r| < 0.95$. The most important criterion for the final base model selection was to match the WDS index because it is a well-designed survey that should accurately track population abundance. Additionally, we also compared the values of the negative log likelihood for the WDS index and length- and sex-composition among models.

The criteria to determine a base model evolved throughout the model development process. Furthermore, extensive work was done to determine the proper weighting of datasets. Models were initially evaluated based on how well they fit both the MD and VIMS trawl length compositions because they contained the most information about growth among the data sets because they provide monthly length compositions during spring-fall. However, higher weighting of these surveys caused a worse fit to the WDS. It became a priority among the group to improve the fit to the WDS index, so we down-weighted the other survey data (and the sex- and length composition of the WDS) in relation to the winter dredge survey (higher survey CVs and lower effective sample sizes). Final values of effective sample size were iteratively determined, and the best model was able to match the winter dredge survey index as close as possible while also matching the remaining data sources relatively well.

Much of our model development focused on estimating temperature-dependent growth, which was ultimately unsuccessful. We began by modeling growth using a von Bertalanffy model with the *K* parameter as a function of cumulative growing degree days. However, this model tended to overestimate growth of small crabs and underestimate growth of large crabs. Therefore, we switched to a Gompertz growth model, which was better able to match the apparent size-dependent changes in the survey length compositions during the year. We attempted several types of temperature-dependent growth with Gompertz models including models with linear increasing b as a function of temperature and b as a normal (i.e., domed) function of temperature. We also attempted models with the distribution of the growth increment as normal or lognormal. Ultimately, we could not find a temperature-dependent growth function that matched the observed monthly changes in the length composition because temperature-dependent models consistently underestimated growth in the spring and overestimated growth in the summer and fall (see TORs 9 and 10). Because of this inability to fit the data, we chose to use monthly, temperature-independent *b* parameters for the Gompertz increment model that used a normal distribution for the growth increment. After including additional variance in the growth increment, we were able to track monthly changes in the survey length distributions reasonably well.

With our final growth model, we made a concerted effort to thoroughly explore the parameter space for the growth parameters to best match the monthly changes in the length compositions across surveys. The WDS, Maryland Trawl Survey and VIMS Trawl Survey consistently observed the widest size range of blue crabs, so we selected models based on how well they matched the sex- and length- compositions over time. Because our initial efforts to estimate the growth parameters within the model were unsuccessful, we extensively tested combinations of parameter values for the growth model (Tables 4.2 and 4.3). This included increasing and decreasing the parameters in small increments for different model runs. For the Gompterz $b_{m,x}$ parameters, values were iteratively determined based on patterns in the data.

We also conducted thorough testing of natural mortality and maturity parameters because they were unable to be estimated by the model. A range of values of M_{Scale} and M_{ref} were tested to decide on the final values that allowed the model to best match the data (Table 4.6). Our criterion for selecting the best parameter values was the overall negative log likelihood value of the model. The intercept, slope, and variability of growth associated with the maturation molt relationship for females were also tested (Table 4.4). We ran >100 versions of the model with slight modifications to all growth, natural mortality, and maturation parameters (Tables 4.2 and 4.3) to understand how each change affected model fit.

4.2.1. Jitter Analysis

To test model stability, we conducted jitter analyses. A jitter analysis runs replicates of the base model with starting parameters values that were drawn from a uniform distribution and could be up to 2.5% smaller or larger than original starting values. This was done to ensure that the model converged on the same objective function value and that a better solution (i.e., lower objective function value) was not found (Karp et al. 2022). Replicates that converge on different solutions indicate instability in model estimation. We ran jitter analyses for three versions of our base model that altered which surveys and survey months were included. A final base model was chosen based on model diagnostics and jitter performance results.

In preliminary jitter runs, we found that parameters associated with PEARL catchability and ChesMMAP selectivity were the most problematic to estimate and likely contributed to model instability that led to runs that converged on alternate solutions. Therefore, we tested three variations of the base model that removed the PEARL pot survey and included different combinations of months to find a model that produced more consistent convergence in the jitter analyses. The three base model variants that we looked at were referred to as: 1) Limited PEARL and limited ChesMMAP model, 2) No PEARL and full ChesMMAP model, and 3) No PEARL and limited ChesMMAP model. Models with limited ChesMMAP only included the months May, June, July, and September for that survey. Models with limited PEARL only included the months of June, July, August, and September for that survey. Models with no PEARL removed the PEARL Pot Survey from the data inputs and estimation. We considered three factors when choosing the final base run: 1) the base model should be able to match the data, 2) the jitter analyses should converge on the same solution >85% of the time with both 20 and 50 iterations, 3) the base model should include as much data as possible.

4.2.2 Simulation Self-Test

To verify functionality and model performance, we ran a simulation self-test. For each of the three base models, parameter estimates were used to simulate data sets. Each data set used the same values for abundance and fishing mortality rates but had different observation errors. Simulation runs were compared using relative error. 20 simulations were run, and the relative error for total abundance, fishing mortality, and recruitment were summed across sex. In general, the three base models appear to be stable, estimating abundance and fishing mortality as expected with relatively low bias. Median relative error (as a metric of bias) was very similar across the three base runs (Table 4.11). There were small amounts of bias across the three runs, where abundance and recruitment were slightly underestimated and fishing mortality was slightly overestimated. When relative error was assessed by sex (aggregated over base runs), mature females were the most biased. This bias exists because the original estimates used to simulate data sets had sex-specific residual patterns for catch, which were not present for the simulated data sets.

4.3. Results

4.3.1. Convergence

The base model had 2,639 estimated parameters. It appeared to converge on a unique solution with a maximum gradient component of 0.054 (associated with the logit of the proportion male for recruits), and all except one other parameter had first partial derivatives < 0.001. No parameters were estimated to be on their upper or lower bounds. The model was able to estimate the variance-covariance matrix by inverting the Hessian, and the maximum absolute value of correlations among parameters of 0.91 (spline parameters for Maryland Trawl Survey selectivity). Only 80 parameters had correlations with $|r| > 0.7$; fishing intensity and spline selectivity parameters were the only ones that exceed 0.7. Most model parameters estimates were reasonably precise with only 12 parameters having CVs > 0.3 (all survey selectivity parameters). The objective function and values of the individual likelihood components are listed in Table 4.10.

4.3.2. Model Fit

Fishery

For all fleets and sexes, the model fitted the observed catch well (Figures 4.12-4.23). The model was able to match seasonal patterns for all fleets and sexes. The pattern for most of the fleets was an increase in catch during the summer months followed by a decrease in the fall. In contrast, the Virginia dredge fishery was the only fishery that occurred in winter. For many of the fleet and sex categories, catch declined over time with the strongest declines in the Virginia dredge fishery, which was closed in 2008, and the peeler fishery. All fleets and sexes had lower landings in recent years compared to the beginning of the time series. Standardized residuals across all fleets were small (between -0.75 and 0.5; Figure 4.24 and Drzewicki and Wilberg 2026), but most fleets had the largest standardized residuals in the mid-1990s. The model tended to fit male catch better than that of females for all fleets except for the Virginia dredge fleet and the peeler fleet as indicated by lower negative log likelihood values (Table 4.10).

Residuals in the catch had very clear temporal or cyclical patterns that differed by fleet and sex (Figure 4.24; Drzewicki and Wilberg 2026). For most fleets, male and mature female residuals had opposing patterns. Males often had negative residuals (indicating overestimation) while mature females usually had positive residuals (indicating underestimation), on average. However, this opposing pattern was not as clear in the peeler fleet. Note that these residual patterns are an improvement over the previous assessment that had stronger patterns of consistent bias in fits to sex-specific catch data. We believe the main improvement that helped reduce the residual pattern is that

SLAM was better able to account for sex-specific differences in the amount of time before recruits entered the fishery, with females recruiting more quickly than males due to different minimum size regulations and growth patterns.

The fit to the sex- and length-compositions for the catch was more variable across fleets, sexes, and time (Figures 4.25-4.36). For all fleets except for the Virginia dredge fishery, the model fit the male length compositions better than the females. The size of standardized residuals for all fleets and sexes was usually less than 10; note that these are Pearson residuals as the way the model handled missing data precluded calculating one-step-ahead residuals. Only immature females in the peeler fleet and males in the Virginia dredge fleet had residuals as large as 10-15. Both sexes in both Maryland fleets had standardized residuals that were 6-7.5 at their largest. Both sexes from the Virginia pot and PRFC fleets had the smallest standardized residuals. Many of the fleets had residual patterns that switched from over to underestimating mature females and switched from under to overestimating males around the length bin of the minimum size, for a given fleet. These patterns were especially apparent in the Maryland fleets. For many of the fleets, catches of the largest males were somewhat overestimated.

Surveys

For most surveys and months, the model was able to fit the indices relatively well with model estimates usually within the 95% confidence intervals of the data (Figures 4.37-4.42; Drzewicki and Wilberg 2026). We selected the log-scale SDs of the surveys to prioritize fitting to the Winter Dredge Survey because it is the survey that should most closely tracked Chesapeake Bay-wide abundance given its design. The WDS had high abundance in the early 1990s that decreased through the early 2000s. It increased again after fishery reductions and reached a high in 2010, but it has trended downwards since then. The model was able to track much of the trend of the WDS, but it estimated higher abundance than was observed during the early 2000s. Similarly, 2012 was an abnormally high recruitment year that no models we tried were able to match, but the model was able to track the WDS index relatively well after 2012. The VIMS Trawl Survey had many of the largest standardized residuals, but it also had the most observations (Figure 4.43). Standardized residuals did not have substantial patterns over time for the winter dredge survey, VIMS trawl survey, and the newer time series of ChesMMAP (2019-2023). The older time series of ChesMMAP (2002-2018), Maryland Trawl Survey, and PEARL Pot Survey had distinct cyclical residual patterns that were similar to the patterns observed in the residuals of the catch time series.

Standardized residuals for the fits to the sex- and length-composition were < 6 for most surveys and sexes (Figures 4.44-4.60), except for mature females in the older time series of ChesMMAP (2002-2018), males in MD trawl, males in VIMS trawl, immature females in VIMS trawl, males in PEARL pot, and mature females in the new time series of ChesMMAP (2019-2023). Mature females were usually the best fit sex category across all surveys. Across all surveys, effective sample sizes were highest in the late spring and summer months, so those months often had the best fits. Effective sample sizes were usually smaller in the fall months, so this was a common place for misfits to occur. We prioritized a model that had the best fit to the sex- and length-compositions of the winter dredge, MD trawl, and VIMS trawl surveys because they were the most informative surveys on growth patterns. The WDS had slight over estimation of mid-sized immature females and slight under estimation of larger immature females. Larger mature females were also somewhat underestimated by the WDS. The MD and VIMS trawl surveys were fitted well for all sexes and most years, except in the fall when sample sizes were smaller. Misfits in certain months highlighted some data conflicts between MD and VIMS trawl surveys. This model did a much better job of simultaneously matching the sex ratios of the catch and surveys than the 2011 assessment. However, data conflicts still remain between the catch and survey sex ratios given the other model constraints (e.g., mortality rate and growth assumptions).

The model tracked the proportions by sex in the WDS with slight underestimation of males and mature females and slight overestimation of immature females, on average (Figure 4.61). The estimated proportion male was on the low end of observations from the WDS (Figure 4.62).

4.3.3. Model estimates

Survey Selectivity and Catchability

Selectivity was estimated for all surveys except the WDS. The WDS was assumed to have a very steep increase in selectivity in the first length bin (Figure 4.63; Wilberg and Drzewicki 2026). The two sets of ChesMMAP indices and the PEARL Pot Survey had constant selectivity over months, whereas the Maryland Trawl Survey and VIMS Trawl Survey had selectivity patterns that differed among months (Figures 4.64-4.68). The older time series of ChesMMAP (2002-2018) had a steeper selectivity function than the newer time series because the newer survey catches more small crabs, which is why the survey time series was split. The Maryland and VIMS trawl surveys were estimated using splines which allowed for greater flexibility, however, some months had selectivity patterns with unique shapes. The differences in the length compositions of these two surveys may be due to different size distributions of recruits in winter in Maryland and Virginia, which appear to become well mixed by summer. For July-November, selectivity was assumed to be constant at 1 for the Maryland and VIMS Trawl surveys because the censoring of recruits from the data precluded estimation of the increasing limb and the size distributions in both surveys were quite similar.

Seasonal patterns were apparent when examining monthly catchability estimates (Figures 4.69-4.74). In many of the surveys, catchability for mature females followed a different pattern over the year than males and immature females, likely due to migration of mature females associated with maturation. Because the survey indices had different units, comparison of values across surveys is not informative.

Fishing Mortality

Fishing mortality rates that were aggregated over fleets and months differed by sex (Figure 4.75). Fishing mortality of males decreased in the 1990s but averaged about 1.4 yr^{-1} since 2004. Mature female fishing mortality showed a declining trend over time with values < 0.5 yr^{-1} since 2012. Fishing mortality rates for immature females also showed a declining trend over time since the early 2000s.

Monthly fishing mortality rates had clear seasonal patterns during a year with F peaking in the late summer-fall for most fleets (Drzewicki and Wilberg 2026). For all fleets except the Virginia dredge and peeler fleets, fishing mortality was lower for females than males. Fishing mortality rates for females usually had a declining trend over time, but it was relatively stable for males. Fishing mortality was 0 for the Virginia winter dredge fleet for both sexes after 2008 (except for a small study in 2013) due to the closure of this fishery.

Recruitment and Abundance

Estimated recruitment averaged approximately 1.5 billion blue crabs per year (Figure 4.76). Estimated recruitment was highest in 1996 and 2010. A period of low estimated recruitment occurred between 1998-2007, and estimated recruitment has declined since 2010 with the lowest level estimated in 2021.

Abundance of males and immature females showed wide swings each year associated with recruitment and high natural mortality rates on small crabs (Figures 4.77-4.78). Abundance of mature females was lower in the first half of the time series and increased after additional restrictions on fishing for females were implemented in 2008. Harvestable abundance was higher for mature females than males (harvestable size approximately ≥ 13cm). Estimated abundance of mature females fluctuated through the 1990s and remained low until the 2010s after which it increased to higher levels. After about 2017, estimated abundance has declined. Estimated abundance of harvestable-sized males declined since the late 1990s but has not shown a clear trend since about 2005. Both sexes showed seasonal fluctuations in harvestable abundance during the year.

TOR 5: Estimation of Uncertainty

5.1. Estimation of parameter uncertainty

We estimated the uncertainty of the parameters using the asymptotic standard errors from the estimated variance-covariance matrix. The uncertainty for quantities that were a function of derived parameters were calculated using the delta method (Kristensen 2025).

5.2. Sensitivity Analysis

We conducted sensitivity analyses to evaluate the effect of alternative assumptions on model estimates. We focused the sensitivity analyses on parameters that were fixed in the base model: growth parameters, maturation parameters, and natural mortality parameters. For each of the parameters tested, the value of the parameter was adjusted up and down for a different run. All other parameters were held constant at the levels of the base run. Additional sensitivity runs tested the inclusion of the fit to the recruitment sex ratio in the likelihood statement, a run that dropped all surveys except for the winter dredge survey, and two runs that either doubled the amount of recreational catch and dead discards or removed recreational catch while doubling the dead discards. In total, 18 runs (not including the recreational and dead discard runs) compared by their objective function values and the negative log likelihood components for the winter dredge survey (Table 5.1). Additionally, we compared the estimated abundance and fishing mortality rates to the base model.

Several model runs had one or more of the likelihood components that were lower than those from the base model run. For the growth parameters (L_{∞_x}, $b_{t,x}$, $\sigma_{b_{t,x}}$), the overall objective function was always larger. For runs where the likelihood components of the winter dredge survey index or length and sex composition were better, the results were not satisfactory because the fishing mortality rates increased to unrealistic levels. Some of the model runs with alternative maturity parameter values had lower likelihood components, but only one run had lower values for all three components (slightly increasing the CV for the growth increment associated with female maturity). Runs that increased the slope or decreased the intercept of the relationship between CW and growth increment associated with female maturation improved the objective function. All sensitivity runs with alternative natural mortality values had lower overall objective functions and sometimes the lower values for the component for the winter dredge survey index. The model run with the same natural mortality reference level (M_{ref}) and a decreased natural mortality scaling value (M_{Scale}) was preferred by all three likelihood components. The model with modified selectivity parameters for the winter dredge survey was also preferred by all three likelihood components. For all models where one or more of the likelihood components were lower, the results and diagnostic plots were largely unchanged. We did not change the base model from the original model agreed upon by the assessment group due to time constraints.

Comparisons of estimated abundance and fishing mortality rates indicated substantial sensitivity to the growth parameters (Figures 5.1-5.2), which was also observed during model development. Models with parameters that caused faster growth estimated lower abundance (runs 1 and 3) and models with parameters that indicated lower growth (runs 2 and 4) estimated higher abundance than the base model. Models 1 and 3 estimated extremely high fishing mortality rates in the first year as well such that they were not included in Figure 5.2. The other sensitivity runs had more modest effects on model estimates and were generally within about 10% of the base model, which indicates low sensitivity to the alternative values that were tested. The two runs that altered the amount of recreational catch and dead discards did not produce estimates of harvestable abundance or fishing mortality that differed substantially from the base model (Figures 5.3 and 5.4).

5.3 Retrospective Analysis

To determine whether retrospective patterns exist, three additional versions of the base model were run with different terminal years (2020, 2021, and 2022). We could not set the terminal year prior to 2020 because the older time series of the ChesMMAP would not have enough years for the model to be stable. Harvestable abundance and fishing mortality were used to compare the base model to the shorter runs. There was some bias evident in the retrospective analysis, with estimates of harvestable abundance underestimated for the shorter runs and estimates of fishing mortality overestimated in the shorter runs (Figures 5.5 And 5.6). To measure retrospective patterns, we calculated Mohns ρ (Hurtado-Ferro et al. 2015). This calculation quantifies the relative difference between an estimate from the reduced time series and the same estimate from the full time series. For harvestable abundance, Mohns ρ was -0.11 for females and -0.13 for males. For fishing mortality, Mohns ρ was 0.21 for males, 0.18 for immature females, and 0.15 for mature females.

TOR 6: Comparison with previous assessment model

We conducted a set of analyses that provide context for understanding the results of the new 2026 stock assessment for Chesapeake Bay blue crab. The full methods and results are provided in Miller et al. (2026). The comparisons conducted were.

1) Comparisons of the reported removals from the stock using assumptions and approaches that were adopted in the 2005 and 2011 assessments with those used in the current assessment. These analyses seek to understand possible impacts on our understanding of population trajectories of the changes in reporting.

2) Comparisons of relative abundances from fishery-independent surveys developed using the design-based approach that predominated in the 2005 and 2011 assessments with those developed using the model-based approaches adopted in this assessment. These analyses seek to understand possible impacts on our understanding of population trajectories of the changes in the analytical frameworks used to analyze surveys.

3) Continuity runs of the 2011 assessment model (Miller et al., 2011). These runs used existing approaches to analyzing removals and fishery-independent surveys to provide managers with an updated understanding of stock status relative to the current reference points. We present results for models from three frames: the original assessment, the 1968-2023 period, and a shortened 1994-2023 period that matches that used in the current assessment. As a result of some numerical instabilities in the application of the existing 2011 SSCMSA model to data for the period 1994-2023, we present model results for the 2011 SSCMSA model developed in both ADMB and in STAN.

4) Comparison of estimates from STAN models for the period 1994-2023 that used the prior approaches to fishery-dependent and fishery-independent data with parallel

models that use modified versions of the fishery-dependent and fishery-independent data developed for this assessment.

6.1. Patterns of removals

Each of the three different assessments have considered fishery-dependent removals from the population. However, each assessment has considered different periods of landings and different methods for calculating removals.

The 2005 assessment considered landings for 1929 – 2003 but only used data for 1968-2003 in the CMSA (Miller et al. 2005). Landings were assumed to be a census, and there was no attempt to account for dead discards or discard mortality. Catch is typically reported in bushels and was converted to pounds and then numbers (for the 2005 and 2011 assessments) based on data from fishery-independent surveys. The recreational harvest was assumed to be a constant 8% of the commercial harvest, and thus the commercial harvest data in each year was expanded by a factor of 1.08. To account for changes in reporting practices, intervention analysis was used to adjust reported commercial harvests in Virginia and in Maryland prior to their use in the CMSA. In particular, these analyses focused on reporting changes in 1992-1994 in Virginia when mandatory reporting was adopted. In Maryland, the intervention analysis focused on 1981 when a statistical survey of catch was implemented and in 1994 when mandatory reported was instituted.

The 2011 assessment considered landings for 1950 – 2009 but only used data for 1968 – 2009 in the SSMCA. Landings were again assumed to be a census, and there was no attempt to account for discard mortality. The recreational catch was assumed to be 8% of the commercial catch. An intervention analysis was used to adjust reported commercial harvests in both states prior to their use in the SSCMSA to account for reporting changes documented above.

The current assessment uses data for 1994 – 2023, a period in which reporting has been mandatory and consistently implemented. Dead discards were included in the estimated removals based on observations of dead crabs in the Maryland Cooperative Fishery Program data. Dead discards were assumed to be 13.1% of the commercial landings for the winter dredge fishery in Virginia, which was still in operation during the 1994-2008 period. Studies on recreational harvest were reviewed and resulted in sex-specific recreational harvest as a fraction of commercial harvest that differed by year and jurisdiction (Ashford and Jones, 2001, 2002; Ashford et al. 2009; Semmler et al. 2021). The current assessment also modified the approach for calculating sex-specific harvest in years where it was not fully report compared to the 2011 assessment.

We compared reported removals from the Chesapeake Bay blue crab population for the period of overlap between the 2005, the 2011, and the current assessment. The commercial data in the 2005 assessment were not sex-specific. Accordingly, in making these comparisons, we assumed the sex ratio in the aggregate state specific catch data was 50:50 for the estimates from the 2005 assessment. There are only minor changes in the reported removals in the different assessments (Figure 6.1). The consistency of reporting methods since 1994 removed the need for any adjustments for reporting changes, and only relatively minor adjustments removals resulting from the addition of dead discards and recreational harvest have been made.

The removals data for the different assessments were strongly correlated, with the distribution close to the 1;1 line (Figure 6.1). The analyses presented here do not provide strong evidence to expect differences in pattern among the three different assessments based on the removals data used in each of the assessments.

6.2. Fishery-independent survey CPUE data

Both the 2005 and the 2011 assessments as well as the current assessment make use of three long standing surveys: the WDS (1990-2023), the VIMS Trawl Survey (1968 – 2023) and the Maryland Trawl Survey (1977-2023). However, the three assessments have adopted significantly different approaches to the analyses of these surveys and accordingly, to the use of data from these surveys in the assessment models.

Both the 2005 and 2011 assessments adopted a design-based approach to analyzing data from the three surveys, particularly for the WDS. Model-based analyses of the winter dredge survey were presented in 2005 assessment (Miller et al. 2005), but the results of these analyses were not used in the CMSA. The extensive, annual experiments to measure catchability in the dredge survey meant that the assessment team and others felt that the WDS gave highly reliable estimates of abundance, based on the number of stations sampled and the relative consistency of the design. Ultimately, the index of recruited abundance from the WDS was assumed to represent absolute abundance in both the 2005 and 2011 assessments (i.e., the catchability of the survey in the assessment model, q, = 1). This assumption was criticized by the reviewers of the 2011 assessment in their report. Other concerns emerged over the 30-year history of the WDS that led the current assessment team to re-evaluate the role of the WDS. For example, based on the annual experiments, estimated catchabilities increased over time – likely not because catchabilities were increasing, but more because vessel captains became better at undertaking the catchability experiments. This led researchers to explore alternative designs for the catchability experiments (Wilberg et al. 2013). Ultimately, this body of evidence led to a decision to explore model-based approaches to developing survey indices in the current assessment.

Approaches to analyzing the three principal surveys differed. The WDS and VIMS trawl surveys were analyzed with spatio-temporal models (Thorson and Barnett 2017). The Maryland summer trawl survey was analyzed using gamlss modeling. These analyses yielded monthly indices of abundance. To compare the current model-based estimates and the traditional design-based estimates, we developed composite indices from the month-specific ones presented in TOR 2.

1) WDS survey. The VAST model produced an index of abundance for February, the mid-point of the WDS. Data were available for 1994-2023. We standardized this

composite index by dividing by the area of the VAST model domain, 9,167 km2, to standardize the index to crabs/m^2.

2) VIMS trawl survey. Monthly outputs from VAST were provided for pre-recruit sized crabs (≤ 6 cm) as well as fully recruited male and female crabs. The 2011 assessment developed indices based on the average relative abundance in the VIMS trawl for April – June for three western shore tributaries. Accordingly, we developed a new composite index that was the average of the VAST indices for April -June. These composite indices related to the entire model domain, so indices were divided by the area of the VAST model domain, 2990 km^2, to standardize the index to crabs/m^2.

3) The MD summer trawl survey has undergone changes in design. Before 2004, the regions that were sampled varied over time with the survey generally adding more sampling locations. The survey only became consistent after 2004, and thus gamlss-standardized indices are only available for 2004-2023. The composite index for pre-recruits was defined as gamlss index for October. In contrast the composite index for fully-recruited male and female crabs was defined as the average May – July index.

We compared patterns in fishery-independent survey indices used in earlier assessments with those used in the current assessment to assess patterns that may lead to possible differences in results among the assessments. Indices were not consistent between the current assessment and the 2005 assessment.

Figure 6.2 presents the relationships between the survey data used in the 2011 assessment and that used in the current assessment. For all three survey pairs, but particularly of the VIMS trawl survey and the WDS, there are strong correlations between the survey CPUE estimates for the two different time periods. The weaker fits for the MD summer trawl are likely related to the shorter available time series (2004 – 2023) leading to an even more reduced overlap between MD summer trawl survey data from the 2011 assessment with the current assessment (6 years– 2004-2009). In general, the strong linear relationships between the two datasets suggest that differences in fishery-independent indices should not have a large effect on possible differences in model outputs.

6.3. Continuity model runs

1) SSCMSA 1968 – 2023

The SSCMSA has been consistently updated by state biologists and academic researchers since it was accepted as the best scientific information available for management in 2011. The model continues to fit the time series about as well as it did in the 2011 assessment.

2) STAN 1968-2023 using 2011 assessment style indices

Efforts to fit the ADMB version of the model to the shorter time series, 1994 – 2023, that is being used in the current assessment revealed some numerical stability issues in the ADMB implementation. Accordingly, we developed a parallel modeling environment in STAN. We compared the ratio of parameter values from STAN to ADMB. If the two models produced identical estimates, this ratio would be 1. Because of differences in scale, we found it more convenient to report the comparison as the log(STAN:ADMB) ratio (Figure 6.3). Figure 6.3 shows that STAN produced parameter values slightly less than those produced by ADMB for catchability coefficients (qs), as well as for the stock and recruitment parameters.

The STAN model results in population trajectories that were broadly similar in pattern and scale to those developed in ADMB. The abundance of pre-recruit stages estimated in STAN closely resembled those estimated in ADMB (Figure 6.4). There was also a high concordance in population trajectories for fully-recruited female and male crabs (Figure 6.5), as well as for the exploitation rates.

3) STAN 1994-2023 using 2026 assessment style indices

In this version of the model, we used the fishery-dependent and fishery-independent data developed for this current assessment in place of the traditional design-based approach. Fishery independent data were rescaled to have the same mean for the two different approaches to account for differences in units among the surveys.

There were similar patterns in the log ratio of STAN:ADMB estimates that were evident in the previous model. Estimates of pre-recruit abundance from the STAN and the ADMB implementation of SSCMSA did exhibit some differences. Similarly, estimates of fully-recruited female and male abundances also differed between the STAN and ADMB model implementations. This was particularly the case for fully-recruited male abundance. However, these differences were not substantial and were consistent differences in scale and pattern between the two models. Finally, there were also differences in estimated exploitation rates for fully-recruited female and male crabs. These differences were more substantial than for the abundance estimates, but they did not suggest a fundamentally different understanding of the stock history.

4) Comparison between the updated 2011 base model and SLAM

The new model estimates abundance about twice as high as the old model (Figure 6.6). This difference is most likely caused by different assumptions about the size distribution of recruits, selectivity of the WDS, and length-specific natural mortality. The new model assumes that the WDS only observes a relatively small fraction of the age-0 blue crabs in winter (<10%), whereas the 2011 model estimated that the WDS abundance estimates represent about 60% of the age-0 blue crabs in winter.

TOR 7: Estimate Reference Points

The previous Chesapeake Bay blue crab stock assessment (Miller et al. 2011) estimated maximum sustainable yield-based reference points for females using a sex-specific version of a Ricker stock-recruitment model. The parameters of the stock-recruitment relationship were estimated in the assessment model, but subsequent evaluations and simulation studies have suggested substantial difficulty in estimating these parameters and the potential for bias.

Spawning potential ratio (SPR) reference points are widely used to manage fish stocks around the world (Gabriel et al. 1989; Clark 1991). SPR estimates the fraction of lifetime reproduction that should be realized when a stock experiences fishing mortality. The model typically estimates the spawning stock biomass (SSB) per recruit (SSB/R) that would result when a stock is fished, and this value is compared to the SSB/R that is estimated to occur when there is no fishing. However, despite the availability of a method called length-based SPR (a data-poor assessment approach that uses an age-based model and assumptions about mean length-at-age and variability in length-at-age), SPR models have not generally been developed for length-based models with subannual time steps.

The management agencies responsible for managing blue crabs in the Chesapeake Bay have requested an evaluation of recruitment reference points to potentially provide additional information for management. Recruitment reference points are not a common feature of most fishery management systems, but recruitment is often considered either explicitly through forecasts or implicitly when making management decisions. Recruitment reference points have the potential to allow proactive management during times when recruitment is lower than expected because there is some lead time between when recruitment is observed in the Chesapeake Bay Blue Crab Winter Dredge Survey (WDS) and the time when those recruits would begin to enter the hardshell fisheries (autumn of that year).

This section describes an approach to estimate sex-specific SPR reference points for the Chesapeake Bay blue crab stock. The objectives are to 1) describe an approach for estimation of sex-specific SPR abundance and fishing mortality rate reference points, 2) apply the approaches given the stock assessment model estimates, and 3) develop and apply an approach for estimating recruitment reference points.

Methods

SPR approach

We developed separate SPR models for male and female blue crabs based on the population dynamics equations of the length- and sex-based stock assessment model (SLAM). The SPR reference points are calculated separately for males and females. We used 40% SPR to calculate the threshold reference points based on the goal of having reference points that are robust to potential climate effects on population dynamics (Shertzer et al. 2024). Additional factors that led to the choice of 40% included the recent decline in recruitment without an identified cause (see TOR 9) and recent collapses of other crab stocks due to environmental changes (Szuwalski et al. 2023). The target fishing mortality rate reference points were calculated as 0.75 of $F_{40\%}$ and the target abundance reference points were calculated as the equilibrium abundance that resulted from median recruitment fished at the target fishing mortality rate (Restrepo et al. 1998).

Recruitment occurs in February as is assumed in SLAM and recruits have CWs that follow a lognormal distribution. After recruitment, abundance-at-length changes each month based on overwinter mortality, natural mortality, fishing mortality, and growth. Overwinter mortality is included using the mean CW- and sex-based survival rates during 1994-2023 (Figure 7.1). The SPR models are implemented differently for males and females because growth ceases with maturation for females and fishing mortality for females is a function of CW and maturity.

The vector of abundance-at-length in the first month ($\boldsymbol{N_1}$) of a cohort is the product of recruitment (R), proportion of recruits that are sex *x* (φ_x), and the vector of proportions-at-length for recruits ($\boldsymbol{\omega}$),

Eq. 7.1 $$\boldsymbol{N_1} = R\varphi_x\boldsymbol{\omega},$$

The model for abundance calculates the abundance at each age as the matrix product of growth and the element-wise product of abundance at the previous age, survival from overwinter mortality, and survival from total instantaneous mortality,

Eq. 7.2 $$\boldsymbol{N_{t+1}} = \boldsymbol{G_t}(\boldsymbol{N_t}[1-\boldsymbol{O}]e^{-\boldsymbol{Z}_t}),$$

where $\boldsymbol{G_t}$ was the growth matrix (dimensions for the month associated with age t, $\boldsymbol{N_t}$ was the vector of abundance in each length bin, $\boldsymbol{O}$ was the vector of proportions that die due to overwinter mortality for each length bin (which was the mean over 1994-2023), and $\boldsymbol{Z_t}$ was the vector of total instantaneous mortality rate for the each length bin. The model includes a specification for the maximum age, which is assumed to be 96 months. The total instantaneous mortality rate was the sum of the vector of length-based natural mortality ($\boldsymbol{M}$) and fishing mortality ($\boldsymbol{F_t}$) rates,

Eq. 7.3 $$\boldsymbol{Z_t} = \boldsymbol{M} + \boldsymbol{F_t}.$$

Because SLAM has six fleets that differ in the fishing mortality rates among months and years, characterizing fishing mortality for an SPR model is somewhat complicated. The annual length-based patterns of fishing mortality rates in each month are calculated by using a separable process in which the fishing mortality rate is the product of an overall fishing mortality rate scalar ($\tilde{F}$) and the fishing mortality rate for each length bin and month relative to that scalar during a year ($r_{t,l}$),

Eq. 7.4 $$F_{t,l} = \tilde{F}r_{t,l}.$$

In this formulation, the $\tilde{F}$ represents the maximum fishing mortality rate experienced on a single length bin during a month within a year. Relative fishing mortality ($r_{t,l}$) is calculated for each year as the vector of length-specific fishing mortality rates for each month and fleet within a year, summed over fleets and divided by the maximum value,

$$r_{t,l} = \frac{\sum_f F_{t,l,f}}{\max\left(\sum_f F_{t,l,f}\right)},$$

where $\max$ is the maximum function taken over months and length bins.

After calculation of the equilibrium abundance, lifetime equilibrium SSB can be calculated as the product of abundance-at-length ($N_{t,l}$), weight-at-length (w_l), maturity-at-length (m_l; Figure 7.2), and proportion mating within a month (p_t) summed over months and length bins,

Eq. 7.5 $$SSB = \sum_t \sum_l N_{t,l} w_l m_l p_t.$$

The proportion mating within a month was assumed to be two for April-November and zero for other months for males. This assumes that each male is able to mate twice per month on average during April-November. The above equations are used to calculate the fishing mortality rate ($F_{X\%}$) that is expected to achieve a specific fraction (X%) of lifetime equilibrium reproductive potential. First, abundance and SSB are calculated assuming no fishing mortality (i.e., $\tilde{F}$=0). Next, a numerical search is conducted over values of $\tilde{F}$ to find the value that achieves the prespecified X% of unfished SSB.

The goal of the abundance reference point is to compare the model estimated abundance at a fixed point in time to the reference point. For the abundance reference point, the calculations for abundance in Eq. 7.2 are conducted assuming $\tilde{F} = F_{X\%}$. The abundance reference point ($N_{X\%}$) is then calculated as the sum of abundance in all ages that corresponds to the month for which we want to compare abundance to the reference point when $\tilde{F} = F_{X\%}$,

Eq. 7.6 $$N_{X\%} = \sum_{t=February} \sum_l N_{t,l}.$$

For example, the abundance reference point is calculated for the month of February, which involves summing abundance for the 2nd, 14th, 26th, and so on, monthly time steps. For males, the abundance reference point includes all ages including recruits and immature individuals.

A similar approach is used for females, but the abundance and SSB equations are modified to account for the effect of maturation on growth. For immature females (*x*=2), the abundance-at-length calculations are the same as for males, but $\boldsymbol{G}_{t,x=2}$ also allows for maturation, which transitions females to the mature class (*x*=3),

Eq. 7.7 $$\boldsymbol{N}_{t+1,x=2} = \boldsymbol{G}_{t,x=2}\left(\boldsymbol{N}_{t,x=2}[1-\boldsymbol{O}_{x=2}]e^{-\boldsymbol{Z}_{t,x=2}}\right).$$

For mature females (x=3), the vector of abundance-at-length in the next time step ($\boldsymbol{N}_{t+1,x=3}$) is the sum of the mature females at length that survive from the previous time step and the immature females that survive and become mature females that time step,

Eq. 7.8
$$\boldsymbol{N}_{\boldsymbol{t+1},\boldsymbol{x=3}} = \boldsymbol{N}_{\boldsymbol{t},\boldsymbol{x=3}}[1-\boldsymbol{O}_{\boldsymbol{x=3}}]e^{-\boldsymbol{Z}_{\boldsymbol{t},\boldsymbol{x=3}}} + \boldsymbol{G}_{\boldsymbol{t},\boldsymbol{x=3}}\left(\boldsymbol{N}_{\boldsymbol{t},\boldsymbol{x=2}}[1-\boldsymbol{O}_{\boldsymbol{x=2}}]e^{-\boldsymbol{Z}_{\boldsymbol{t},\boldsymbol{x=2}}}\right).$$

The separable function for fishing mortality is also slightly modified to allow for two maturity classes of females that differ in their fishing mortality rates,

Eq. 7.9
$$F_{t,l,x} = \tilde{F} r_{t,l,x}.$$

Here, $\tilde{F}$ is the maximum fishing mortality rate for a length bin and month within a year across mature and immature females.

Egg production is used for the spawning potential calculations for females, where egg production is the product of abundance of mature females at length, batch fecundity given their length (g_l), and probability of spawning within a month summed over ages and length bins,

Eq. 7.10
$$SSB = \sum_t \sum_l N_{t,l,x=3} g_l p_{t,x=3}.$$

We used the relationship of batch fecundity and carapace width of blue crabs from Schneider et al. (2024a; Figure 7.3) except that we assumed females 5 cm CW and smaller could not reproduce. The probability of spawning within a month was calculated as the proportion of mature females with eggs in a given month using data from the Maryland Trawl Survey, ChesMMAP, and VIMS Trawl Survey. Similar to males, $F_{X\%}$ and $N_{X\%}$ were calculated, but $N_{X\%}$ only for females only includes mature females (Figure 7.4).

Recruitment

The goal for the recruitment reference point was to provide a level of recruitment that indicates impairment. We chose an empirical reference point as the 25th percentile of estimated recruitment. The working group noted that individual years of low recruitment were less concerning than multiple sequential years of low recruitment. Therefore, the value of recruitment that is compared to the reference point is the three-year running average of recruitment.

TOR 8: Estimate Stock Status

The achieved $\tilde{F}s$ and the estimated target and threshold fishing mortality rate reference points varied over time with different patterns for males and females (Figure 8.1). The upper threshold $F_{40\%}$ reference points averaged 0.54 mo^{-1} for males and 0.21 mo^{-1} for females, and the targets were 0.41 mo^{-1} for males and 0.16 mo^{-1} for females. The reference points for males are likely higher than those for females because males have minimum size limits that are larger than the CW at 50% maturation. Estimated $\tilde{F}s$ were usually less than the threshold except for 1994, 1996, 2010, and 2011 for males and 1994 for females (Figure 8.2). $\tilde{F}s$ relative to $F_{40\%}$ decreased over time for males and females, with females having a more consistent decline. In the most recent year, fishing mortality rates were well below the threshold or target fishing mortality rate reference points for males and females.

The $N_{40\%}$ reference points averaged 862 million for males and 128 million for mature females (Figure 8.3). The abundance reference points fluctuated somewhat over time, but less than the fishing mortality rate reference points. Estimated abundance was usually higher than the $N_{40\%}$ lower threshold reference point for females, but it was usually lower than the $N_{40\%}$ reference point for males (Figure 8.4). The status of males relative to $N_{40\%}$ appeared to decline over time and was lowest in 2021. The lowest values for females were in 2005 and 2008. In the most recent year, abundance was below $N_{40\%}$ for males but was slightly above $N_{40\%}$ for females. The Kobe plots show substantial change in the status of the population over time, which differed between males and females (Figure 8.5).

Estimated recruitment varied substantially over time with a median of 1.49 billion blue crabs (Figure 8.6). The lower threshold recruitment reference point was estimated to be 1.19 billion blue crabs. Although the three-year average recruitment was above the lower threshold reference point for most of the time series, it dipped below it in the two most recent years, 2022 and 2023.

TOR 9: Ecosystem effects on blue crabs

We evaluated several hypotheses related to ecosystem effects on blue crabs as part of this stock assessment. Our principal lines of inquiry were related to blue catfish effects on blue crab recruitment, characterizing temperature and salinity conditions spatially for Chesapeake Bay, estimating overwinter mortality and effects of winter severity, effect of temperature on blue crab growth, and effects of hypoxia on blue crab abundance.

9.1. Effects of blue catfish

Invasive blue catfish (*Ictalurus furcatus*) are found in every major tributary in the Chesapeake Bay and are thought to contribute to the declines of native species. The contribution of blue catfish predation to the decline of the Chesapeake Bay blue crab population is unknown. Our goal was to estimate the effect of blue catfish on blue crabs in Chesapeake Bay. The specific objectives were to 1) estimate the relationship between blue catfish and blue crab catch per unit effort (CPUE) in four Chesapeake Bay tributaries, 2) estimate potential future effects of blue catfish on blue crabs should they become abundant throughout the oligo- and mesohaline regions of the Chesapeake Bay, and 3) estimate the expected abundance of juvenile blue crabs that would have been present in the Chesapeake Bay in the absence of blue catfish during 1995-2023. The details of the analyses are provided in Sholes et al. (2026).

9.1.1. Methods

The effects of blue catfish on blue crab were estimated using generalized additive models (GAMs) of tow-specific blue crab CPUE as a function of blue catfish regional relative abundance. The estimated relationship between blue crab CPUE and blue catfish relative abundance was then used to estimate the potential future effects of blue catfish on blue crabs in the Chesapeake Bay and to estimate the level of blue crab abundance in the absence of blue catfish. We estimated blue catfish relative abundance to more accurately represent the number of blue catfish in each tributary. The analyses for Objectives 2 and 3 used estimated blue crab abundance from the WDS, which we adjusted using the estimated relationship between blue crabs and blue catfish from Objective 1.

9.1.2. Results and Discussion

Estimated blue catfish relative abundance increased over time in each of the tributaries (Figure 9.1). Blue catfish relative abundance first increased in the Rappahannock and James rivers in the late 1990s. Blue catfish relative abundance growth occurred later in the York River around the early-to-mid 2000s. The Rappahannock River generally had the highest blue catfish relative abundance, and the Patuxent River had the lowest. All tributaries reached their highest relative abundance at the end of the time series (2023). The highest estimated relative abundance in the Patuxent River was 2,121.5 blue catfish/km^2 in October 2023. The highest estimated relative abundance in the York and James rivers was in November 2023 and the Rappahannock River in October 2023 was an order of magnitude higher at 12,964.7, 25,581.2, 46,165.2 blue catfish/km^2, respectively.

Blue crab CPUE had a negative, almost linear relationship with blue catfish relative abundance (Figure 9.2). Blue crab CPUE was estimated to decrease by about 90.4% on average for an increase of 40,000 blue catfish/km^2.

The five-year average blue catfish relative abundance in the Rappahannock and James rivers during 2019-2023 was 18,340 blue catfish/km^2, which was used to represent “high” blue catfish abundance. The predicted blue crab CPUE when blue catfish relative abundance was high was 39% (8,980 blue crab/km^2) of the observed blue crab CPUE in the absence of blue catfish. Adjusting the WDS abundance estimate of juvenile blue crabs in low salinity waters by “high” Blue Catfish abundance resulted in lower juvenile blue crab abundance, but the decrease varied over time. On average, juvenile blue crab abundance was expected to decrease 13.7% in any given year with the largest reduction of 42.2% occurring in 2012, and the smallest reduction of 2.0% occurring in 2001 (Figure 9.3). The amount of reduction directly reflected the proportion of juvenile blue crabs that were found in low salinity waters each year.

Blue catfish appeared to have a negative effect on juvenile blue crab abundance in the Chesapeake Bay that generally increased over time (Figure 9.4). After adjusting for a blue catfish effect in the low salinity portions of the James, York, Rappahannock, Potomac, and Patuxent rivers, juvenile blue crab abundance was estimated to be 2.8% higher, on average, in the absence of blue catfish. The largest difference between observed juvenile blue crab abundance and adjusted juvenile blue crab abundance if there had been no blue catfish present was 7.9% in 2023, and the smallest was 0.4% in 2015.

Our study provides the first estimates of the Chesapeake Bay-wide effect of blue catfish on blue crab abundance in low salinity waters (< 10 psu). We found a negative relationship between blue catfish and juvenile blue crab abundance across several Chesapeake Bay tributaries. The most likely mechanism for this negative relationship is that blue catfish are consuming juvenile blue crabs. Estimates of blue catfish consumption of blue crab in Chesapeake Bay vary and are hard to compare. Hilling et al. (2023) estimated that 400.7 metric tons of blue crab was consumed by blue catfish in the James River during 2015. To convert Hilling et al.'s (2023) consumption estimate to numbers, we calculated an average weight of consumed blue crabs using data on the length frequency of consumed blue crabs from Fabrizio et al. (2025) and CW-weight relationships (Liang et al. 2026a), which resulted in a mean weight of 0.032 kg/juvenile blue crab. Applying this conversion factor to the Hilling et al. (2023) consumption estimate resulted in approximately 13 million blue crabs consumed in 2015. These estimates are difficult to compare or validate because they represent consumption of blue crabs calculated for different portions of the James River, using different methods, and for different times.

Our approach did not estimate the number of crabs consumed, but we did estimate the number of juvenile blue crabs expected in the absence of blue catfish in the James River. Fabrizio et al. (2025) estimated that 564,365 blue crabs were consumed annually by blue catfish in the lower James River between 2018-2020. Our estimated number of missing blue crabs in the James River was about 1.6 million/yr during 2018-2020. However, this estimate assumes that the WDS has a catchability of one. If we adjust the consumption estimate for the catchability of the WDS in Virginia during 2018-2020 (approximately 0.15; Sharov et al. 2003), the estimated number of missing juvenile blue crabs increases an order of magnitude to about 10.7 million individuals/yr. It should be noted that the WDS catchability is representative of the whole population of blue crab and the catchability of juvenile blue crab is unknown. The study area in Fabrizio et al. (2025; 199.2 km^2) was smaller than ours and that from Hilling et al. (2023) was larger than ours. While this study, Hilling et al. (2023), and Fabrizio et al. (2025) estimate a large number of blue crabs consumed by blue catfish, it is difficult to directly compare our estimates of blue crabs removed with the past estimates due to differences in sampling area, time, and methods.

The effect of blue catfish on blue crabs in Chesapeake Bay has increased over time because of the increasing abundance of blue catfish (Fabrizio et al. 2025). We also estimated increasing blue catfish abundance and an increasing effect of blue catfish on juvenile blue crabs in Chesapeake Bay. For example, in 2023 we estimated that

Chesapeake Bay juvenile blue crab abundance would have been 7.8% higher in the absence of blue catfish. We expect the effect of blue catfish predation will continue to increase as blue catfish continue to increase in abundance across Chesapeake Bay (Nepal et al. 2019; Fabrizio et al. 2025).

If blue catfish become as abundant in all low salinity (<10 psu) regions of the Chesapeake Bay as they are in the low salinity portions of the James and Rappahannock rivers, juvenile blue crab abundance may decline substantially from recent levels. This decline would likely vary over time depending upon the proportion of juvenile blue crabs in low salinity habitats. In our results, the maximum decrease in Chesapeake Bay-wide juvenile blue crab abundance was 42% in 2012, and the average was 13.7%. The portion of the Bay characterized by salinity <10 changes each year, and habitat use by blue crabs changes each year such that the fraction of juvenile blue crab in low salinity (<10 psu) changes each year.

9.2. Development of Daily Temperature Time Series for the Bay, a 4D Interpolation Approach

Environmental parameters such as temperature and salinity were routinely collected during the fishery-independent surveys included in this stock assessment. These monitoring efforts have yielded a big collection of data and insight into the habitat conditions for blue crabs in the Bay. But this information is underutilized in documenting the fine-scale variability of the tidal water of the Chesapeake Bay, partly due to the challenges of integrating monitoring data collected at different frequencies and locations. The long-term, fixed-station seasonal monitoring conducted by the Chesapeake Bay Program provides a spatially balanced representation of the Bay and estuary. These monitoring data can be used to synthesize the environmental data collected during the blue crab surveys. In order to understand the variability of temperature and the changing environmental suitability of the blue crab population, we developed a spatiotemporal synthesis of the survey environmental samples with data from the long-term fixed survey. We presented a 4-Dimensional interpolation approach to predict temperature at a daily frequency and fine spatial resolution over Chesapeake Bay. Predictive performance was evaluated to be between 1 and 2 degrees Celsius using a validation approach. The resulting data could provide insights into the environmental variability of the blue crab population, such as the changes in population growth and recruitment. Details are provided in Liang et al. (2026c).

9.2.1. Material and Methods

The long-term Chesapeake Bay monitoring program is a comprehensive water quality and habitat monitoring program. The program collects data at 133 stations in the Bay; bimonthly in warmer months (May through September) and monthly throughout the year, with vertical profiles collected at 1-meter resolution. The program has assessed water quality since 1984 by measuring nutrients and habitat conditions such as temperature, salinity, dissolved oxygen, and water clarity (Figure 9.5).

The surveys record water temperature, with coverages varying across surveys and years (Figure 9.5). For the Winter Dredge Survey, environmental samples were collected via a cable, with varying lengths depending on the state. The cable length is 50 feet in the Maryland portion. Thus, the temperature reading was assumed to be the bottom reading for the shallow portion of the Bay (<20 meters), and otherwise at mid-depth until the length of the cable (~ 50 feet). The Virginia portion of the survey used a 100-feet cable, but a 50 feet threshold was still applied, assuming the water column is mixed during winter. For the Maryland Trawl Survey, temperature and salinity readings in the trawl survey are taken at the end of the tow. Typically, they were taken a few feet beneath the surface. For the VIMS Trawl Survey, both surface and bottom readings were taken. Bottom reading was assumed to be taken at the recorded total depth. For the ChesMMAP surveys, samples were taken at the bottom, and the recorded depth and temperature were used. For the SERC Trawl survey, the bottom temperature was recorded. For the MD seine survey and VIMS Seine surveys, surface temperature was recorded. No environmental samples were available from the PEARL Pot Survey.

We developed an interpolator over depth, space, and time to aggregate the temperature samples into a Chesapeake Bay-wide growing degree day metric. First, for each cruise and sampling station, water temperature was vertically interpolated among the observed profiles. Only vertical locations within 2 meters of an observed sample were interpolated. Extrapolation was limited using the estimated bottom depth at each station, which was the maximum of the observed depth. Next, the vertically interpolated profiles were discretized into half-meter water layers, and for each layer, the time series at a station were temporally filled-in to the daily resolution using linear interpolation. Extrapolation was limited to within 15 days of the observed samples. Lastly, within each day and depth layer, an inverse distance weighting spatial interpolation was conducted to expand the samples to the entire study region. The spatial interpolation scheme was based on the Bay program three-dimensional interpolator (Bahner 2006).

The skills of the interpolation method were evaluated by de novo prediction at the fishery independent survey locations using the spatially balanced long-term fixed fortnightly monitoring data. The neighbor search algorithm was applied to identify the nearest neighboring long-term monitoring data for each crab survey water quality sample. Neighbor search was limited to 25 kilometers in space and 2 meters in depth. The averages of the nearest neighbors were used to predict the observed water temperature at the crab locations. Up to eight neighbors were retained in the search, and when fewer than three neighbors were found, interpolation was not conducted.

The Chesapeake Bay Program's interpolator team uses a voxel scheme to describe the spatial extent of the segment. Each voxel is defined by a pixel of varying size (from 5 meters to 1,000 meters) and 1-meter vertical depth. The Bay is represented by 238,669 voxels for 77 management segments. The 4-D interpolator method was applied to all available water temperature samples (including the crab survey samples and the long-term fixed station monitoring) to estimate the daily temperature at each voxel. The proportion of the daily volumes in the Bay with at least three neighbors was computed for the Bay. Volume-weighted average temperature was computed for the entire bay for each day between 1990 and 2024. Averaging was also conducted for sub-areas of the bay representing the shallow water, the open water, the deep water, and the deep channel habitats of the Bay (U.S. EPA 2003).

9.2.2. Results and Discussion

The measured and interpolated water temperatures were compared to evaluate the skills of the interpolation method. Limited spatiotemporal variability exists within the chosen 4D neighborhood (Figure 9.6). The spatially balanced design of the long-term fixed stations monitoring provides a good framework to represent the Chesapeake Bay-wide temperature dynamics.

The spatiotemporal variability of the survey coverage affected the 4D interpolation algorithm (averages) to predict water temperature (Figure 9.7). For most of the Bay, the interpolated water temperature was within 1.5 degrees Celsius of the observed temperature in terms of root mean squared error (RMSE). The interpolation performance was consistent spatially across the salinity regimes and survey implementations. Occasionally, the RMSE can be as large as 3 degrees Celsius in a sparsely sampled region.

Habitat-specific temperature anomalies from the seasonal averages of the shallow habitat were computed for each habitat type of the Bay (shallow, open water, deep water, and deep channel). A positive trend was observed in water temperature for each habitat of the Bay (Figure 9.8). The bay habitat-specific temperature contrast (from the shallow water) showed no trend, and some evidence of a thermocline in the deep water and deep channel habitats during the warmer months (Figure 9.9).

9.3. Overwinter mortality

Natural mortality is a key parameter of population dynamics and stock assessment models. Data on observed dead individuals can be used to estimate time-varying natural mortality rates (Doering et al. 2021). In particular, overwinter mortality (OWM) has been observed to vary over time, associated with winter severity (Rome et al. 2005). The WDS collected mortality status on blue crabs. These data have been used to infer the natural mortality of blue crabs due to the harsh winter conditions, i.e., OWM (Rome et al. 2005). Estimates of OWM in the Chesapeake Bay were obtained previously using the percentage of dead crabs caught during the WDS. This approach was based on strong assumptions of independence and did not consider the overwinter habitat conditions, the potential effects of fisheries, and spatial autocorrelation. Moreover, raw counts of dead crabs were only possible when field samples were collected and had limited capability for predictions. We developed a Bayesian model as an alternative to the independence assumptions and applied it to blue crabs in Chesapeake Bay during 1996-2024. The OWM estimates from the Bayesian model were used to infer the natural mortality of blue crabs by sex, CW, and maturity stage (for females) during winter. Full details are provided in Liang et al. (2026b).

9.3.1. Materials and methods

Blue crabs were characterized as either dead or alive using the on-board protocols and data handling procedures of the main survey. Individual biological variables were recorded following the survey protocol. Size was defined at 10 mm bins and a plus bin for crabs larger than 190 mm. Sex was defined as males, immature females, and mature females.

In Maryland, data are collected from additional WDS sites focused on areas with high blue crab abundance from the random sites in order to obtain large enough samples of blue crabs to estimate mortality. These samples are taken at the end of the survey when most of the OWM should have already occurred. Sites with high crab abundance are selected, because tows with zero crabs have no information about mortality. Virginia data were taken from the main WDS in late winter, generally during March, when most overwinter mortality should have already occurred and dead blue crabs are seen more frequently. The criteria for selecting the starting date were (1) they were as late in the season as possible, and (2) there were enough crabs for estimates to be meaningful (~200+) with as broad a habitat distribution as possible (several rivers + mainstem sites). Analyses used interpolated temperature data from section 9.2.

Bayesian Model

OWM rates were estimated for Maryland and Virginia separately. Within each state/region, the main variable was the percentage of dead crabs. The number of live crabs and dead crabs were aggregated to estimate the percentage of dead crabs for each station. The average March OWM at length for each sex was estimated by averaging the annual percentage of dead crabs across the years. Total OWM (aggregated across sex and size categories) was also computed for each year and region.

A Bayesian generalized linear mixed model was developed to estimate the drivers of OWM and make predictions of OWM in the assessment model periods without field data. An interaction was assumed between sex and size categories to allow a separate estimation of OWM for each sex. Environmental drivers such as winter severity index, salinity, and dredge fishery effects were modeled as fixed effects. Because these drivers were annual effects, random year effects were also assumed to account for the potential pseudo-replication of these covariates within years. Lastly, a spatial random effects model was used to capture latent environmental drivers of OWM that remained homogenous over time and life stages. A Stochastic Partial Differential Equation prior was assumed for the spatial random effects. Model comparisons were based on the Watanabe–Akaike Information Criteria.

Chesapeake Bay-wide estimates of OWM at length for each sex and year were estimated based on the abundance of crabs from Maryland and Virginia. The abundance was estimated using the WDS samples for each state. A design-based estimate was calculated, assuming simple random sampling within each state. The depletion-based catchability was used to correct the survey catch into estimated abundance. The proportion of crabs in Maryland and Virginia was estimated for each sex, size category, and year, and used as weights to compute the Bay-wide OWM.

9.3.2. Results and discussion

Chesapeake Bay-wide mortality rates were estimated to be increasing with the size of the crab and exhibited interannual variability (Figure 9.10), which was consistent with the state-specific results. For male crabs, smaller male crabs experienced lower rates of OWM when compared with larger male crabs, which was also reported in Rome et al. (2005). In Maryland, the OWM increased with size for males. In Virginia, the OWM showed a concave relationship with size for males. For immature females, OWM increased with size in Maryland and Virginia. For mature females, the OWM decreased as a function of size for both states, after considering the statistical variability due to small sample sizes at the extreme sizes.

Mortality rates observed in the field varied between 1% and 13% over the years (Figure 9.11). Mortality rates were relatively higher for years with harsh winter conditions, defined as a WSI higher than 10. The effects of WSI tended to be stronger in Maryland, where winter conditions are colder than in Virginia. Mortality rates for those winters rose above 10%.

This analysis assumes that all blue crabs that die during winter due to natural mortality sources can be observed by the WDS and that the WDS has equal catchability for live and dead crabs. Because blue crabs are usually buried in the sediment during the winter, dead crabs would generally not be as available to large scavengers as they would at other times of the year. However, mortality due to predation would not be captured in our estimation approach. We suspect that predation of blue crabs in winter is low, though. We do not have information about catchability of live versus dead blue crabs in winter, but we expect it should be similar because live blue crabs are largely inactive at this time.

9.4. Effects of temperature on growth

Temperature has been widely reported to affect blue crab growth and has been used in models of blue crab growth (e.g., Bunnell and Miller 2005; Brylawski and Miller 2006). Therefore, we attempted to include temperature effects in the SLAM model to help describe seasonal patterns in growth and interannual variability. This section describes our unsuccessful efforts to link temperature to growth in this assessment.

Several different growth models have been used to describe blue crab growth including von Bertalanffy models and molt increment models. Given its common usage in length-structured assessments, we began SLAM development by describing growth with a von Bertalanffy increment model. The model was modified so that the K parameter of the von Bertalanffy model was a linear increasing function of growing degree days (GDD). The von Bertalanffy model resulted in too much growth for small blue crabs in the spring and was not able to describe the change in the size mode of recruits from spring to fall that is observed in the Maryland and VIMS trawl surveys.

To address the issue of too much growth of small blue crabs in the von Bertalanffy model, we changed to a Gompertz increment model. The Gompertz model allows for smaller individuals to have slower growth and for intermediate-sized individuals to have the largest growth rates. The Gompertz model was better able to describe changes in the size distribution of recruits over the course of the year than the von Bertalanffy model.

We tried several versions of temperature-dependent Gompertz models including one where the Gompertz *b* parameter was a linear increasing function of temperature and one where the *b* parameter was a normal (dome-shaped) function of temperature. The normal function of temperature allowed for somewhat better fits to spring-fall length composition data than the linear function, but neither model was able to describe the seasonal changes in the size distribution of recruits. The general problem was that the models predicted too much growth in the summer and fall and not enough growth in the spring. Ultimately, we abandoned using temperature to describe seasonal patterns of growth and adopted month-specific *b* parameters for the Gompertz model.

This is a curious issue because several lab-based studies have found increased growth with increased temperature. However, none of these studies included spring-like conditions in which blue crabs were coming out of their winter resting state. It is also likely that the food availability for blue crabs in Chesapeake Bay varies seasonally in a manner that was not replicated in the lab studies. Additional research on the effects of environmental conditions on blue crab growth would be valuable for future length-based assessments of Chesapeake Bay blue crabs.

9.5 Hypoxia effects

Blue crabs are considered well adapted to hypoxic conditions, with critical oxygen concentrations (i.e., the oxygen concentration below which metabolic activity declined) low relative to other crustaceans (Brill et al. 2015). However, blue crab exhibits behavioral changes in response to hypoxia, typically avoiding areas with oxygen concentrations < 2-4 mg/L (e.g., Bell et al. 2003a,b). Population-level impacts of this avoidance, such as increased mortality, have not been reported. We conducted correlative analyses to explore potential population-level effects of hypoxia on blue crab abundance.

9.5.1. Methods

We used three annual metrics of hypoxia from the Chesapeake Bay Environmental Forecast System (CBEFS), downloaded from https://www.vims.edu/research/products/cbefs/hypoxic-volume/, December 2025, including hypoxic duration (hd, in days), average daily hypoxic volume (avg hv, in km^3), and total annual hypoxic volume (tot hv, km^3 days). For these metrics, hypoxia is defined as oxygen concentrations < 2 mg/L; all metrics are based on outputs from computer models that continue to be improved. Daily hv and total hv were calculated from the daily-averaged 3D model output following Bever et al. (2018). Average hv is the average volume of hypoxic water on each day from June through September and hd was calculated from the daily estimates of hypoxic volume following Bever et al. (2013).

Two indices of blue crab total abundance were used to explore potential impacts of hypoxia on the crab population based on plausible mechanistic and spatiotemporal relationships between hypoxia and blue crabs. Both indices are based on spatiotemporal models, providing estimates of minimum abundance in the survey's spatial domain (see Ralph et al. 2026 working paper for more information). The Chesapeake Bay Multispecies Monitoring and Assessment Program (ChesMMAP) September index, reflecting the crab population in the Bay's mainstem, provides a concurrent view of potential impacts, as ChesMMAP is the only survey that samples in the hypoxia zone during summer months. The Winter Dredge Survey (WDS), lagged by one year, provides a cumulative view of potential impacts in the following year.

9.5.2. Results

Relationships between blue crab indices and the three annual hypoxia metrics were variable, with no consistent patterns (Figure 9.12). Based on Kendall τ, there were slight negative correlations between the ChesMMAP September indices and all three of the hypoxia metrics and moderate positive correlations between the lagged WDS indices and the hypoxia metrics (Table 9.1). Lack of clear, negative relationships between the hypoxia metrics and abundance indices may be due in part to mismatches in the spatial and temporal overlap between the primary hypoxic zone and the surveys. Refinement of the indices, particularly as a function of size and sex, may be needed to support further work on impacts of hypoxia.

TOR 10: Data Gaps and Uncertainty

While many data gaps were identified in this stock assessment, several aspects of blue crab biology and data quality were considered highly consequential for the stock assessment modeling effort. The research recommendations in section 11.2 describe efforts that would help fill in these data gaps.

Understanding blue crab growth is essential for developing an accurate length-structured model. We were able to develop a model that characterized changes in the blue crab size distributions in surveys reasonably well, but important uncertainties remain. Growth is also affected by maturation, particularly for female blue crabs. However, information to estimate probability of maturing was only available for a small portion of the Chesapeake Bay. It is possible that size-based patterns of female maturation differ spatially, and that spatial differences may explain some of the lack of fit of the model to some data sets. Changes in growth and maturation in the model can lead to very different estimates of fishing mortality rates.

Another major uncertainty that this assessment was not able to resolve was drivers of recruitment. Recruitment has been declining over the last 10 years without a clear causal driver despite mature female abundance remaining at levels above previous lower threshold reference points. Previously, in the 2011 stock assessment, we modeled recruitment as a Ricker function of spawning stock size, but subsequent studies indicated that the stock-recruitment relationship was not as well estimated in the 2011 assessment as we thought at the time. Predation by blue catfish did not explain the observed decline in recruitment. It is possible that predation by other predators may play a role, but data on some potential predators (e.g., red drum) is sparse, and predation is poorly characterized. Additionally, we had intended to try to characterize changes in juvenile blue crab habitat over time, but we were unable to within the time frame of this assessment. Lastly, we did not focus on potential oceanographic drivers of blue crab recruitment because a currently ongoing parallel study is investigating that topic.

Some of the key continuing uncertainties from previous assessments were that aspects of fisheries removals are not fully characterized. In particular, recreational harvest is widespread but we have few estimates of it for blue crabs in Chesapeake Bay. Estimates for Virginia and the Potomac River are particularly sparse. We have attempted to quantify dead discards for the first time, but these are likely underestimates because they only used observed dead crabs from commercial monitoring data in Maryland. We assumed similar dead discards for Virginia, but it is unknown how similar dead discards are spatially in Chesapeake Bay, and work by Lipcius and colleagues has suggested higher sex-specific mortality rates in pots in Virginia than what was observed in the Maryland data. Lastly, blue crab regulations are complicated in that they are sex and size-specific and have changed frequently over the last 20 years. In order to estimate the effects of these changes, data on the harvest by sex and size are needed. Additional size and sex data from the catch would be beneficial for future assessments.

Although we had a wealth of surveys to use for this assessment, they conflicted in some important ways, particularly with regard to changes in the size distribution during the spring to fall. While it is likely that some of the differences observed are due to spatial recruitment and growth differences, we have not yet been able to develop a spatial model of blue crab dynamics in Chesapeake Bay that describes the data well enough to use it for stock assessment or management evaluation.

Like almost all stock assessments, we have substantial uncertainty about natural mortality. We modeled natural mortality as a size-dependent process based on relative survival from a tethering study in lower Chesapeake Bay. The degree to which the tethering study we used accurately represents relative survival spatially across the Chesapeake Bay and how much it varies over time is unknown. Similarly, we have two long-term tagging efforts for blue crabs that allow for some estimation of survival. This assessment was hindered by the U.S. government shutdown, which caused us to not be able to analyze the SERC tagging data. For the VIMS tagging data, it is difficult to disentangle fishing and natural mortality. Furthermore, the VIMS tagging model suggested constant survival of mature females in the lower Chesapeake Bay over periods with very different fishing mortality rates, which remains perplexing.

The WDS remains the most important data source for tracking the blue crab population in Chesapeake Bay, but several important uncertainties were highlighted during this assessment. Given the length-specific natural mortality and growth model, the model was unable to generate enough crabs to match the observed catches when traditional catchability values from depletion experiments were used (approximately 0.15-0.4). We had to make three modifications to the model to address this issue: 1) we modified the size distribution of recruits in winter, 2) we specified selectivity based on the observed size distribution in the WDS and additional studies in habitats that are not sampled by the WDS, and 3) we estimated WDS catchability in the model (about 0.08). This resulted in much higher recruitment and abundance in SLAM than in previous assessments, and a lower idea of the WDS catchability. One issue is that the WDS does not sample in all blue crab habitat in Chesapeake Bay, and the estimates from the VAST analysis were only expanded to the areas sampled, which is one reason why catchability was estimated to be lower. Catchability could also be lower than has been estimated in depletion experiments because the catchability of the first tow is what is needed for the assessment model, but depletion experiments estimate an average catchability by repeatedly sampling the same area. If the catchability increases during the course of the depletion experiment, the estimate will be biased high. We have also had ongoing discussions about potential effects of bottom type on catchability but have not been able to determine whether bottom type affects catchability. Lastly, there has been some drift in the survey design and implementation since it was initially developed in the 1990s. The effects of drift in stratification were estimated to be small, but overall changes in the survey implementation remain poorly understood. The current assessment still has issues resolving the sex ratios of the WDS and the catch as evidenced by the residual patterns in the catch. Therefore, a new effort to document current practices is needed, and a potential re-evaluation of survey design could be conducted using the wealth of information currently available.

TOR 11: Research Recommendations

11.1. Work done on previous research recommendations

11.1.1. 2011 Chesapeake Bay Blue Crab benchmark stock assessment research recommendations

1. Assessment models
    a. The new SSCMSA is a substantial step forward as it provides integrated estimation of reference points and stock status. However, a more complete understanding of the **sensitivity of model outputs to parameter values**. We also recommend an **evaluation of the impacts of uncertainty in parameter estimates on reference points**.

Wilberg et al. (2019) evaluated the development of MSY-based reference points that accounted for parameter estimation uncertainty. That analysis revealed that it is more *difficult to estimate stock-recruit parameters in the SSCMSA than was previously thought. This finding was confirmed in a simulation study (Liang et al. unpublished).*

b. **Evaluate the effects of possible miss-specification of model structure to explain the inability to match the sex-specific catch levels in the model** (sex specific ratio at recruitment, sex-specific differences in M, sex-specific differences in catchability, alternative stock recruitment models).

The new length- and sex-structured model estimates the sex ratio of recruits, but it does not estimate sex-specific M. By allowing for sex-specific growth and maturation, it improved the model's ability to match the sex ratio in the fishery catches and the winter dredge survey. However, the fishery catch residuals still had some sex-specific patterning.

c. The **efficacy of alternative fishery-independent time series**, such as the ChesMAPP samples, in assessment models should be evaluated.

The current assessment considered several additional surveys that were not used in the 2011 assessment, including ChesMMAP and the PEARL Pot Survey.

d. The ecology and fisheries for blue crab exhibit considerable spatial variability – much of which coincides with the divisions among management jurisdictions. We recommend **evaluation of spatially explicit assessment models**.

We initially tried to develop a spatially explicit simulation model but had substantial issues matching spatial survey data sets (Miller et al. unpublished). In retrospect, this was likely because our growth model contained assumptions that did not match patterns of blue crab growth in the Chesapeake Bay. For this assessment, we focused on developing a length- and sex-structured model on a monthly time step, and we did not have sufficient time to also expand it to a spatial model. We used a fleets-as-areas model to try to capture some of the spatial differences of several commercial fleets.

e. Additionally **modeling work that specifically represents the diversity of fishery sectors, with different seasonalities and catchabilities** would be beneficial.

The current assessment model includes six fleets that represent different jurisdictions, gears, and crab conditions (e.g., peelers). We also used a monthly time step to better incorporate seasonality.

2. Fishery-dependent data

a. The monitoring of removals by the different fisheries has improved. However, efforts to validate landings are currently inconsistently implemented across jurisdictions. **Efforts to validate landings should be a high priority. These approaches could include directing monitoring of**

purchases by wholesalers or by indirect expansion of sentinel fishery data.

This was partially addressed. Virginia conducts limited validation of the catch. It remains a research priority.

b. Although time series approaches to correcting landings for reporting changes appear successful, their use for any future reporting changes should be discouraged in favor of **direct empirical estimates of the effects of the change from studies implemented contemporaneously with the reporting change**.

The current model avoids this issue because it starts after mandatory reporting was implemented in all jurisdictions in 1994.

c. We recommend that attention be given to **ensuring that the biological characteristics of each fishery be quantified, and that the spatial and temporal distribution of the removals be quantified**.

Additional data were collected and used in the assessment on the biological characteristics of the catch. Also, the length- and sex-structured model has a monthly time step to account for the within-year temporal variation in catches by fleet. The ongoing MD Sentinel Fishery Program provided information on the biological characteristics of catches in MD and the Potomac River, and Virginia conducted biological sampling of the catch in 2016 and 2017.

d. The recreational catch remains poorly described and its inter annual variability is largely unknown. **Monitoring programs and surveys to quantify the recreational harvest should have a high priority.**

SERC conducted a tagging study in Maryland to quantify recreational harvest and fishing mortality rates, but similar information is not available for Virginia. This continues to be a high priority.

e. There have been efforts to improve information on the distribution and dynamics of effort in the different fisheries exploiting blue crab in the Chesapeake Bay. These efforts should be expanded to a consistent baywide coverage and continued.

As part of this assessment, we compiled available metrics of effort. However, these metrics were thought to be too coarse to describe fishing mortality well in most cases.

3. Fishery-independent data

a. Fishery-independent surveys are critical to the assessment, particularly the **winter dredge survey. Continuing investments** in these surveys are important for ongoing assessment efforts.

There has been continued investment in the winter dredge survey as well as efforts to improve the survey over time.

b. **Efforts to estimate gear catchability coefficients should be expanded.** In particular, these efforts should focus on the interaction between the spatial distribution of crabs and area-specific patterns in catchability.

Work on this has been done through additional data collection in the WDS to allow comparisons between the vessels. These new data were used in the VAST standardization approach for the WDS. TOR 2 describes the VAST modeling. However, uncertainty remains regarding WDS catchability given the lower estimates relative to the depletion studies.

c. Additional analysis of the survey time series to understand their coherence, and their ability to track population variation would be beneficial. A thorough **evaluation of survey efficiency and options for enhancing their utility** should be undertaken.

We evaluated the coherence of the monthly survey indices in TOR 2. Other than the WDS, the other surveys do not have efficiency estimates.

d. Indices for age-0 and recruits are lacking other than for WDS. **Exploration of alternative indices of age-0 crabs is a priority.**

A previous simulation study attempted to track recruitment starting in the fall (Miller et al. unpublished), but it was determined that this was very challenging and became less of a priority. All of February-July indices include age zero blue crabs and they inform recruitment.

4. Ecology and Biology

a. **Research that quantifies size-dependent, sex-specific and inter-annual patterns in natural mortality** would greatly improve future assessments.

Additional work has been done to evaluate size-specific natural mortality for small blue crabs (Bromilow and Lipcius 2017; Hines et al. 2026), and an updated analysis of VIMS tagging experiments was conducted to evaluate evidence for changes in M over time for mature females (Lipcius et al. 2026a). Liang et al. (2026b) also evaluated changes over time in overwinter mortality.

b. Understanding of growth as it affects recruitment of age-0 crabs to different fishery sectors is uncertain. **Studies of the temporal and spatial variability in growth** would improve our understanding.

The length- and sex-structured model includes growth using a Gompertz growth model that allowed us to track the population length distribution over time by sex. We were not able to expand the model to also be spatial due to time constraints.

c. The reproductive potential of the crab population likely varies with stock abundance and the sex ratio on the stock. **Research on the variability of reproductive parameters (e.g., maturity, fecundity and batch production) is a high priority.** Additionally, research on the **impact of variation in the sex-ratio on the reproductive potential of the population** would be beneficial.

Schneider et al. (2023a; 2024a) conducted research on blue crab reproductive potential and phenology. Additional work was done to understand the potential for sperm limitation by Rains et al. (2016; 2018) and Ogburn et al. (2014; 2019). The group at Smithsonian Environmental Research Center has several additional studies to further our understanding of reproduction. They have also developed methods to classify pre-pubertal crabs in the field (Ogburn et al. 2026) which we hope to implement in other surveys throughout the Bay.

d. Evaluation of **how productivity may have changed over time in response to changes in availability of quality habitat**.

Several studies have looked at effects of habitat on blue crab abundance, but none have linked those changes to population productivity. One study looked at the effects of habitat on population density (Hyman et al. 2024); another assessed the impacts of oyster reefs as nursery habitat (Lipcius 2023); additionally, ontogenetic variation in seagrass nurseries was examined (Lipcius 2023).

5. Management
    a. Coordination among management jurisdictions is commendable. However, there remain important difference in the availability and format of data. We recommend that efforts be implemented to **make harvest and survey data widely available and consistently managed.** This would reduce time invested in data qa/qc during the assessment process and likely improve the reliability of future assessments.

Our group has discussed developing a data hub where data can be shared widely among jurisdictions. We plan to investigate this further and to integrate it with planned updates of the assessment model.

b. The sex-specific approach to management recommended here has implications for new decisions management has to make regarding the future of the fisheries. **Management should engage stakeholders to develop a vision for the fishery in light the adoption of a sex-specific approach.**

There have not been any formal efforts to engage stakeholders to inform reference points. However, the three agencies have processes to gather public input on management-related topics.

c. There have been no efforts in this assessment to consider blue crab management from an ecosystem viewpoint. **The exploration of both the impact of the ecosystem on the productivity of blue crab fisheries and of the impacts of the blue crab fisheries on the ecosystem are warranted.**

Ecosystem effects were evaluated through studies to understand interactions with blue catfish and overwinter mortality. Substantial efforts were made to model growth in relation to temperature, but temperature did not seem to be the main driver for growth. Hypoxia effects were also evaluated. An ongoing effort by NOAA is looking at physical forcing effects on blue crab population dynamics.

11.1.2. Research recommendations from the 2017 Chesapeake Bay Blue Crab update stock assessment

In the conduct of this update, several potential improvements to data collection, management and modeling were identified that are likely to improve model performance. In addition, many of the research and modeling recommendations from the last benchmark stock assessment remain relevant for this update stock assessment. This proposed list of recommendations is not exhaustive.

During the assessment update, the issues encountered were difficulty in duplicating prior results, errors in the datasets, incomplete description of methodology, and availability of data. Recommendations to address these issues include:

- Increased cooperation and data sharing between state agencies and academia, and a central repository of data and coding used in the assessment.

Efforts to expand data sharing through the creation of a data hub were briefly mentioned above. Through this assessment we have learned that the states are not able to share data through Google Drive. For this assessment we have set up a file sharing system through ASMFC and we will evaluate whether it will be possible to maintain this system into the future. Additional efforts will also be made to encourage CBSAC to update this assessment model yearly which would require ongoing data sharing. All code used to organize and process raw data, standardize indices, and run the assessment model will be archived. Methods have been better documented than occurred in the previous assessment.

- Documentation and standardization of VIMS methodology and estimates for trawl efficiency.

The new methodology for the VIMS trawl survey has been well documented. However, efficiency has not been estimated.

- Development of efficiency estimates for the Maryland trawl survey.

Efficiency has not been estimated.

There was poor correlation between age-0 and age-1+ for all indices. Understanding the reasons for this would improve model performance and help if a shorter time step were introduced. Recommendations include:

- Thorough analysis of growth to identify seasonal (monthly) change in the size range and overlap among age-0 and age-1+ age classes and improve age-specific index calculation and achieve better tracking of year classes through time.

This was briefly described above. Growth was an important aspect of the new model that was estimated each month. We have made progress understanding temporal patterns in growth for each sex category. However, this model tracks proportions at length and does not evaluate age-based patterns in growth. However, there is relatively good consistency among the surveys and months included in the assessment model.

- Evaluation of winter dredge survey results for Virginia and Maryland to investigate whether they correlate with trawl survey indices in the two states. This analysis could help develop more robust trawl indices by better defining the temporal and spatial criteria for data inclusion.

Survey indices at the monthly scale seem to be fairly consistent. We hoped to explore spatial patterns further but ran out of time. It remains a research recommendation.

- Evaluation of other survey time series for potential inclusion in the assessment, such as the Chesapeake Bay Multispecies Monitoring and Assessment Program and the Maryland DNR cooperative commercial data collection program.

We used both of these data sources in the new model.

- Examination of gear efficiency differences between sampling vessels.

Relative gear efficiency for the MD and VA vessels was estimated using VAST and data on paired tows and tows in the same regions, which is described in TOR 2. The VIMS vessel was slightly less efficient than the MD vessel, with smaller differences than indicated in previous depletion catchability experiments.

- Additional formal evaluation of various forms of fishery independent indices (GLM, GLMM, GAMs, etc.) to identify the most appropriate form and standardize indices development.

Extensive work was done to consider standardization methods for all surveys. VAST was used for surveys with designs that included randomly selected stations. Surveys such as MD Trawl and PEARL Pot surveys had GAMs applied. These decisions are described in TOR 2.

The accuracy of catch estimates has always been questioned due to changes in data collection procedures, bias from reporters, unknown variability in the recreational harvest, and unknown biases due to non-reported losses. Recommendations include:

- Development of a system to verify catch and effort data reported by the commercial fishery.

This is partially done, but efforts are different in each jurisdiction. Corrections were not applied to reported commercial catches.

- Quantitative assessment of under-reporting rates.

There is no information to inform under-reporting (or over-reporting) rates. It is not clear which issue is more relevant. We also do not have a good understanding of how these reporting issues may have changed over time. This remains a research recommendation.

- Improved documentation of sex ratio and the effect of shedding mortality on reported harvest in the peeler/soft crab fishery.

There is no information on shedding mortality in peeler operations, but it is not believed to be very important because peelers are supposed to be reported at capture rather than reporting soft-shell crabs at sale (TOR 3). Some sex ratio information for peeler crabs is available in the MD sentinel program. However, we do not have information from all fisheries or jurisdictions.

- Estimation of incidental mortality and discard mortality rates for pots, trot lines and other gears.

We produced estimates of dead discards for each gear using data on dead crabs from the Maryland Sentinel Program. This work could be expanded because these are likely minimum estimates.

- Sensitivity modeling to test the effect of historical changes in harvest reporting procedures.

This was not addressed because we started the model after mandatory reporting was implemented in 1994. The last assessment had to correct for this issue because voluntary reporting was present prior to 1994 in Virginia and mid-1980s in Maryland.

- A baywide survey of recreational catch, with regular updates.

This is not available and remains a research recommendation although Semmler et al. 2021 provides more recent estimates for Maryland.

Additional exploration of model sensitivity to model structure, parameters and inputs is needed to better describe blue crab population dynamics. Recommendations include:

- Investigation of the model's poor fit to the sex-specific catch and abundance indices, including evaluation of higher male natural mortality and higher proportion of recruiting females as reasons.

Some exploration has been done to assess the poor fit to sex-specific catch and differences in growth between males and females appears to be important. Because growth is described on a monthly time step and selectivity patterns are sex-specific, it does a better job matching the sex ratio of catch and the winter dredge survey than the previous SSCMA model.

- Investigation of the effect of alternative forms of the sex-specific stock recruitment relationship on productivity and biological reference points.

We did not use a stock recruit relationship in the model. Other research suggests stock recruit parameters were not well estimated in the 2011 assessment model.

- Modeling gear-specific selectivity as well as sex-specific growth rates to quantify the sensitivity of model results to the partial recruitment parameter.

We partially addressed this. Growth in the new model is sex-specific. We allowed for gear-specific selectivity functions, but it was not possible for the model to estimate the parameters. Instead, we accounted for annual and historical size regulations in each jurisdiction and gear in our specified selectivity functions.

- Incorporation of finer scale processes, such as season- and sex-specific growth and mortality rates at shorter time steps as well and spatial dynamics.

We accounted for this by estimating sex specific growth and mortality using monthly time steps. This model was not spatially explicit, but that is an ongoing research recommendation.

11.2. Research recommendations developed by the 2026 Chesapeake Bay Blue Crab stock assessment team

During the stock assessment, the team developed an updated set of research recommendations. The team notes that in the current funding environment these research recommendations will likely not be answered without additional resources. Furthermore, the research team strongly recommends that progress on addressing these research recommendations be a collaborative effort among researchers. The research recommendations are organized by TOR.

TOR 1

1. Improve understanding of growth either through lab or field methods (preferably field methods that can track individuals over time)

    a. Understand temperature and growth relationship throughout the entire year

2. Better understand how many crabs are in shallow waters that are not surveyed by the WDS
3. Improve estimates of M
    a. Potential analysis: Combine catch data with WDS data and tagging data to estimate changes in mature female natural mortality
4. Improve understanding of the size-specific and monthly patterns of female maturation and female growth at maturity and whether these processes vary spatially
5. Improve understanding of the spatial patterns of recruitment and how they have changed over time
    a. Potential analysis: develop a VAST model to combine MD Trawl, VIMS Trawl, and ChesMMAP to estimate spatial recruitment patterns over time

TOR 2

6. Standardize biological data collection across surveys (e.g., record pre-pubertal females across all surveys)
7. Evaluate alternative ways to get length compositions and indices from fixed site surveys like the MD Trawl survey, or expand fixed site surveys to include random stratified sampling locations
8. Reconsider design and estimators used for the WDS. The WDS now has a substantial amount of information that can be used to evaluate modified designs
9. Evaluate the potential consequences and need for the current spatial sub stratification in WDS
10. Validate SERC methods for identifying pre-pubertal females and determine the time between when females begin to be identified as pre-pubertal females and when they molt
11. Reconsider removing recruits from the surveys in the fall, and develop an assessment model that allows for recruitment to occur over several months instead of just one
12. Use a VAST model to estimate differences in catchability among surveys
13. Collect blue crab carapace width, sex, and maturity data in the seine survey in Maryland, and continue to collect it in the VIMS seine survey

TOR 3

14. Increase port sampling of commercial catch for length and sex composition
15. Better understand discards and discard mortality in the commercial fishery
16. Better understand recreational harvest
17. Conduct independent validation of catch reporting
    a. Potential analysis: Check regulation infractions with law enforcement

18. Review sex- and market-specific unit conversions used by jurisdictions for harvest data

TOR 4

19. Attempt to model recruitment with a stock-recruit function which would allow estimation of MSY-based reference points
20. Develop a spatial model that allows for spatial patterns of fishing mortality and growth

TOR 7

21. Develop and test harvest control rules to inform selection and use of reference points

TOR 9

22. Improve understanding of over winter mortality of blue crabs in Chesapeake Bay
23. Estimate effects of temperature on growth; determine if effects of climate change are apparent
24. Examine the effects of marine heat waves on survival during molting at all stages from zoea to adults
25. Expand spatial analyses to estimate the effects of blue catfish on blue crabs
26. Projections of future salinities to forecast blue catfish expansion
27. Determine the effect of hypoxia on blue crab habitat use

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Tables

Table 2.1. Comparison of the fishery-independent surveys considered for inclusion in the stock assessment: gear used, survey design (random- vs. fixed-site), temporal resolution, and length of the available time-series. Surveys include: PEARL Pot (PEARL Pot Survey) managed by Patuxent Environmental & Aquatic Research Laboratory (PEARL) at Morgan State University; ChesMMAP (Chesapeake Bay Multispecies Monitoring and Assessment Program), at the Virginia Institute of Marine Science (VIMS); Maryland Seine (Maryland Juvenile Striped Bass Survey) and Maryland Trawl (Blue Crab Summer Trawl Survey), both managed by Maryland Department of Natural Resources (MD DNR); SERC Trawl, Smithsonian Environmental Research Center Trawl Survey; VIMS Seine (VIMS Juvenile Striped Bass Seine Survey) and VIMS Trawl (Juvenile Finfish & Blue Crab Trawl Survey), both run by VIMS; and WDS (Winter Dredge Survey), cooperatively conducted by MD DNR and VIMS.

Name	Gear	Design	Temporal resolution	Years
PEARL Pot	Peeler pot	Fixed	2x monthly, Jun - Nov	1968-2021
ChesMMAP	Bottom trawl	Random	4-5 cruises, approx. bimonthly	2002-2023
Maryland Seine	Beach seine	Fixed	Monthly, July - Sept	1954-2023
Maryland Trawl	Bottom trawl	Fixed	Monthly	1989-2023
SERC Trawl	Bottom trawl	Fixed	3x monthly, Apr - Dec	2004-2023
VIMS Seine	Beach seine	Fixed	Biweekly, Jun - Sep	1967-2023
VIMS Trawl	Bottom trawl	Random	Monthly	1955-2023
WDS	VA crab dredge	Random	Annually	1990-2023

Table 2.2. Model parameterizations used to evaluate support for including spatial (ω) and spatiotemporal (ε) random fields in the first (p1) and second (p2) linear predictors when developing indices of abundance for surveys with random-site designs. Support for modeling spatial correlation using geometric anisotropy (A) or isotropy (I) was also evaluated.

Model	p1	p1	Correlation
m1	ω, ε	ω, ε	A
m2	ω, ε	ω, ε	I
m3	ω, ε	ω	A
m4	ω, ε	ω	I
m5	ω, ε	-	A
m6	ω, ε	-	I
m7	ω	ω	A
m8	ω	ω	I
m9	ω	-	A
m10	ω	-	I
m11	-	-	-

Table 2.3. Index of abundance from the Winter Dredge Survey (in millions of Blue Crabs, representing the minimum dredgeable abundance in the Bay). Although the survey occurs over several months in the winter, Blue Crabs are typically torpid and the survey index was assigned to the median date at which the survey occurs annually (early February).

Year	Feb
1994	86.30
1995	55.24
1996	120.73
1997	151.82
1998	71.60
1999	60.97
2000	65.74
2001	48.05
2002	55.66
2003	60.82
2004	61.16
2005	103.71
2006	93.95
2007	68.22
2008	74.47
2009	88.35
2010	164.35
2011	119.94
2012	187.38
2013	68.54
2014	72.04
2015	103.60
2016	125.20
2017	100.49
2018	89.44
2019	110.90
2020	91.35
2021	59.56
2022	59.06
2023	76.17

Table 2.4. Monthly index of abundance from the VIMS Trawl index (in millions of Blue Crabs, representing the minimum trawlable abundance in the Bay south of the Rappahannock River). Survey operations did not occur in January and February 2018 and April and May 2020.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1994	0.02	1.87	4.15	16.79	12.90	7.43	5.54	7.29	3.61	5.26	4.16	1.70
1995	0.09	1.17	3.63	6.75	5.29	7.00	6.80	6.74	4.31	4.59	8.92	2.74
1996	0.31	2.76	5.33	12.50	12.63	7.75	9.41	11.03	9.12	8.54	7.57	2.47
1997	0.11	1.70	7.69	9.00	7.10	6.51	11.25	10.10	7.72	6.34	4.88	2.56
1998	1.63	3.27	7.49	12.67	7.09	6.37	5.99	4.89	3.14	2.87	3.72	4.29
1999	0.18	2.49	1.95	8.41	4.72	2.93	4.23	7.80	4.11	2.74	4.28	1.99
2000	0.30	0.53	5.27	5.87	3.98	2.64	2.90	5.67	2.67	2.33	1.52	0.56
2001	0.32	2.77	3.06	4.45	6.47	5.84	7.57	6.82	4.21	3.02	2.01	1.52
2002	0.05	1.06	2.76	4.61	6.14	5.60	5.44	7.64	2.46	2.15	3.37	0.37
2003	0.24	0.48	1.14	5.42	3.55	2.77	4.56	4.52	3.31	3.27	2.99	1.27
2004	0.59	0.72	3.03	8.17	5.90	4.89	5.64	4.59	3.72	2.57	1.28	0.48
2005	0.15	0.50	1.23	2.75	4.47	2.35	2.54	2.73	1.89	2.11	3.67	1.00
2006	0.44	1.25	2.40	6.22	2.01	3.25	3.93	3.46	1.39	2.42	2.97	1.51
2007	0.61	0.37	1.89	1.90	2.42	3.59	1.93	2.81	1.35	1.35	2.85	1.57
2008	0.32	4.15	3.15	6.81	8.60	10.84	8.18	10.47	3.86	3.09	4.46	2.32
2009	0.13	1.20	2.14	10.28	5.66	4.88	6.47	5.35	2.10	2.19	4.84	1.08
2010	0.14	1.03	1.24	4.55	4.48	9.84	7.02	6.83	4.34	3.05	5.33	1.02
2011	0.04	1.92	4.55	13.48	11.31	11.22	10.16	10.77	6.08	4.09	5.26	3.84
2012	0.54	4.08	10.07	13.18	12.25	17.48	8.13	8.11	2.26	1.43	1.19	0.41
2013	0.37	0.95	1.07	6.82	4.67	6.93	4.68	3.64	0.96	0.79	0.87	0.23
2014	0.04	0.95	0.98	2.64	6.98	6.27	6.62	4.18	2.11	1.92	5.29	2.23
2015	0.06	1.05	1.21	3.65	5.24	6.17	6.42	5.55	2.86	4.33	2.28	1.25
2016	0.20	0.31	1.57	4.64	3.43	4.56	2.19	2.81	1.24	2.24	1.05	0.79
2017	0.31	0.59	1.37	2.12	5.77	19.11	6.23	2.69	2.15	1.61	2.38	0.76
2018	-	-	1.72	2.78	3.56	7.12	7.49	11.58	9.58	5.69	9.25	5.71
2019	1.10	1.39	2.15	6.02	8.05	16.71	7.36	6.86	2.73	0.84	1.47	1.23
2020	0.77	1.22	1.71	-	-	2.23	5.37	4.31	1.85	1.44	0.72	0.69
2021	0.32	0.34	0.70	1.32	2.24	1.64	2.65	1.65	1.17	0.52	0.94	0.72
2022	0.09	0.16	0.91	1.49	2.08	10.00	10.37	8.77	4.17	0.65	4.43	2.42
2023	1.05	1.67	6.65	5.39	6.52	6.32	7.37	6.90	2.80	0.66	1.33	0.76

Table 2.5. Most supported model parameterizations for each month of the Chesapeake Bay Multispecies Monitoring and Assessment Program (ChesMMAP) survey, including the preferred distributions for the first (p1) and second (p2) linear predictors, the supported spatial (ω) and spatiotemporal (ε) random fields, and the correlation structure of the spatial random field.

Month	p1 link	p2 distribution	p1	p2	Correlation
Mar	logit	gamma	ω, ε	ω, ε	I
May	Poisson	lognormal	ω, ε	ω	A
Jun	logit	lognormal	ω, ε	ω, ε	I
Jul	logit	generalized gamma	ω, ε	ω, ε	A
Sep	Poisson	gamma	ω, ε	ω, ε	A
Nov	Poisson	lognormal	ω, ε	ω, ε	A

Table 2.6. Monthly index of abundance from the Chesapeake Bay Multispecies Monitoring and Assessment Program (in millions of Blue Crabs, representing the minimum trawlable abundance in the mainstem Bay). Survey operations did not occur in Sep 2007, May 2009, Mar 2012 & 2012; survey design changed in 2019 from two cruises occurring in May and July to a single June cruise.

Year	Mar	May	Jun	Jul	Sep	Nov
2002	0.73	1.56	-	2.14	4.03	5.33
2003	0.52	0.86	-	0.93	2.84	5.89
2004	0.32	0.76	-	3.07	0.77	3.54
2005	0.77	5.50	-	3.06	3.71	8.00
2006	1.15	2.61	-	7.02	5.60	8.41
2007	0.46	4.85	-	3.64	-	3.42
2008	2.72	3.31	-	5.36	7.48	12.38
2009	0.57	-	-	2.93	3.11	6.31
2010	1.02	2.86	-	8.62	14.61	15.70
2011	1.57	5.41	-	7.22	9.47	6.24
2012	-	5.72	-	5.33	2.43	5.00
2013	0.09	3.15	-	2.02	0.11	1.72
2014	0.19	0.43	-	1.00	0.25	1.14
2015	0.19	1.31	-	2.31	3.40	6.67
2016	1.48	4.15	-	4.88	12.66	9.77
2017	0.53	6.13	-	6.09	1.33	1.66
2018	-	1.74	-	4.24	8.74	5.43
2019	0.20	-	4.48	-	0.60	3.09
2020	1.00	-	1.69	-	1.95	4.76
2021	0.49	-	2.18	-	0.59	2.02
2022	0.39	-	2.03	-	3.76	4.56
2023	0.31	-	1.31	-	0.74	1.10

Table 2.7. Monthly index of abundance from the Maryland Trawl Surveys (Blue Crabs tow^{-1}).

Year	May	Jun	Jul	Aug	Sep	Oct
2004	10.95	12.88	20.12	14.67	8.64	3.56
2005	11.14	21.95	27.62	20.85	16.51	5.97
2006	-	15.08	19.55	17.49	11.98	4.64
2007	7.47	13.45	17.10	13.62	5.17	1.79
2008	12.51	17.15	25.42	12.08	11.63	5.19
2009	14.65	21.16	28.65	28.70	17.47	6.98
2010	37.68	50.31	71.46	37.57	20.83	18.05
2011	38.09	57.41	52.11	37.13	21.18	12.35
2012	48.53	51.98	44.75	30.98	13.15	7.73
2013	24.23	23.66	20.14	17.44	8.64	5.49
2014	12.91	28.97	28.18	18.17	9.44	4.00
2015	16.21	37.83	53.58	35.03	15.94	7.39
2016	23.78	36.40	41.78	57.42	21.40	25.67
2017	23.19	26.02	31.31	29.15	14.51	7.98
2018	19.65	42.34	36.29	28.35	16.33	8.28
2019	31.53	33.10	33.85	31.34	14.44	11.21
2020	-	24.61	30.32	38.47	16.38	12.16
2021	20.40	23.12	26.68	23.79	12.46	5.49
2022	20.00	24.55	31.92	21.32	8.90	4.91
2023	19.21	22.39	30.52	27.14	13.53	8.14

Table 2.8. Monthly index of abundance from the PEARL Pot Survey (Blue Crabs per sampling round, equivalent to 20 pot-days). No survey operations occurred in 2012-2013, 2020, Nov 2017 & 2018, and 2022-2023.

Year	Jun	Jul	Aug	Sep	Oct	Nov
1994	4.10	8.63	5.47	5.58	4.91	5.60
1995	3.27	4.52	5.25	3.04	1.66	1.24
1996	1.90	7.11	7.34	2.38	4.64	1.11
1997	3.86	5.47	8.20	3.78	6.43	3.36
1998	2.77	2.18	3.49	2.71	4.00	1.22
1999	2.64	5.10	5.51	10.17	8.04	2.43
2000	4.15	5.04	3.78	2.93	2.62	0.90
2001	2.17	4.04	2.86	2.44	3.21	1.59
2002	2.97	4.73	5.52	3.73	6.38	1.10
2003	2.93	3.56	6.48	5.97	5.99	1.98
2004	3.46	3.24	5.86	4.95	7.30	1.41
2005	3.80	8.41	7.04	4.50	4.63	3.35
2006	2.89	11.09	7.99	6.95	6.69	1.83
2007	2.62	3.91	4.50	2.77	4.16	1.82
2008	6.29	10.90	7.81	6.40	6.87	3.96
2009	3.70	5.37	8.47	4.83	3.26	1.19
2010	4.20	7.05	9.04	6.22	9.97	7.26
2011	6.72	9.74	8.12	4.79	3.70	1.33
2012	-	-	-	-	-	-
2013	-	-	-	-	-	-
2014	2.10	3.18	4.15	1.35	1.40	0.51
2015	3.33	8.56	5.71	2.20	1.94	0.68
2016	2.21	5.81	8.82	4.79	4.98	2.49
2017	3.87	3.00	4.17	2.43	1.58	-
2018	2.17	3.79	7.28	9.34	4.62	-
2019	3.41	10.13	7.68	3.66	5.64	3.93
2020	-	-	-	-	-	-
2021	2.33	3.04	3.91	3.21	3.62	3.41
2022	-	-	-	-	-	-
2023	-	-	-	-	-	-

Table 2.9. Kendall rank correlation coefficient (τ), comparing the standardized indices within a given survey. The WDS (Winter Dredge Survey), with only one monthly index per year, was compared across years. For VIMS Trawl (Juvenile Finfish & Blue Crab Trawl Survey), with monthly indices year-round, comparisons were by month (e.g., Jan to Feb, Feb to Mar). The MD Trawls, including the MD DNR Blue Crab Summer Trawl Survey and SERC Trawl Survey (Smithsonian Environmental Research Center Trawl Survey) and PEARL Pot (PEARL Pot Survey), with monthly indices in the summer and fall, were also compared by month, but months without a survey were excluded from comparisons.

Survey	τ
WDS	0.30
VIMS Trawl	0.51
Maryland Trawls	0.53
PEARL Pot	0.26

Table 3.1. Regulations over years and months and within a year for hard, peeler, and sponge crabs in the Potomac River, Maryland, and Virginia. Differences for sex categories (male, immature female, or mature females) are indicated.

PRFC (Potomac River Fisheries Commission) Size Limits				
Time Period	**Hard Crabs**	**Peeler Crabs**	**Sponge / Mature Female Crabs**	
1968–2002	5.0"	3.25"	No size limit	
2003–2007	5.0" (5.5" from 7/15–11/30); mature females excepted	3.5"	No size limit	
2008–2015	5.25" (5.5" from 7/15–11/30); mature females excepted	3.5"	No size limit	
2015–Present	5.25"; mature females excepted	3.5"	No harvest of sponge, spawn, blooming female, mother crabs, or females with egg pouch/bunion removed	
Maryland Size Limits				
Time Period	**Male Hard Crabs**	**Peeler Crabs**	**Notes**	
Prior to 2003	5.0"	3.0" (4/1—7/14); 3.25" (7/15—11/30)	Single size limit	
2002	5.0" → increased to 5.25” Aug. 1	—	Transition year	
2003–Present (Apr. 1–Jul. 14)	5.0"	3.25"	Seasonal limits begin	
2003–Present (7/15–11/30)	5.25"	3.5"	No harvest of females with eggs after 2008	
Virginia Size Limits				
Time Period	**Hard Crabs (Male & Immature Female)**	**Peeler Crabs**	**Softshell Crabs**	**Mature Females**
Entire time series	5.0"	—	—	No size limit

1996–Present	—	—	3.5"	—
2002–2007	—	3.0"	—	—
2008–Present (1/17–7/15)	—	3.25"	—	—
2008–Present (7/16–end of season)	—	3.5"	—	—

Table 4.1. List of selected parameter names, abbreviations, and whether quantities are estimated. Estimated quantities include the estimated parameters and values calculated from estimated parameters. Asterisks (*) indicate that some values are estimated and some are not.

Parameter Name	Parameter Abbreviation	Estimated or not
Total recruitment per year	R_y	Yes
Proportion at sex x for recruits	κ_x	Yes
Proportion at length bin for recruits	p_l	No
Abundance in timestep t, length bin l, and sex x	$N_{t+1,l,x}$	Yes
Probability of growing from length bin l' to l in timestep t, and sex x	$G_{t,l',l,x}$	No
Overwinter mortality in timestep t, length bin l, and sex x	$O_{t,l,x}$	No
Total instantaneous mortality rate in timestep t, length bin l', and sex x	$Z_{t,l',x}$	Yes
Equilibrium abundance in the first year for timestep t and sex x	$\bar{N}_{0_{l,x}}$	Yes
Gompertz a parameter for each timestep t and sex x	$a_{t,x}$	No
Gompertz b growth rate parameter for each timestep t and sex x	$b_{t,x}$	No
Variance of the growth increment for each timestep length bin and sex	$\sigma^2_{\Delta,t,l,x}$	No
Maximum size parameter for each sex	L_{∞_x}	No
Variance of the Gompertz a parameter for each timestep and sex	$\sigma^2_{a_{t,x}}$	No
Variance of the Gompertz b parameter for each timestep and sex	$\sigma^2_{b_{t,x}}$	No
Additional growth variation	σ_2	No
Correlation between Gompertz a and b parameters	$\rho_{a,b}$	No
Probability of maturation	ψ	No
Maturation molt slope	β	No
Maturation molt intercept	ϑ	No
Maturation molt variance	σ_{mat}	No
Natural mortality	$M_{m(t),l,x}$	No
Relative natural mortality	M_{rel}	No
Reference natural mortality	M_{ref}	No
Scaling term for natural mortality	M_{Scale}	No
Fishing mortality rate for each timestep, length bin, sex, and fleet	$F_{t,l,x,\zeta}$	Yes
Fishing intensity in each timestep, sex, and fleet	$F^*_{t,x,\zeta}$	Yes*
Length and fleet specific selectivity	$s_{l,\zeta}$	No
Increasing logistic parameter 1 for each fleet	$p_{1,\zeta}$	No

Increasing logistic parameter 2 for each fleet	$p_{2,\zeta}$	No
Total catch for each timestep, length bin, sex, and fleet	$C_{t,l,x,\varsigma}$	Yes
Proportions at length in the catch for each timestep, length bin, sex, and fleet	$P_{C_{t,l,x,\varsigma}}$	Yes
Total catch in weight for each timestep and fleet	$T_{t,\varsigma}$	Yes
Estimated survey indices for each timestep	$i_{t,v}$	Yes
Catchability for each month, sex, and survey	$q_{mo(t),x,v_m}$	Yes
Selectivity for each month, sex, survey, and length bin	$s_{mo(t),x,v_{m,l}}$	Yes*
Estimated survey indices for each timestep, length, sex, and survey	$i_{t,l,x,v}$	Yes
Proportion by length and sex in the survey index	$P_{I_{t,l,x,v}}$	Yes

Table 4.2. Values of the Gompertz *b* parameter specified for each month. These values of *b* were estimated by iteratively modifying them until the model matched the monthly length distributions in the WDS, Maryland Trawl Survey, and VIMS Trawl Survey.

Month	***b***
January	0.00
February	0.00
March	0.00
April	0.70
May	0.60
June	0.45
July	0.50
August	0.75
September	0.65
October	0.50
November	0.20
December	0.00

Table 4.3. Values of growth parameters. These values were estimated by iteratively modifying them until the model matched the monthly length distributions in the WDS, Maryland Trawl Survey, and VIMS Trawl Survey.

Parameter	Males	Immature Females	Mature Females
L_{∞_x}	15	15	1
$\sigma_{\tilde{\Delta}_{t,l',mf}}$	0.1	0.1	1
$\sigma^2_{\Delta,t,l,x}$	0.05	0.05	1
$\sigma^2_{a_{t,x}}$	0.01	0.01	1
$\rho_{a,b}$	0.25		
σ^2_G	1.5		

Table 4.4. Female maturation growth parameters used in the model. These values were estimated by iteratively modifying them until the model matched the monthly length distributions in the WDS, Maryland Trawl Survey, and VIMS Trawl Survey.

Parameter	Value
Maturation molt intercept	0.70
Maturation molt slope	-0.035
Maturation molt CV	0.02

Table 4.5. Values of relative natural mortality by length bin. Estimates of relative natural mortality were calculated using the relationship of survival versus length of tethered blue crabs from Bromilow and Lipcius (2017). Length bin 6+ indicates the 6 cm and larger length bins.

Length Bin (cm)	Relative Natural Mortality
1	14.57
2	8.73
3	5.14
4	3.00
5	1.73
6+	1.00

Table 4.6. Model runs with alternative values for the reference level natural mortality (M_{ref}) and natural mortality scaling parameter (M_{Scale}). Values were chosen based on the model run with the lowest objective function value (bolded).

Model Run	M_{ref}	M_{Scale}	Objective Function
1	0.60	0.65	79921
2	0.50	0.55	81074
3	0.50	0.60	80815
4	0.50	0.65	80748
5	0.50	0.70	80544
6	0.50	0.75	80215
7	0.55	0.55	79915
8	0.55	0.60	79679
9	0.55	0.65	80196
10	0.55	0.7	79294
11	0.55	0.75	79142
12	0.6	0.55	79571
13	0.6	0.6	79363
14	0.6	0.65	79921
15	0.6	0.7	79044
16	0.6	0.75	79653
17	0.65	0.55	79322
18	0.65	0.6	79147
19	0.65	0.65	79008
20	0.65	0.7	78902
21	0.65	0.75	**78828**
22	0.7	0.55	79924

Table 4.7. Fixed values of the $p_{2,\zeta}$ fishery selectivity parameter (in cm) for increasing logistic functions for each fleet. Parameters varied over year and month based on regulation changes outlined in Table 3.1. Adjustments were made to improve shape of selectivity pattern for some fleets by adding a constant. Adjusted values used in the base model where specified.

Fleet	Year	Month	Unadjusted P2	P2 adjusted POT (+0.5)	P2 ADJUSTED TROTLINE (+0.65)	P2 ADJUSTED PEELER
MD (see column for specific fleet)	1994—2001	All		13.2	13.35	
	2002	Jan—Jul		13.2	13.35	
	2002	Aug-Dec		13.84	13.99	
	2003-2023	Jan—Jul		13.2	13.35	
	2003-2023	July		13.52	13.67	
	2003-2023	Aug—Dec		13.84	13.99	
VA (POT AND DREDGE)	1994-2023	All	12.7			
PRFC	1994–2002	All	12.7			
	2003–2007	Jan–Jun	12.7			
	2003–2007	July	13.34			
	2003–2007	Aug–Dec	13.97			
	2008–2015	Jan–Jun	13.34			
	2008–2015	July	13.65			
	2008–2015	Aug–Dec	13.97			
	2016–2023	All	13.34			
PEELER (USING MD REGULATIONS)	1994–2002	All				7.52
	2003–2023	Jan–Jun				8.66
	2003–2023	July				8.97
	2003–2023	Aug–Dec				9.29

Table 4.8. Effective sample sizes for all fleets, surveys, and timesteps. Fleets include: Maryland Pot (MD Pot), Maryland Trotline (MD Trot), Virginia Pot (VA Pot), Virginia Dredge (VA Dredge), the Potomac River Fisheries Commission (PRFC), and the Peeler fleet (combined over jurisdictions and gears). Surveys include the winter dredge survey (WDS), the Maryland trawl survey (MD Trawl), the Virginia Institute of Marine Science trawl survey (VIMS Trawl), the Patuxent Environmental & Aquatic Research Laboratory (PEARL) pot survey (PEARL), the Chesapeake Bay Multispecies Monitoring and Assessment Program 2002-2019 (ChesMMAP old), and ChesMMAP 2019-2023 (ChesMMAP new).

Time Step	MD Pot	MD Trot	VA Pot	VA Dredge	PRFC	Peeler	WDS	MD Trawl	VIMS Trawl	PEARL	ChesMMAP old	ChesMMAP new
1	0	0	0	15	0	0	250	0	0.25	0	0	0
2	0	0	0	15	0	0	250	0	6.75	0	0	0
3	0	0	0	15	0	0	250	0	4.75	0	0	0
4	0	0	0	0	0	0	250	0	9.5	0	0	0
5	0	0	0	0	0	0	250	0	13.25	0	0	0
6	0	0	0	0	0	0	250	0	12.5	1.5	0	0
7	0	0	0	0	0	0	250	0	12.5	1.5	0	0
8	0	0	0	0	0	0	250	0	11.75	1.5	0	0
9	0	0	0	0	0	0	250	0	11.5	1.5	0	0
10	0	0	0	0	0	0	250	0	13.25	1.5	0	0
11	0	0	0	0	0	0	250	0	10.25	0.75	0	0
12	0	0	0	15	0	0	250	0	4	0	0	0
13	0	0	0	15	0	0	250	0	0.75	0	0	0
14	0	0	0	15	0	0	250	0	4.25	0	0	0
15	0	0	0	15	0	0	250	0	5	0	0	0
16	0	0	0	0	0	0	250	0	8.5	0	0	0
17	0	0	0	0	0	0	250	0	10	0	0	0
18	0	0	0	0	0	0	250	0	9	1.5	0	0
19	0	0	0	0	0	0	250	0	9	1.5	0	0
20	0	0	0	0	0	0	250	0	10.25	1.5	0	0
21	0	0	0	0	0	0	250	0	8.5	1.5	0	0
22	0	0	0	0	0	0	250	0	7.25	1.5	0	0
23	0	0	0	0	0	0	250	0	10.5	0.75	0	0
24	0	0	0	15	0	0	250	0	5	0	0	0
25	0	0	0	15	0	0	250	0	4.5	0	0	0
26	0	0	0	15	0	0	250	0	12.75	0	0	0
27	0	0	0	15	0	0	250	0	13.75	0	0	0
28	0	0	0	0	0	0	250	0	17.75	0	0	0
29	0	0	0	0	0	0	250	0	17.75	0	0	0
30	0	0	0	0	0	0	250	0	18.25	1.5	0	0
31	0	0	0	0	0	0	250	0	20.5	1.5	0	0
32	0	0	0	0	0	0	250	0	20.5	1.5	0	0
33	0	0	0	0	0	0	250	0	19.5	1.5	0	0

34	0	0	0	0	0	0	250	0	23.5	1.5	0	0
35	0	0	0	0	0	0	250	0	19.75	0.75	0	0
36	0	0	0	15	0	0	250	0	14	0	0	0
37	0	0	0	15	0	0	250	0	2.5	0	0	0
38	0	0	0	15	0	0	250	0	11.25	0	0	0
39	0	0	0	15	0	0	250	0	13.25	0	0	0
40	0	0	0	0	0	0	250	0	20.75	0	0	0
41	0	0	0	0	0	0	250	0	19.25	0	0	0
42	0	0	0	0	0	0	250	0	20.25	1.5	0	0
43	0	0	0	0	0	0	250	0	21.75	1.5	0	0
44	0	0	0	0	0	0	250	0	23.25	1.5	0	0
45	0	0	0	0	0	0	250	0	21.5	1.5	0	0
46	0	0	0	0	0	0	250	0	21.25	1.5	0	0
47	0	0	0	0	0	0	250	0	21	1.5	0	0
48	0	0	0	15	0	0	250	0	13.25	0	0	0
49	0	0	0	15	0	0	250	0	7.25	0	0	0
50	0	0	0	15	0	0	250	0	11.25	0	0	0
51	0	0	0	15	0	0	250	0	11.75	0	0	0
52	0	0	0	0	0	0	250	0	19.75	0	0	0
53	0	0	0	0	0	0	250	0	21.5	0	0	0
54	0	0	0	0	0	0	250	0	20.5	1.5	0	0
55	0	0	0	0	0	0	250	0	19.25	1.5	0	0
56	0	0	0	0	0	0	250	0	12	1.5	0	0
57	0	0	0	0	0	0	250	0	16	1.25	0	0
58	0	0	0	0	0	0	250	0	16.25	1.5	0	0
59	0	0	0	0	0	0	250	0	18.25	1.5	0	0
60	0	0	0	15	0	0	250	0	12.75	0	0	0
61	0	0	0	15	0	0	250	0	2.75	0	0	0
62	0	0	0	15	0	0	250	0	12	0	0	0
63	0	0	0	15	0	0	250	0	9.75	0	0	0
64	0	0	0	0	0	0	250	0	19.75	0	0	0
65	0	0	0	0	0	0	250	0	17.75	0	0	0
66	0	0	0	0	0	0	250	0	15.25	1.5	0	0
67	0	0	0	0	0	0	250	0	19.25	1.5	0	0
68	0	0	0	0	0	0	250	0	22.25	1.5	0	0
69	0	0	0	0	0	0	250	0	17.5	0.75	0	0
70	0	0	0	0	0	0	250	0	16.25	1.5	0	0
71	0	0	0	0	0	0	250	0	18	1.5	0	0
72	0	0	0	15	0	0	250	0	9	0	0	0
73	0	0	0	15	0	0	250	0	3	0	0	0
74	0	0	0	15	0	0	250	0	10.25	0	0	0
75	0	0	0	15	0	0	250	0	12.5	0	0	0
76	0	0	0	0	0	0	250	0	17.25	0	0	0

77	0	0	0	0	0	0	250	0	17.25	0	0	0
78	0	0	0	0	0	0	250	0	18	1.5	0	0
79	0	0	0	0	0	0	250	0	15.25	1.5	0	0
80	0	0	0	0	0	0	250	0	21.5	1.5	0	0
81	0	0	0	0	0	0	250	0	19.75	1.5	0	0
82	0	0	0	0	0	0	250	0	18.75	1.5	0	0
83	0	0	0	0	0	0	250	0	12	0.75	0	0
84	0	0	0	15	0	0	250	0	6.25	0	0	0
85	0	0	0	15	0	0	250	0	1.5	0	0	0
86	0	0	0	15	0	0	250	0	5.5	0	0	0
87	0	0	0	15	0	0	250	0	5.5	0	0	0
88	0	0	0	0	0	0	250	0	13	0	0	0
89	0	0	0	0	0	0	250	0	21.5	0	0	0
90	0	0	0	0	0	0	250	0	19.5	1.5	0	0
91	0	0	0	0	0	0	250	0	21.75	1.5	0	0
92	0	0	0	0	0	0	250	0	22.25	1.5	0	0
93	0	0	0	0	0	0	250	0	20.5	1.5	0	0
94	0	0	0	0	0	0	250	0	18.25	1.5	0	0
95	0	0	0	0	0	0	250	0	15.25	0.5	0	0
96	0	0	0	15	0	0	250	0	8.25	0	0	0
97	0	0	0	15	0	0	250	0	1	0	0	0
98	0	0	0	15	0	0	250	0	10.25	0	0	0
99	0	0	0	15	0	0	250	0	11	0	4.5	4.5
100	2	0	0	0	0	0	250	0	16	0	0	0
101	6	3	0	0	0	12	250	0	16	0	10.25	10.25
102	12	8	0	0	2	12	250	0	18	1.5	0	0
103	13	15	0	0	4	21	250	0	17	1.5	10.25	10.25
104	16	15	0	0	1	20	250	0	20.25	1.5	0	0
105	18	15	0	0	2	23	250	0	16.5	1.5	11.25	11.25
106	24	12	0	0	0	14	250	0	15.25	1.5	0	0
107	16	3	0	0	0	2	250	0	17	0.75	13.75	13.75
108	6	0	0	15	0	0	250	0	6.25	0	0	0
109	0	0	0	15	0	0	250	0	4	0	0	0
110	0	0	0	15	0	0	250	0	8.25	0	0	0
111	0	0	0	15	0	0	250	0	9.75	0	6	6
112	9	7	0	0	2	0	250	0	15.75	0	0	0
113	13	8	0	0	5	3	250	0	16.25	0	1.75	1.75
114	15	11	0	0	4	15	250	0	15	1.5	0	0
115	20	21	0	0	6	14	250	0	14.25	1.5	7	7
116	17	21	0	0	4	20	250	0	19.25	1.5	0	0
117	17	18	0	0	4	16	250	0	14.5	1.5	7.5	7.5
118	25	16	0	0	4	5	250	0	17.25	1.5	0	0
119	13	5	0	0	3	0	250	0	16.5	1.25	20	20

120	0	0	0	15	0	0	250	0	11.25	0	0	0
121	0	0	0	15	0	0	250	0	4.5	0	0	0
122	0	0	0	15	0	0	250	0	8.5	0	0	0
123	0	0	0	15	0	0	250	0	10	0	4.25	4.25
124	3	2	0	0	0	0	250	0	20.75	0	0	0
125	14	12	0	0	1	12	250	14	19	0	6.5	6.5
126	17	17	0	0	4	22	250	13.75	19	1.5	0	0
127	17	25	0	0	5	26	250	15	18	1.5	6.75	6.75
128	9	25	0	0	4	27	250	15.25	17.25	1.5	0	0
129	12	23	0	0	5	23	250	14	15.75	1.25	5.5	5.5
130	22	13	0	0	5	17	250	14	13.25	1.5	0	0
131	21	4	0	0	0	2	250	0	10.75	0.75	15.75	15.75
132	1	0	0	15	0	0	250	0	4.75	0	0	0
133	0	0	0	15	0	0	250	0	2.25	0	0	0
134	0	0	0	15	0	0	250	0	8.25	0	0	0
135	0	0	0	15	0	0	250	0	11	0	4.75	4.75
136	3	4	0	0	0	0	250	0	16.25	0	0	0
137	13	8	0	0	3	8	250	13.5	18.5	0	12.75	12.75
138	18	19	0	0	1	27	250	14.75	15.5	1.5	0	0
139	17	28	0	0	1	29	250	15.75	16	1.5	12.5	12.5
140	19	28	0	0	4	36	250	14.75	16	1.5	0	0
141	19	27	0	0	5	34	250	15.75	14	1.5	11.75	11.75
142	22	22	0	0	1	15	250	15.75	15	1.5	0	0
143	20	8	0	0	0	1	250	0	19.5	1.5	17.25	17.25
144	5	0	0	15	0	0	250	0	6	0	0	0
145	0	0	0	15	0	0	250	0	4.25	0	0	0
146	0	0	0	15	0	0	250	0	8.5	0	0	0
147	0	0	0	15	0	0	250	0	11.25	0	7.25	7.25
148	10	6	0	0	1	1	250	0	17.25	0	0	0
149	17	13	0	0	2	18	250	2.25	16.25	0	10.5	10.5
150	21	17	0	0	0	29	250	14.5	19	1.5	0	0
151	22	26	0	0	0	29	250	14.5	18.5	1.5	11.75	11.75
152	25	28	0	0	0	32	250	13.25	17	1.5	0	0
153	19	23	0	0	4	22	250	15.75	14	1.5	11.25	11.25
154	28	18	0	0	5	13	250	13.75	15.5	1.5	0	0
155	24	1	0	0	0	2	250	0	11.5	0.75	16.5	16.5
156	0	0	0	15	0	0	250	0	8.5	0	0	0
157	0	0	0	15	0	0	250	0	3.25	0	0	0
158	0	0	0	15	0	0	250	0	6.75	0	0	0
159	0	0	0	15	0	0	250	0	10.25	0	2.75	2.75
160	3	3	0	0	0	3	250	0	16	0	0	0
161	11	17	0	0	2	12	250	10.25	16	0	12.5	12.5
162	20	24	0	0	1	35	250	13.75	19.5	1.5	0	0

163	22	21	0	0	2	29	250	16.25	14.75	1.5	11.75	11.75
164	21	21	0	0	1	36	250	15.25	15	1.5	0	0
165	13	25	0	0	0	28	250	12.75	11	1.5	0	0
166	24	14	0	0	0	7	250	10.25	14.5	1.5	0	0
167	16	1	0	0	0	1	250	0	14.25	0.75	12.75	12.75
168	1	0	0	15	0	0	250	0	11.25	0	0	0
169	0	0	0	15	0	0	250	0	3.5	0	0	0
170	0	0	0	15	0	0	250	0	12.5	0	0	0
171	0	0	0	15	0	0	250	0	12.25	0	10.25	10.25
172	3	6	0	0	0	0	250	0	15.5	0	0	0
173	10	15	0	0	0	11	250	9.5	19.75	0	9	9
174	14	23	0	0	0	22	250	14.5	22	1.5	0	0
175	18	32	0	0	0	37	250	15.5	20.25	1.5	9	9
176	17	24	0	0	0	25	250	14.25	24.75	1.5	0	0
177	15	24	0	0	0	24	250	15.5	18	0.75	13	13
178	16	14	0	0	0	7	250	13.5	17.25	1.5	0	0
179	6	0	0	0	0	1	250	0	19.75	0.75	19	19
180	0	0	0	0	0	0	250	0	13.75	0	0	0
181	0	0	0	0	0	0	250	0	2.75	0	0	0
182	0	0	0	0	0	0	250	0	9.25	0	0	0
183	0	0	0	0	0	0	250	0	11.25	0	5.75	5.75
184	1	4	0	0	0	0	250	0	20.25	0	0	0
185	16	19	0	0	0	9	250	9.5	21.5	0	0	0
186	16	33	0	0	1	27	250	15.25	20.75	1.5	0	0
187	21	32	0	0	2	32	250	15.75	20	1.5	10.25	10.25
188	24	39	0	0	0	40	250	15.75	19	1.5	0	0
189	26	35	0	0	0	28	250	14	15.25	1.5	9	9
190	31	21	0	0	1	11	250	14.75	16.25	1.5	0	0
191	17	2	0	0	0	1	250	0	21	1.5	14.25	14.25
192	0	0	0	0	0	0	250	0	8.5	0	0	0
193	0	0	0	0	0	0	250	0	2.75	0	0	0
194	0	0	0	0	0	0	250	0	9.25	0	0	0
195	0	0	0	0	0	0	250	0	9	0	7.25	7.25
196	4	7	0	0	0	2	250	0	16.5	0	0	0
197	14	17	0	0	1	14	250	15	19.5	0	8.75	8.75
198	31	31	0	0	1	34	250	15.75	20.75	1.5	0	0
199	26	29	0	0	0	26	250	15	21.25	1.5	9.5	9.5
200	35	33	0	0	0	37	250	17.25	24.75	1.5	0	0
201	29	30	0	0	0	29	250	16.25	19.75	1.5	14	14
202	26	19	0	0	2	8	250	15.25	18	1.5	0	0
203	17	2	0	0	0	0	250	0	20.75	1.25	17.5	17.5
204	0	0	0	0	0	0	250	0	9.25	0	0	0
205	0	0	0	0	0	0	250	0	1	0	0	0

206	0	0	0	0	0	0	250	0	14	0	0	0
207	0	0	0	0	0	0	250	0	12	0	7.75	7.75
208	4	7	0	0	0	1	250	0	22.75	0	0	0
209	20	27	0	0	1	9	250	14.75	20	0	12	12
210	31	33	0	0	0	28	250	16.5	22.25	1.5	0	0
211	31	26	0	0	6	18	250	15.75	21.5	1.5	10.25	10.25
212	25	33	0	0	4	20	250	16.25	23.25	1.5	0	0
213	29	28	0	0	5	19	250	15.5	18.25	1.25	11	11
214	30	20	0	0	5	0	250	15.5	18.75	1.5	0	0
215	16	2	0	0	1	0	250	0	22	1.5	15.25	15.25
216	0	0	0	0	0	0	250	0	14.75	0	0	0
217	0	0	0	0	0	0	250	0	5.25	0	0	0
218	0	0	0	0	0	0	250	0	17	0	0	0
219	0	0	0	0	0	0	250	0	14.25	0	0	0
220	4	10	0	0	1	3	250	0	23	0	0	0
221	17	22	0	0	2	15	250	15.75	22.25	0	12.75	12.75
222	29	29	0	0	0	28	250	16	24	0	0	0
223	28	29	0	0	1	30	250	14.5	22.25	0	13	13
224	25	31	0	0	0	30	250	13.25	23	0	0	0
225	28	23	0	0	0	23	250	16	14	0	5.5	5.5
226	26	23	0	0	0	13	250	14.25	12.5	0	0	0
227	10	3	0	0	0	0	250	0	11	0	11.5	11.5
228	0	0	0	15	0	0	250	0	5.25	0	0	0
229	0	0	0	15	0	0	250	0	3.75	0	0	0
230	0	0	0	15	0	0	250	0	8.75	0	0	0
231	0	0	0	15	0	0	250	0	8.75	0	1.75	1.75
232	3	9	0	0	0	0	250	0	16.75	0	0	0
233	19	20	0	0	2	6	250	15.25	19.75	0	10	10
234	18	24	0	0	1	12	250	15.75	20.5	0	0	0
235	28	31	0	0	1	21	250	14.5	19	0	11	11
236	27	26	0	0	2	15	250	14.25	16.5	0	0	0
237	20	28	0	0	2	13	250	13.75	10.75	0	1.25	1.25
238	21	18	0	0	0	7	250	13.25	10.75	0	0	0
239	5	1	0	0	0	0	250	0	9.5	0	8.5	8.5
240	0	0	0	0	0	0	250	0	4	0	0	0
241	0	0	0	0	0	0	250	0	0.75	0	0	0
242	0	0	0	0	0	0	250	0	5.75	0	0	0
243	0	0	0	0	0	0	250	0	8.5	0	2.25	2.25
244	2	0	0	0	0	0	250	0	12.75	0	0	0
245	14	12	0	0	0	13	250	11.75	19.25	0	3.25	3.25
246	25	25	0	0	0	36	250	14.25	16.75	1.5	0	0
247	24	31	0	0	0	41	250	16.75	20	1.5	5.25	5.25
248	20	27	0	0	1	36	250	14.5	17.5	1.5	0	0

249	21	26	0	0	0	32	250	15.75	14	0.75	2	2
250	23	13	0	0	0	9	250	12	15	1.5	0	0
251	6	0	0	0	0	0	250	0	18.5	0.75	9.5	9.5
252	0	0	0	0	0	0	250	0	13.75	0	0	0
253	0	0	0	0	0	0	250	0	1	0	0	0
254	0	0	0	0	0	0	250	0	11.25	0	0	0
255	0	0	0	0	0	0	250	0	8.5	0	2.75	2.75
256	0	2	0	0	0	0	250	0	14	0	0	0
257	10	10	0	0	0	13	250	12.25	19.25	0	6.5	6.5
258	23	28	0	0	0	40	250	15.75	15.75	1.25	0	0
259	23	28	0	0	2	41	250	16	18	1.5	8.25	8.25
260	28	28	0	0	0	43	250	15	15.5	1.5	0	0
261	18	27	0	0	0	36	250	15.75	12.5	0.75	7.75	7.75
262	19	19	0	0	0	13	250	15.25	16.5	1.5	0	0
263	11	3	0	0	0	0	250	0	16	0.75	14.5	14.5
264	0	0	0	0	0	0	250	0	10	0	0	0
265	0	0	0	0	0	0	250	0	2.75	0	0	0
266	0	0	0	0	0	0	250	0	5.25	0	0	0
267	0	0	0	0	0	0	250	0	9.5	0	5.75	5.75
268	2	3	0	0	0	0	250	0	15.5	0	0	0
269	9	10	0	0	1	13	250	14	13.75	0	10.25	10.25
270	19	26	0	0	1	33	250	13.5	16.5	1.5	0	0
271	22	24	0	0	0	32	250	16.5	15	1.5	12	12
272	23	29	0	0	0	39	250	13	13	0.75	0	0
273	14	27	24.46	0	0	24	250	16	9.25	1.5	9.75	9.75
274	13	11	27.6	0	3	14	250	15.25	8.75	1.5	0	0
275	5	3	21.92	0	1	0	250	0	8.5	1.5	15.5	15.5
276	0	0	0	0	0	0	250	0	6.25	0	0	0
277	0	0	0	0	0	0	250	0	1.75	0	0	0
278	0	0	0	0	0	0	250	0	8.5	0	0	0
279	0	0	17.78	0	0	0	250	0	9.25	0	4.25	4.25
280	4	2	37.84	0	0	2	250	0	15	0	0	0
281	12	17	46.58	0	1	16	250	13.5	14.75	0	14.5	14.5
282	14	18	19.2	0	0	26	250	15.75	24	1.5	0	0
283	19	22	6.34	0	0	31	250	14	21	0.75	12.25	12.25
284	21	23	0	0	0	33	250	14	13.25	1.5	0	0
285	15	24	0	0	0	27	250	16.5	13	1.5	4	4
286	17	11	0	0	0	7	250	15.75	10.5	1.5	0	0

287	4	2	0	0	0	0	250	0	13.25	0	8.5	8.5
288	0	0	0	0	0	0	250	0	7	0	0	0
289	0	0	0	0	0	0	250	0	0	0	0	0
290	0	0	0	0	0	0	250	0	0	0	0	0
291	0	0	0	0	0	0	250	0	8.75	0	0	0
292	0	1	0	0	0	0	250	0	14	0	0	0
293	8	9	0	0	1	11	250	12.75	14	0	5.5	5.5
294	14	23	0	0	0	17	250	14	13	1.5	0	0
295	17	21	0	0	0	18	250	14.5	16	0.75	10.5	10.5
296	14	19	0	0	0	17	250	13.25	21	1.5	0	0
297	12	14	0	0	1	12	250	14	19.25	0.75	7.5	7.5
298	17	18	0	0	0	5	250	14.75	17	1.5	0	0
299	5	1	0	0	0	0	250	0	22.25	0	12.75	12.75
300	0	0	0	0	0	0	250	0	12	0	0	0
301	0	0	0	0	0	0	250	0	6	0	0	0
302	0	0	0	0	0	0	250	0	13.5	0	0	0
303	0	0	0	0	0	0	250	0	9.5	0	0.75	0.75
304	1	4	0	0	1	0	250	0	18	0	0	0
305	9	10	0	0	2	17	250	13.5	18	0	0	0
306	12	18	0	0	1	28	250	14.5	20.75	1	13.25	13.25
307	12	20	0	0	1	26	250	15.75	17.75	1.5	0	0
308	12	16	0	0	0	24	250	14.75	16.75	1.5	0	0
309	11	18	0	0	3	19	250	15.25	11	1.5	8	8
310	14	16	0	0	1	7	250	12	8	1.5	0	0
311	5	1	0	0	0	0	250	0	10.75	0.75	10.75	10.75
312	0	0	0	0	0	0	250	0	9.25	0	0	0
313	0	0	0	0	0	0	250	0	5.5	0	0	0
314	0	0	0	0	0	0	250	0	7.25	0	0	0
315	0	0	0	0	0	0	250	0	9.75	0	2.5	2.5
316	0	2	0	0	0	0	250	0	0	0	0	0
317	0	11	0	0	0	7	250	0	0	0	0	0
318	6	11	0	0	0	17	250	14.75	7.25	0	12.5	12.5
319	12	18	0	0	0	23	250	14.75	11.5	0	0	0
320	10	17	0	0	0	23	250	15	10.75	0	0	0
321	10	13	0	0	2	17	250	15.25	10.25	0	6	6
322	8	9	0	0	2	8	250	12	10.25	0	0	0
323	3	1	0	0	0	1	250	0	7.75	0	10.75	10.75
324	0	0	0	0	0	0	250	0	5.75	0	0	0
325	0	0	0	0	0	0	250	0	2	0	0	0
326	0	0	0	0	0	0	250	0	5	0	0	0
327	0	0	0	0	0	0	250	0	6	0	2.5	2.5
328	0	0	0	0	0	0	250	0	10	0	0	0
329	1	9	0	0	0	8	250	15.5	12.25	0	0	0

330	4	20	0	0	0	20	250	15.25	12.75	1.5	15	15
331	5	18	0	0	0	19	250	15.25	13.25	1.5	0	0
332	6	17	0	0	0	22	250	15	10.5	1.5	0	0
333	4	18	0	0	0	17	250	5.75	6.5	1.5	4.5	4.5
334	1	11	0	0	0	5	250	14.25	4.5	0.75	0	0
335	2	4	0	0	0	0	250	0	7.25	0.75	7	7
336	0	0	0	0	0	0	250	0	6.25	0	0	0
337	0	0	0	0	0	0	250	0	1.25	0	0	0
338	0	0	0	0	0	0	250	0	2	0	0	0
339	0	0	0	0	0	0	250	0	6.75	0	1.75	1.75
340	0	0	0	0	0	0	250	0	11	0	0	0
341	3	6	0	0	0	4	250	14.25	13.25	0	0	0
342	4	14	0	0	0	17	250	15.5	20.25	0	15.25	15.25
343	4	14	0	0	0	16	250	15.75	21.25	0	0	0
344	4	17	0	0	0	20	250	16	21.75	0	0	0
345	2	12	0	0	0	11	250	14.75	15	0	10.25	10.25
346	5	15	0	0	0	9	250	14.5	5.75	0	0	0
347	3	6	0	0	0	1	250	0	16.75	0	10.25	10.25
348	0	0	0	0	0	0	250	0	13.25	0	0	0
349	0	0	0	0	0	0	250	0	5.5	0	0	0
350	0	0	0	0	0	0	250	0	9.5	0	0	0
351	0	0	0	0	0	0	250	0	11.75	0	1.25	1.25
352	0	1	0	0	0	0	250	0	17.25	0	0	0
353	4	17	0	0	0	7	250	13.25	16.25	0	0	0
354	2	16	0	0	0	11	250	15.25	18	0	12.25	12.25
355	4	14	0	0	0	9	250	15.75	21.75	0	0	0
356	2	14	0	0	0	10	250	15.25	19	0	0	0
357	4	21	0	0	0	13	250	15	15.25	0	6.75	6.75
358	6	15	0	0	0	5	250	14.5	7.75	0	0	0
359	4	3	0	0	0	0	250	0	10.75	0	7	7
360	0	0	0	0	0	0	250	0	6	0	0	0

Table 4.9. Percentage of model runs that converged on the same solution for three different base model variations during jitter analysis. Note that the runs with 50 iterations were run on a Linux operating system and the runs with 20 iterations were run on a Windows operating system.

Model Type	50 iterations	20 iterations
Limited PEARL limited ChesMMAP	100%	85%
No PEARL full ChesMMAP	100%	100%
No PEARL limited ChesMMAP	100%	95%

Table 4.10. Table of negative log likelihood components for all data sources. Sex- and length-compositions for the fishery are summed over time steps for each sex. Sex- and length-composition for surveys are summed across sexes and timesteps.

Data Source	Negative Log Likelihood
Objective function	16697.64
Recruitment Deviations	48.68
Sex ratio of Recruits	-42.78
Winter dredge survey index	32.85
Winter dredge survey sex- and length-composition	2556.15
MD Trawl index	58.42
MD Trawl sex- and length-composition	2057.05
VIMS Trawl index	477.21
VIMS Trawl sex- and length-composition	4711.67
PEARL index	63.02
PEARL sex- and length-composition	5.66
ChesMMAP (2002—2018) index	65.31
ChesMMAP (2002—2018) sex- and length-composition	392.82
ChesMMAP (2019—2023) index	8.88
ChesMMAP (2019—2023) sex- and length-composition	81.24
MD pot catch length-composition Males	1186.02
MD pot catch length-composition Mature females	1354.12
MD pot sex- and catch Males	- 356.85
MD pot sex- and catch Mature females	- 346.33
MD trotline catch length-composition Males	1324.25
MD trotline catch length-composition Mature females	2080.52
MD trotline catch Males	- 337.84
MD trotline catch Mature females	- 331.90
VA pot catch length-composition Males	69.85
VA pot catch length-composition Mature females	78.00
VA pot catch Males	- 298.81
VA pot catch Mature females	- 291.95
VA dredge catch length-composition Males	214.07
VA dredge catch length-composition Mature females	102.27
VA dredge catch Males	- 85.79
VA dredge catch Mature females	- 86.97
PRFC catch length-composition Males	32.36
PRFC catch length-composition Mature females	80.53
PRFC catch Males	- 338.73
PRFC catch Mature females	- 334.81
Peeler catch length-composition Males	1799.55
Peeler catch length-composition Immature females	1336.52
Peeler catch Males	- 333.36
Peeler catch Immature females	- 333.26

Table 4.11. Table of relative error percentages from simulation self-test for each of the three base models (names explained in section 4.2.1). Relative error was summed across sexes and calculated for estimates of abundance, fishing mortality, and recruitment.

Model	Abundance	Fishing mortality	Recruitment
Base (Limited PEARL and limited ChesMMAP)	-4.10%	3.30%	-2.90%
No PEARL and limited ChesMMAP	-4.00%	3.20%	-2.60%
No PEARL and full ChesMMAP	-3.90%	3.00%	-2.90%

Table 5.1. Description of sensitivity analyses for the length-structured stock assessment model and objective function values and selected negative log likelihood components. The shaded row represents the base model. Each additional row represents a different run with the corresponding overall objective function value ($\mathcal{L}$), the likelihood component for the winter dredge survey index $(nll_{I,WDS})$, and the likelihood component for the winter dredge survey length and sex composition $(nll_{I,l,x,WDS})$. Bold values indicate likelihood components that were lower than the base run.

Run	L_{∞_x}	$b_{t,x}$	$\sigma_{b_{t,x}}$	β_0	β_1	Maturation growth CV	M_{ref}	M_{Scale}	p_1	p_2	$\mathcal{L}$	$nll_{I,WDS}$	$nll_{I,l,x,WDS}$
Base	15	*1	0.05	0.7	-0.035	0.02	0.65	0.75			**17982**	**32.9**	**2556.2**
1	16										17987	**25.5**	2680.5
2	14										18388	37.1	2557.9
3		*1.2									18296	**22.9**	2712.3
4		*0.8									18754	40.6	2669.3
5			0.03								18018	34.3	**2526.4**
6			0.07								18000	**29.5**	2624.8
7				0.66							18542	33.5	2566.4
8				0.74							**17329**	**30.2**	2685.2
9					-0.039								
10					-0.031						**17432**	**29.8**	2705.3
11					-0.037						18544	33.4	2578.9
12						0.01					18119	33	**2568.4**
13						0.025					**17824**	**32.5**	**2550.7**
14							0.7	0.75			**17911**	33.6	2567.6
15							0.6	0.75			**17917**	**31.1**	2556.6
16							0.65	0.7			**17889**	**32.2**	**2553.6**
17							0.65	0.8			**17923**	**32.7**	2559.6
18									5	1.8	**17874**	**32.7**	**2534.9**

Table 9.1. Kendall rank correlation coefficient (τ) comparing indices of blue crab abundance: Chesapeake Bay Multispecies Monitoring and Assessment Program (ChesMMAP) September index and Winter Dredge Survey (WDS) index (lagged by one year) and three annual metrics of hypoxia: hypoxic duration (hd, in days), average daily hypoxic volume (avg hv, in km^3), and total annual hypoxic volume (tot hv, km^3 days), all based on the Chesapeake Bay Environmental Forecast System (CBEFS), available at: https://www.vims.edu/research/products/cbefs/hypoxic-volume/.

Hypoxia metric	**ChesMMAP September**	**WDS**
hd	-0.014	0.216
avg hv	-0.019	0.157
tot hv	-0.019	0.161

Figures

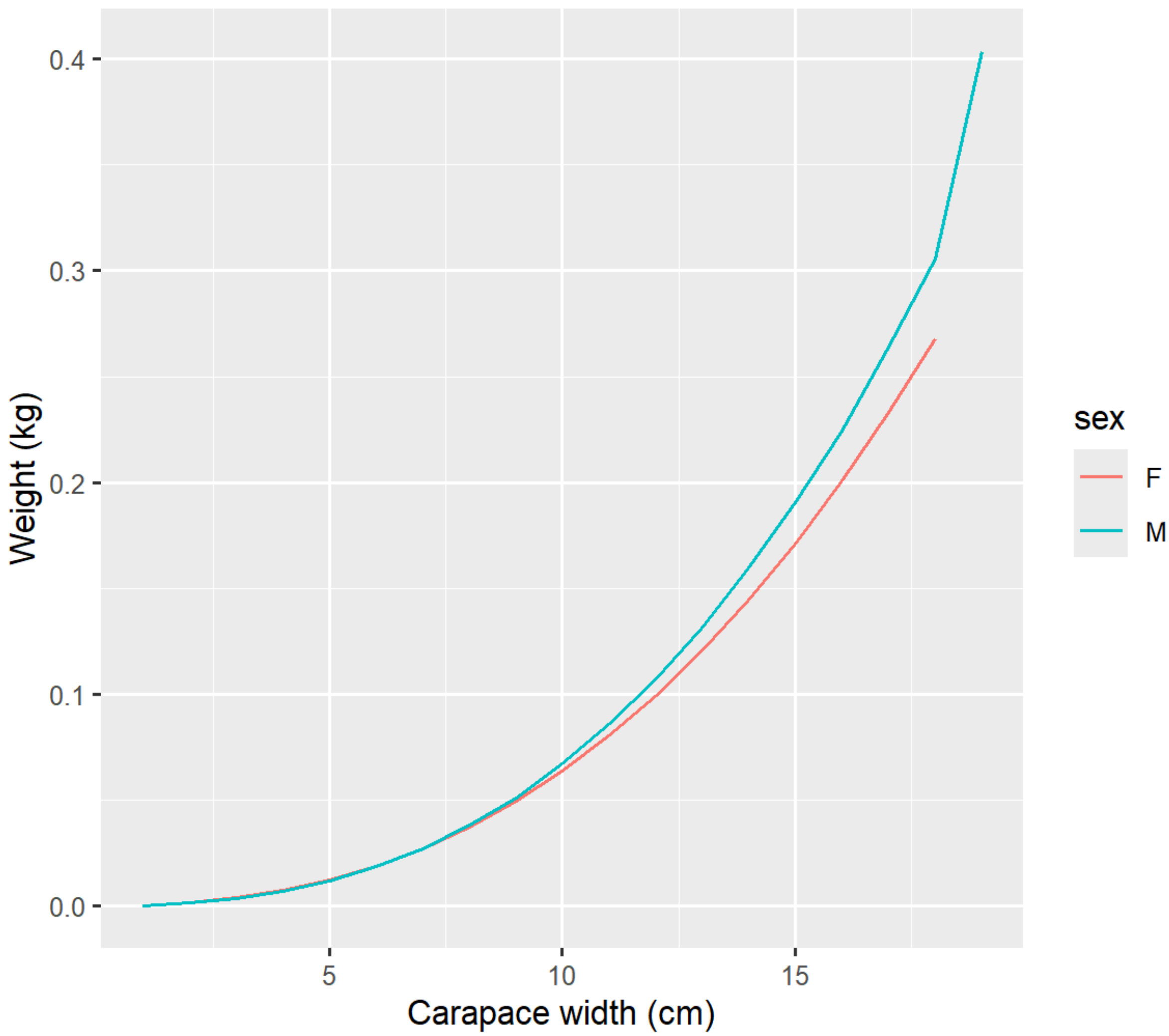

Figure 1.1. Estimated weight as a function of carapace width for female (F) and male (M) blue crabs in Chesapeake Bay.

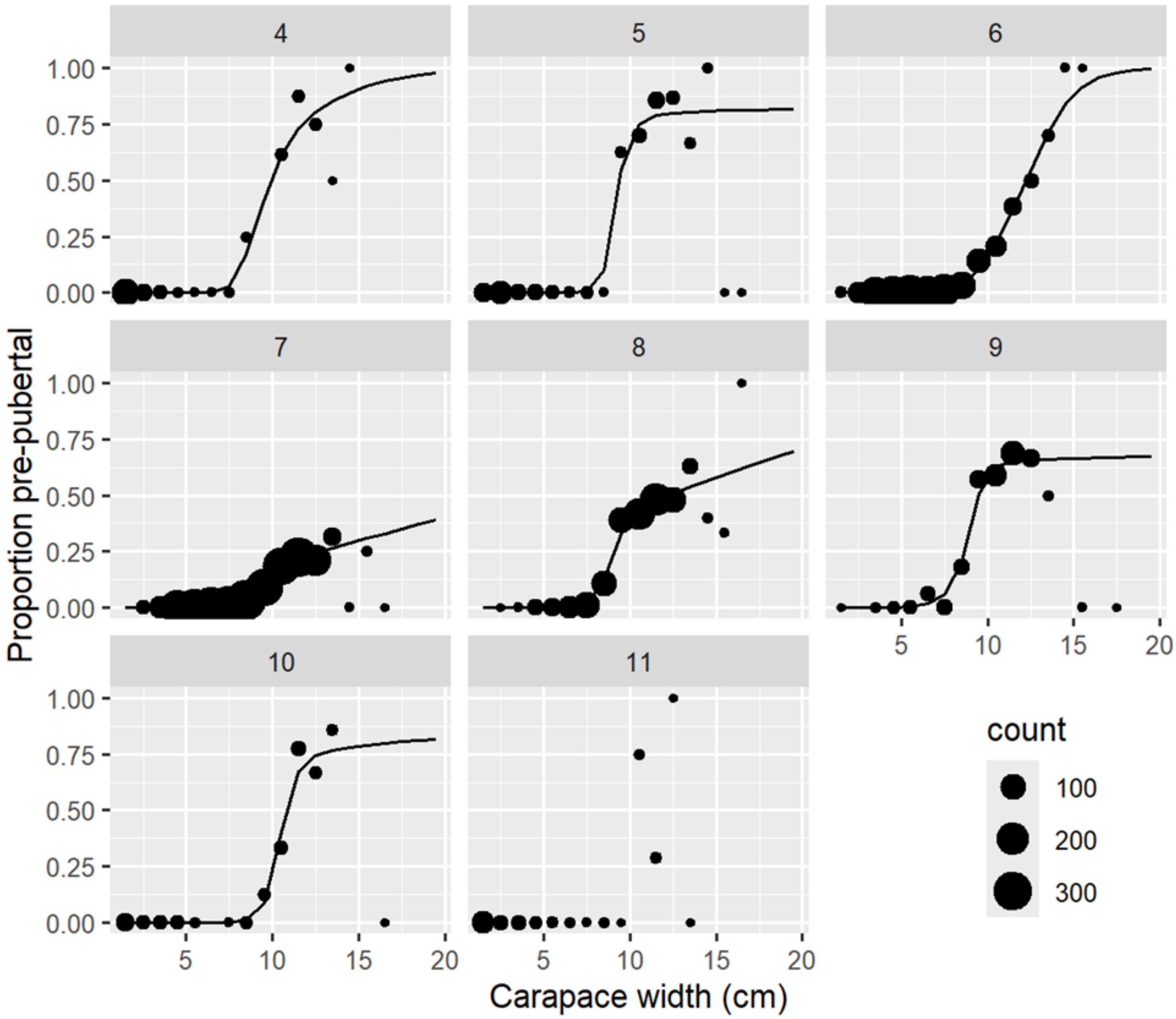

Figure 1.2. Generalized additive model fits to proportion of pre-pubertal female blue crabs by month (panels) from the SERC Trawl Survey for 2004-2023. The points indicate the observed proportions that were pre-pubertal, and the lines indicate the model fit. Point sizes are scaled to the number of observations in each size bin. The model did not include data for November (month 11).

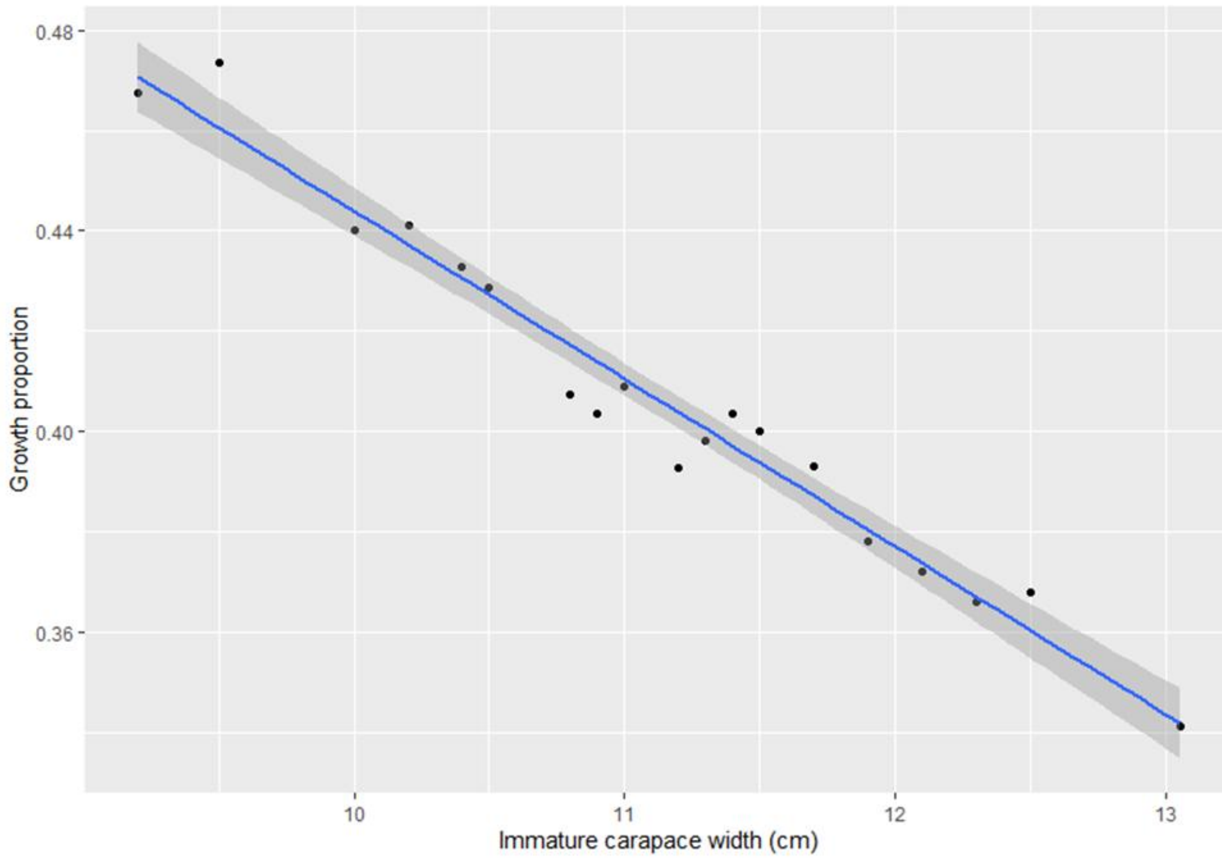

Figure 1.3. Estimated relationship between carapace width and growth proportion for female blue crabs. Growth proportion was estimated as the proportional difference between paired percentiles of the pre-pubertal and mature female carapace width distributions. Each point represents the 5^{th}-95^{th} percentiles in 5% increments.

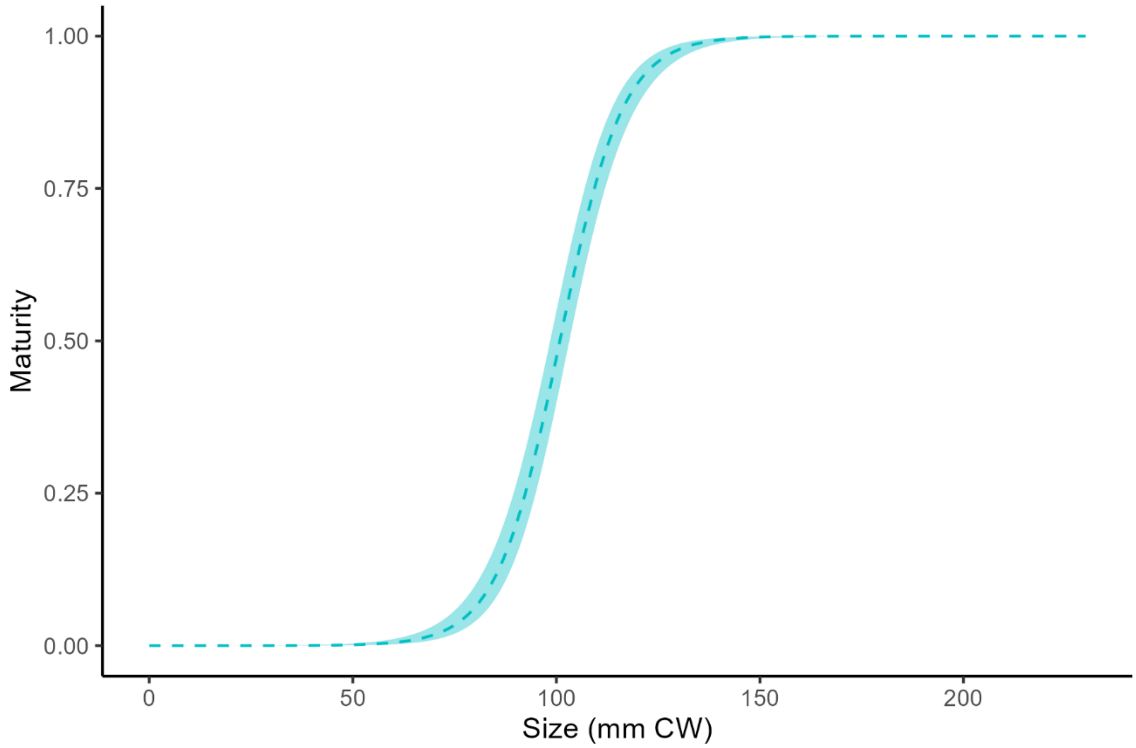

Figure 1.4. Predicted probability (dashed line), and 95% confidence interval (shaded area), of a male blue crab being of mature as a function of size for the chosen model, with size, month, year, and station (as a random effect) included as predictor variables. CW is the crab carapace width, measured as the distance between the tips of the lateral spines, in mm.

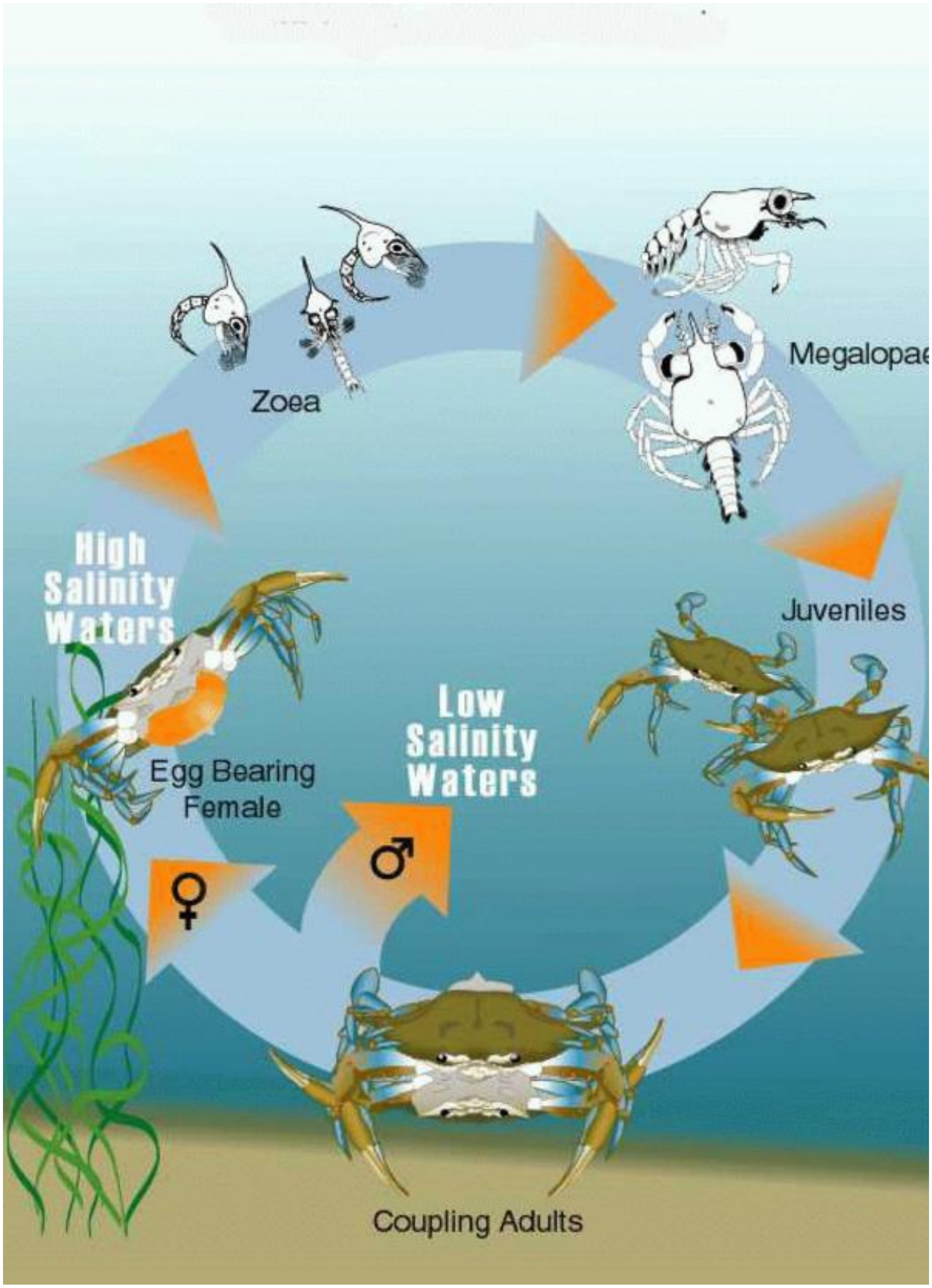

Figure 1.5. Diagram of the blue crab life cycle as it relates to salinity.

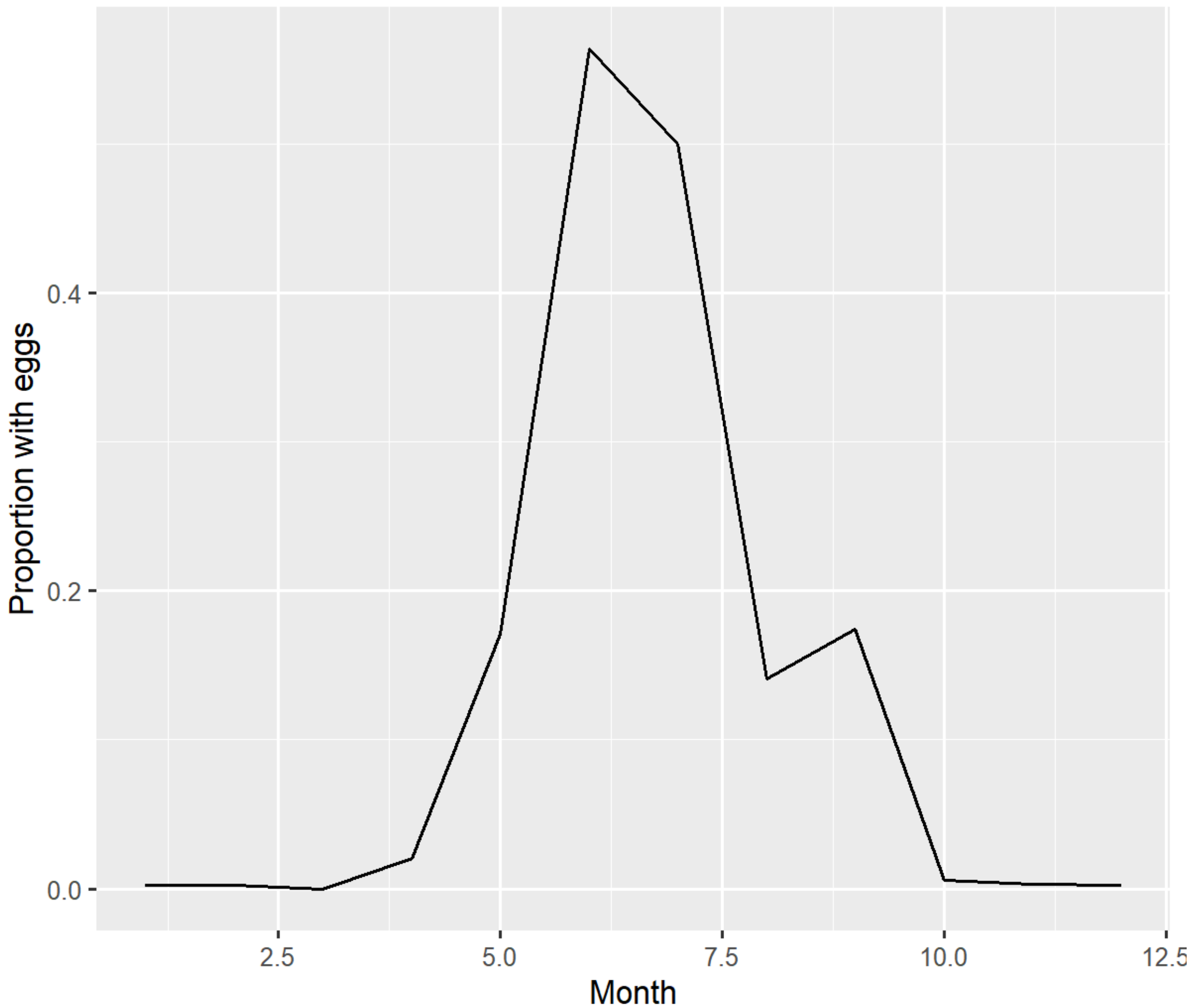

Figure 1.6. Estimated proportion of mature female blue crabs that spawn in each month in Chesapeake Bay from observations of females with eggs from a combination of surveys in Maryland and Virginia.

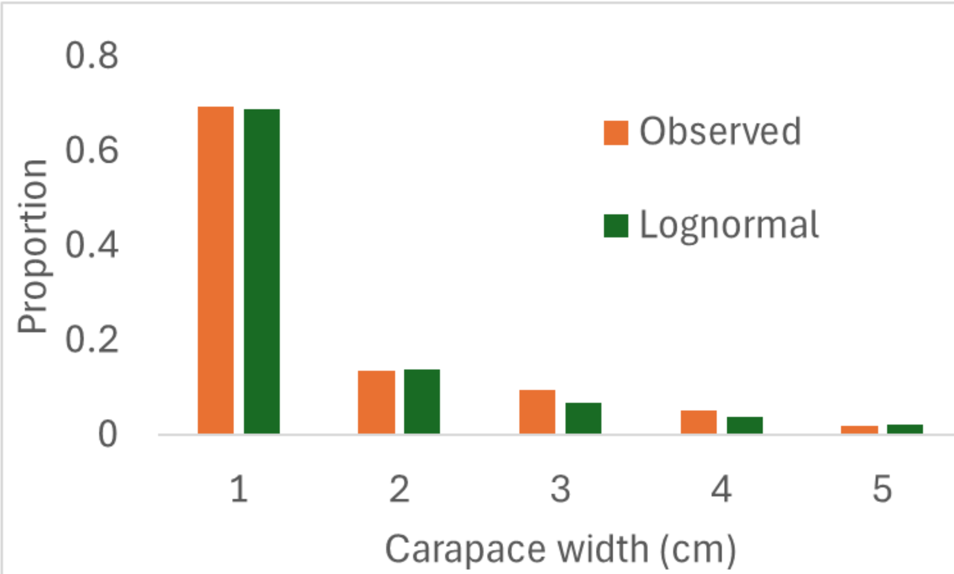

Figure 1.7. Observed and predicted size distribution of age-0 blue crabs in winter in 1 cm carapace width bins. The first bin is an aggregate bin of all crabs < 2 cm.

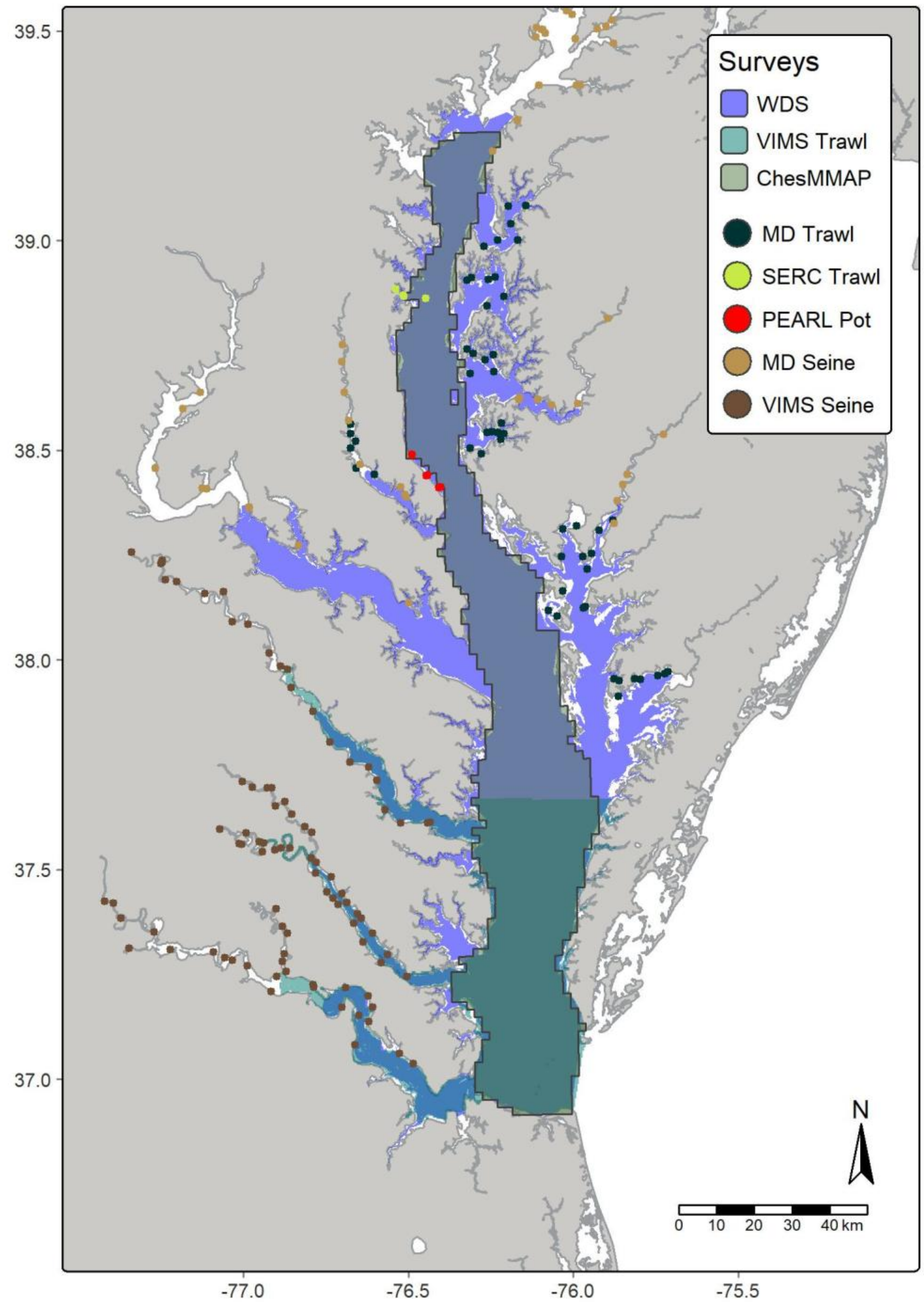

Figure 2.1. Spatial extent of the 8 surveys considered as part of this analysis: WDS (Winter Dredge Survey); VIMS Trawl (Juvenile Finfish & Blue Crab Trawl Survey); ChesMMAP (Chesapeake Bay Multispecies Monitoring and Assessment Program; MD Trawl (Maryland Trawl

Survey); SERC Trawl, Smithsonian Environmental Research Center Trawl Survey; PEARL Pot (PEARL Pot Survey); MD Seine (Maryland Juvenile Striped Bass Survey); VIMS Seine (VIMS Juvenile Striped Bass Seine Survey).

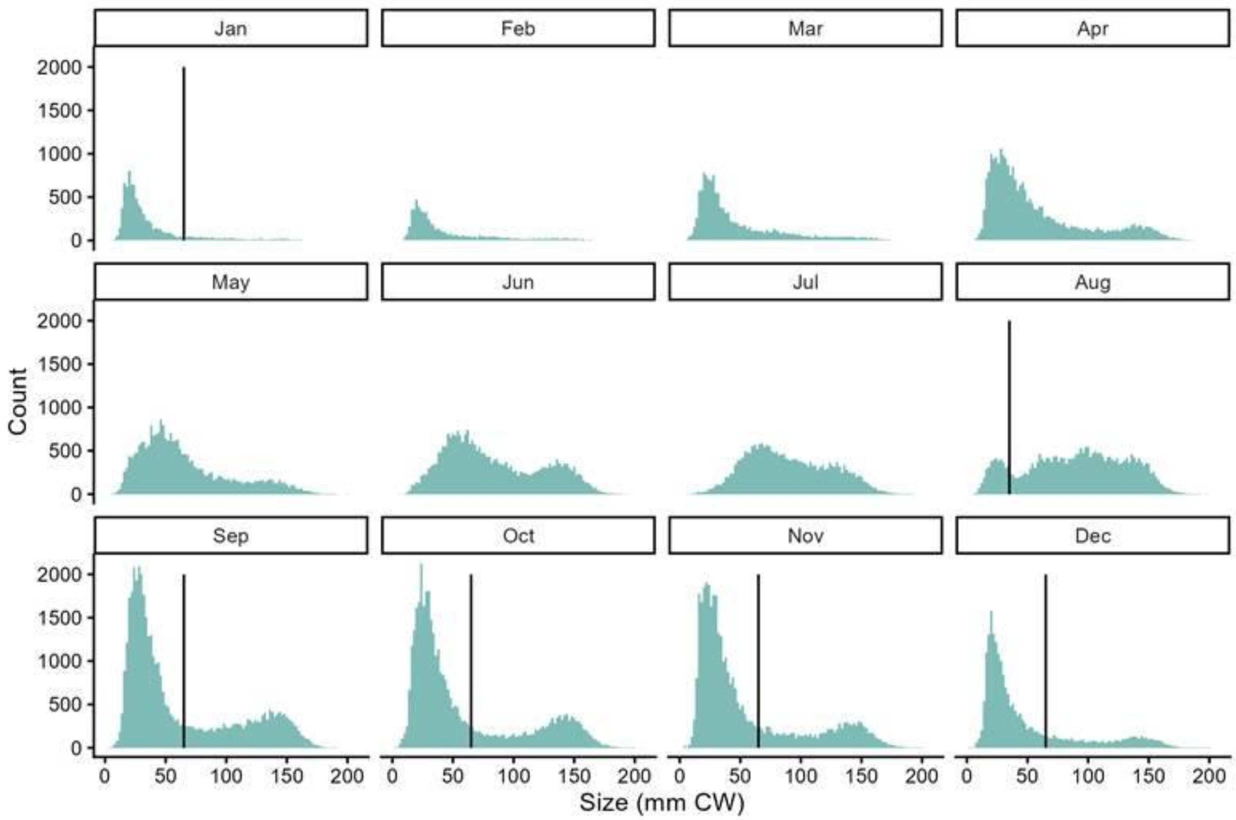

Figure 2.2. Monthly length-frequency distributions of Blue Crabs taken in the VIMS Trawl (Juvenile Finfish & Blue Crab Trawl Survey), 1994-2023. Vertical black bar represents the size-cutoffs used to designate recruits (35 mm in Aug and 65 mm from Sep-Jan).

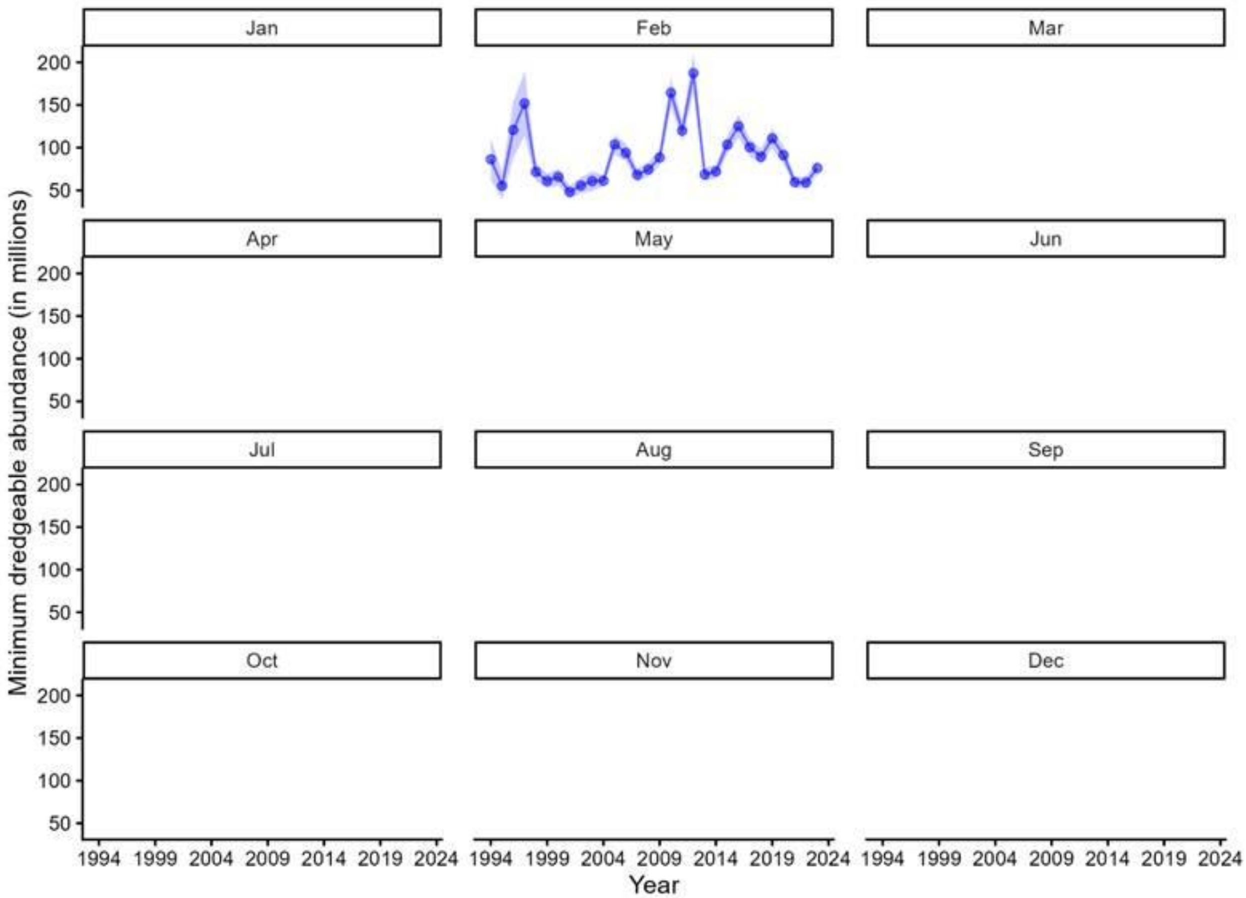

Figure 2.3. Standardized indices of abundance from the Winter Dredge Survey (WDS), from the spatiotemporal (VAST) model. Indices represent minimum dredgeable abundance within the WDS sampling frame.

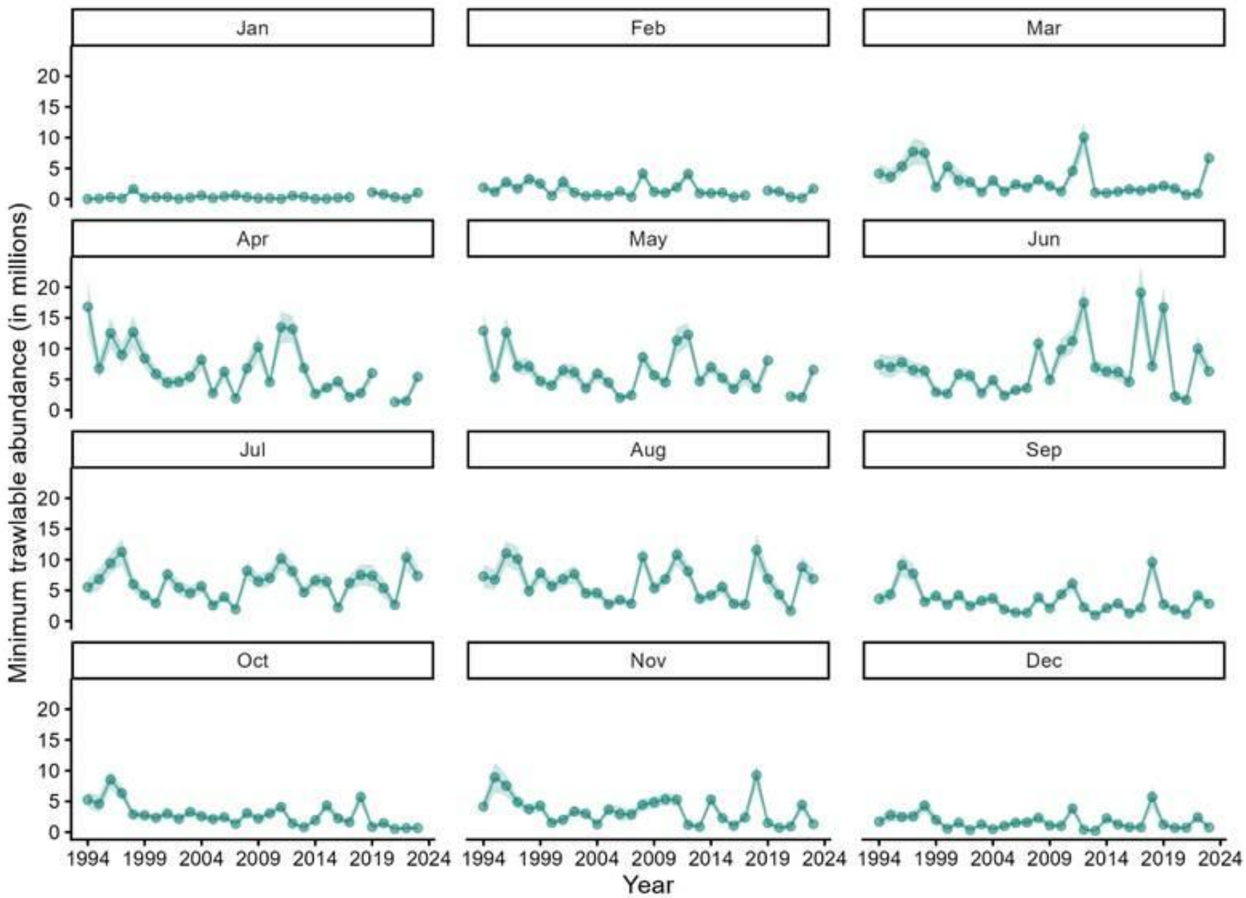

Figure 2.4. Standardized indices of abundance from the Juvenile Finfish & Blue Crab Trawl Survey (VIMS Trawl), from the spatiotemporal (VAST) model. Indices represent minimum trawlable abundance within the VIMS Trawl sampling frame (Virginia waters of Chesapeake Bay south of the Rappahannock River). Note that recruits (< 35 mm CW in Aug and < 65 mm in Sep-Jan) have been removed prior to index standardization.

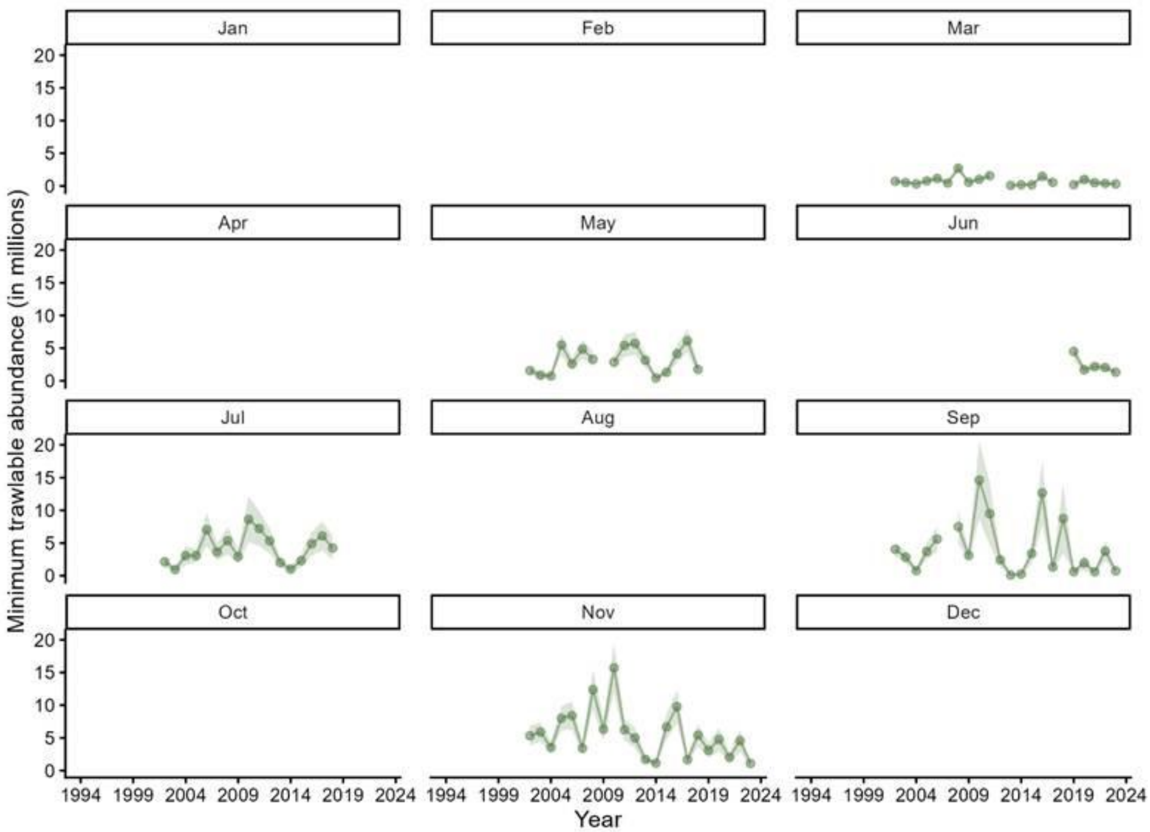

Figure 2.5. Standardized indices of abundance from Chesapeake Bay Multispecies Monitoring and Assessment Program (ChesMMAP), from the spatiotemporal (VAST) model. Indices represent minimum trawlable abundance within the ChesMMAP sampling frame (mainstem Chesapeake Bay). Note that recruits (< 35 mm CW in Aug and < 65 mm in Sep-Jan) have been removed prior to index standardization.

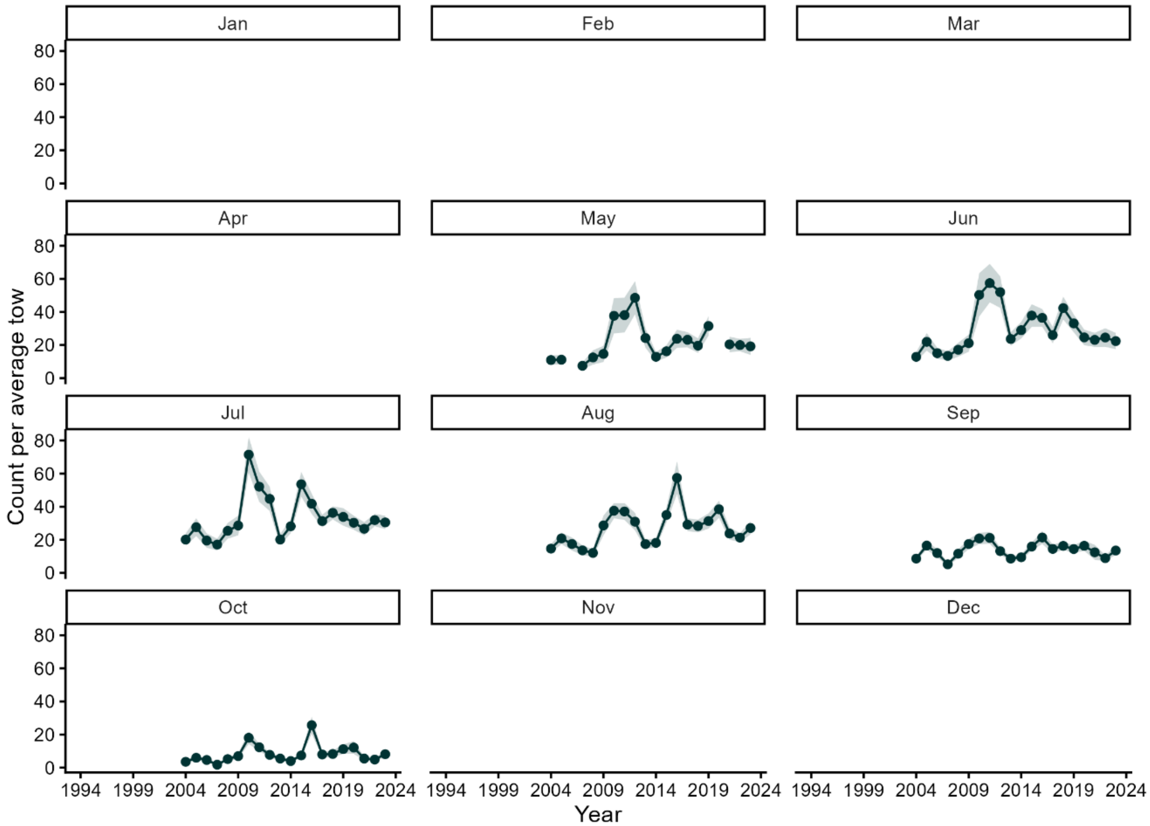

Figure 2.6. Standardized indices of abundance from MD Trawl Surveys (including the Blue Crab Summer Trawl Survey and SERC Trawl Survey), from the gamlss model. Indices represent count per average tow. Note that recruits (< 35 mm CW in Aug and < 65 mm in Sep-Jan) have been removed prior to index standardization.

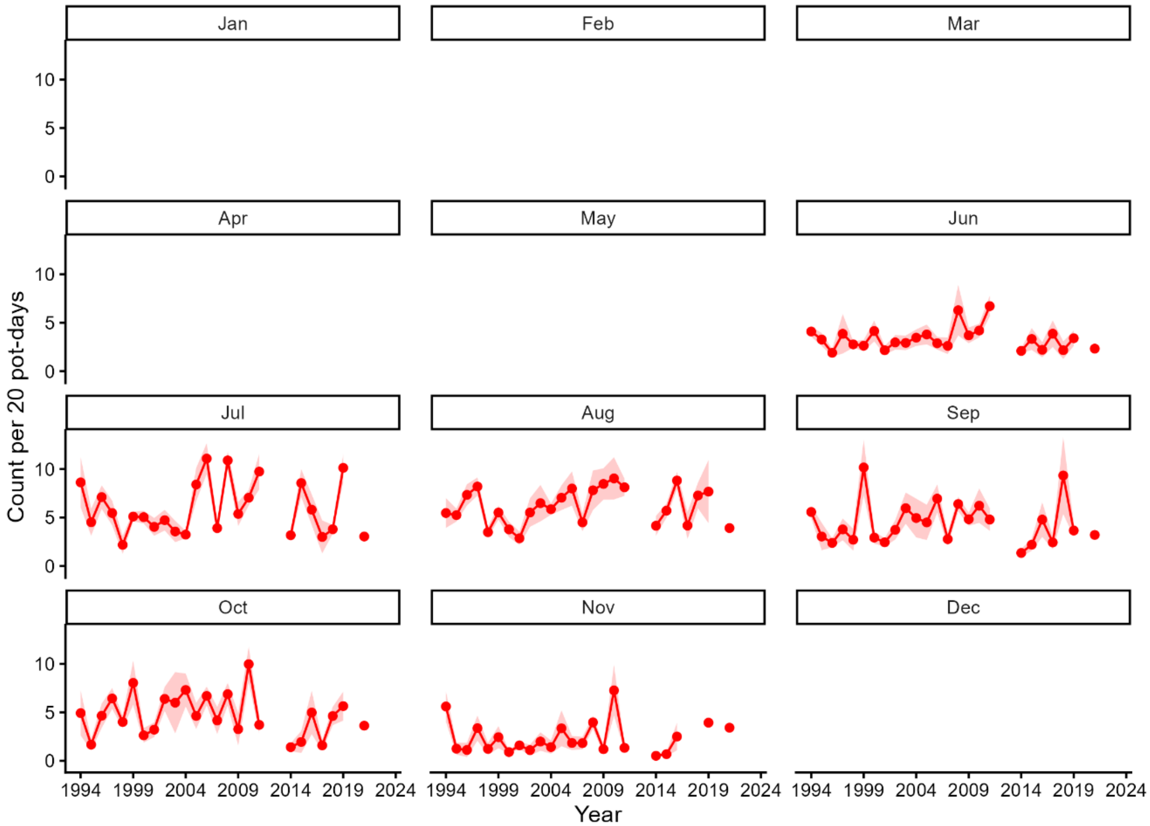

Figure 2.7. Standardized indices of abundance from PEARL Pot Survey (PEARL Pot), from the gamlss model. Indices represent average count per round (20 pot-days). Note that recruits (< 35 mm CW in Aug and < 65 mm in Sep-Jan) have been removed prior to index standardization.

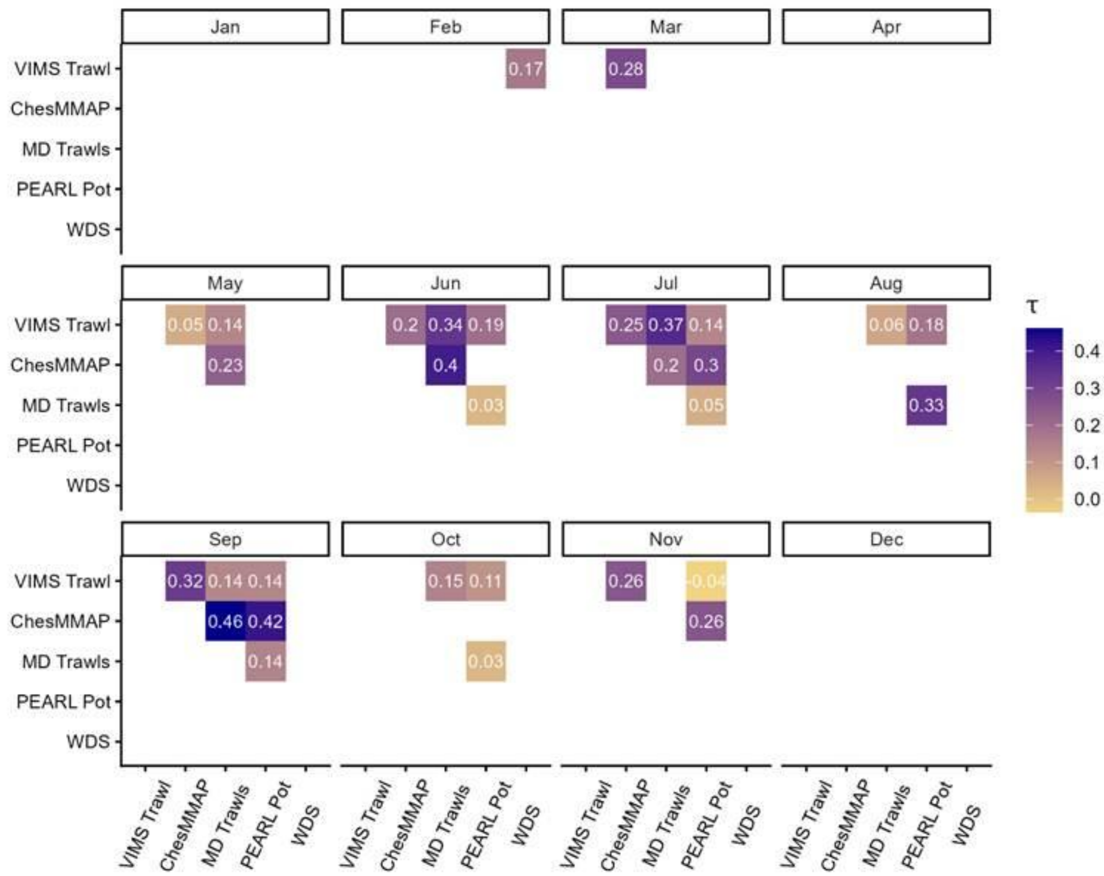

Figure 2.8. Kendall rank correlation coefficient, comparing the monthly standardized indices between the surveys: WDS (Winter Dredge Survey); VIMS Trawl (Juvenile Finfish & Blue Crab Trawl Survey); ChesMMAP (Chesapeake Bay Multispecies Monitoring and Assessment Program; MD Trawls, including the MD DNR Blue Crab Summer Trawl Survey and SERC Trawl Survey (Smithsonian Environmental Research Center Trawl Survey); and PEARL Pot (PEARL Abbe Pot Survey). The June ChesMMAP and PEARL Pot correlation was not provided as only two years of overlap were available.

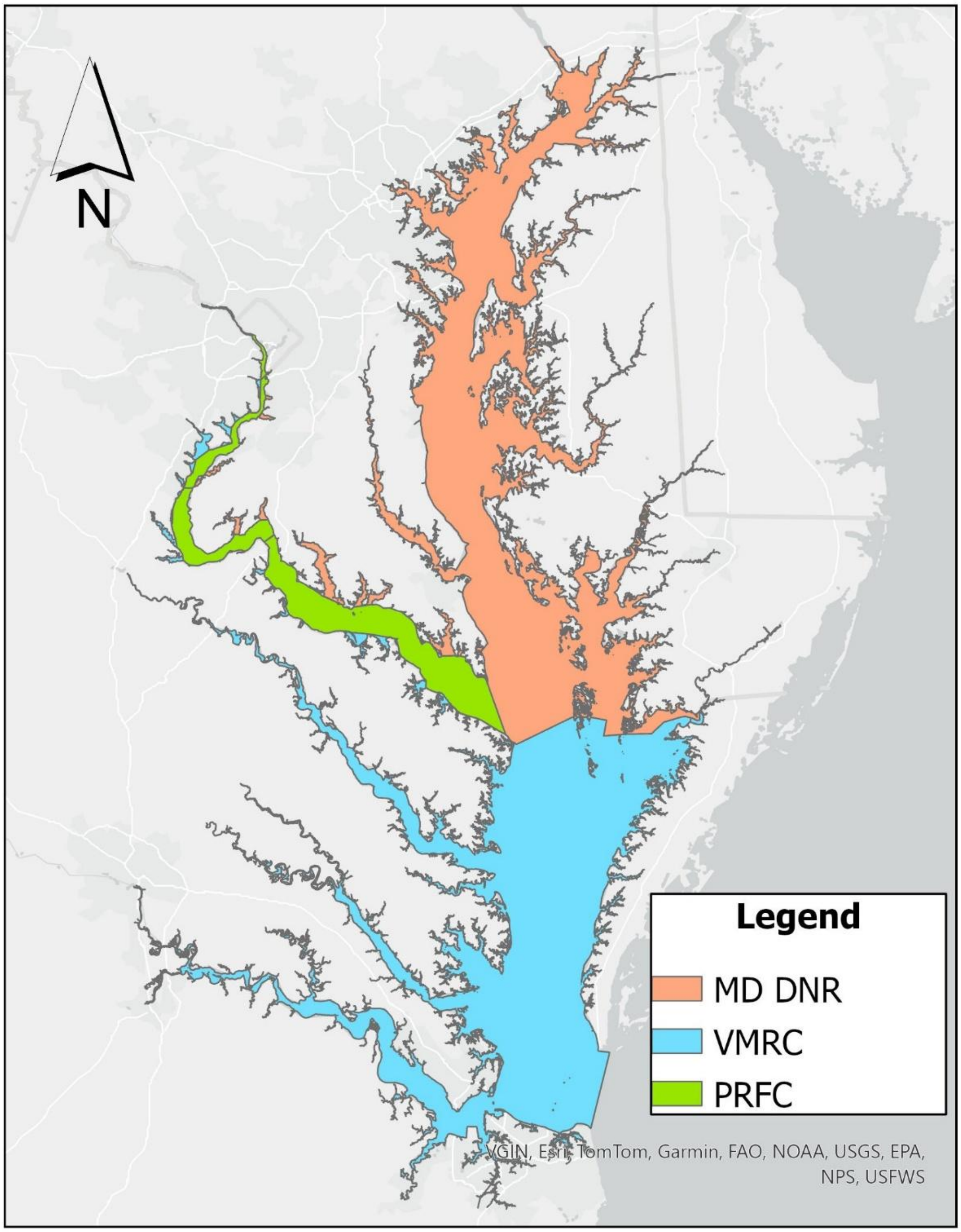

Figure 3.1. Map of fishery management jurisdictions in Chesapeake Bay. The three jurisdictions are Maryland Department of Natural Resources (MD DNR), the Virginia Marine Resources Commission (VMRC), and the Potomac River Fisheries Commission (PRFC).

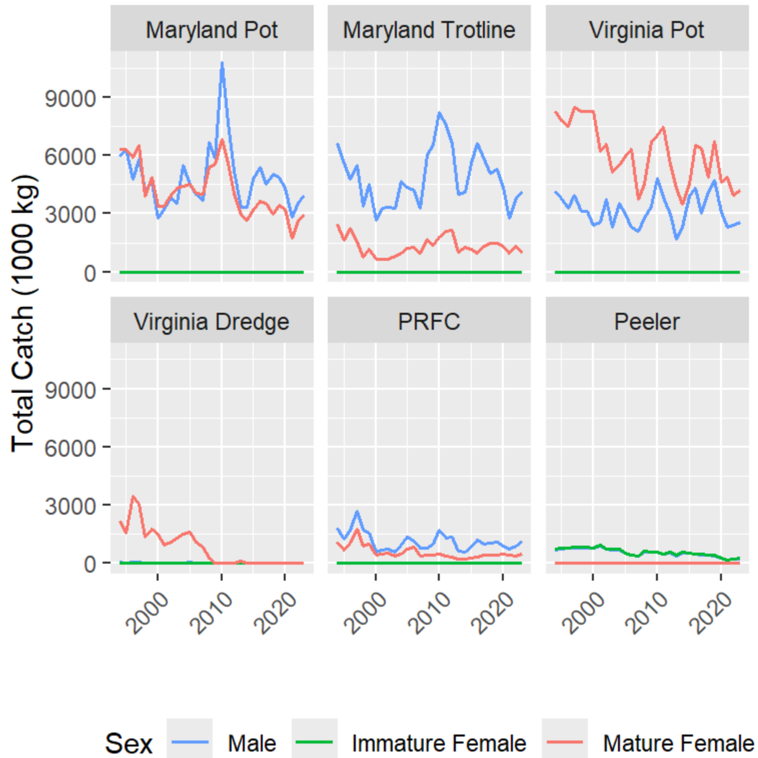

Figure 3.2. Estimated catch of blue crabs by sex and fleet in Chesapeake Bay during 1994-2023. Estimated catch includes adjustments for dead discards from the commercial fishery and recreational catch. Note that there was male catch in the Virginia dredge fishery, but the amounts were small, and that male and immature female catches were assumed to be equal in the peeler fishery.

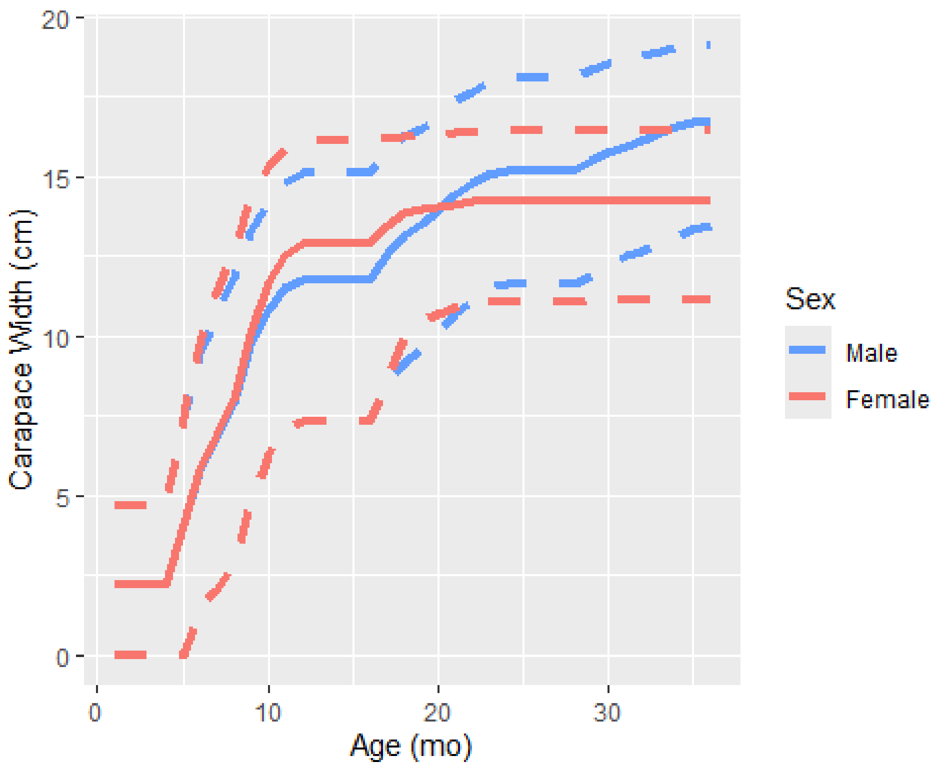

Figure 4.1. Blue crab carapace width (cm) by age in months by sex from the stochastic Gompertz growth. Blue lines represent males and red lines represent females. Dashed lines represent upper and lower 95% intervals of the size distributions.

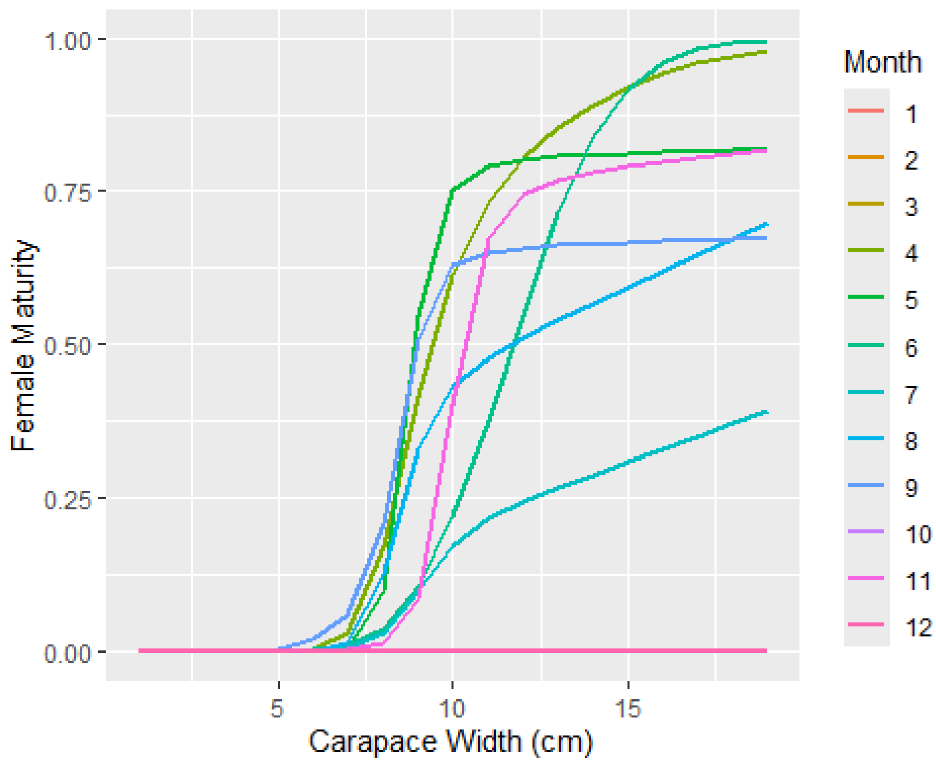

Figure 4.2. Female blue crab maturity at carapace width (cm) for each month as estimated external to the model.

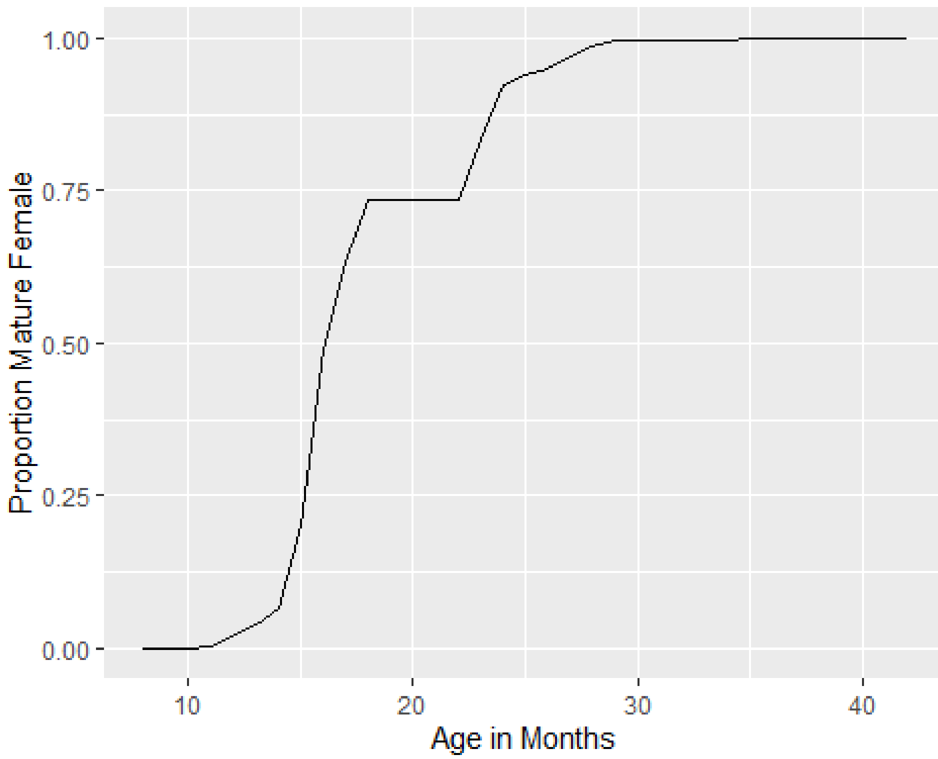

Figure 4.3. Proportion of mature females at age in months given the female growth and maturation models.

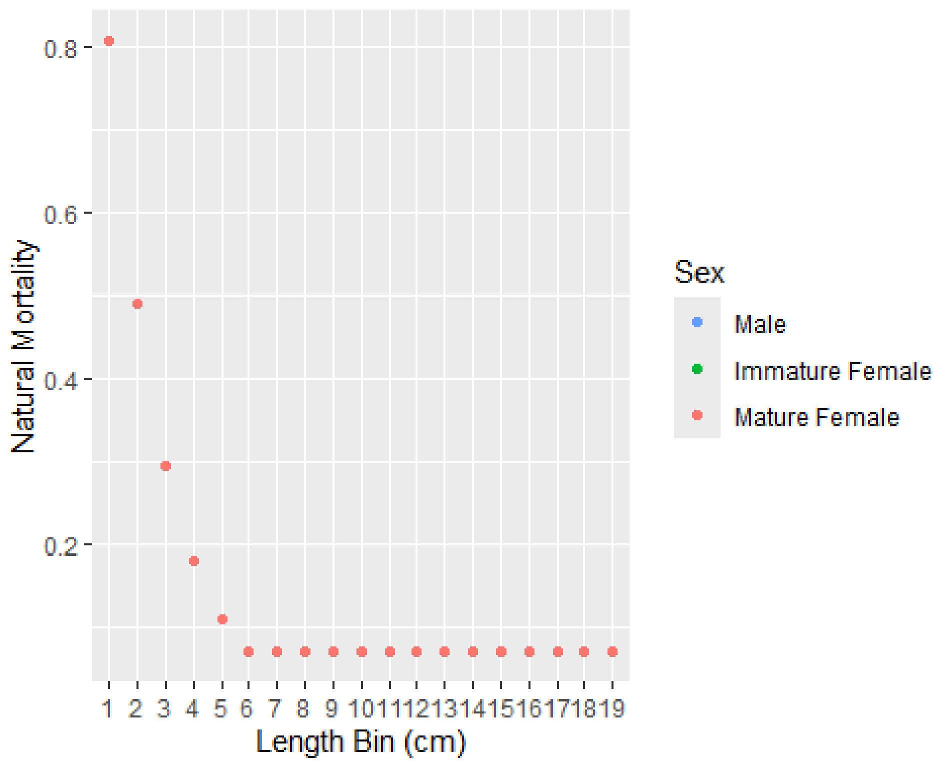

Figure 4.4. Natural mortality (mo^{-1}) by length bin in centimeters for each sex category. Note that all sex-maturity categories had the same natural mortality for a given length bin.

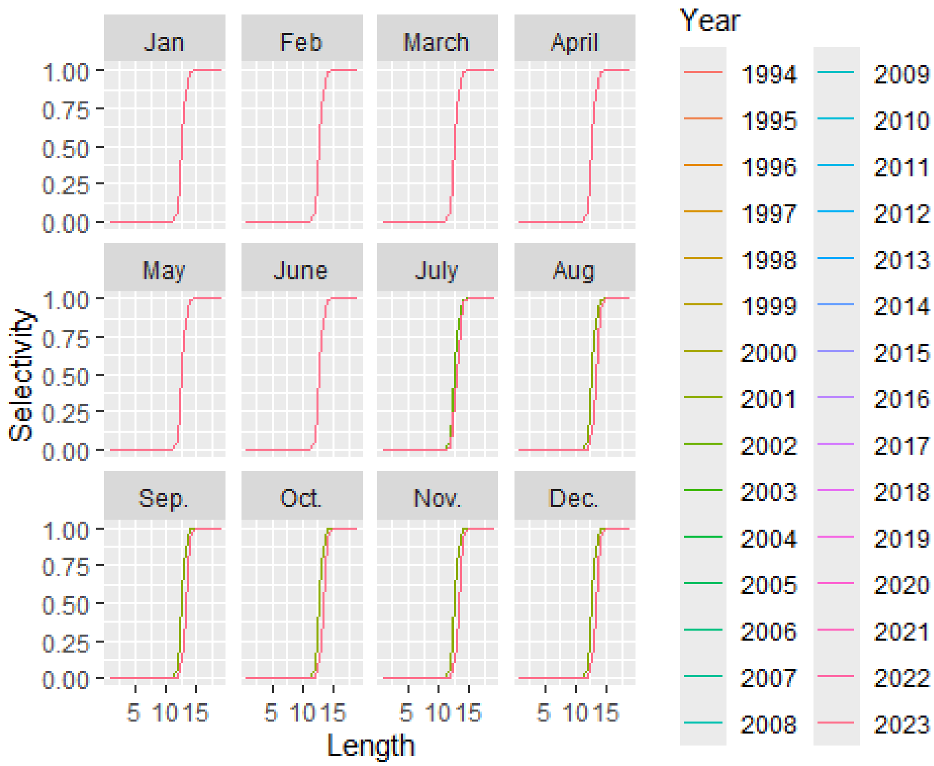

Figure 4.5. Fishery selectivity by length (cm) for Maryland pot fleet. Each panel represents a month.

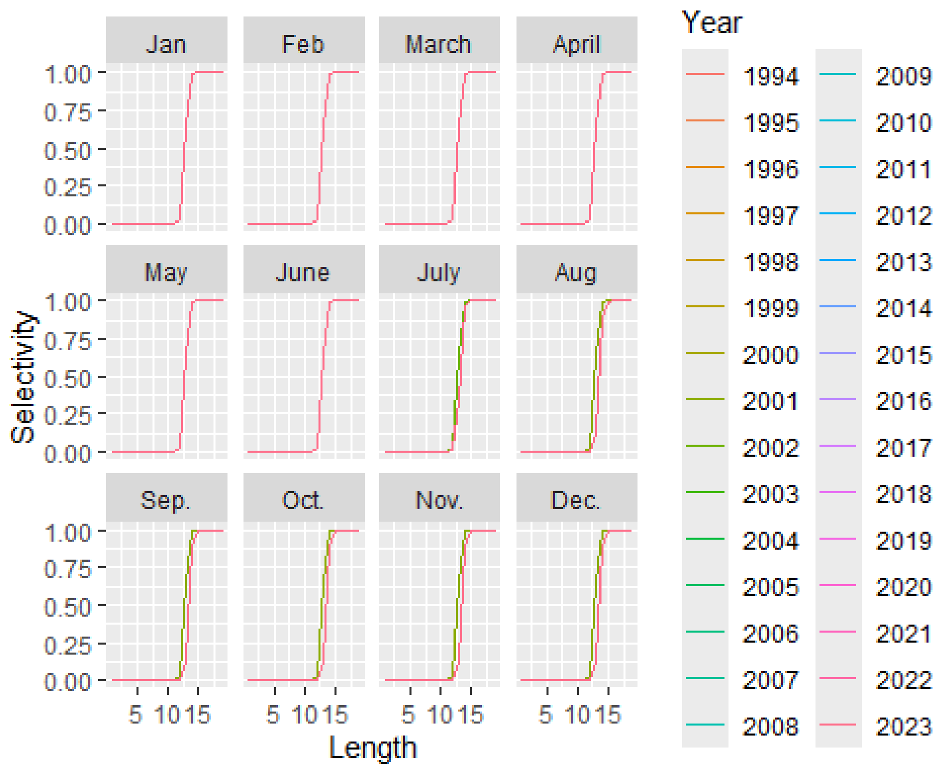

Figure 4.6. Fishery selectivity by length (cm) for the Maryland trotline fleet. Each panel represents a month.

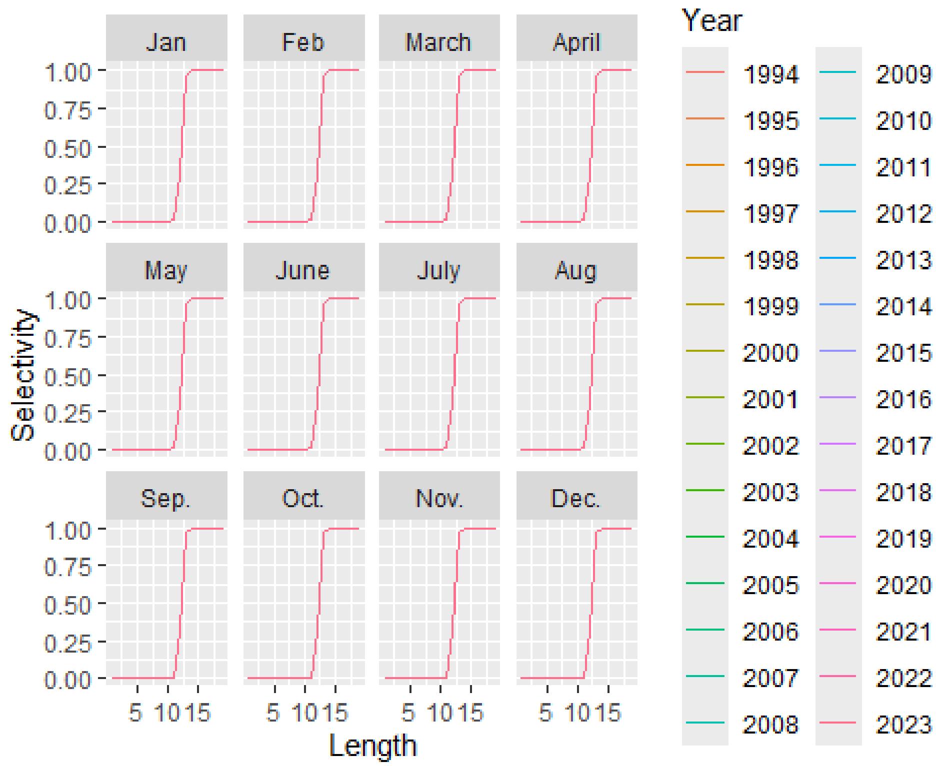

Figure 4.7. Fishery selectivity by length (cm) for Virginia pot fleet. Each panel represents a month.

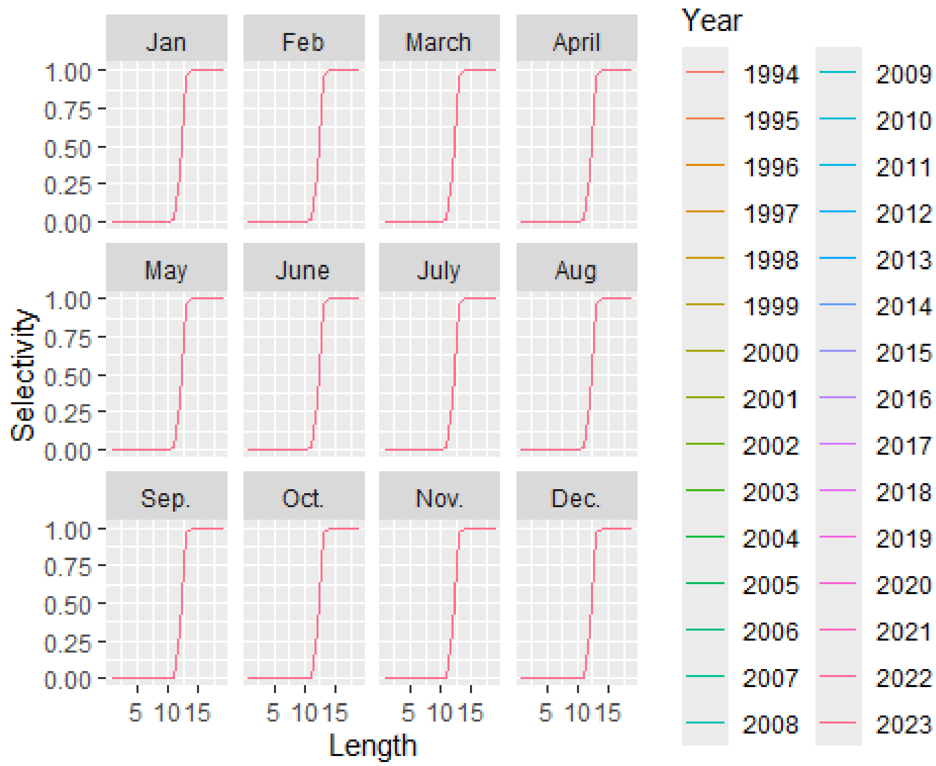

Figure 4.8. Fishery selectivity by length (cm) for Virginia dredge fleet. Each panel represents a month.

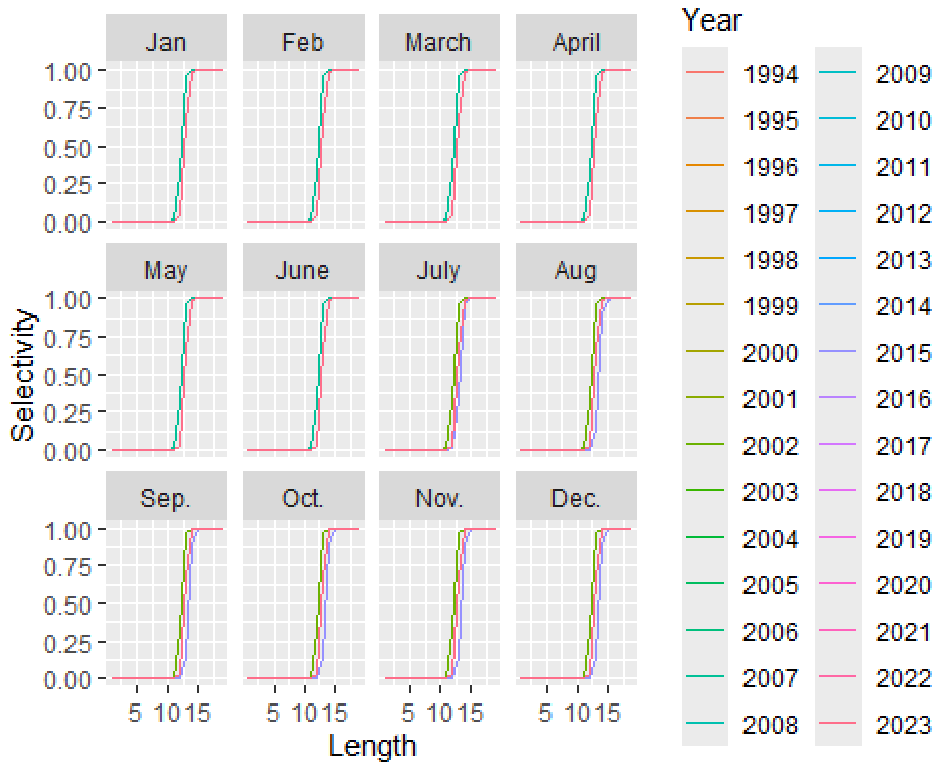

Figure 4.9. Fishery selectivity by length (cm) for the Potomac River hard crab fleet. Each panel represents a month.

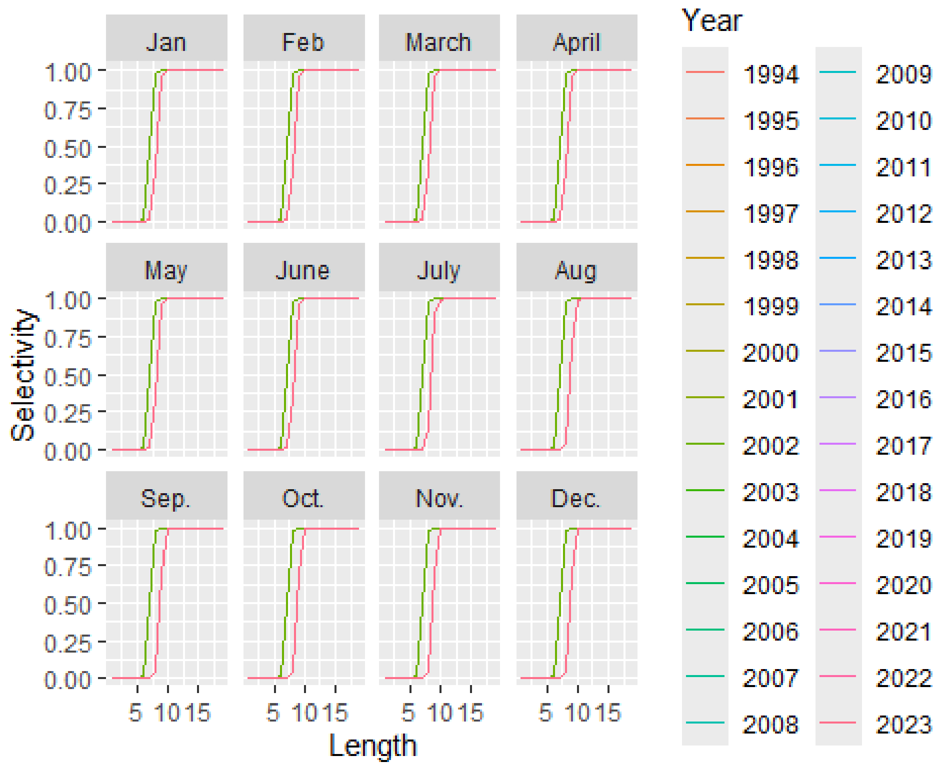

Figure 4.10. Fishery selectivity by length (cm) for peeler fleet. Each panel represents a month.

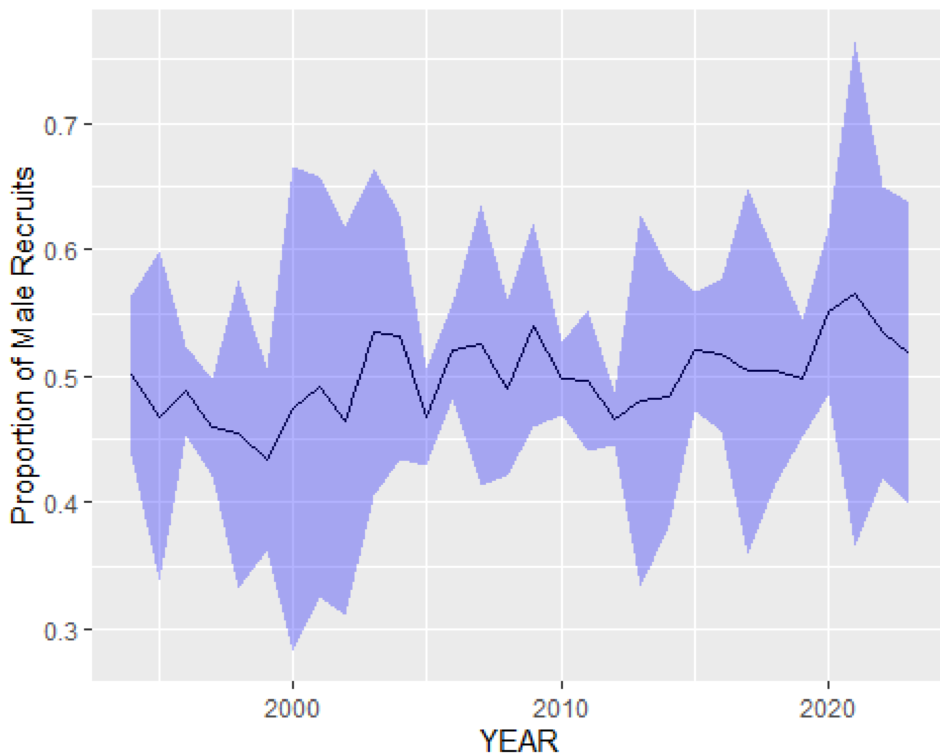

Figure 4.11. Proportion of male recruits (line) during 1994-2023 from the Winter Dredge Survey estimated using a cluster sampling estimator with 95% confidence intervals (shaded region).

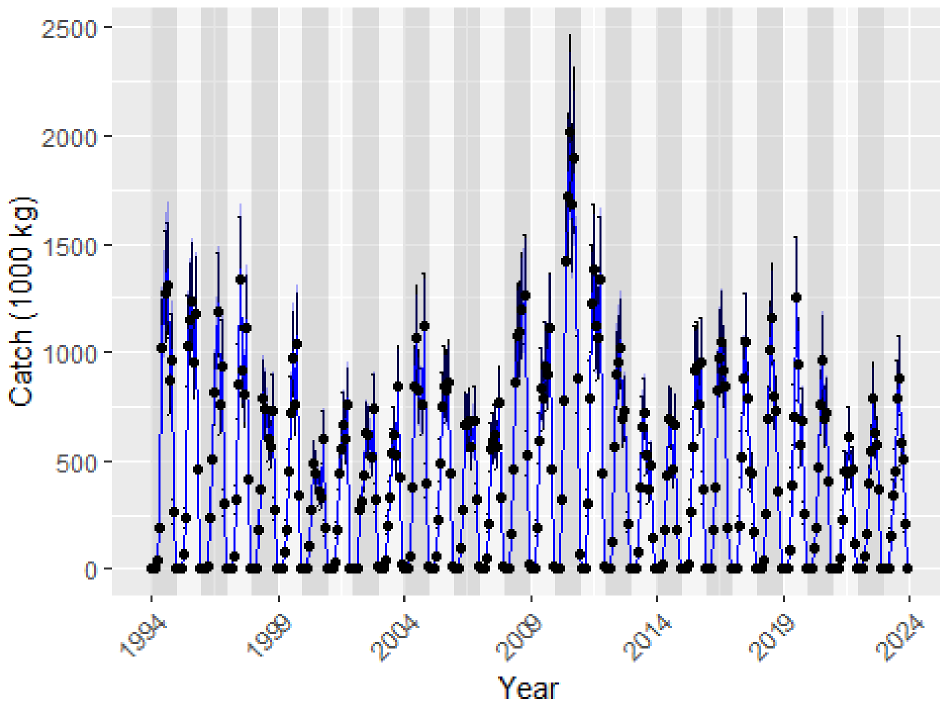

Figure 4.12. Fit of total catch for the Maryland pot fleet males. Model estimates are the solid blue line with 95% confidence intervals in the shaded region and the observed values are the black points with whiskers representing the confidence intervals.

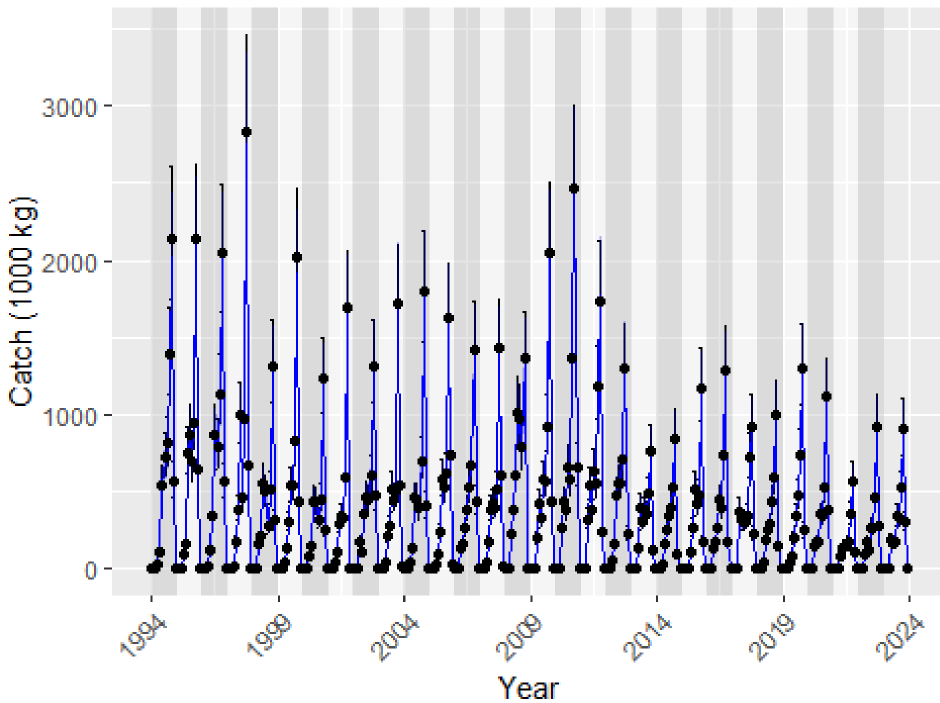

Figure 4.13. Fit of total catch for the Maryland pot fleet mature females. Symbols are the same as Figure 4.12.

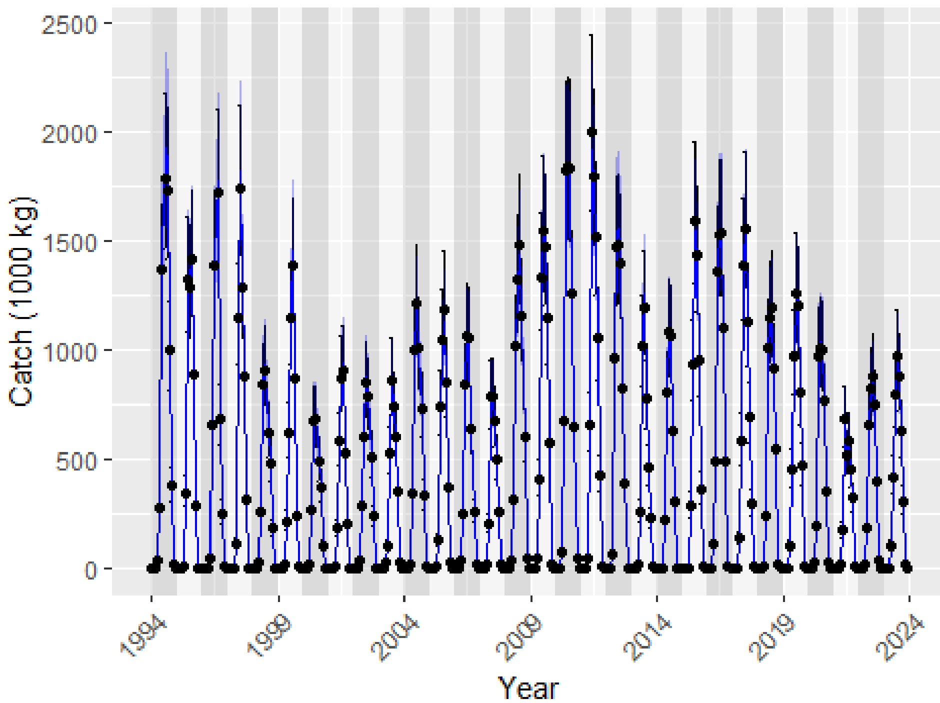

Figure 4.14. Fit of total catch for the Maryland trotline fleet males. Symbols are the same as Figure 4.12.

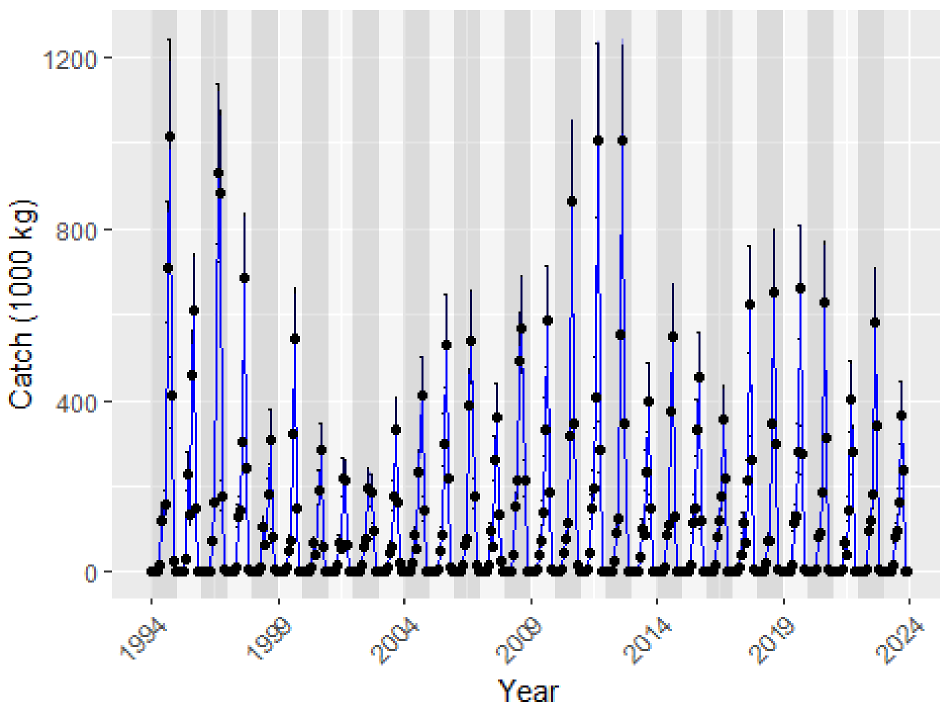

Figure 4.15. Fit of total catch for the Maryland trotline fleet mature females. Symbols are the same as Figure 4.12.

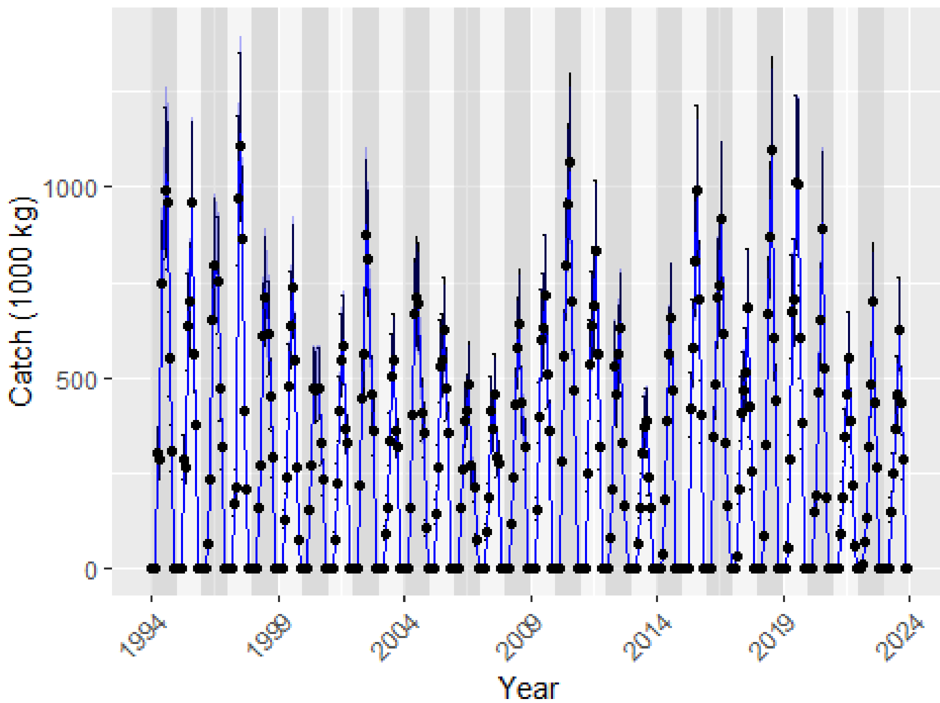

Figure 4.16. Fit of total catch for the Virginia pot fleet males. Symbols are the same as Figure 4.12.

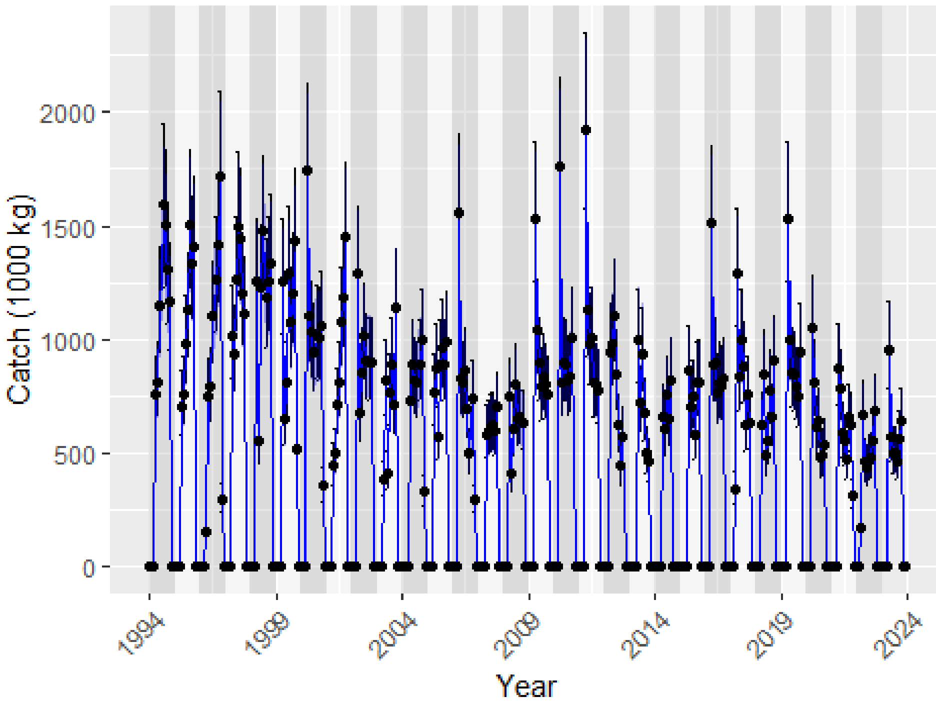

Figure 4.17. Fit of total catch for the Virginia pot fleet mature females. Symbols are the same as Figure 4.12.

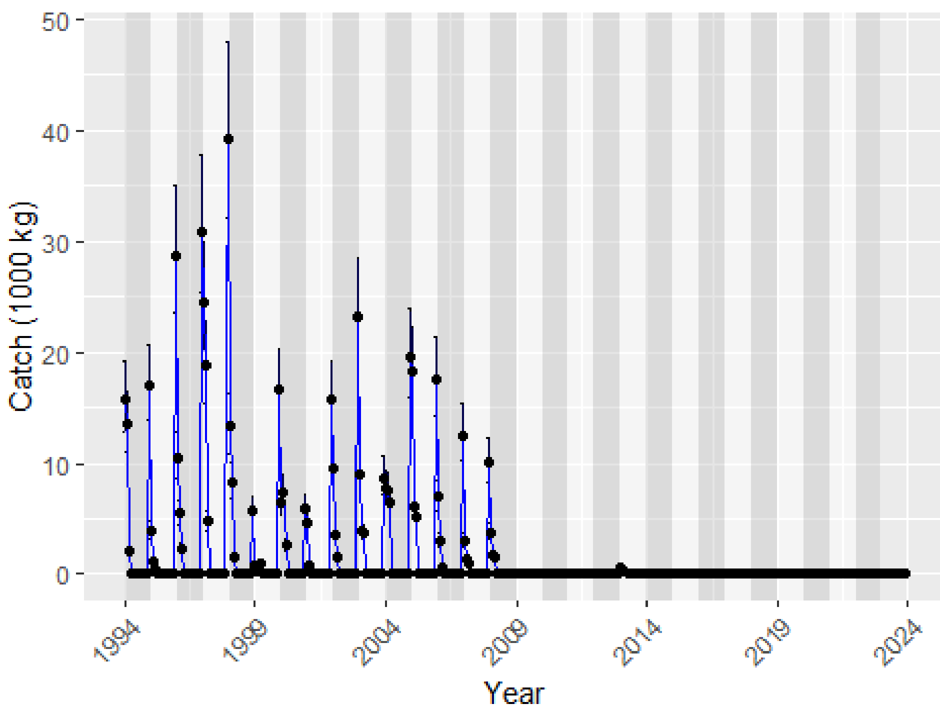

Figure 4.18. Fit of total catch for the Virginia dredge fleet males. Symbols are the same as Figure 4.12.

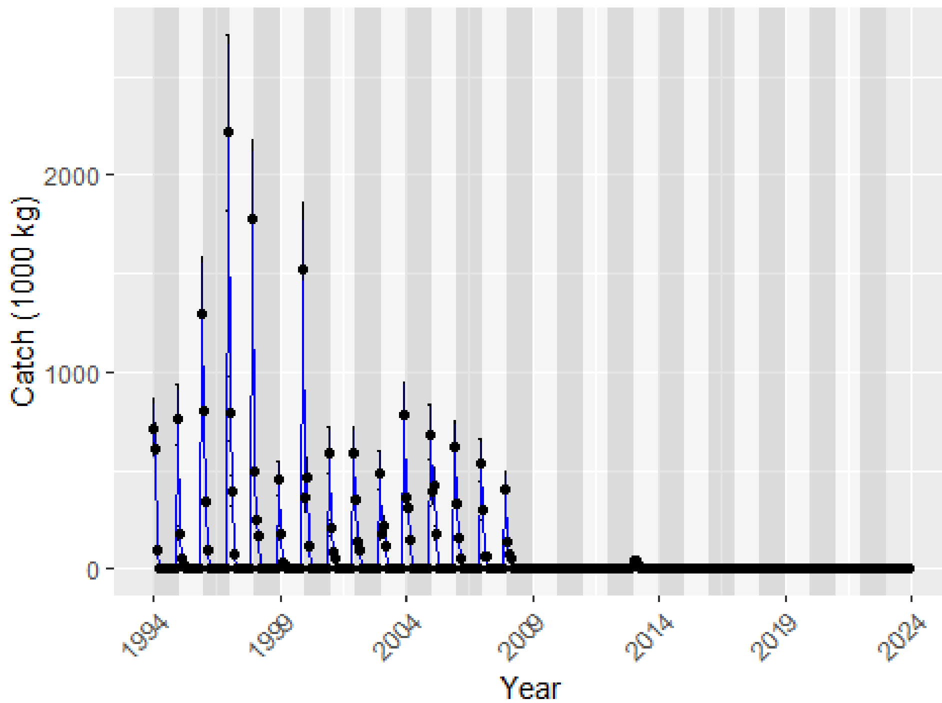

Figure 4.19. Fit of total catch for the Virginia dredge fleet mature females. Symbols are the same as Figure 4.12.

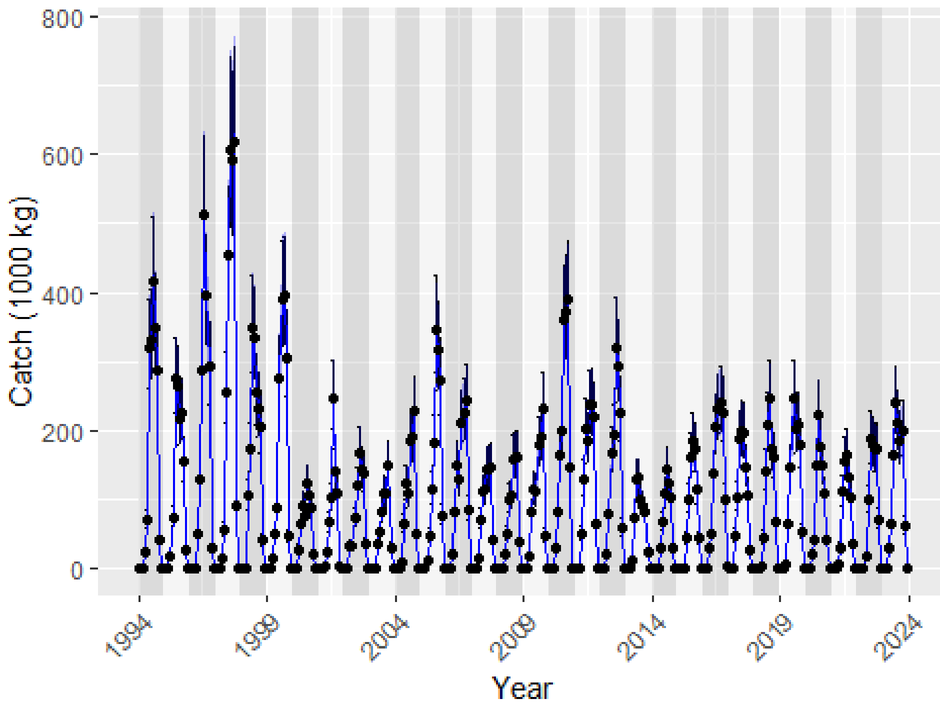

Figure 4.20. Fit of total catch for the PRFC fleet males. Symbols are the same as Figure 4.12.

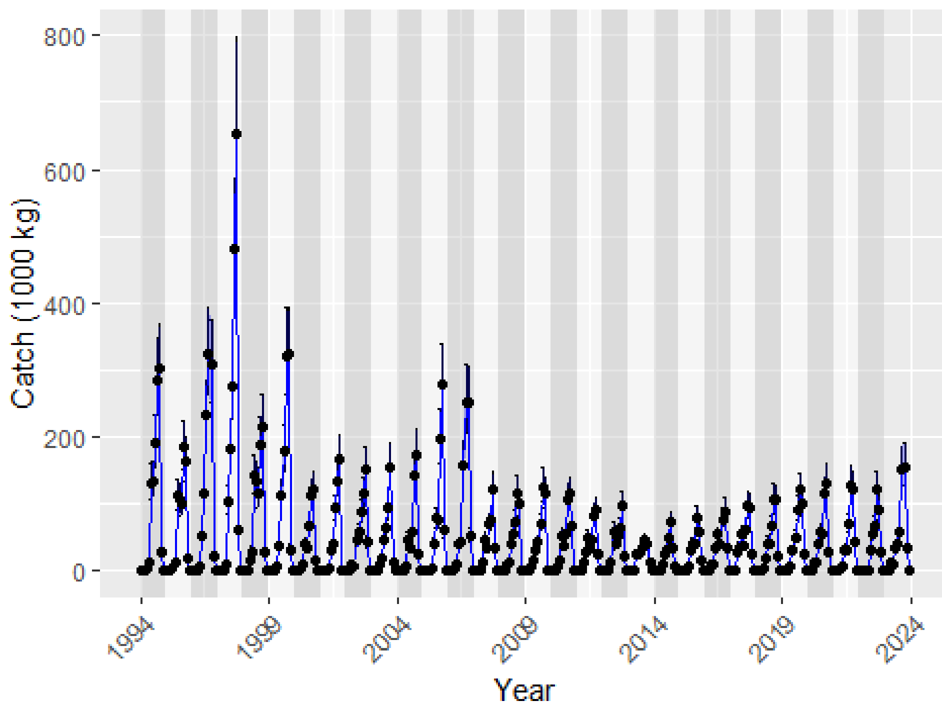

Figure 4.21. Fit of total catch for the PRFC pot fleet mature females. Symbols are the same as Figure 4.12.

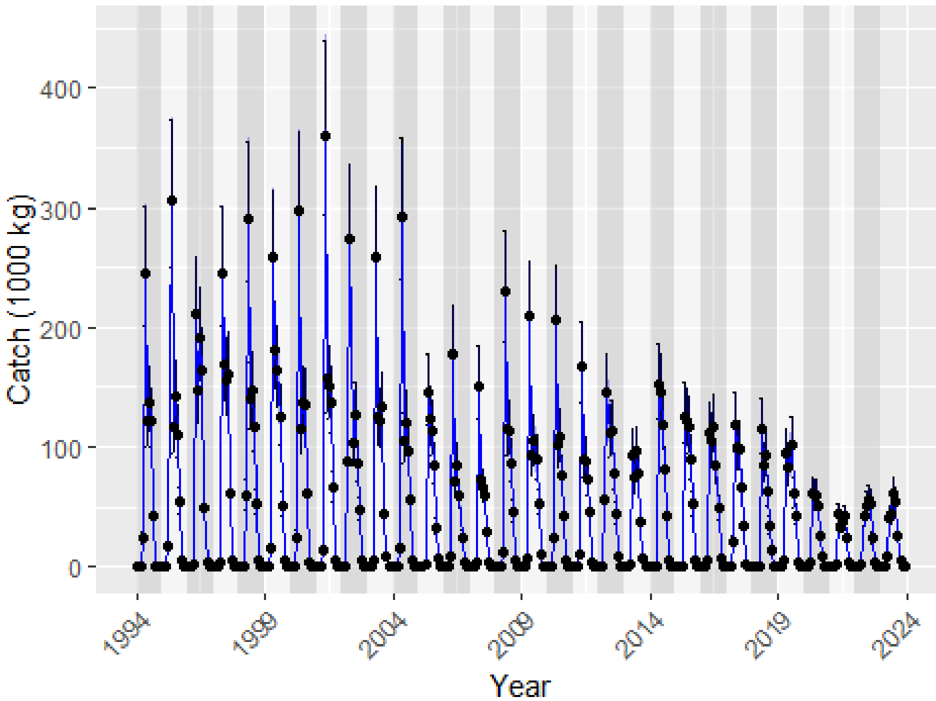

Figure 4.22. Fit of total catch for the peeler fleet males. Symbols are the same as Figure 4.12.

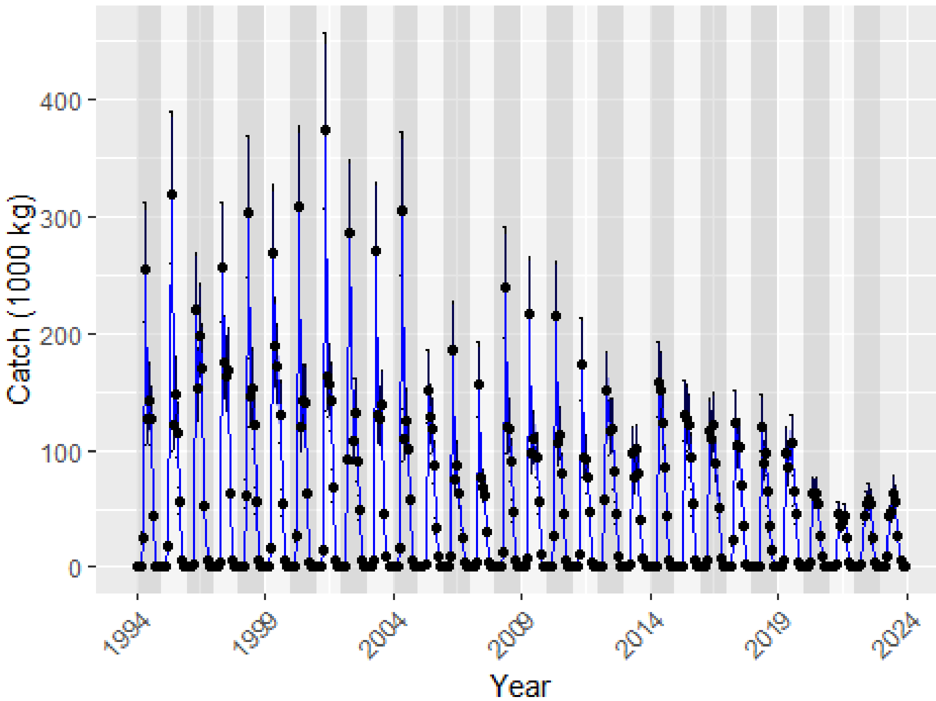

Figure 4.23. Fit of total catch for the peeler fleet immature females. Symbols are the same as Figure 4.12.

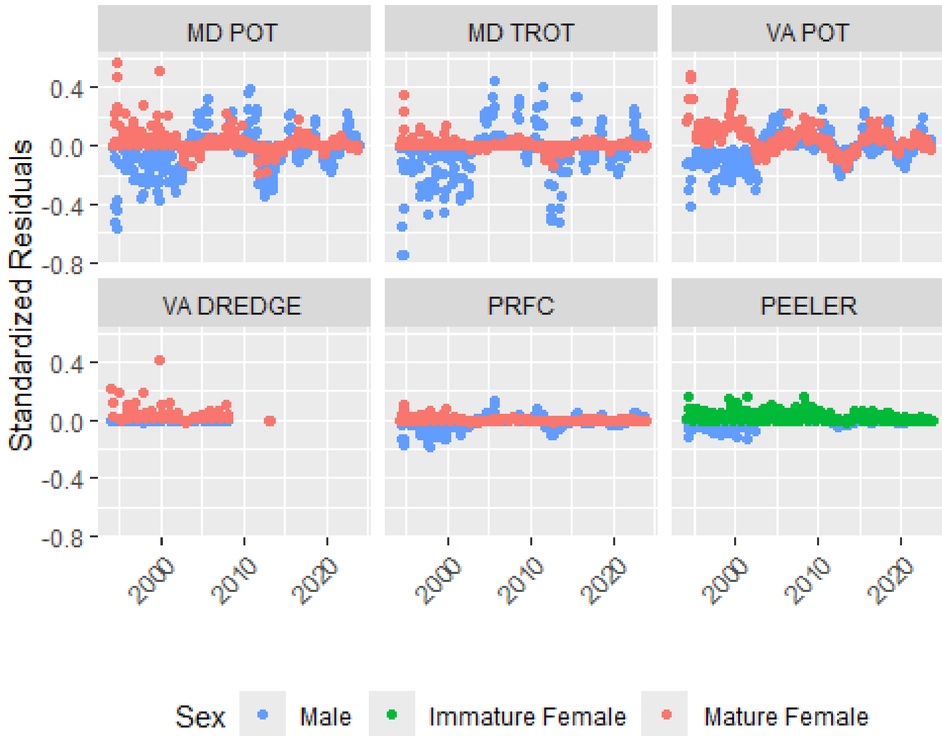

Figure 4.24. Standardized residuals over time for each fleet and sex category.

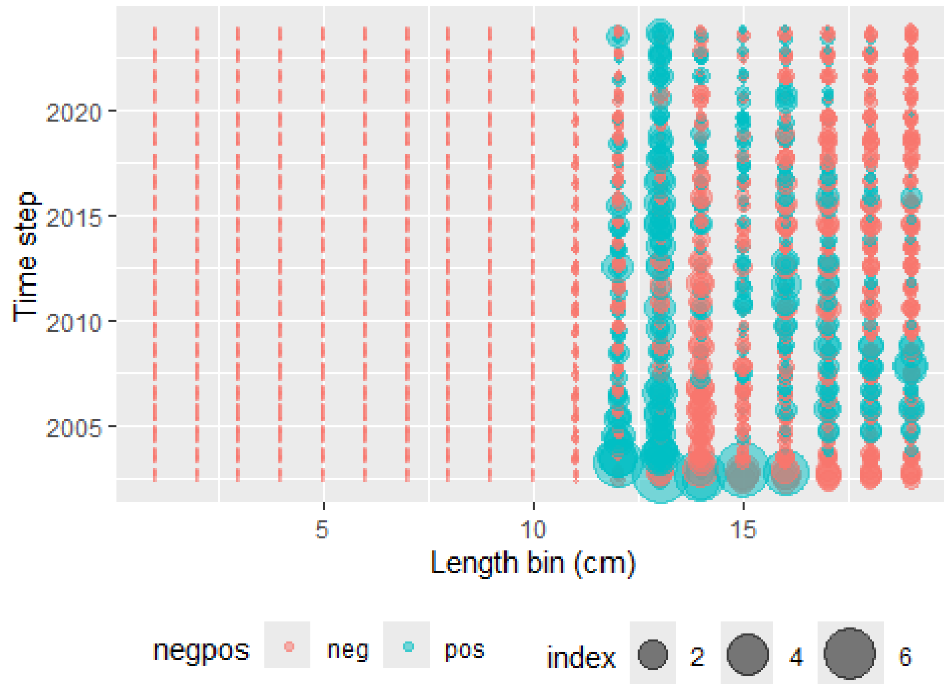

Figure 4.25. Standardized residuals for proportions-at-length over time for Maryland pot fleet males. Negative residuals are red and positive residuals are blue. Size of the bubble reflects size of residual.

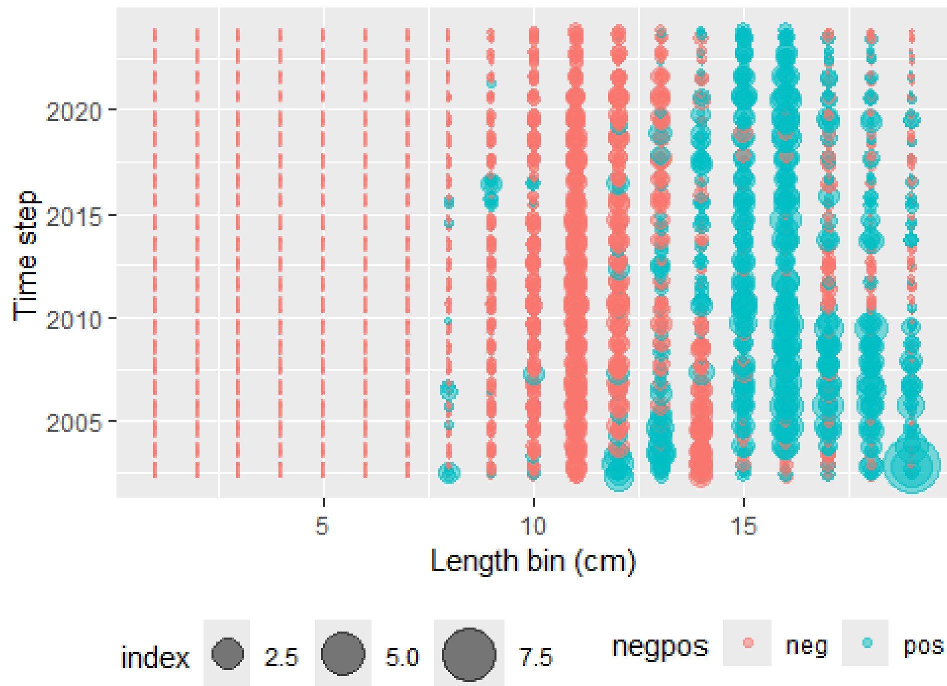

Figure 4.26. Standardized residuals for proportions-at-length over time for Maryland pot fleet mature females. Plot definitions are the same as Figure 4.25.

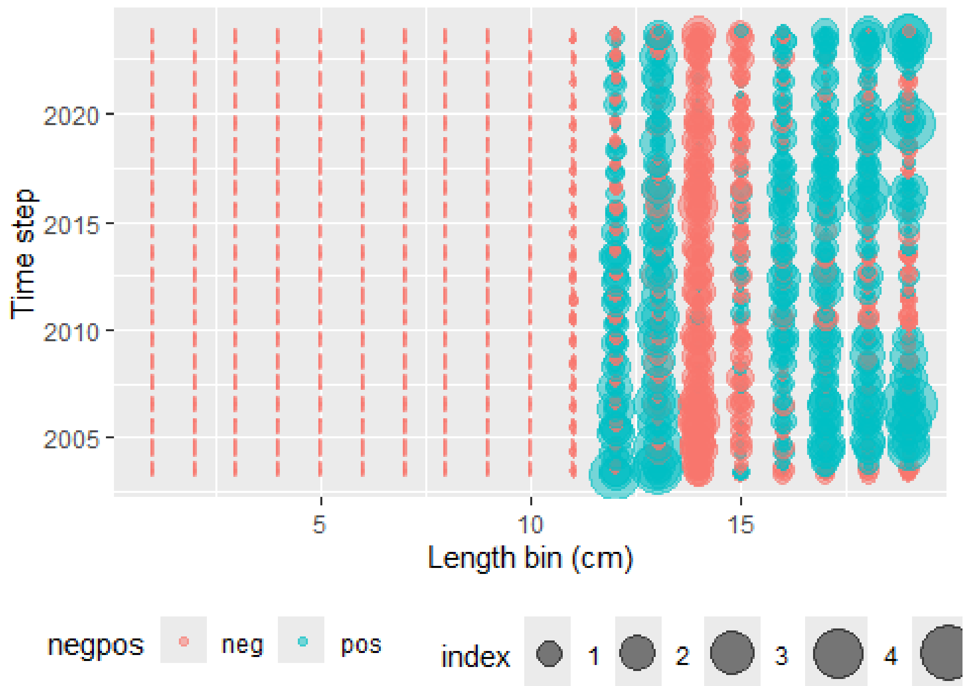

Figure 4.27. Standardized residuals for proportions-at-length over time for Maryland trotline fleet males. Plot definitions are the same as Figure 4.25.

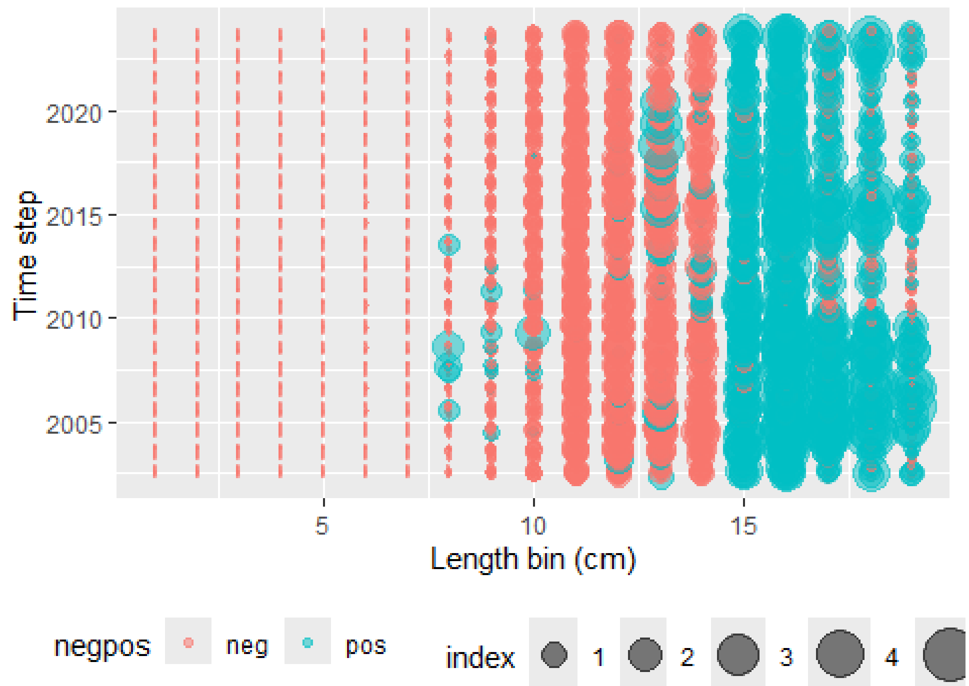

Figure 4.28. Standardized residuals for proportions-at-length over time for Maryland trotline fleet mature females. Plot definitions are the same as Figure 4.25.

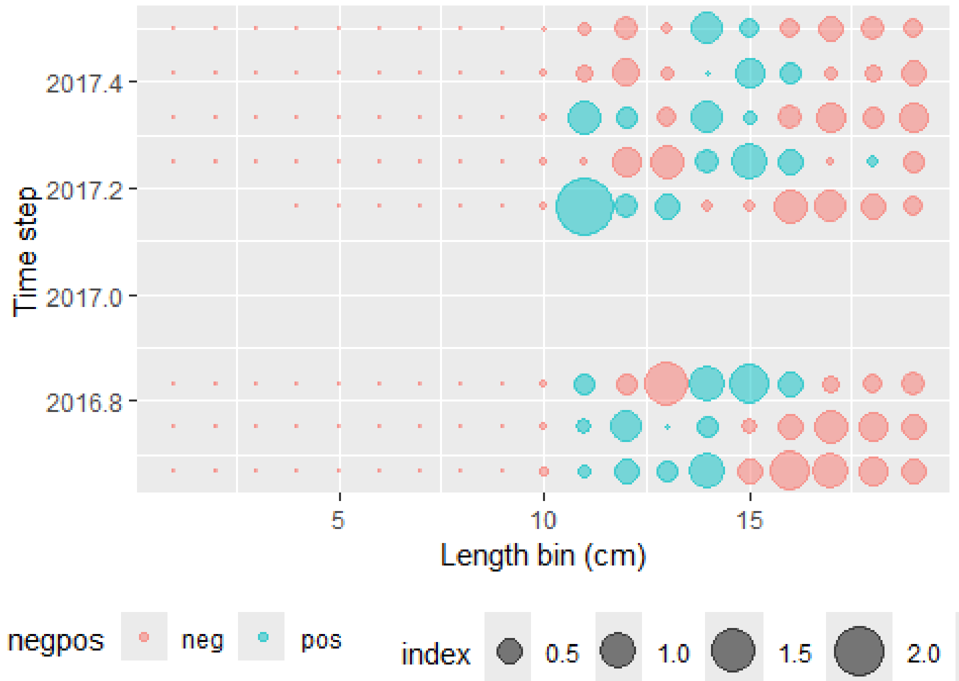

Figure 4.29. Standardized residuals for proportions-at-length over time for Virginia pot fleet males. Plot definitions are the same as Figure 4.25.

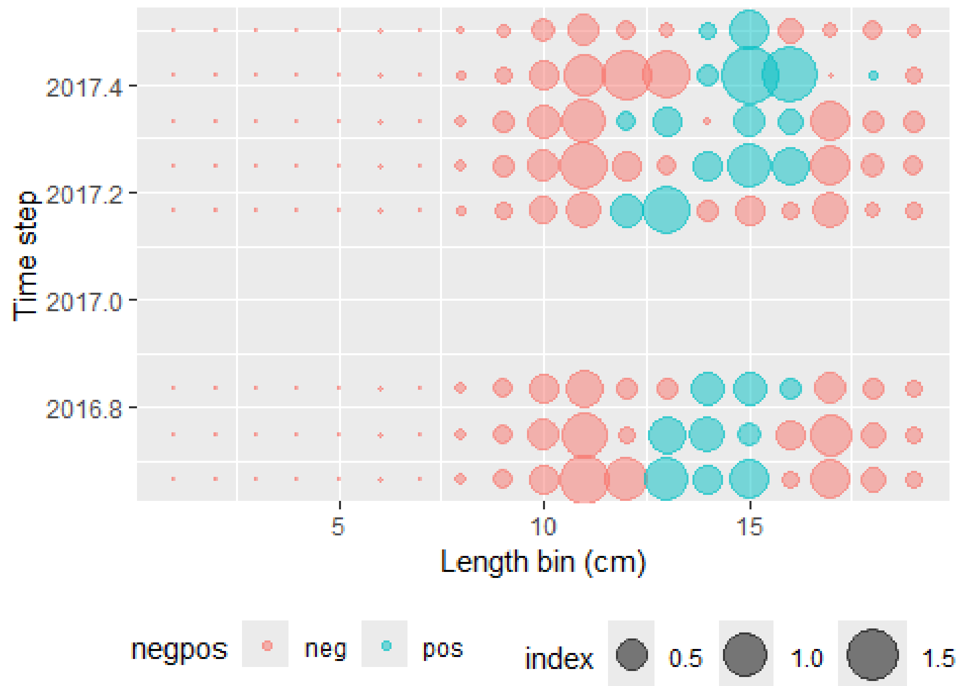

Figure 4.30. Standardized residuals for proportions-at-length over time for Virginia pot fleet mature females. Plot definitions are the same as Figure 4.25.

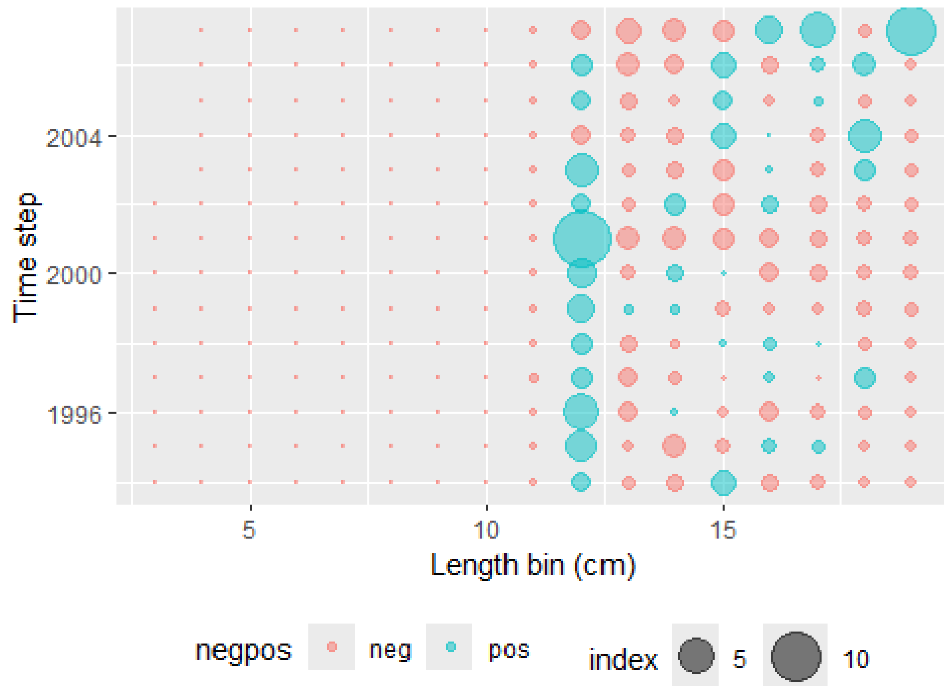

Figure 4.31. Standardized residuals for proportions-at-length over time for Virginia dredge fleet males. Plot definitions are the same as Figure 4.25.

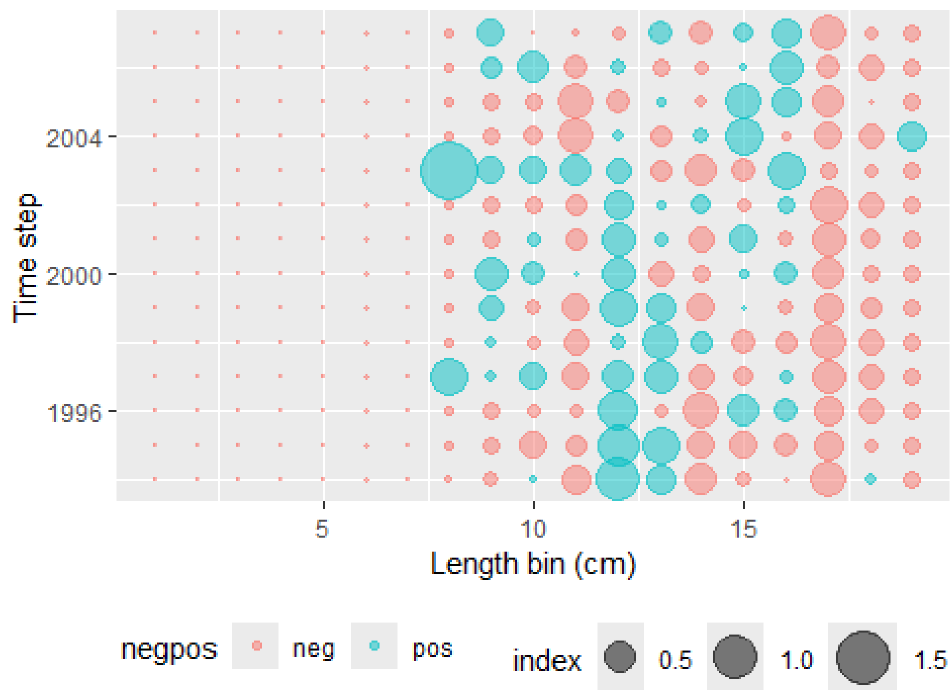

Figure 4.32. Standardized residuals for proportions-at-length over time for Virginia dredge fleet mature females. Plot definitions are the same as Figure 4.25.

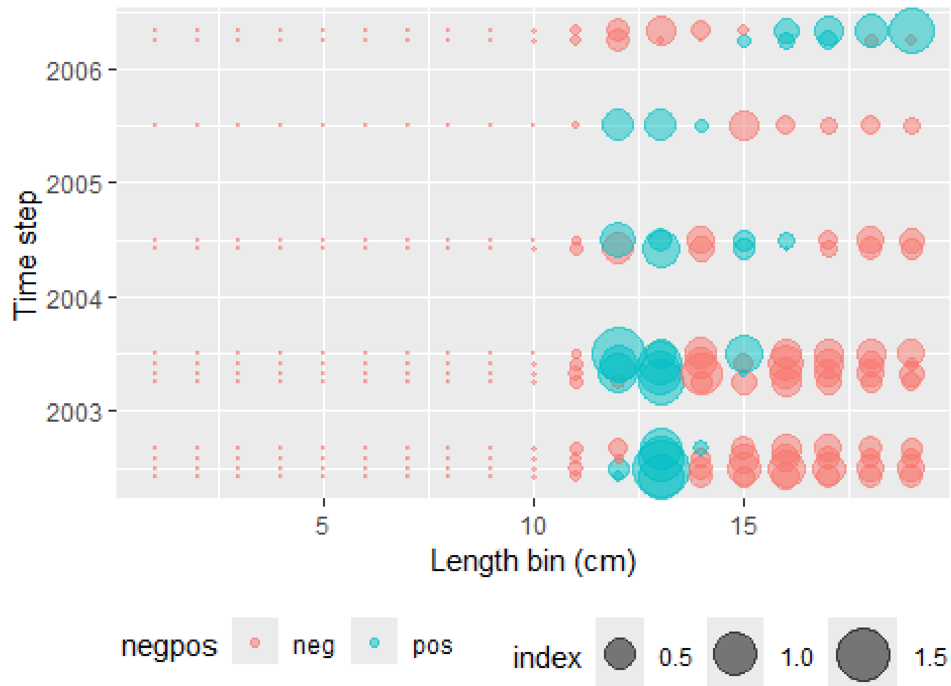

Figure 4.33. Standardized residuals for proportions-at-length over time for PRFC fleet males. Plot definitions are the same as Figure 4.25.

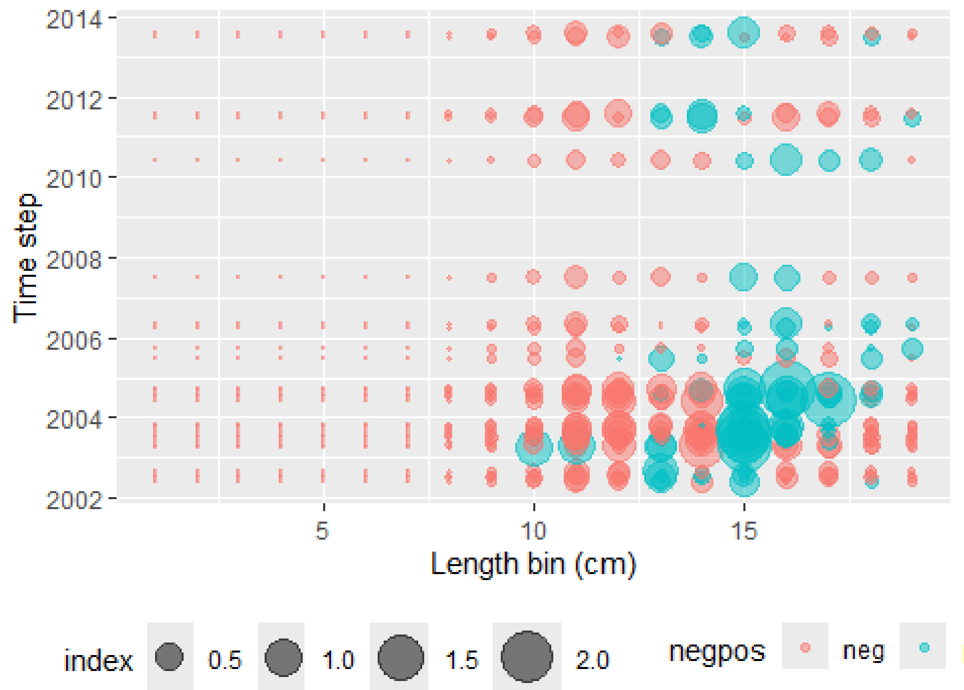

Figure 4.34. Standardized residuals for proportions-at-length over time for PRFC fleet mature females. Plot definitions are the same as Figure 4.25.

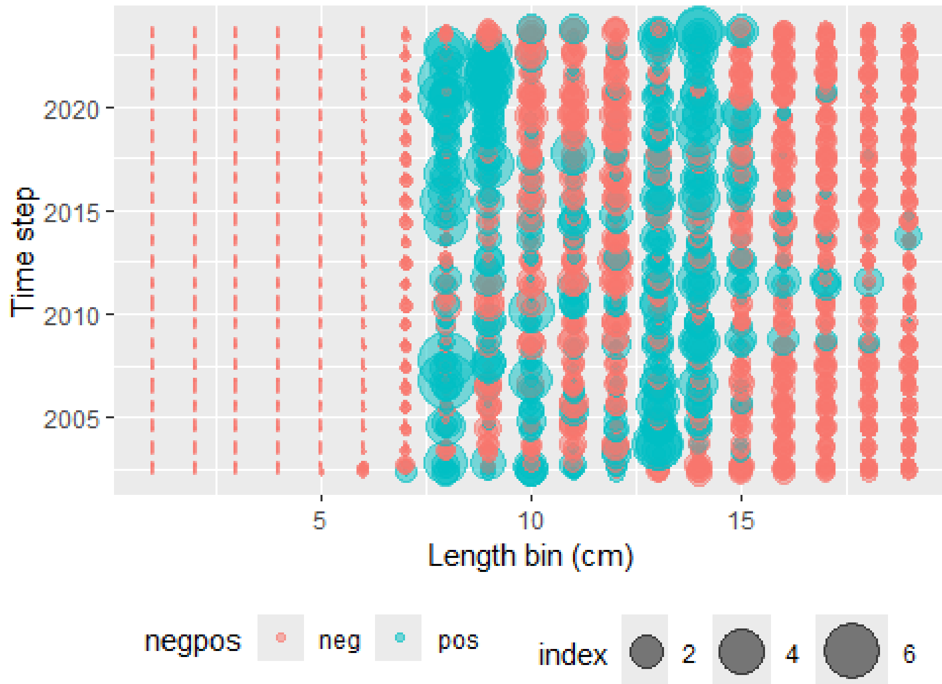

Figure 4.35. Standardized residuals for proportions-at-length over time for peeler fleet males. Plot definitions are the same as Figure 4.25.

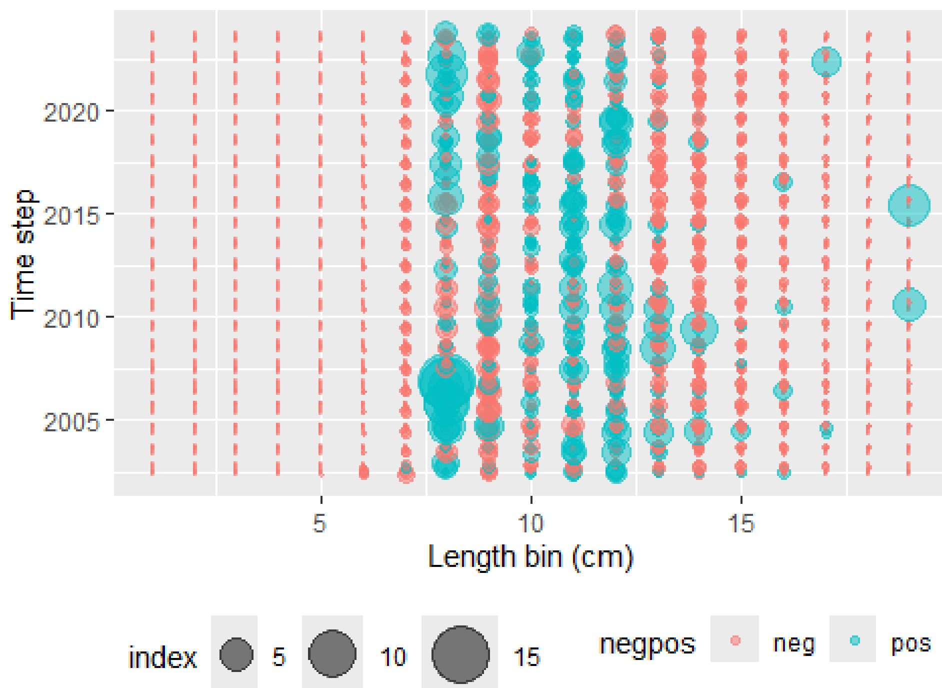

Figure 4.36. Standardized residuals for proportions-at-length over time for peeler fleet immature females. Plot definitions are the same as Figure 4.25.

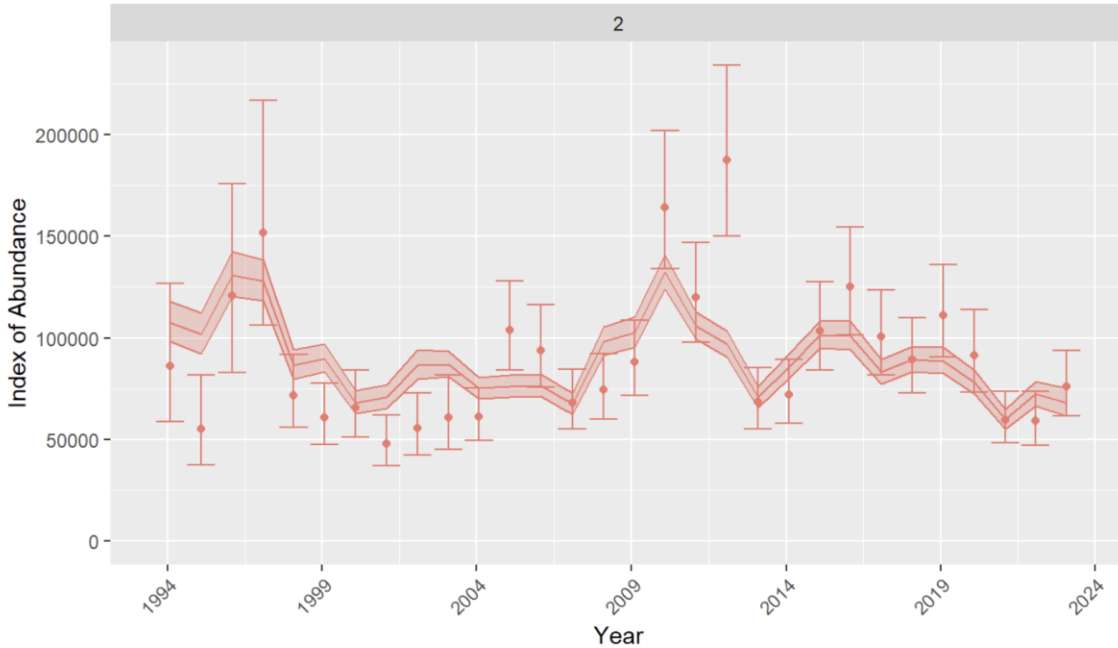

Figure 4.37. Fit to the Winter Dredge Survey index over time. Observed values are the points, whiskers are 95% confidence intervals on the data, and model estimates are the line with 95% confidence intervals indicated by the shaded area. Month of the survey in the model is at the top of the panel. Abundance units are thousands of crabs.

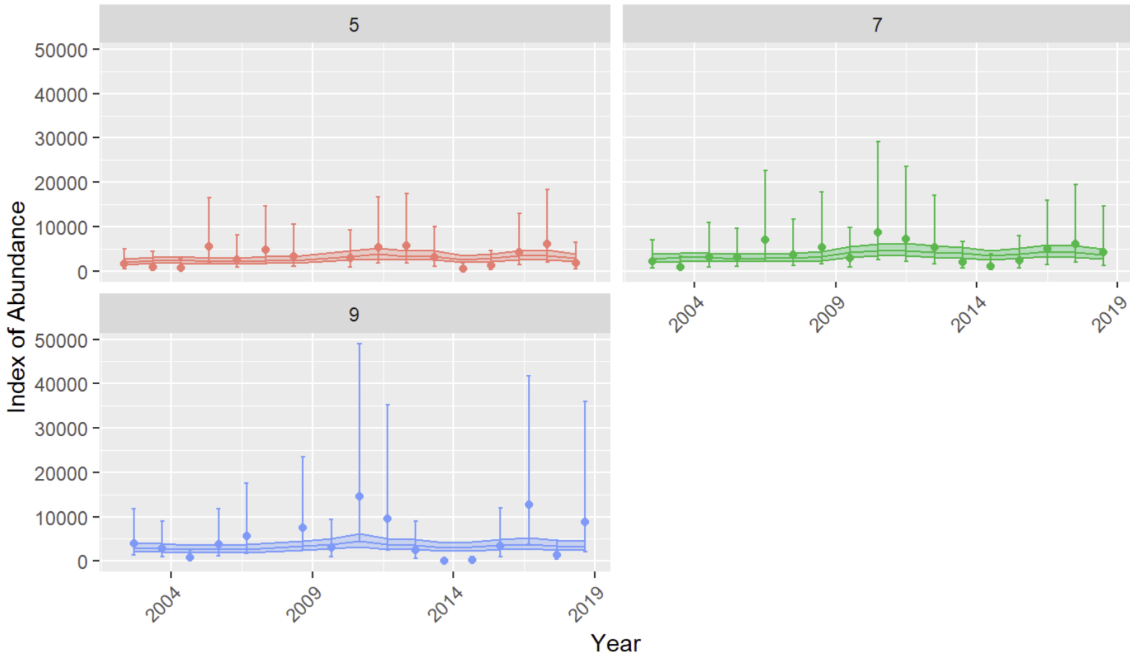

Figure 4.38. Fit to early years of ChesMMAP index over time. Plot definitions are the same as Figure 4.37. Abundance units are thousands of crabs.

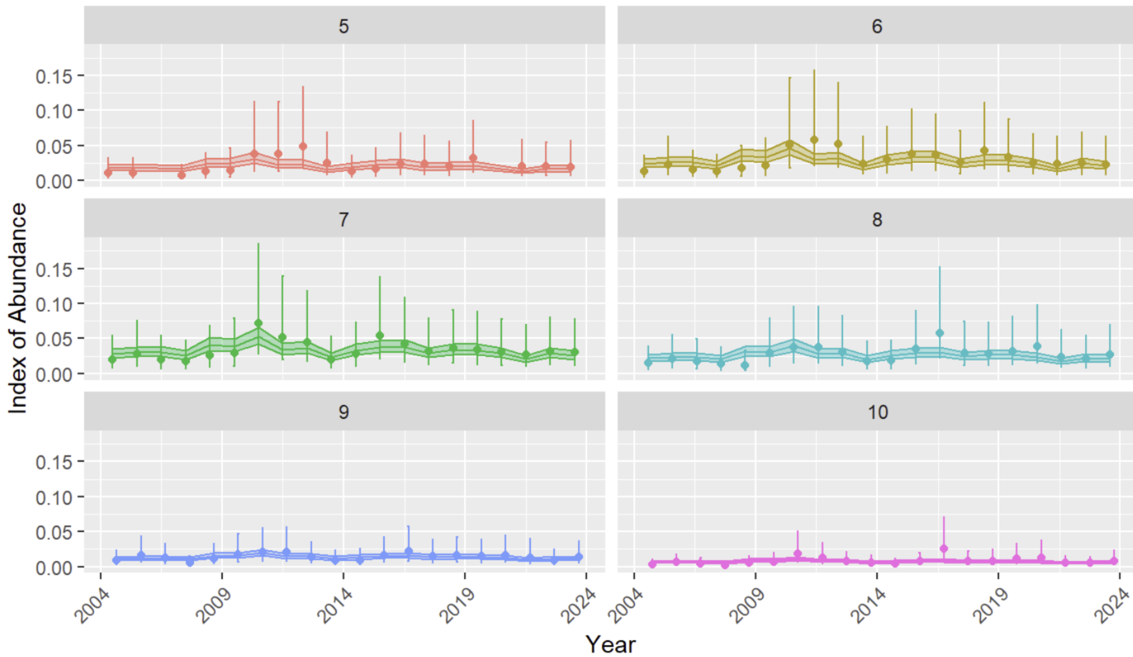

Figure 4.39. Fit to index over time by month for the Maryland Trawl Survey. Plot definitions are the same as Figure 4.37. Abundance units are thousands of crabs per tow.

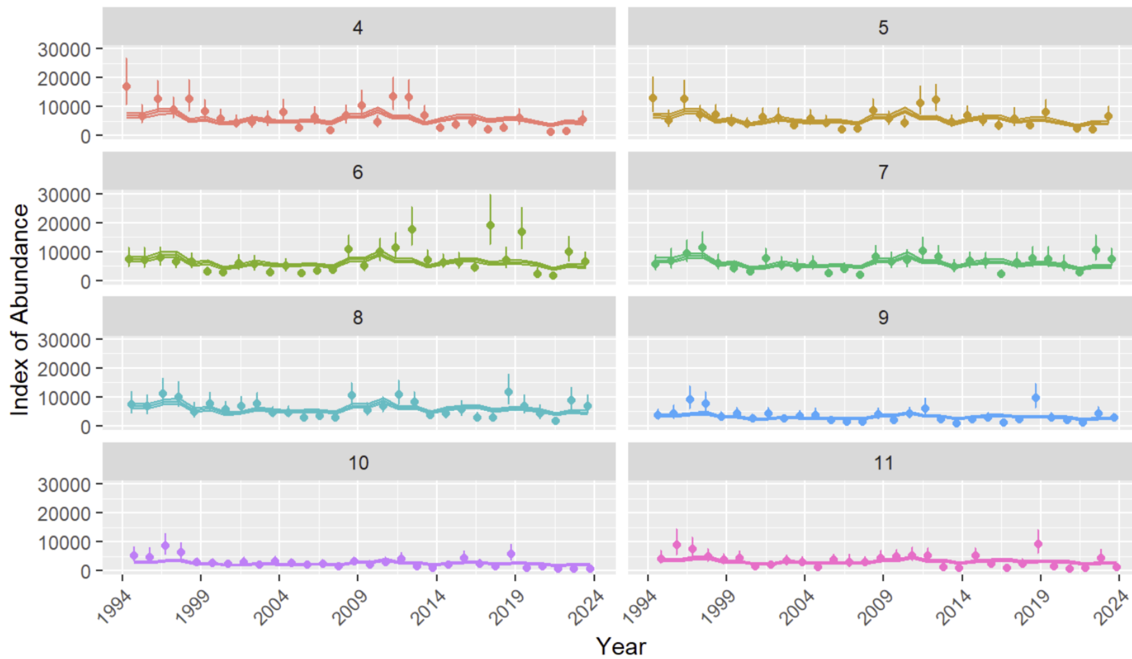

Figure 4.40. Fit to index over time by month for the VIMS Trawl Survey. Plot definitions are the same as Figure 4.37. Abundance units are thousands of crabs.

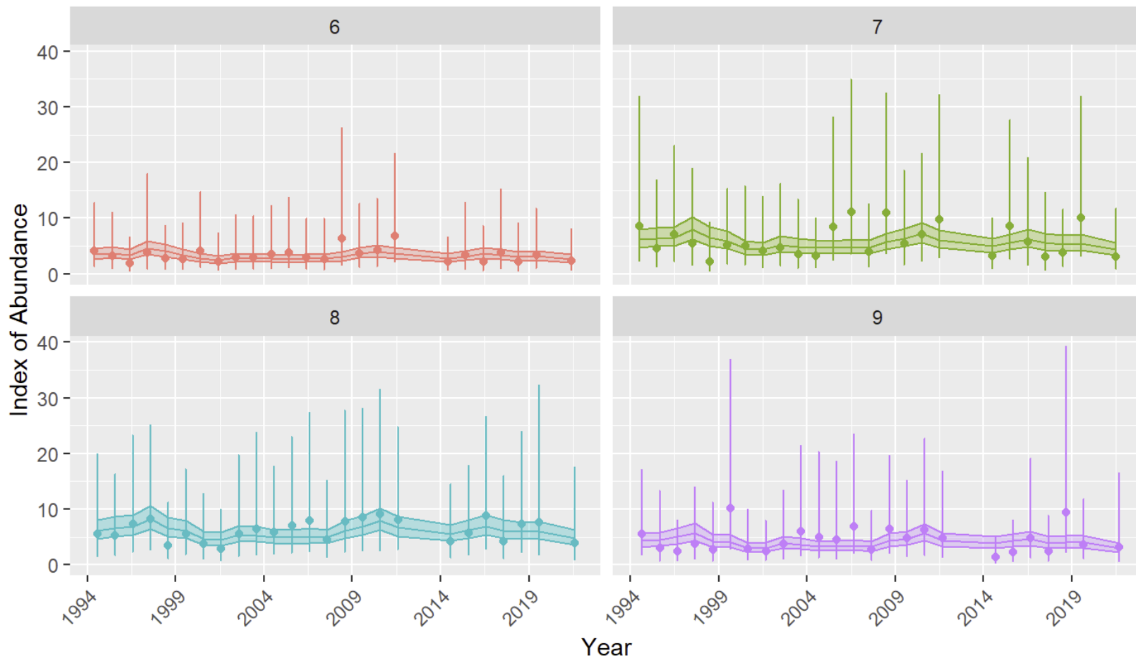

Figure 4.41. Fit to index over time by month for PEARL Pot Survey. Plot definitions are the same as Figure 4.37.

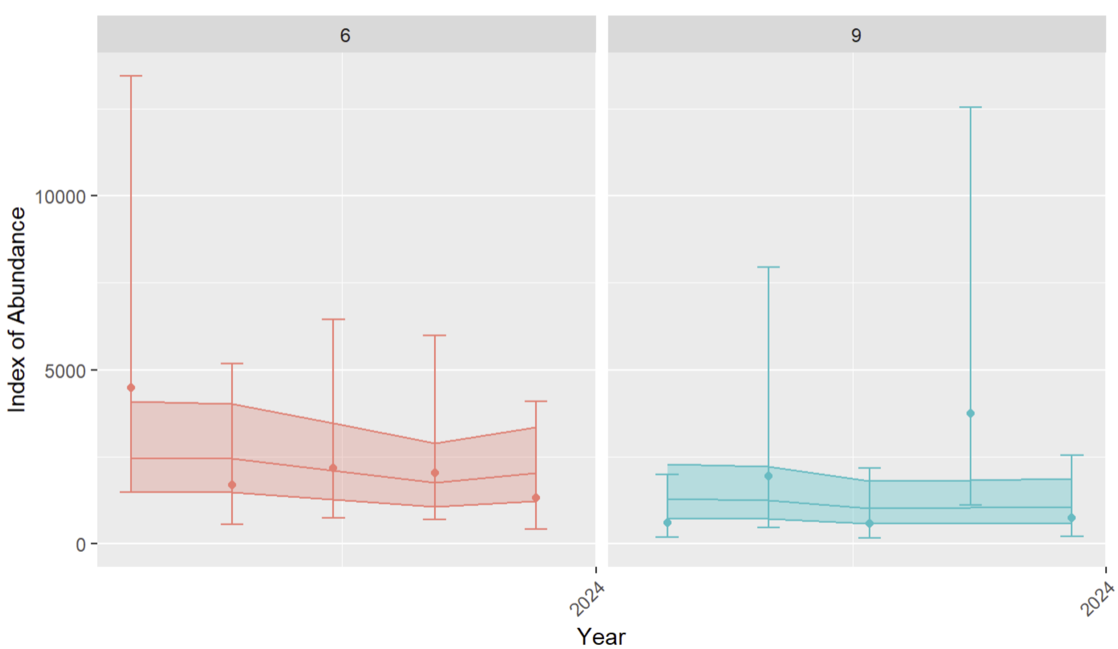

Figure 4.42. Fit to index over time by month for recent years of ChesMMAP. Plot definitions are the same as Figure 4.37. Abundance units are thousands of crabs.

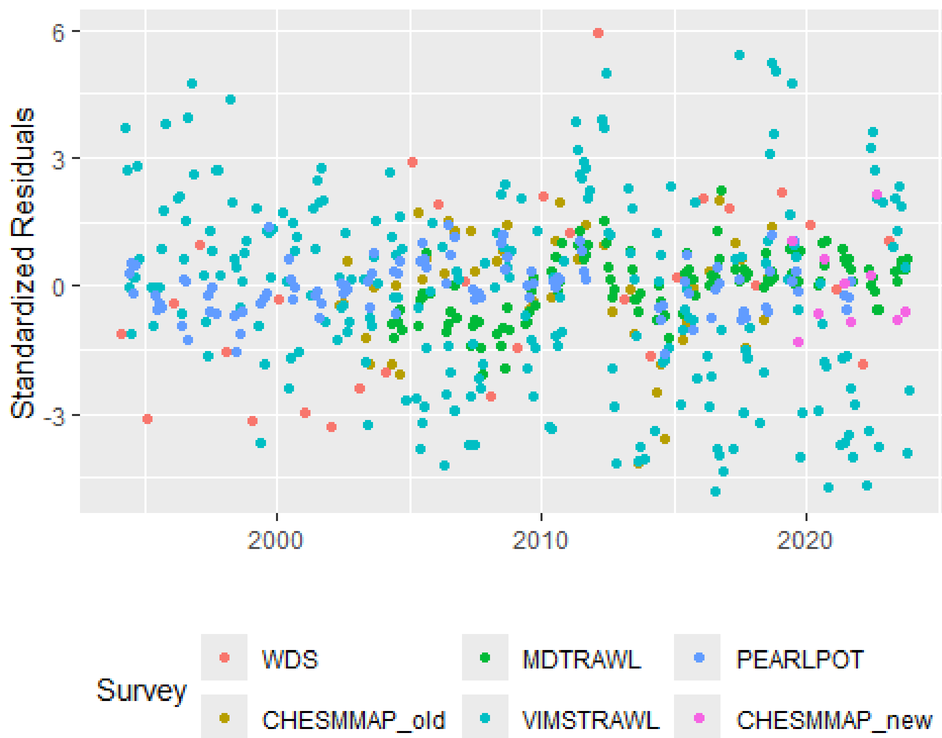

Figure 4.43. Standardized residuals over time for all surveys. WDS is the Winter Dredge Survey, MDTRAWL is Maryland Trawl Survey, PEARLPOT is the PEARL Pot Survey, ChesMMAP_old is the early ChesMMAP survey, VIMSTRAWL is the VIMS Trawl Survey, and CHESMMAP_new is the recent ChesMMAP survey.

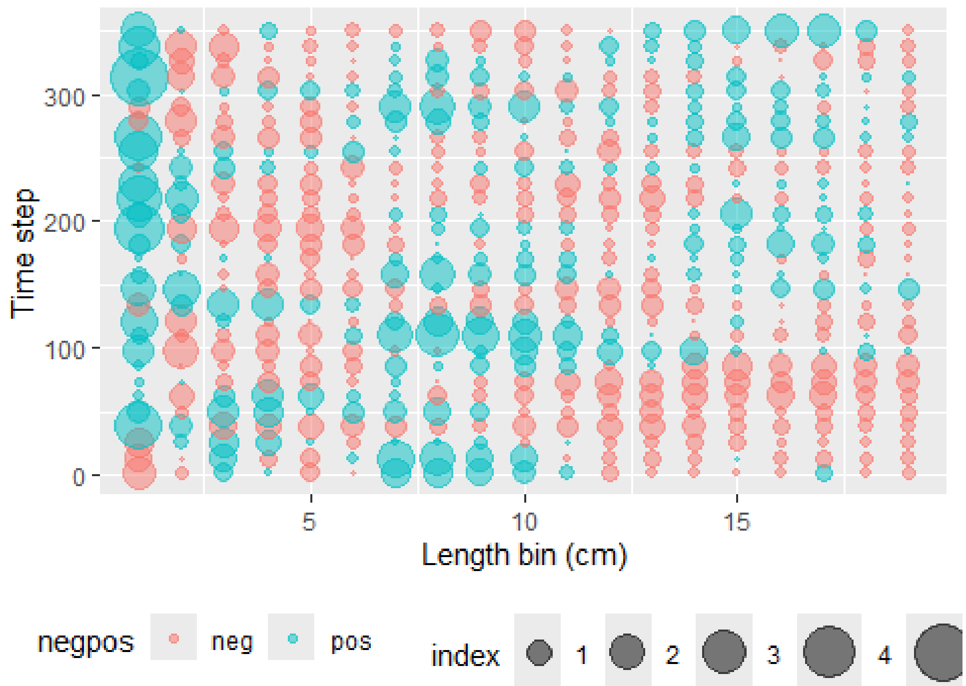

Figure 4.44. Standardized residuals for proportions-at-length over time for males in the Winter Dredge Survey. Plot definitions are the same as Figure 4.25.

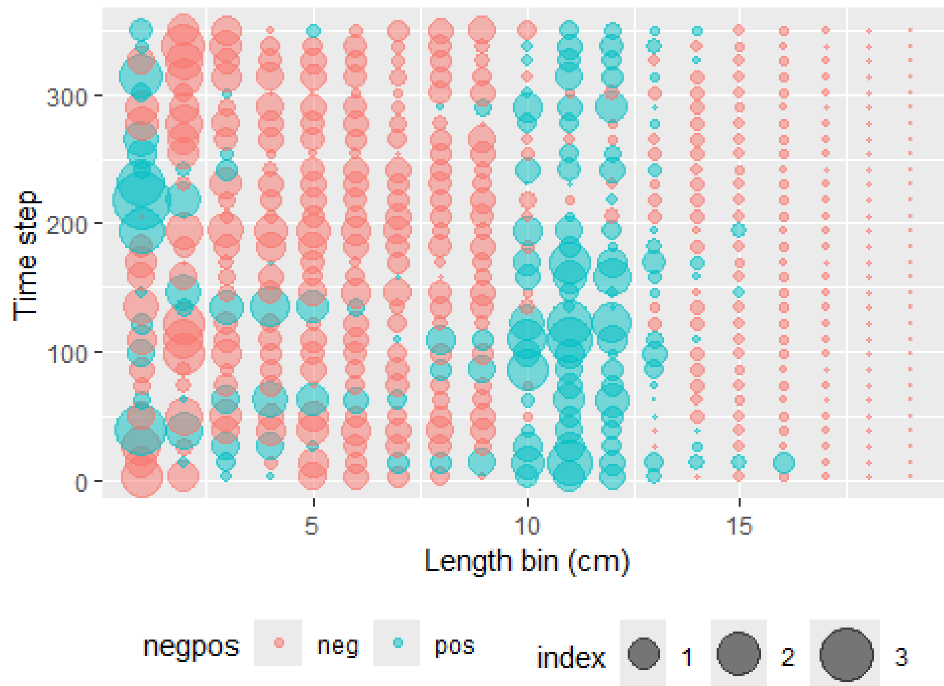

Figure 4.45. Standardized residuals for proportions-at-length over time for immature females in the Winter Dredge Survey. Plot definitions are the same as Figure 4.25.

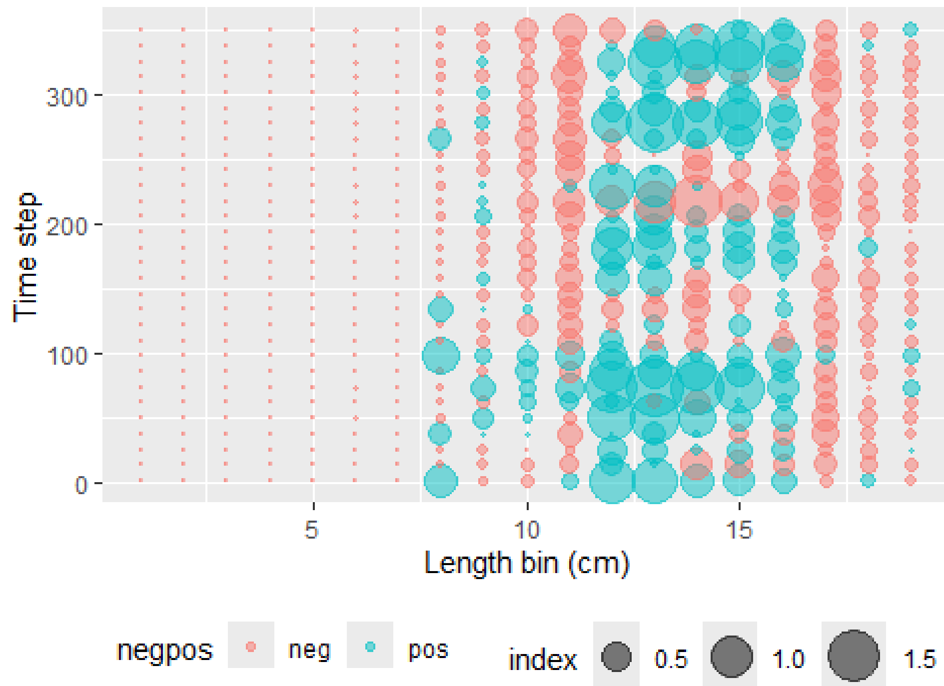

Figure 4.46. Standardized residuals for proportions-at-length over time for mature females in the Winter Dredge Survey. Plot definitions are the same as Figure 4.25.

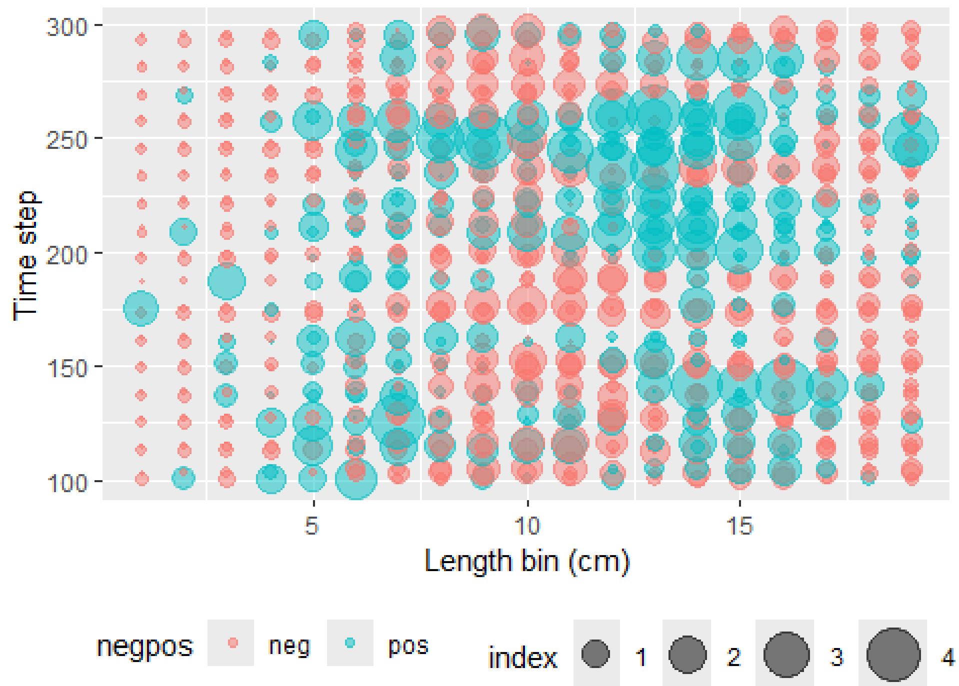

Figure 4.47. Standardized residuals for proportions-at-length over time for males in the old ChesMMAP Survey. Plot definitions are the same as Figure 4.25.

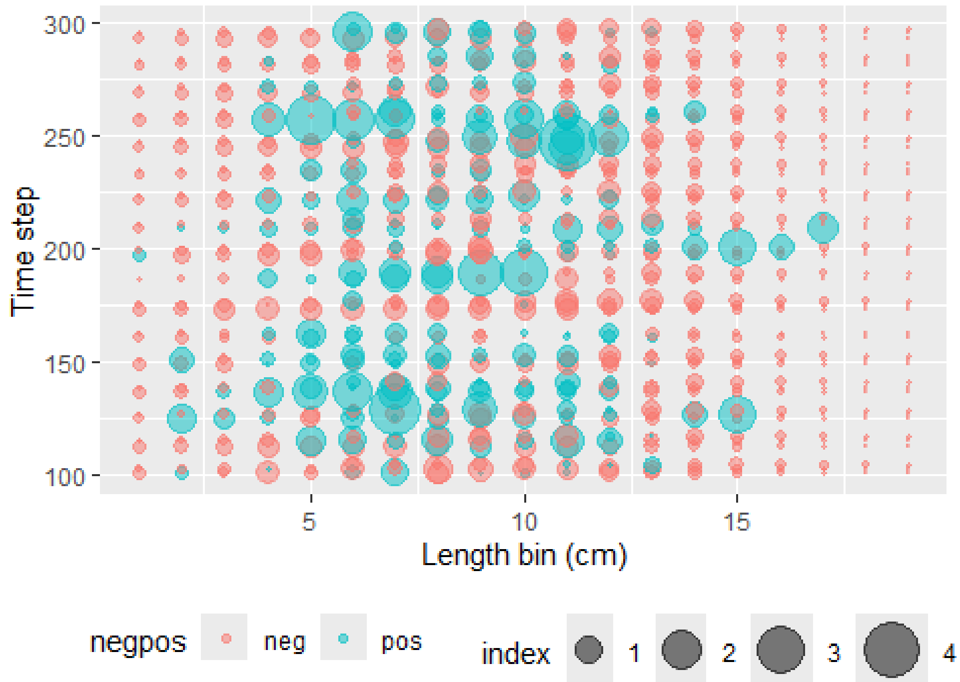

Figure 4.48. Standardized residuals for proportions-at-length over time for immature females in the old ChesMMAP survey. Plot definitions are the same as Figure 4.25.

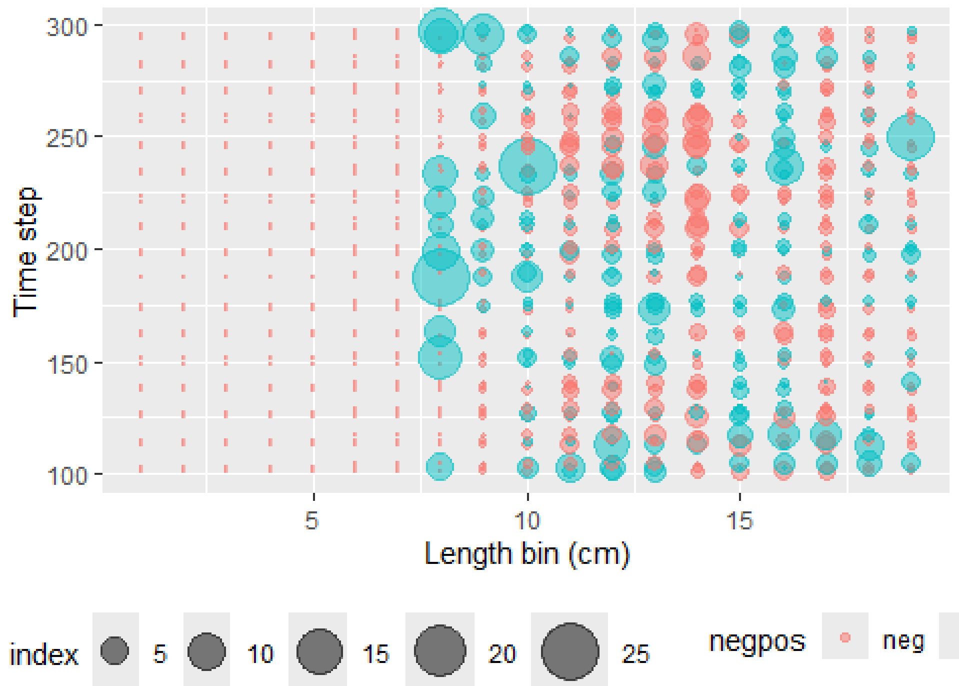

Figure 4.49. Standardized residuals for proportions-at-length over time for mature females in the old ChesMMAP Survey. Plot definitions are the same as Figure 4.25.

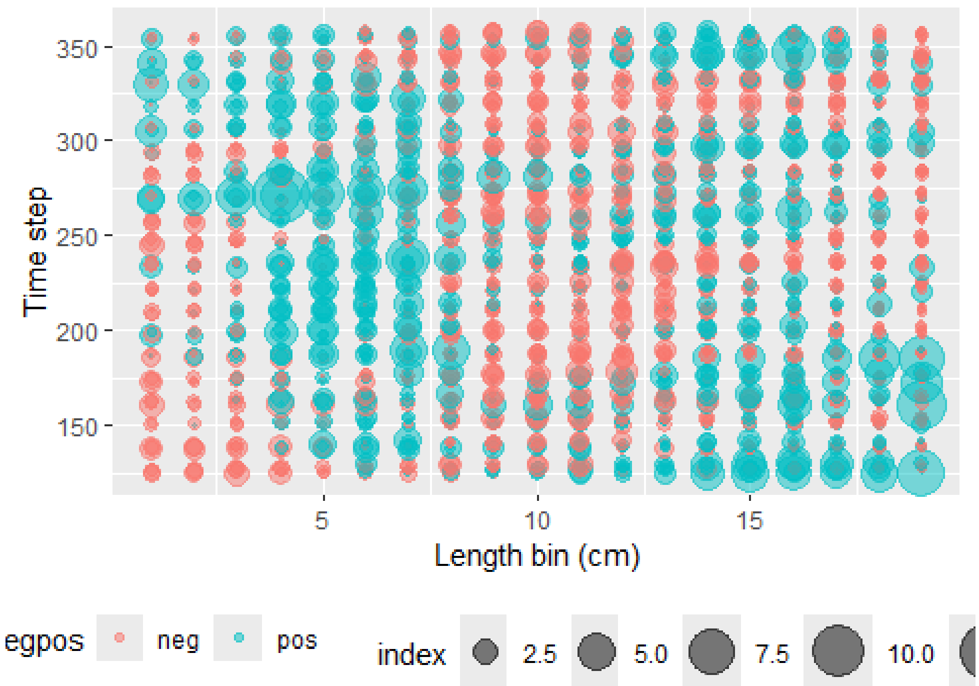

Figure 4.50. Standardized residuals for proportions-at-length over time for males in the Maryland Trawl Survey. Plot definitions are the same as Figure 4.25.

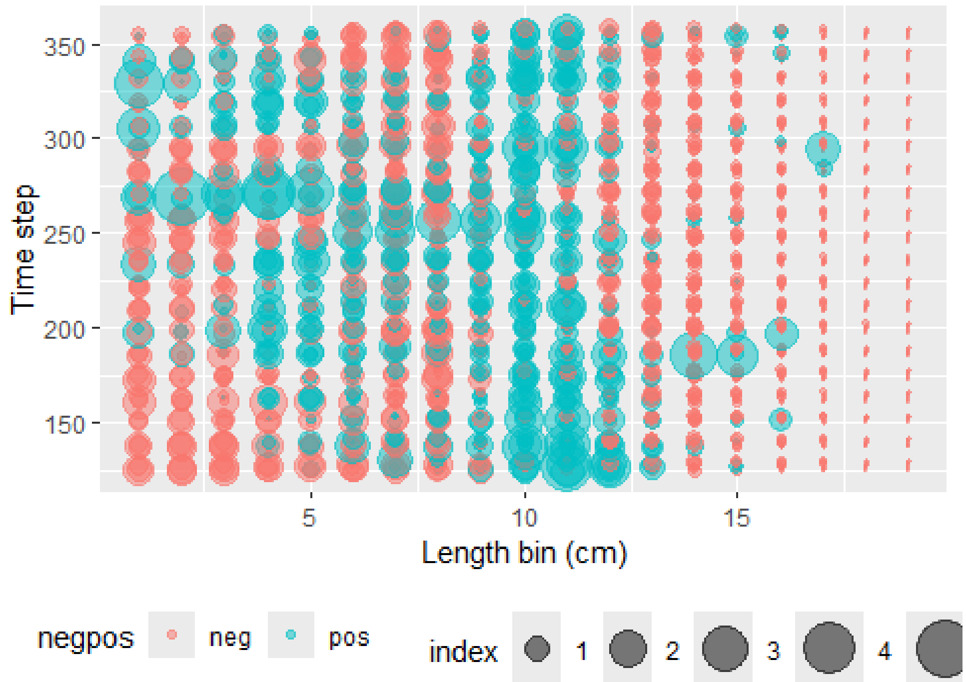

Figure 4.51. Standardized residuals for proportions-at-length over time for immature females in the Maryland Trawl Survey. Plot definitions are the same as Figure 4.25.

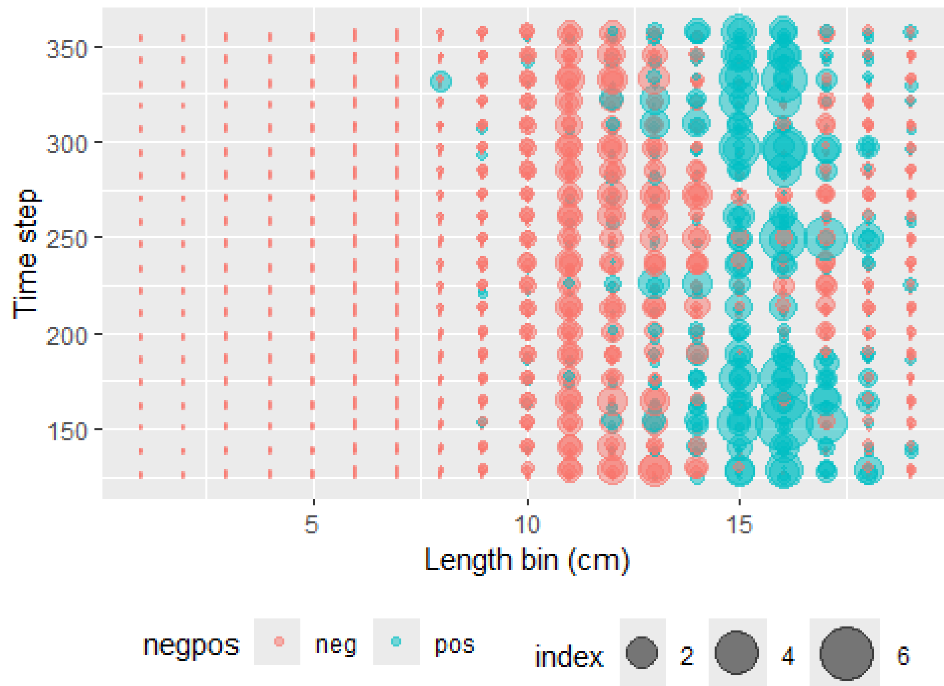

Figure 4.52. Standardized residuals for proportions-at-length over time for mature females in the Maryland Trawl Survey. Plot definitions are the same as Figure 4.25.

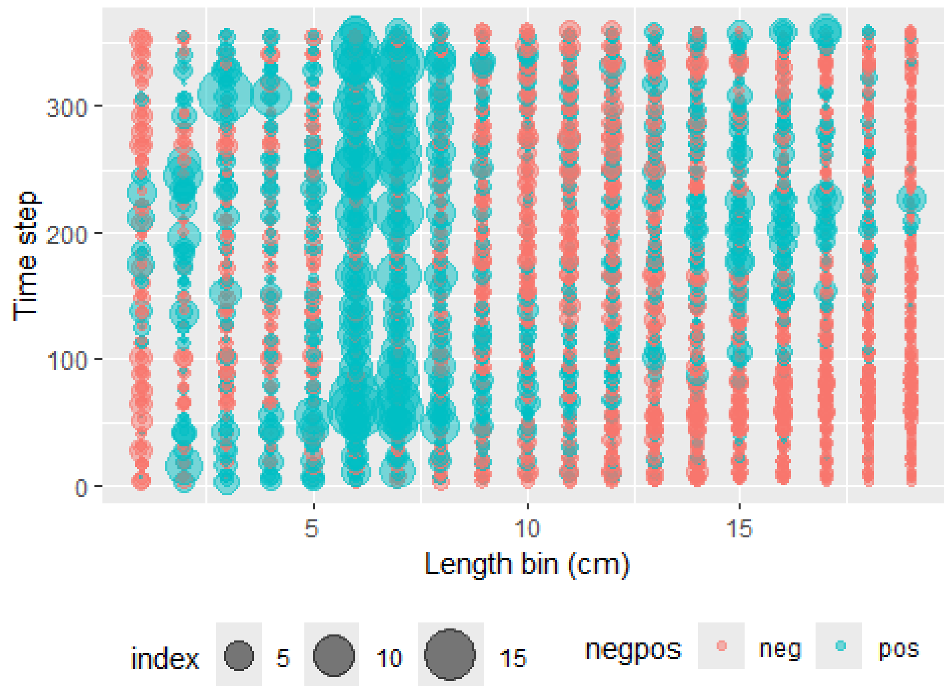

Figure 4.53. Standardized residuals for proportions-at-length over time for males in the VIMS Trawl Survey. Plot definitions are the same as Figure 4.25.

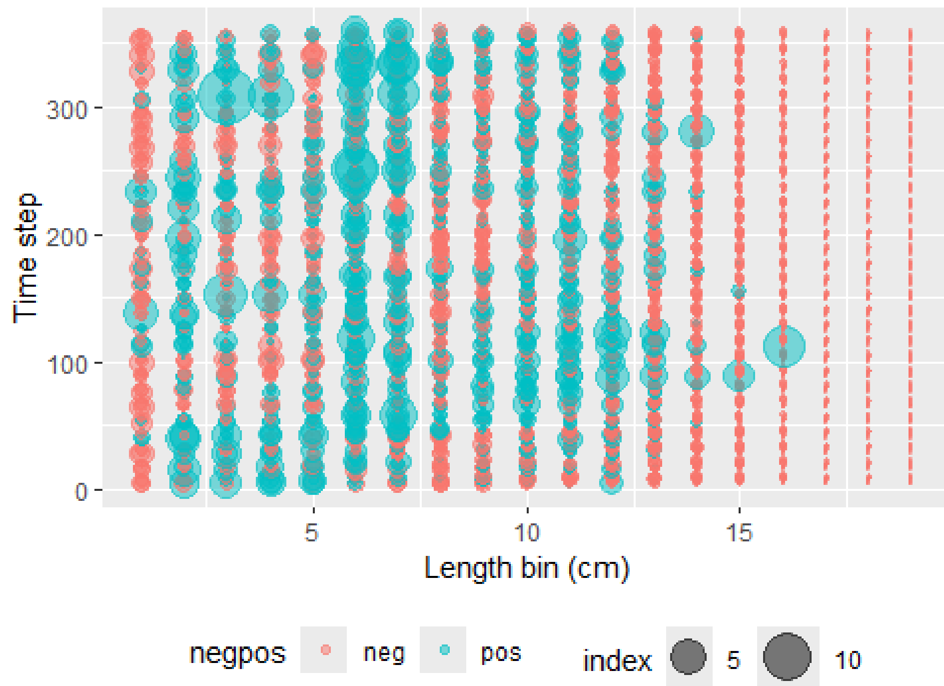

Figure 4.54. Standardized residuals for proportions-at-length over time for immature females in the VIMS Trawl Survey. Plot definitions are the same as Figure 4.25.

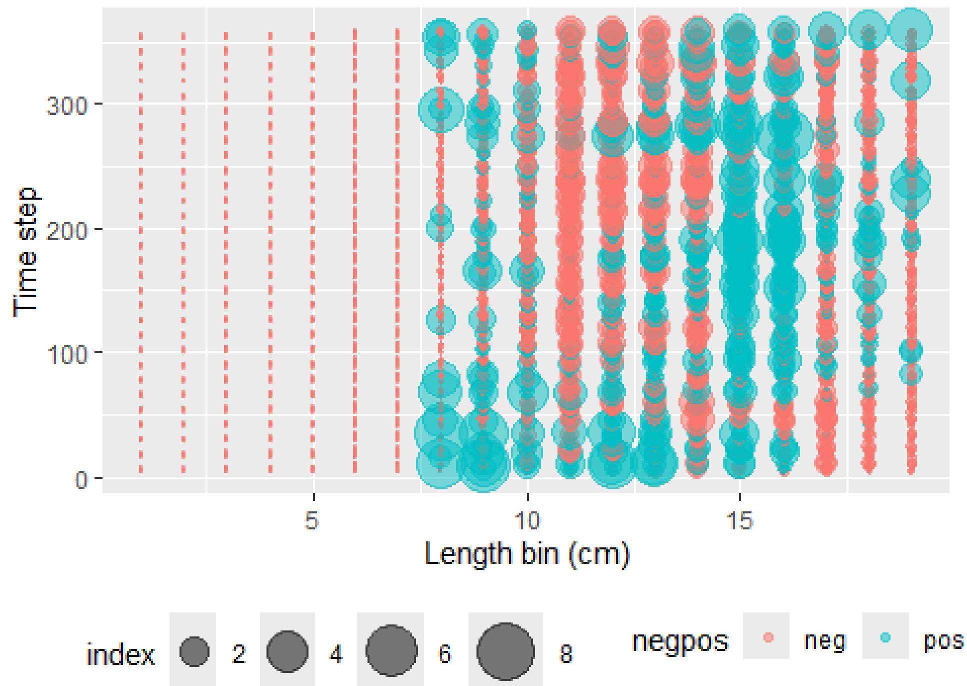

Figure 4.55. Standardized residuals for proportions-at-length over time for mature females in the VIMS Trawl Survey. Plot definitions are the same as Figure 4.25.

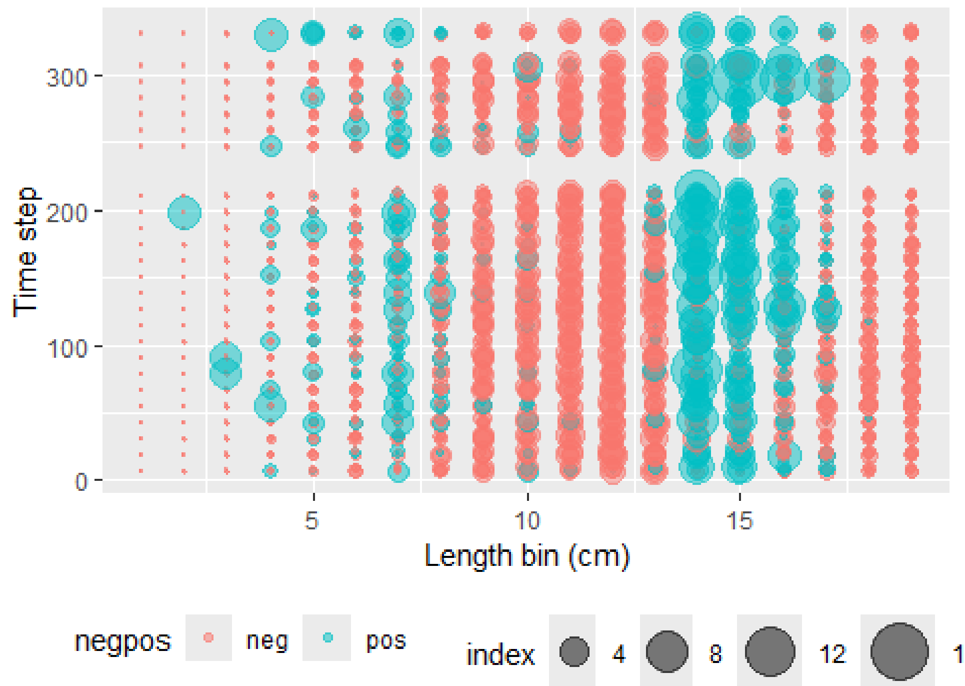

Figure 4.56. Standardized residuals for proportions-at-length over time for males in the PEARL Pot Survey. Plot definitions are the same as Figure 4.25.

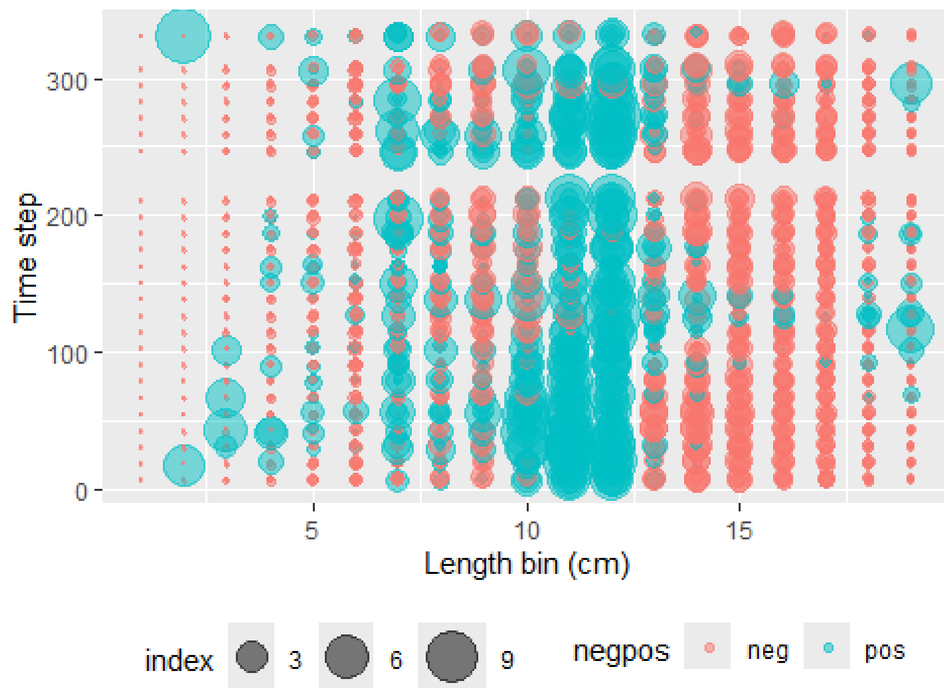

Figure 4.57. Standardized residuals for proportions-at-length over time for all females in the Pearl Pot Survey. Plot definitions are the same as Figure 4.25.

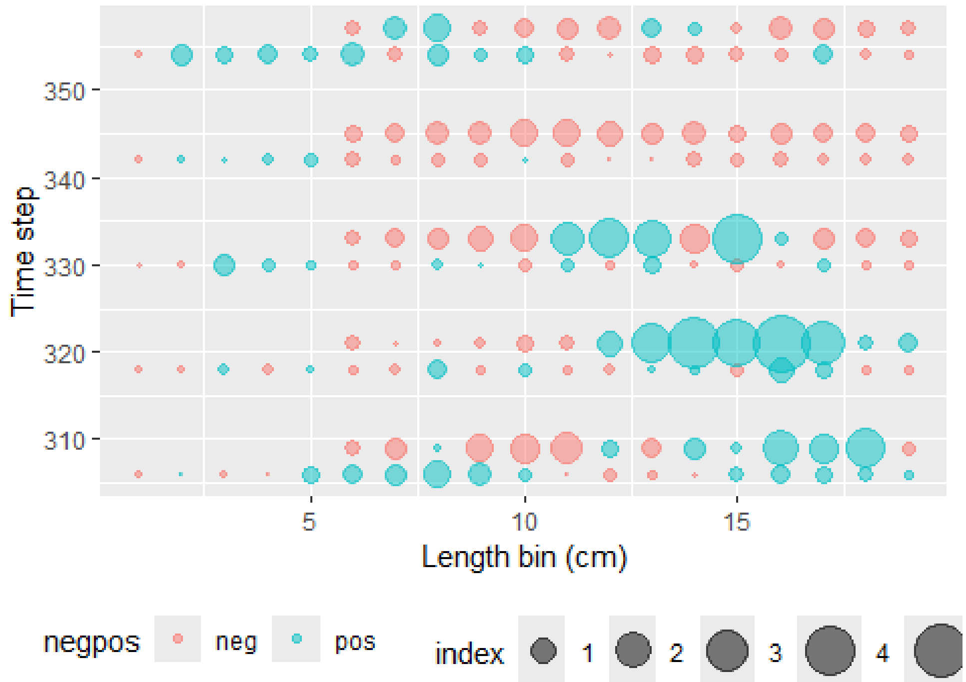

Figure 4.58. Standardized residuals for proportions-at-length over time for males in the new ChesMMAP Survey. Plot definitions are the same as Figure 4.25.

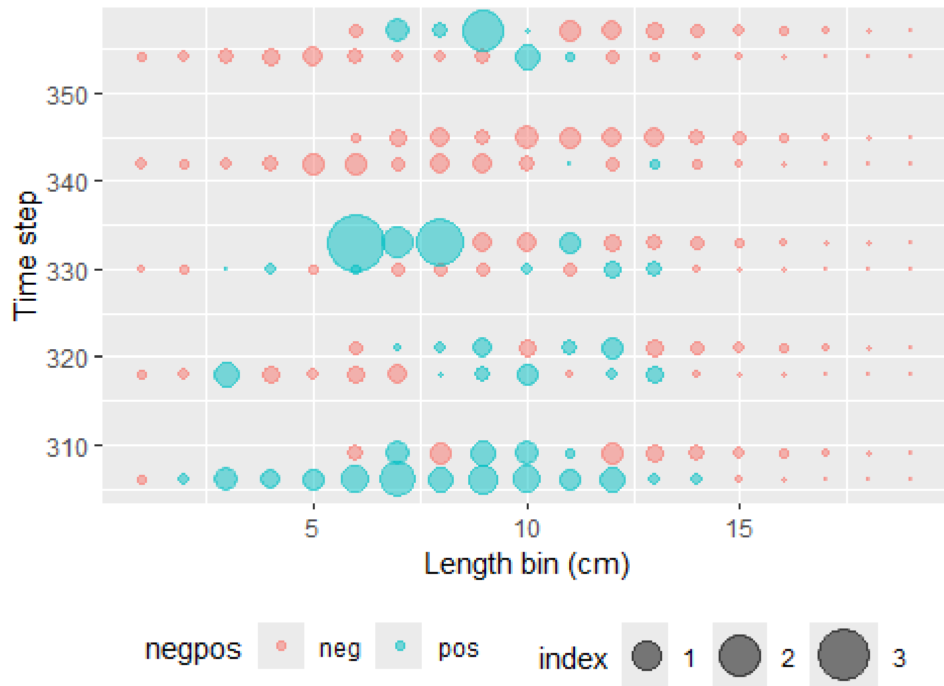

Figure 4.59. Standardized residuals for proportions-at-length over time for immature females in the new ChesMMAP Survey. Plot definitions are the same as Figure 4.25.

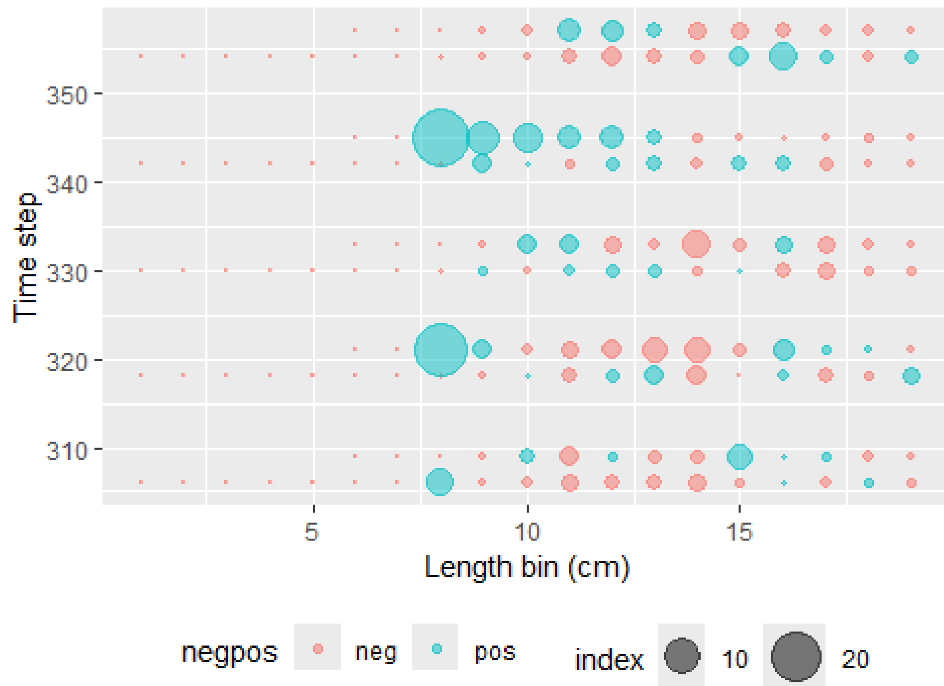

Figure 4.60. Standardized residuals for proportions-at-length over time for mature females in the new ChesMMAP Survey. Plot definitions are the same as Figure 4.25.

Figure 4.61. Model fit to the proportion of crabs by sex-maturity category in the Winter Dredge Survey over time. Red points are the observed values and the lines are the model estimates.

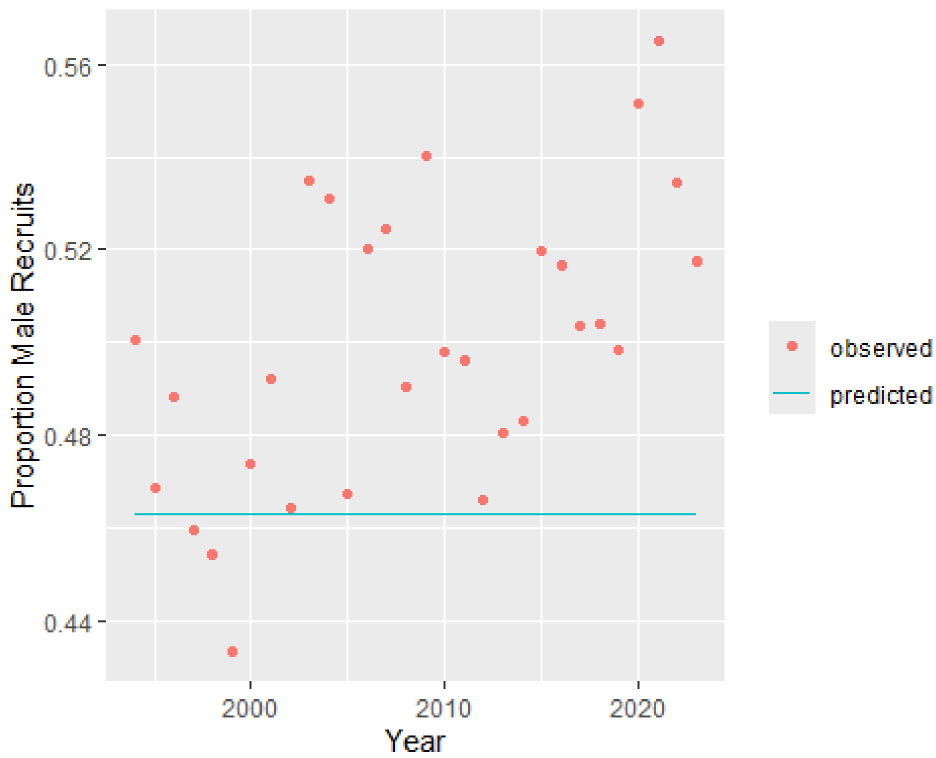

Figure 4.62. Model fit to proportion of male recruits. Red points are the observed proportions from the Winter Dredge Survey estimated using a cluster sampling estimator, and the blue line is the model estimate. The estimated proportion male was constant over time.

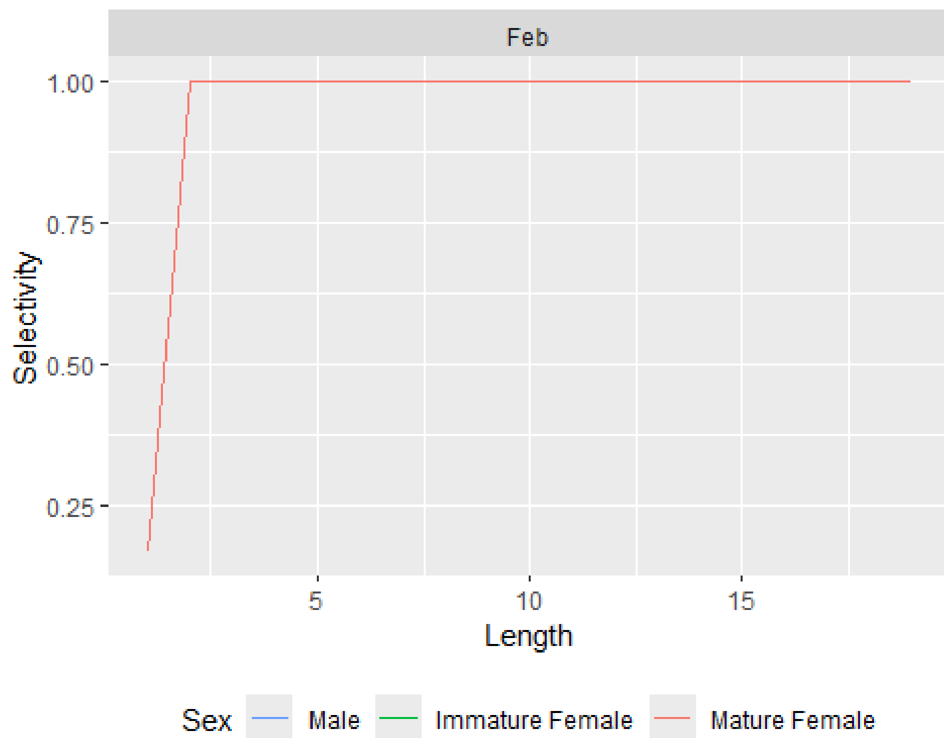

Figure 4.63. Survey selectivity by length (cm) and sex for the Winter Dredge Survey.

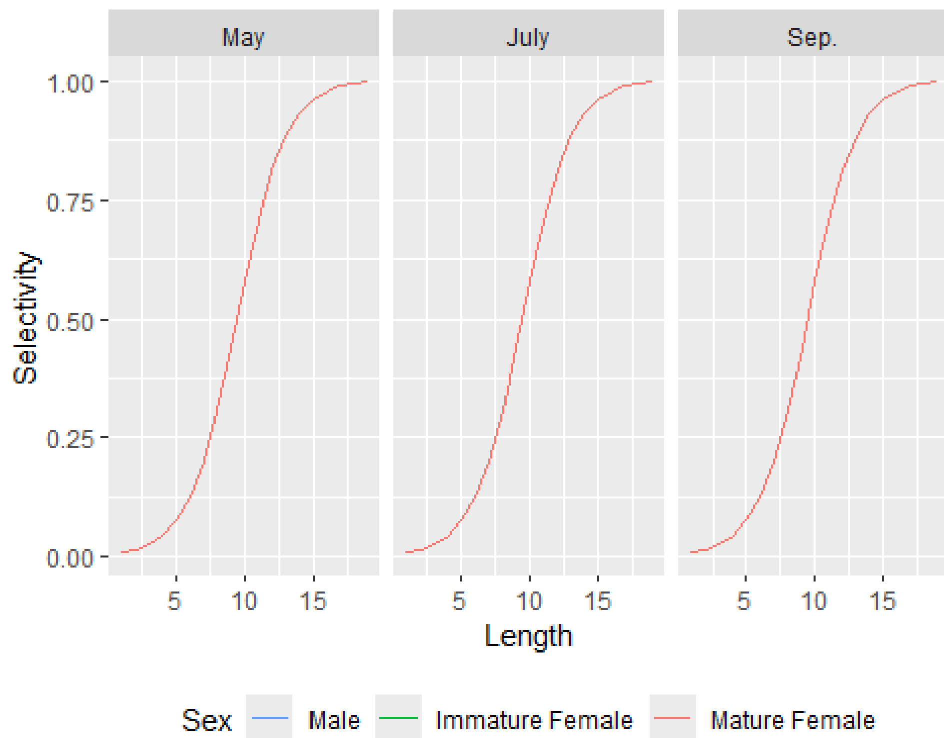

Figure 4.64. Survey selectivity by length (cm) and sex for the older survey of ChesMMAP. Each panel represents a month.

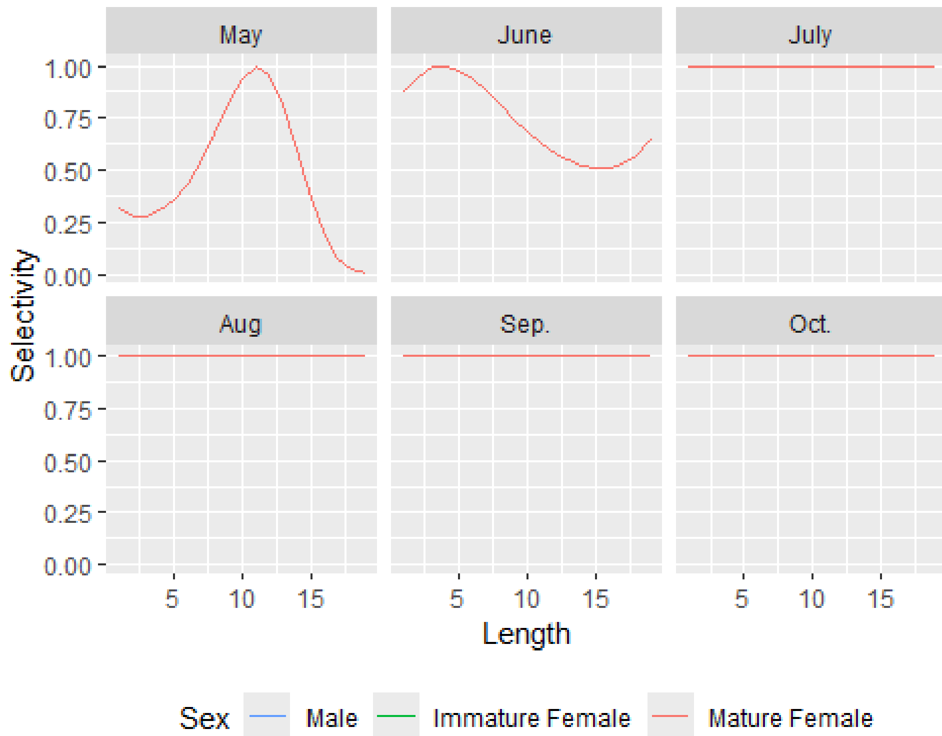

Figure 4.65. Survey selectivity by length (cm) and sex for Maryland Trawl. Each panel represents a month.

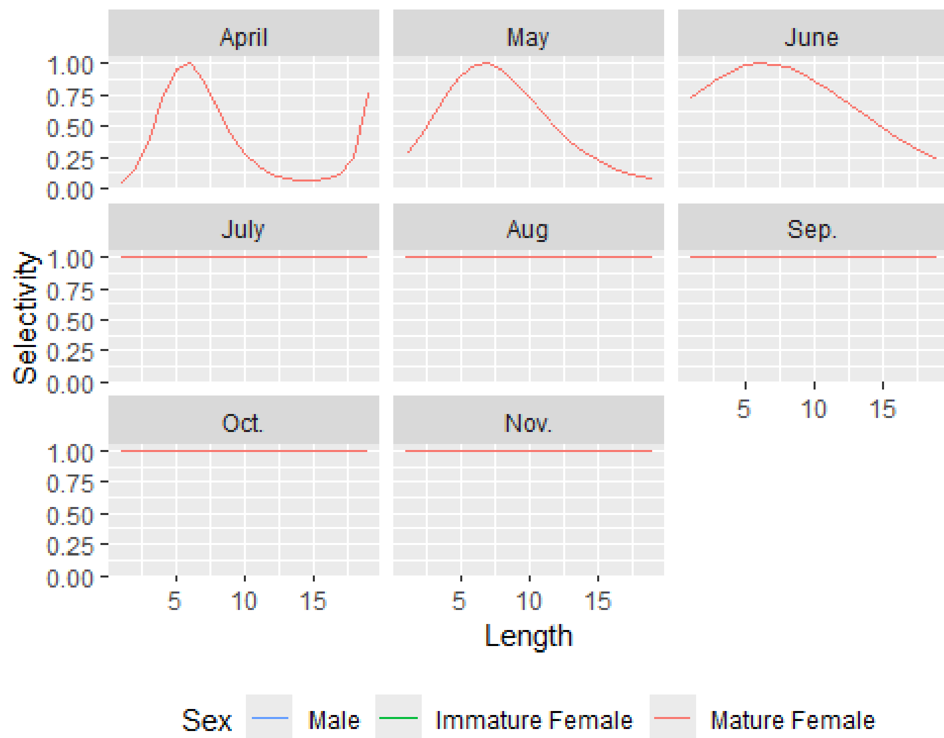

Figure 4.66. Survey selectivity by length (cm) and sex for VIMS Trawl. Each panel represents a month.

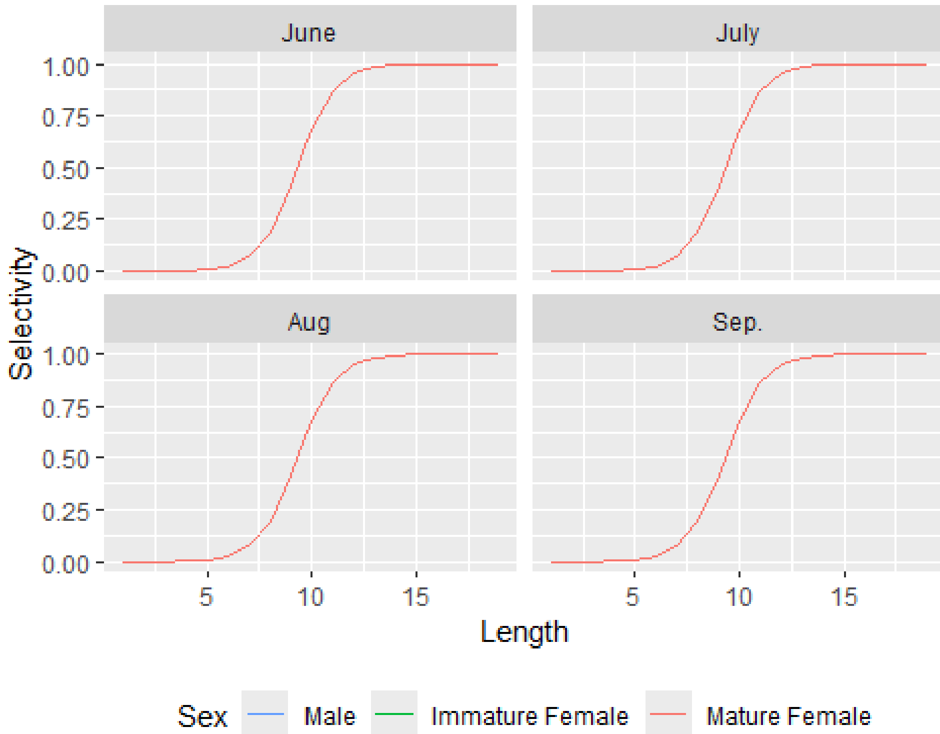

Figure 4.67. Survey selectivity by length (cm) and sex for PEARL Pot. Each panel represents a month.

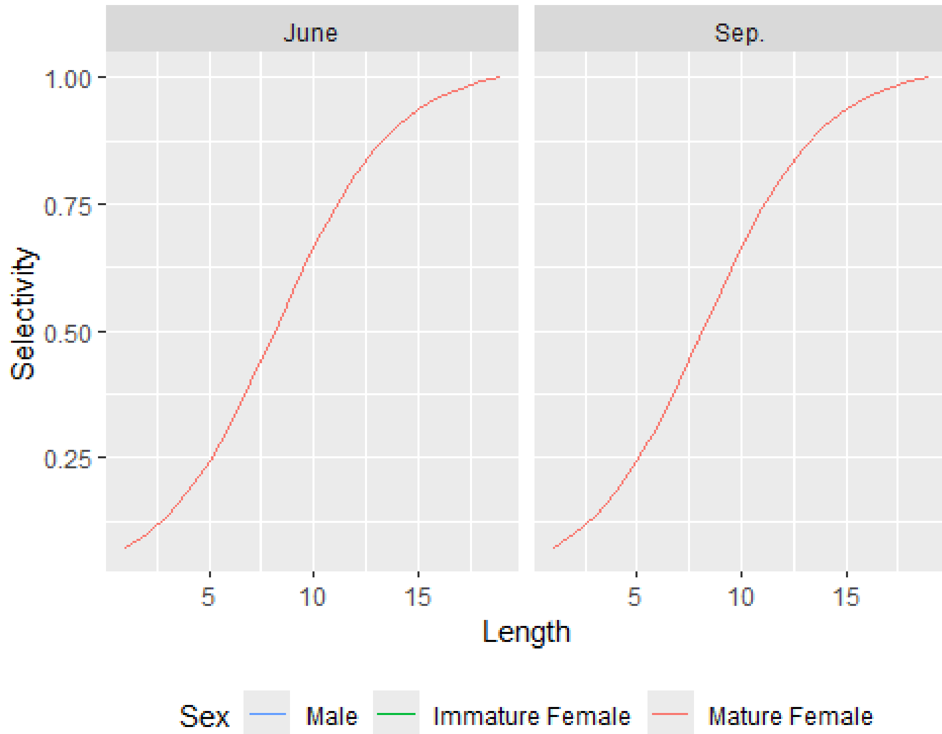

Figure 4.68. Survey selectivity by length (cm) and sex for new survey of ChesMMAP .
Each panel represents a month.

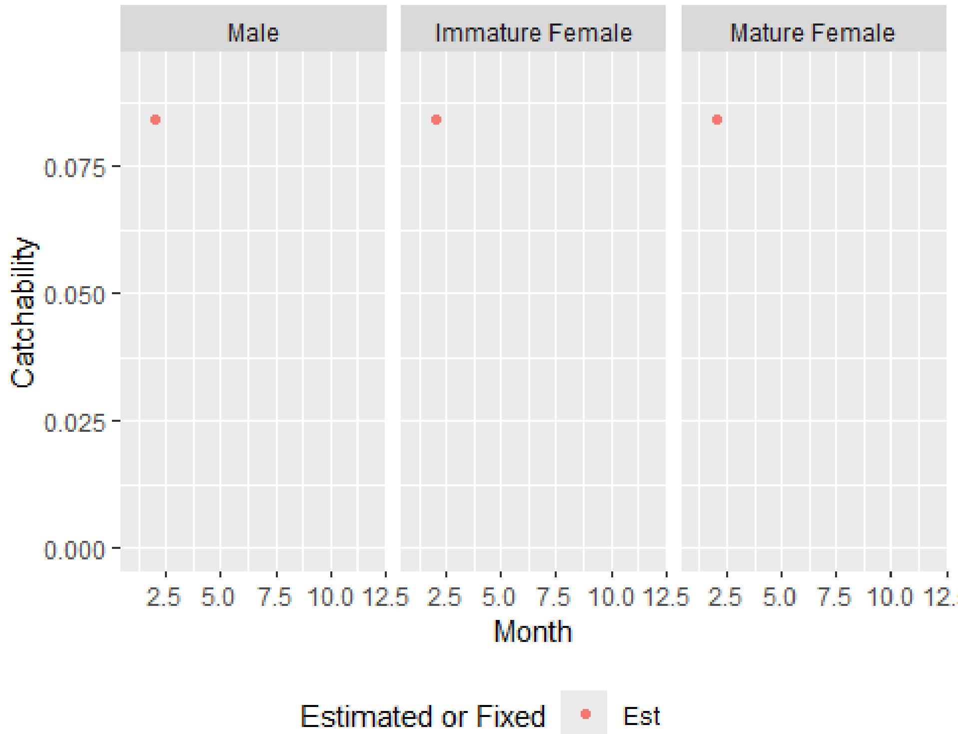

Figure 4.69. Estimated survey catchability for each month and sex for the Winter Dredge Survey.

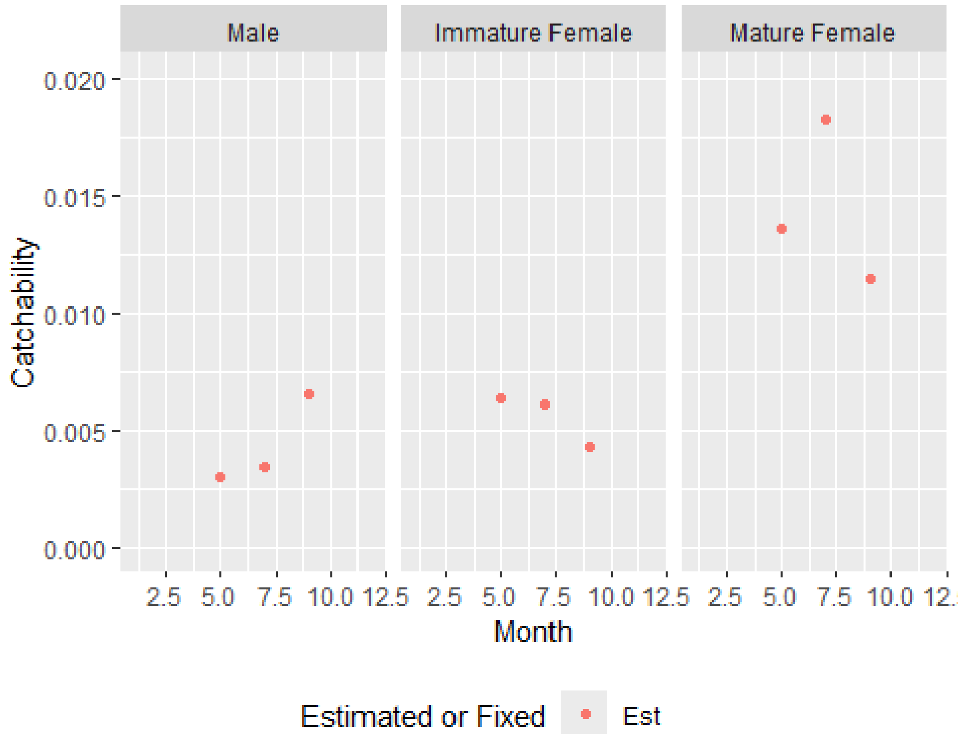

Figure 4.70. Estimated survey catchability for each month and sex for the older years of ChesMMAP.

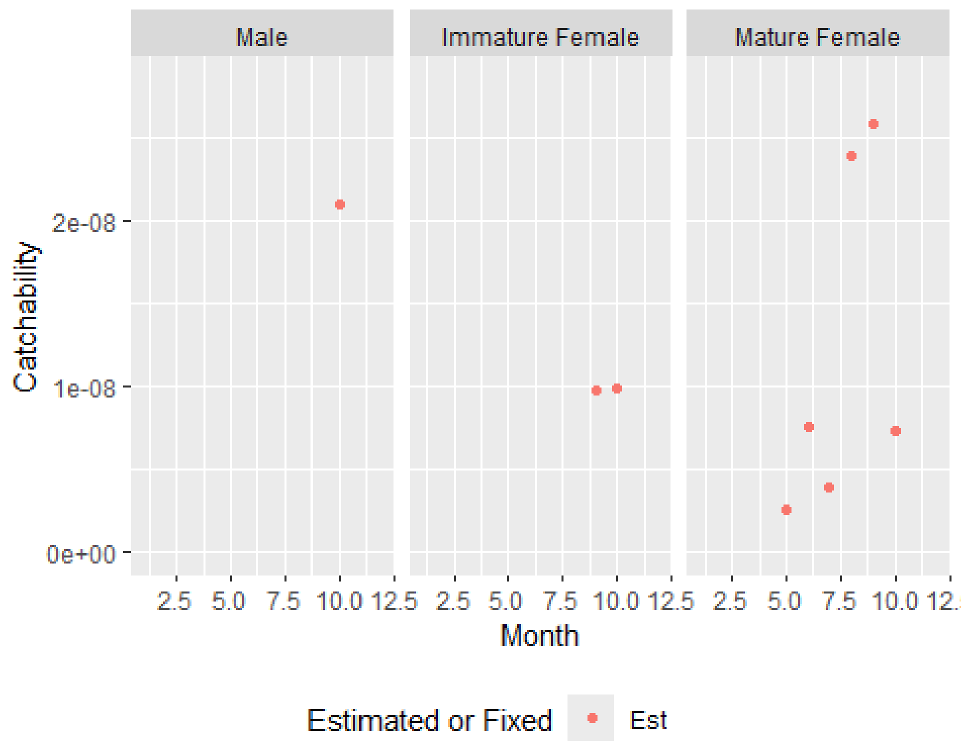

Figure 4.71. Estimated survey catchability for each month and sex for Maryland Trawl.

Figure 4.72. Estimated survey catchability for each month and sex for VIMS Trawl.

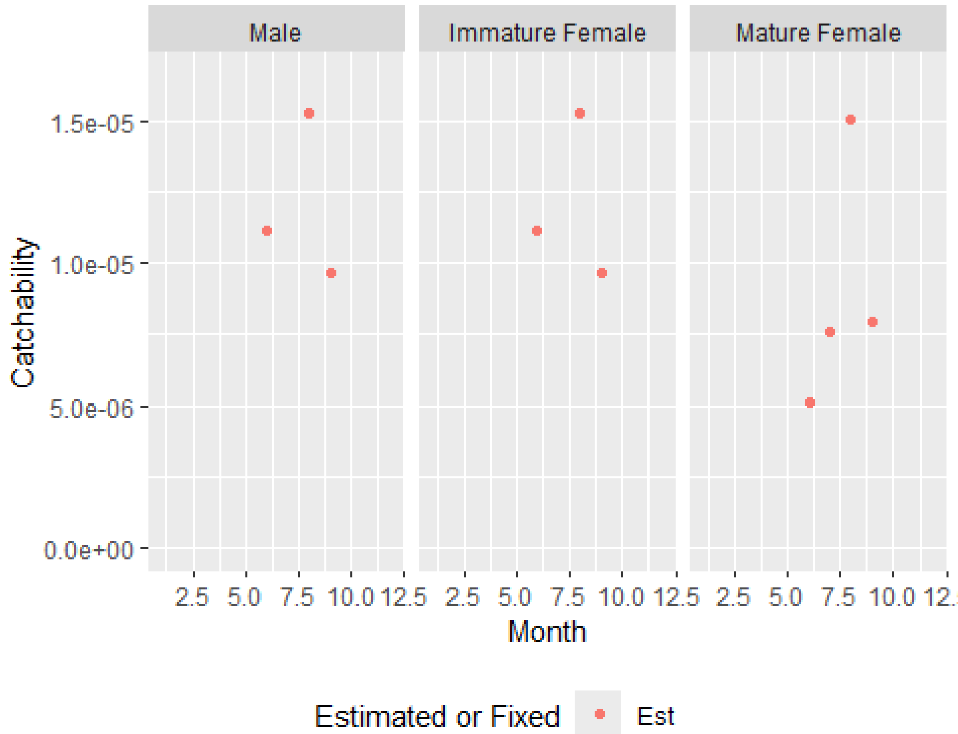

Figure 4.73. Estimated survey catchability for each month and sex for PEARL Pot.

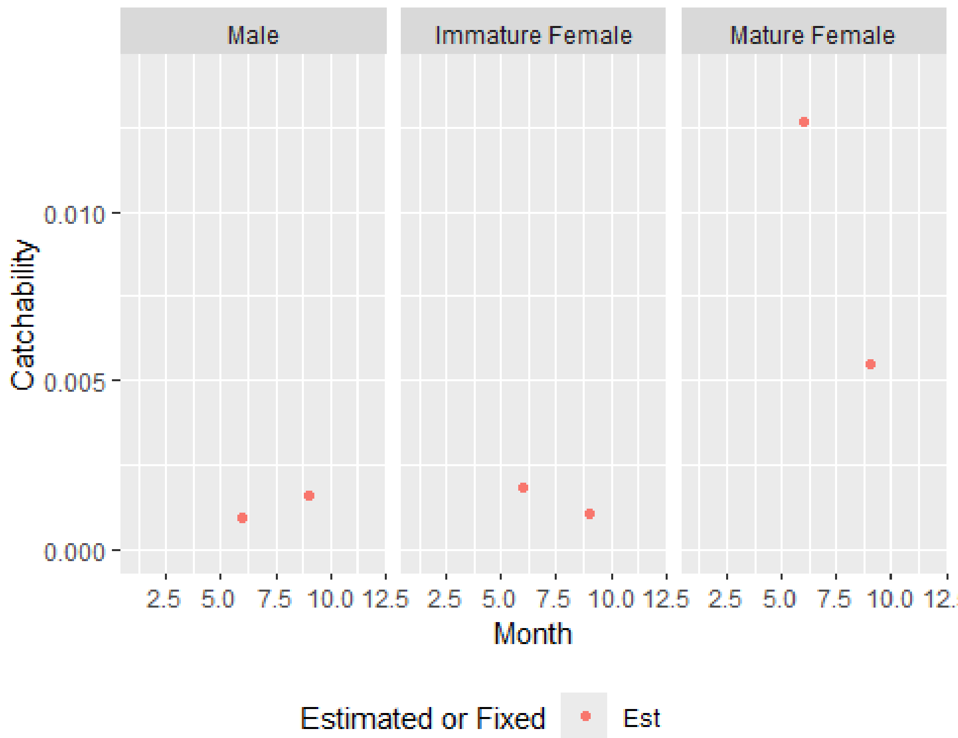

Figure 4.74. Estimated survey catchability for each month and sex for the new years of ChesMMAP.

Figure 4.75. Estimated instantaneous fishing morality rate $yr^{-1}$for fully selected sizes by sex. Shaded regions indicate 95% confidence intervals.

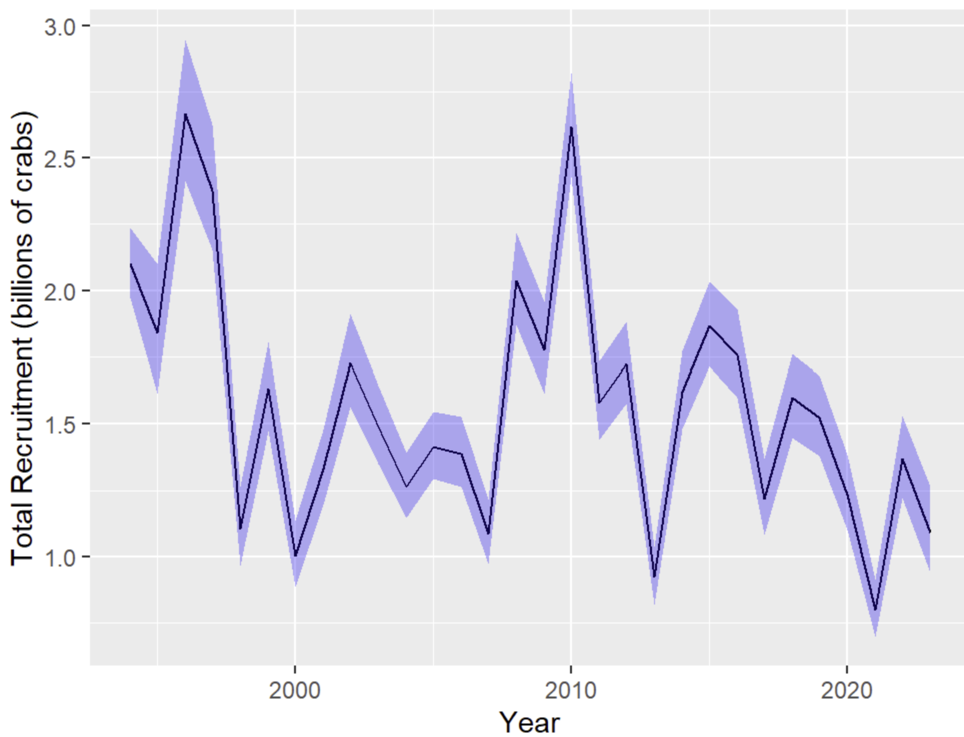

Figure 4.76. Estimated recruitment of blue crabs in Chesapeake Bay during 1994-2023. Shaded region represents 95% confidence intervals.

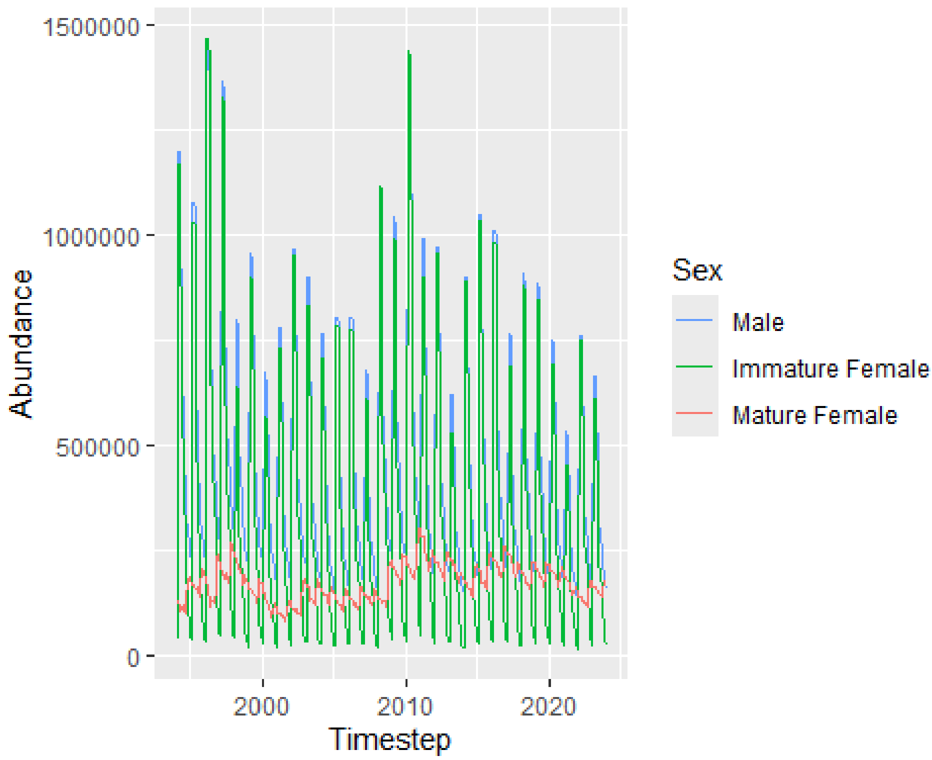

Figure 4.77. Estimated abundance over time by sex. Abundance is in 1000s of crabs.

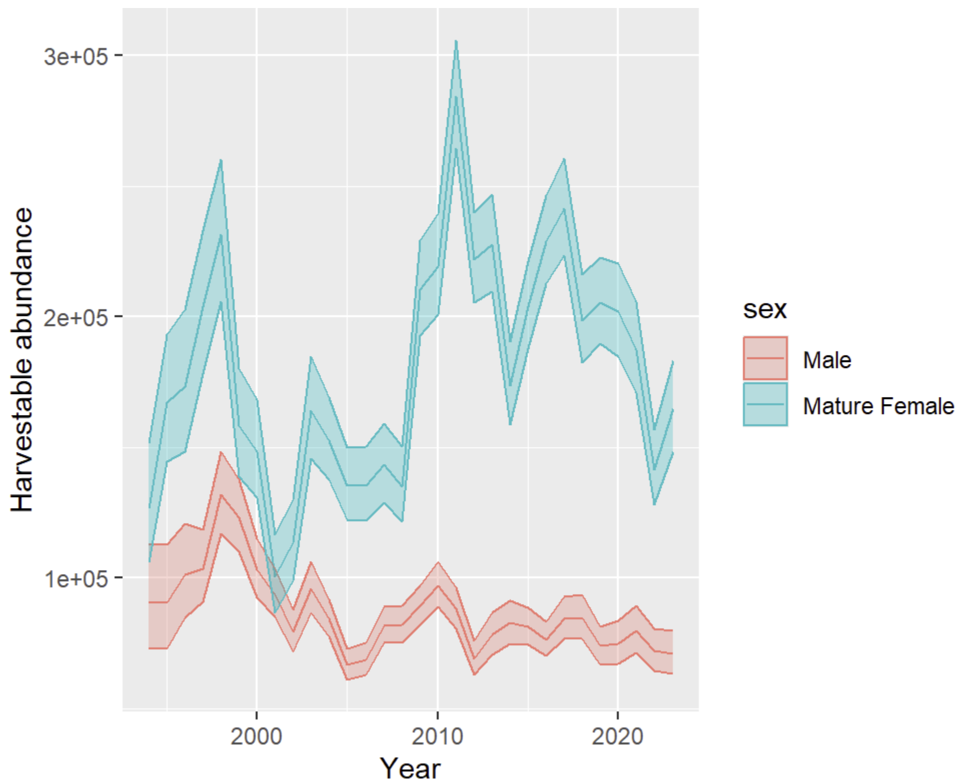

Figure 4.78. Harvestable abundance over time by sex. Shaded region represents 95% confidence intervals. Abundance is in 1000s of crabs.

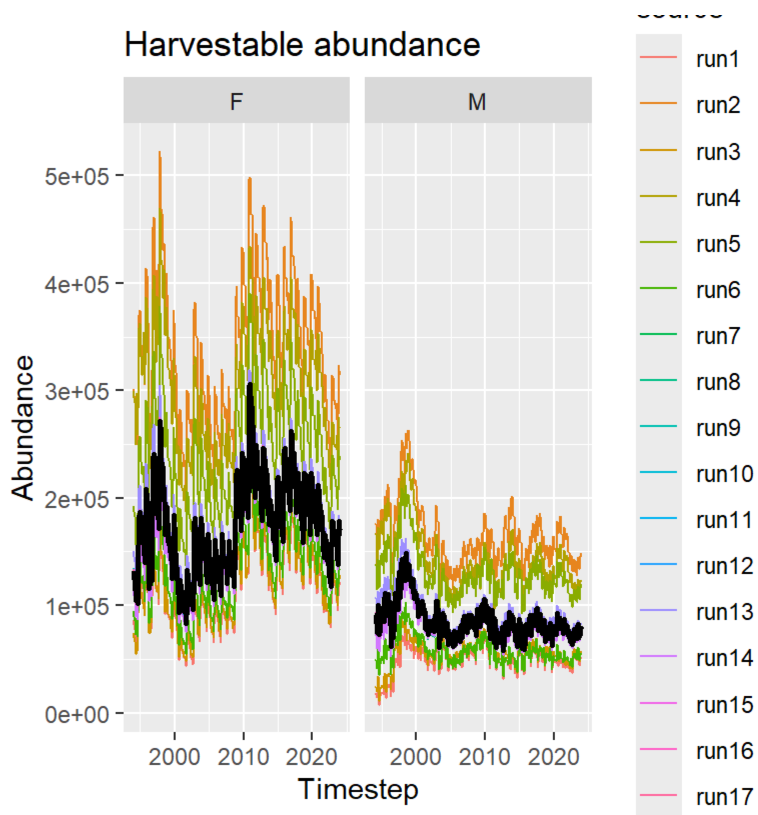

Figure 5.1. Estimated abundance of Chesapeake Bay blue crabs by sex for each sensitivity run. Mature females are in the left panel, and males with carapace widths >13 cm is on the right. Model number (run #) corresponds to the values in Table 5.1. The base model is indicated with the heavy black line. Abundance is in 1000s of crabs.

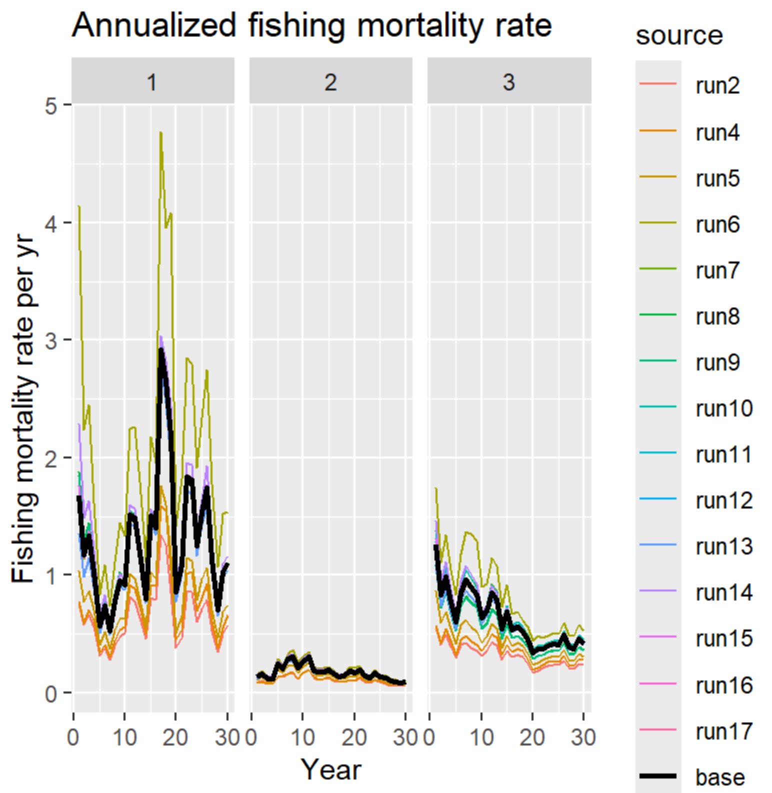

Figure 5.2. Estimated fully selected fishing mortality rates for Chesapeake Bay blue crabs by sex for each sensitivity run. Panel 1 indicates males, panel 2 indicates immature females, and panel 3 is mature females. Model number (run #) corresponds to the values in Table 5.1. The base model is indicated with the heavy black line.

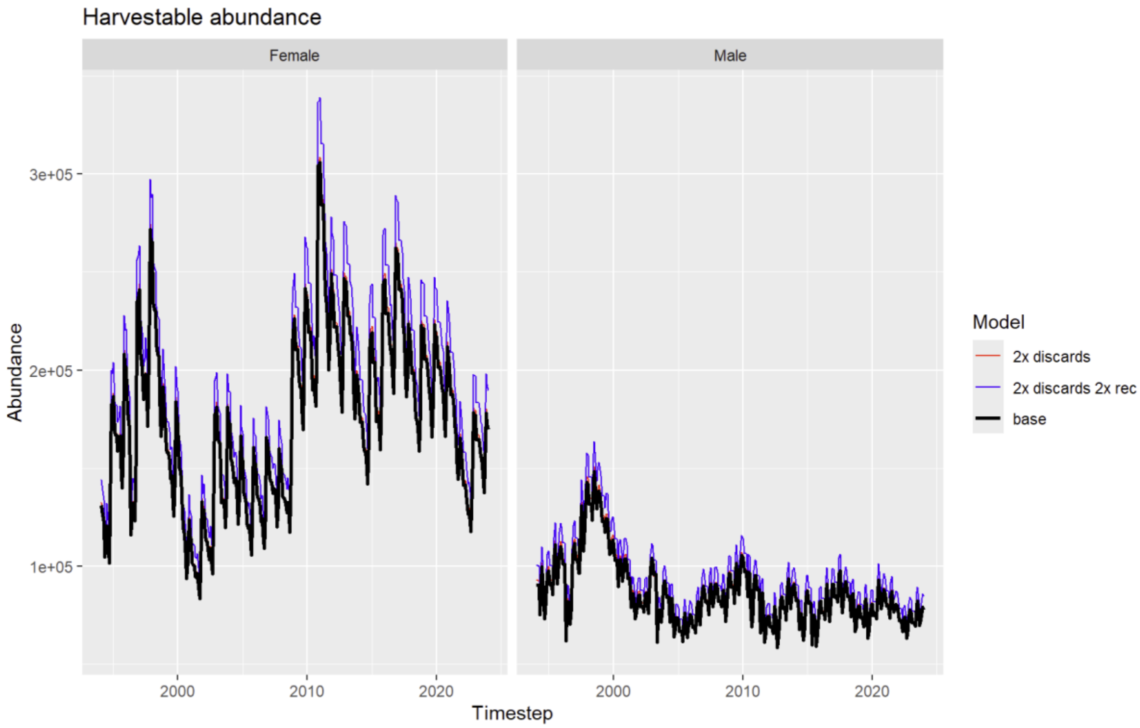

Figure 5.3. Estimated abundance of Chesapeake Bay blue crabs by sex for sensitivity runs that removed recreational catch and doubled the amount of dead discards (red line) or doubled the amount of recreational catch and dead discards (blue line). Mature females are in the left panel, and males with carapace widths >13 cm is on the right. The base model is indicated with the heavy black line. Abundance units are numbers of crabs.

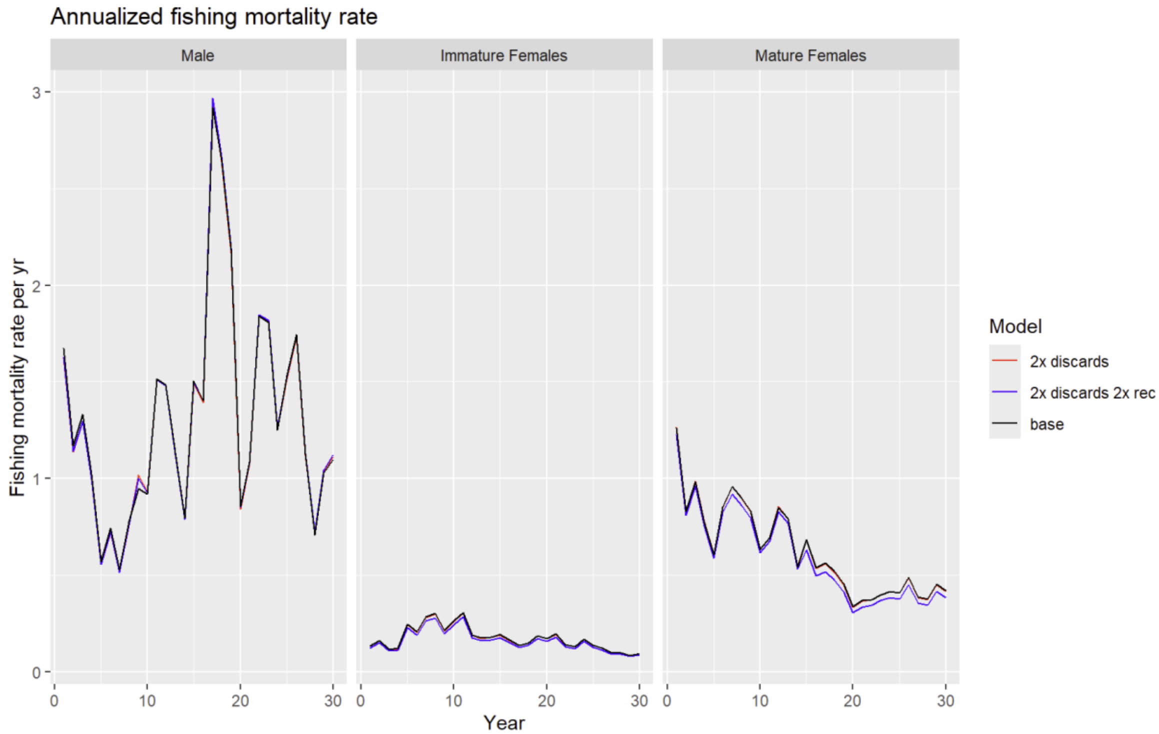

Figure 5.4. Estimated fully selected fishing mortality rates for Chesapeake Bay blue crabs by sex for runs that removed recreational catch and doubled the amount of dead discards (red line) or doubled the amount of recreational catch and dead discards (blue line). Panel 1 indicates males, panel 2 indicates immature females, and panel 3 is mature females. The base model is indicated with the heavy black line.

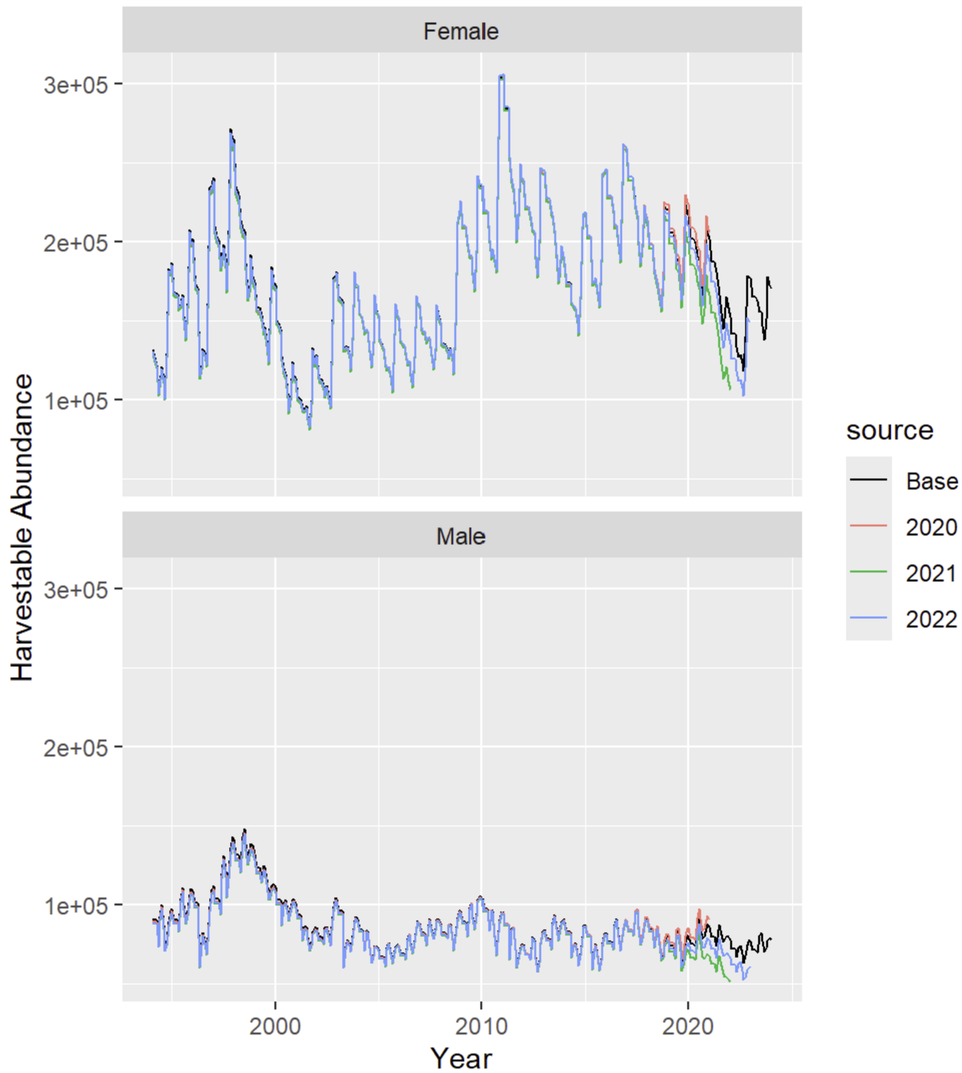

Figure 5.5. Estimated abundance of Chesapeake Bay blue crabs by sex for each retrospective run (run name indicates terminal year of run). Mature females are on the top panel, and males with carapace widths >13 cm is on the bottom. Abundance units are numbers of crabs.

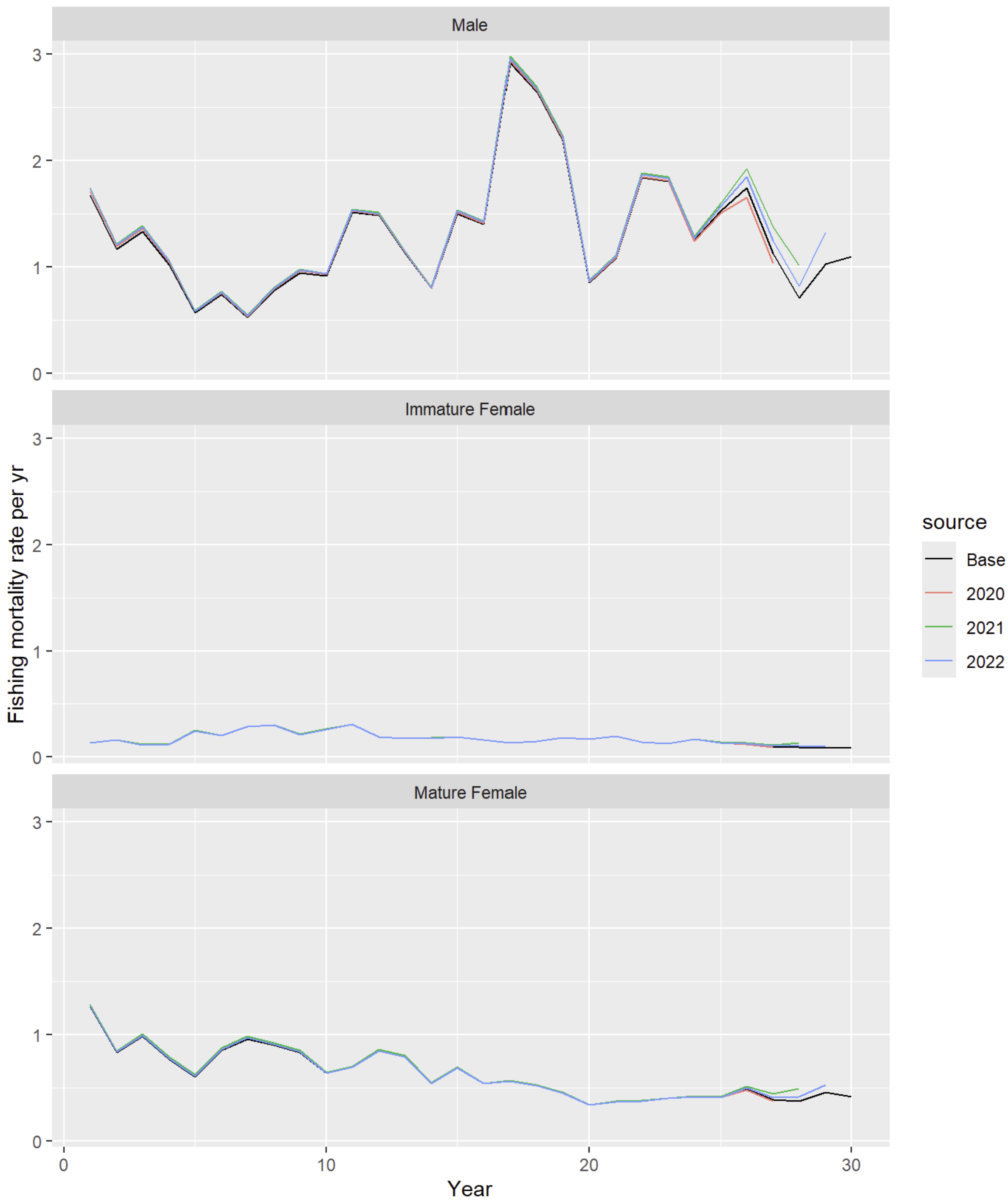

Figure 5.6. Estimated fully selected fishing mortality rates for Chesapeake Bay blue crabs by sex for each retrospective run (run name indicates terminal year of run). The top panel indicates males, the middle panel indicates immature females, and the bottom panel is mature females.

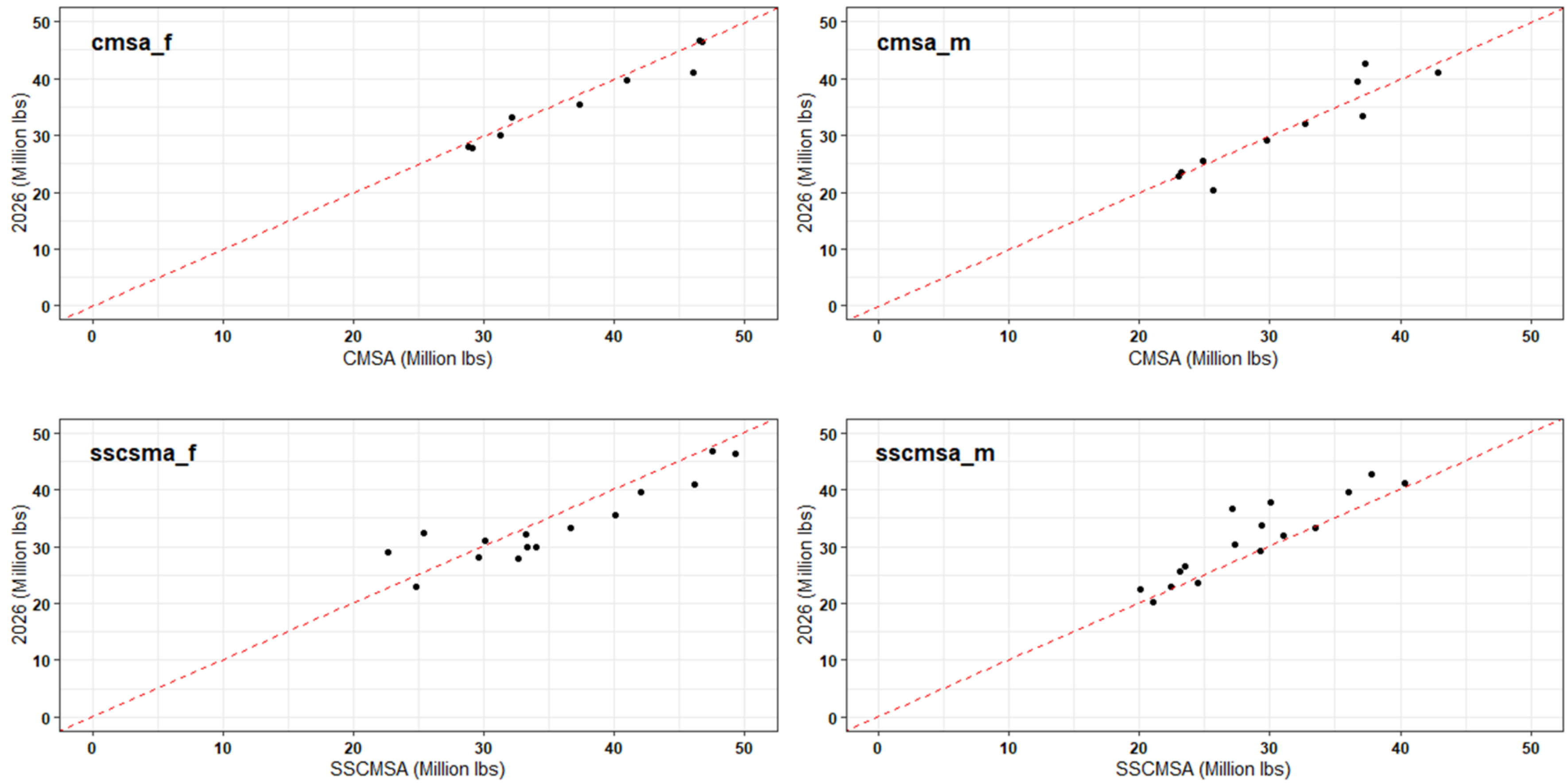

Figure 6.1. Comparisons of reported sex-specific removals of blue crabs from the Chesapeake Bay for prior (2005 assessment in the top row, and 2011 assessment in the bottom row) and current stock assessment. The red dashed line on each panel represents the 1:1 relationship.

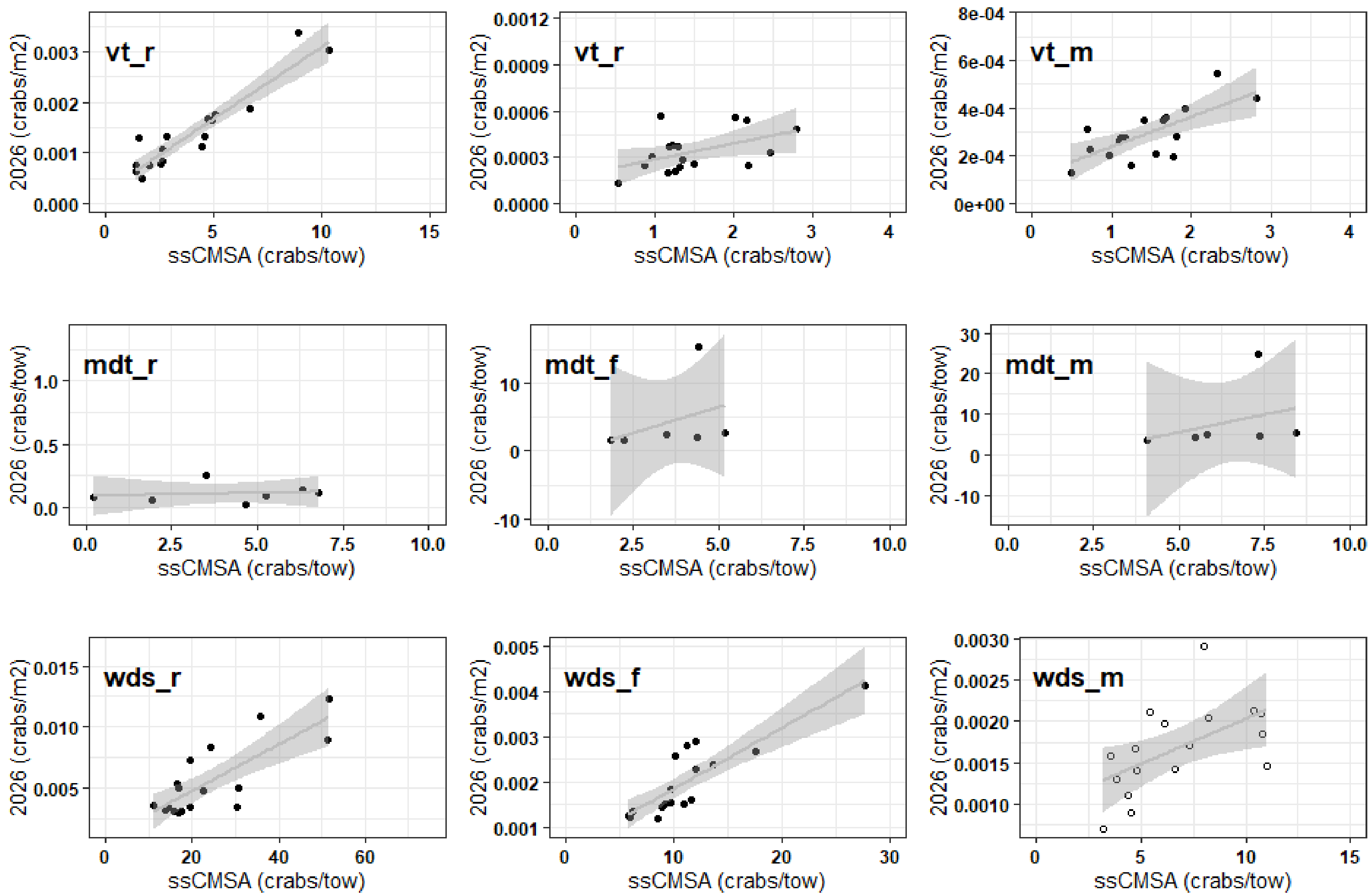

Figure 6.2. Relationship between estimates of survey CPUEs for the three principal surveys used in blue crab stock assessments in the 2011 assessment (ssCMSA) and the 2026 assessment. Each panel shows the relationship between CPUE estimates for a life stage (r = recruit, f- recruited female, m= recruited male) for each survey where vt = VIMS trawl, (upper row), mdt = Maryland

summer trawl (middle row), and wds = Winter dredge survey (lower row). Least squares regression fits are shown in each panel, together with 95% confidence intervals of the mean prediction.

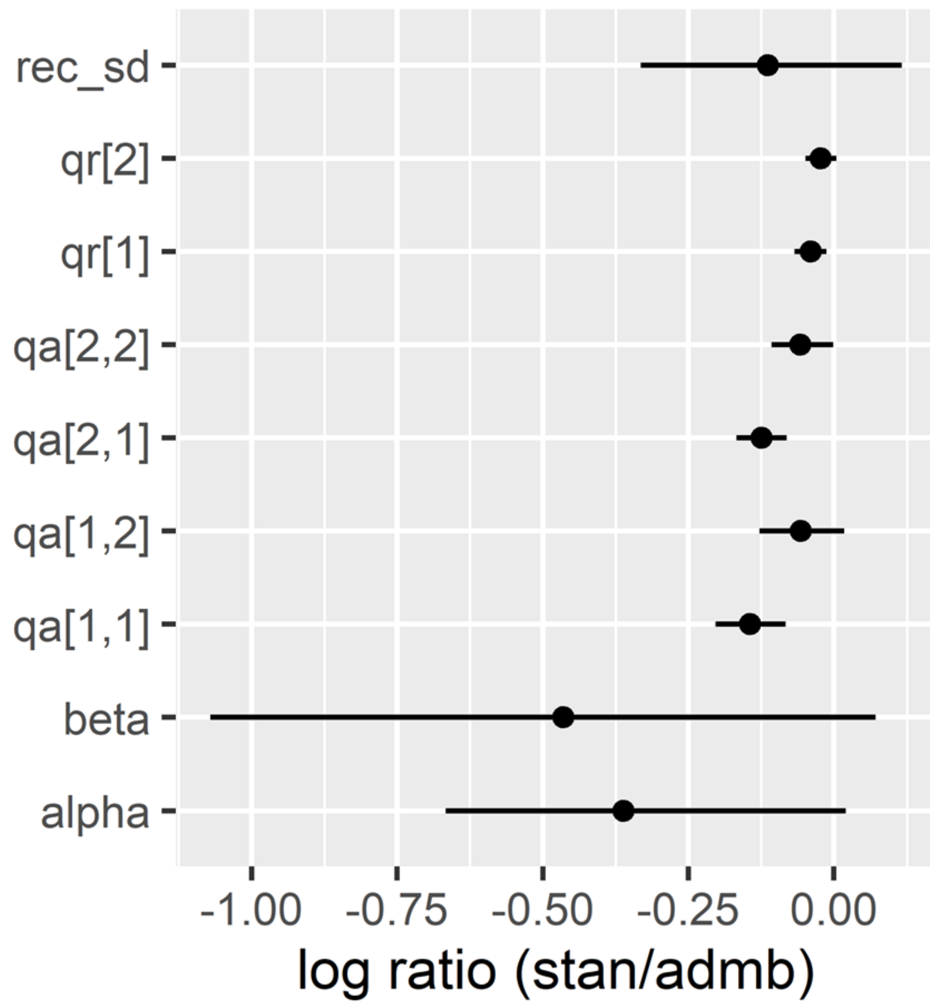

Figure 6.3. A comparison of key parameter values between an SSCMSA model coded in STAN and in ADMB. Values of the log ratio = 0 indicate parameter values between the two models are identical. Log ratio values < 0 indicate parameter values estimate by STAN are smaller than those estimated in ADMB, and value of the log ration > 0 indicate that STAN parameter values are greater than those estimated in ADMB.

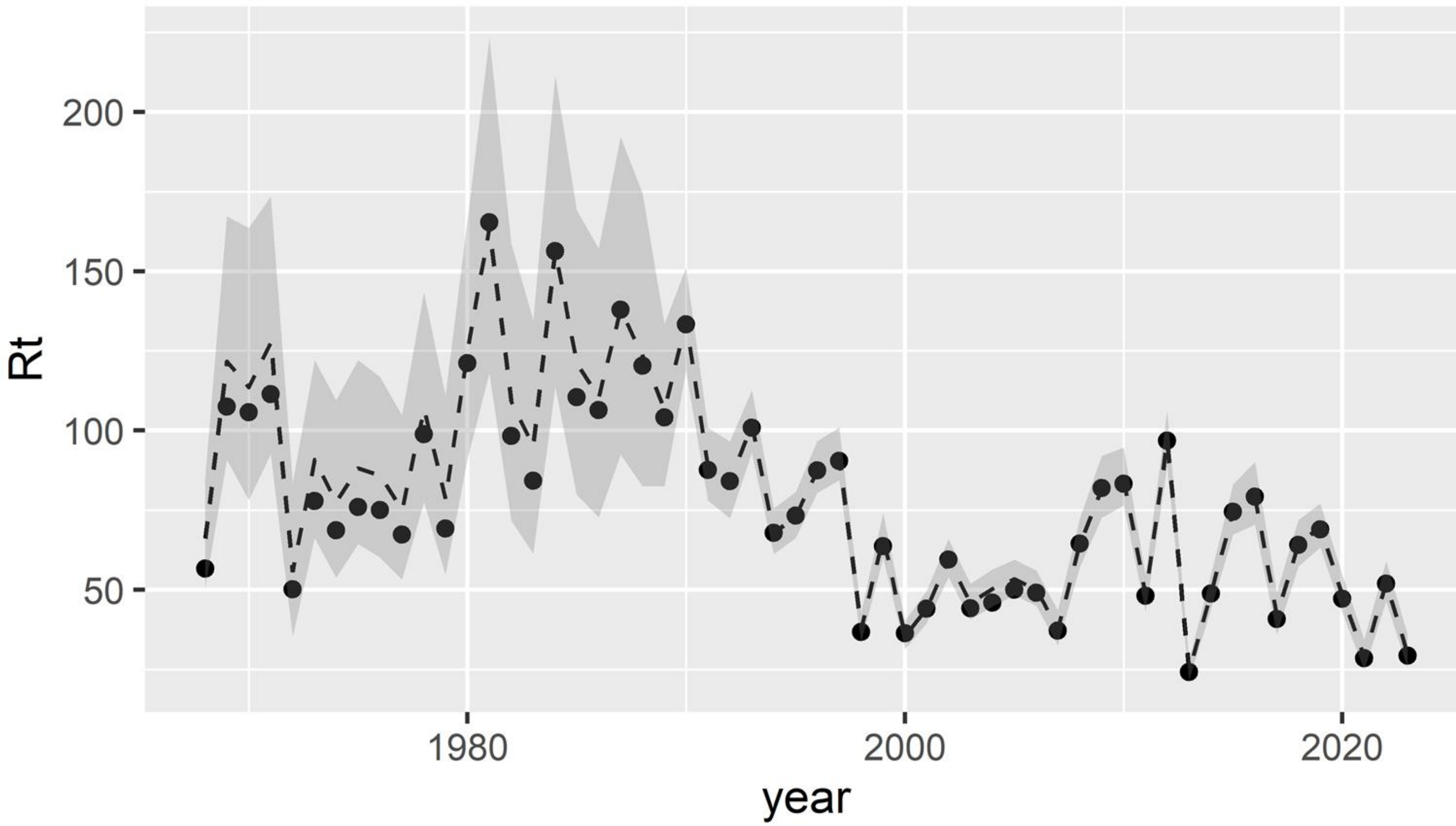

Figure 6.4. Estimates of the abundance of pre-recruit (Rt) blue crabs (millions) in Chesapeake Bay 1968-2023 estimated by SSCMSA models implemented in STAN (dashed line and grey shaded uncertainty bounds) and by DMB (solid points).

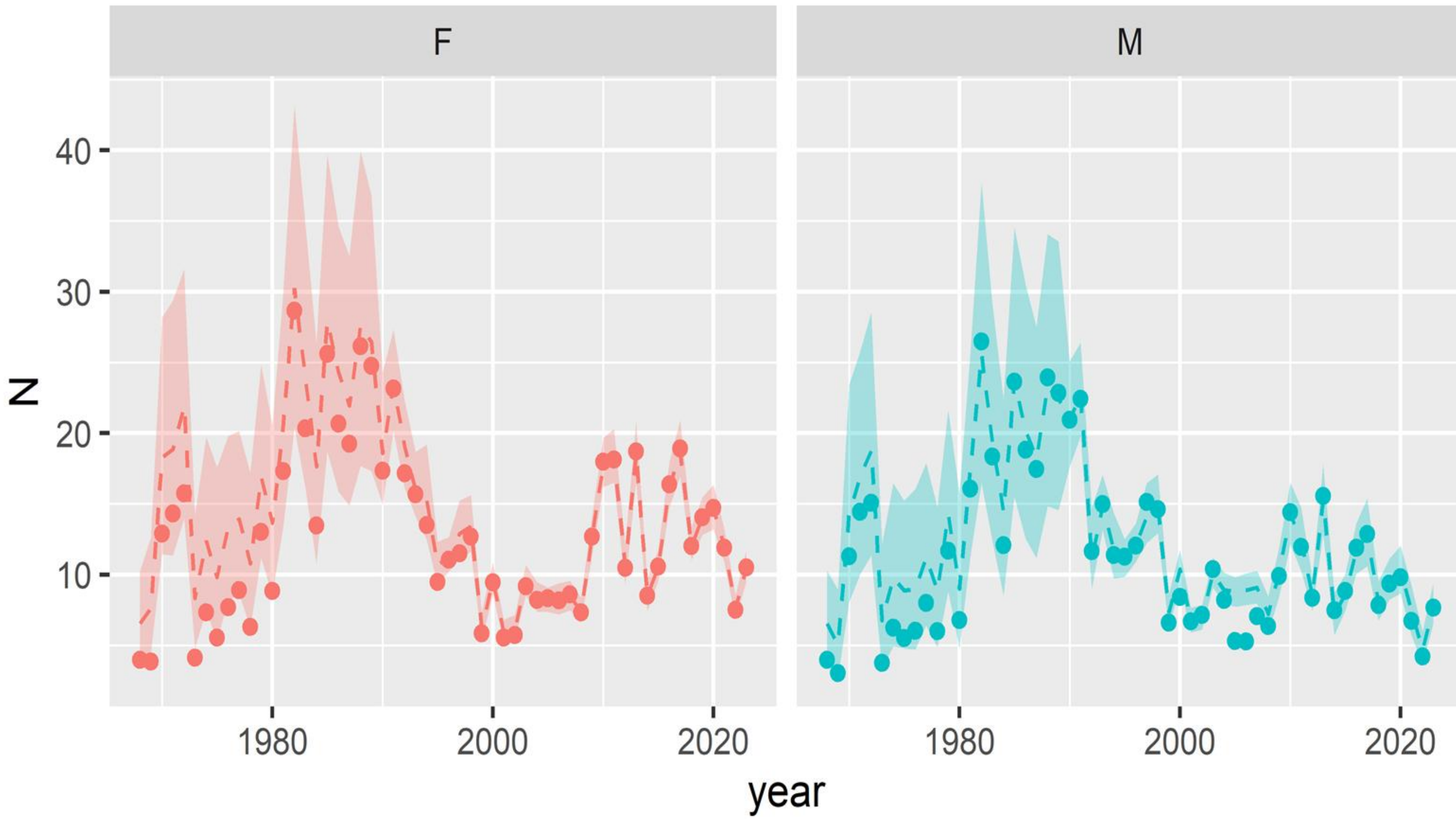

Figure 6.5. Estimates of the abundance (10 millions) of fully recruited female (left panel, salmon colors) and males (right panel and teal colors) blue crab in Chesapeake Bay 1968-2023 estimated by SSCMSA models implemented in STAN (dashed line and grey shaded uncertainty bounds) and by DMB (solid points).

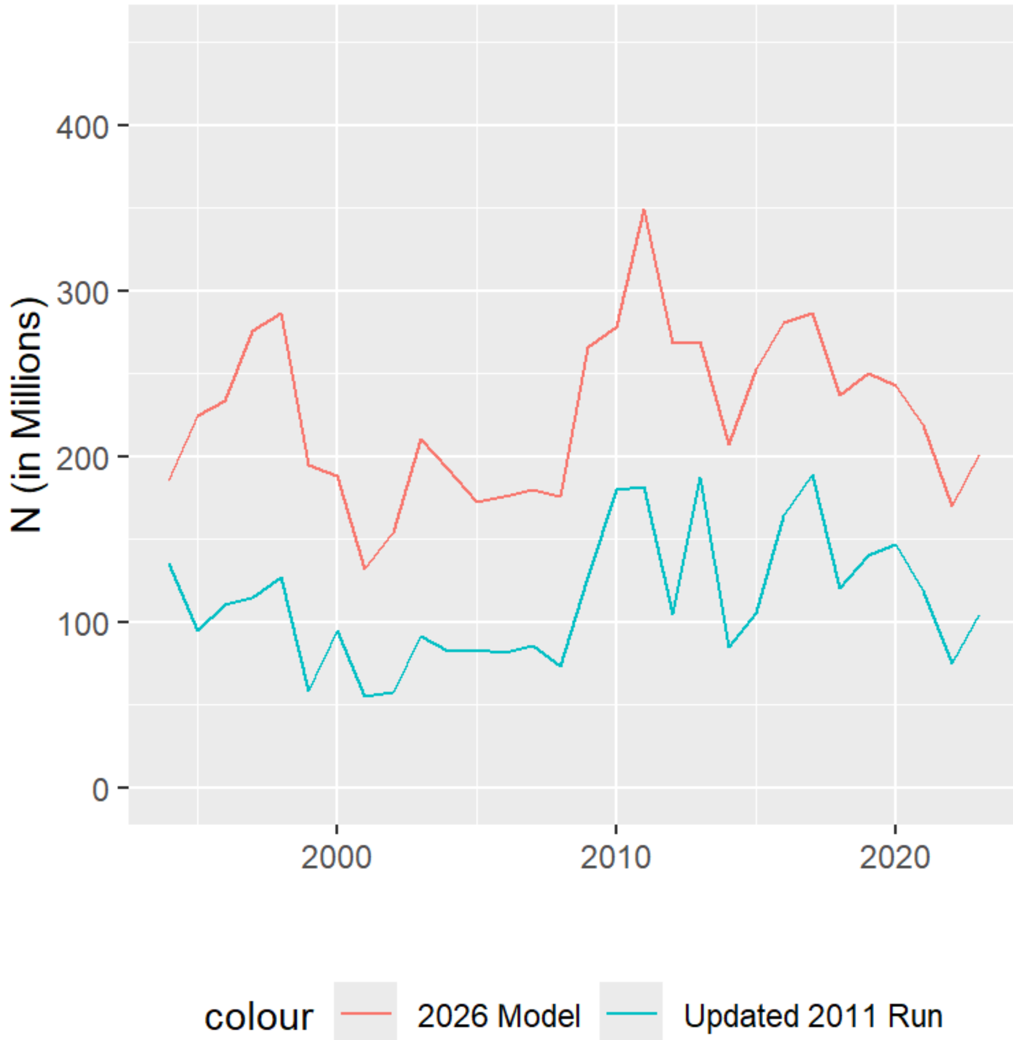

Figure 6.6. Estimated abundance from SLAM (the 2026 model) and the updated 2011 model.

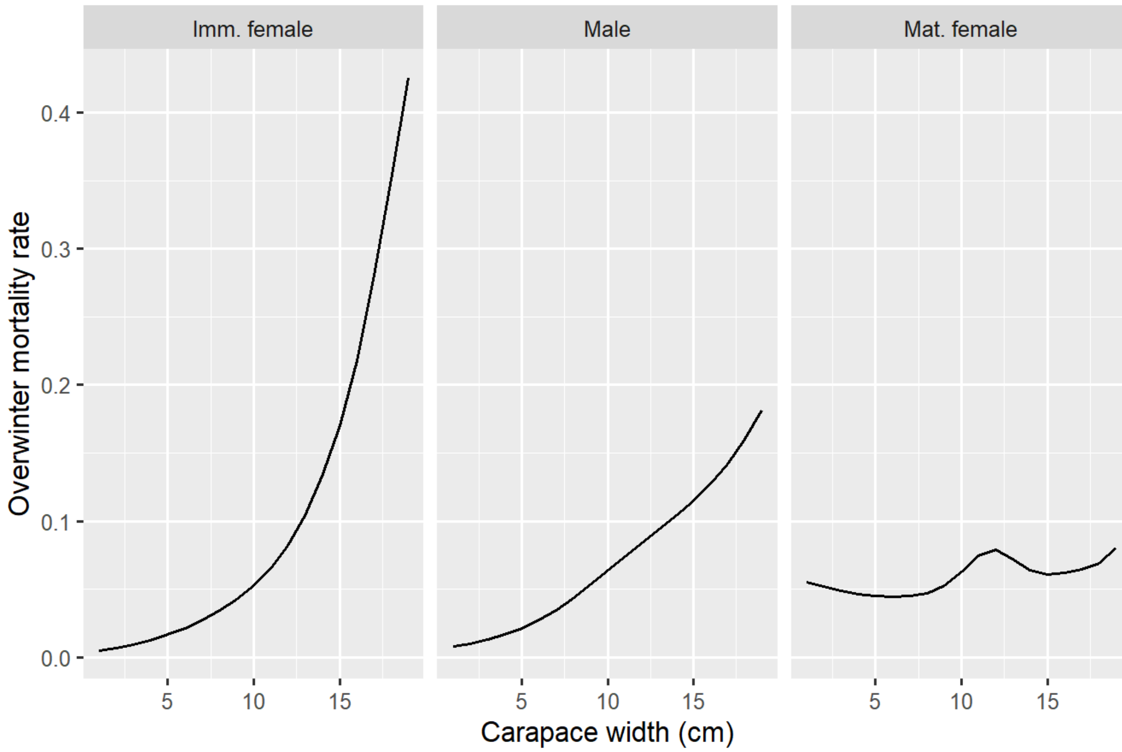

Figure 7.1. Mean overwinter mortality rates (mo^{-1}) by sex and maturity category used in the spawning potential ratio models. Overwinter mortality is only applied in March.

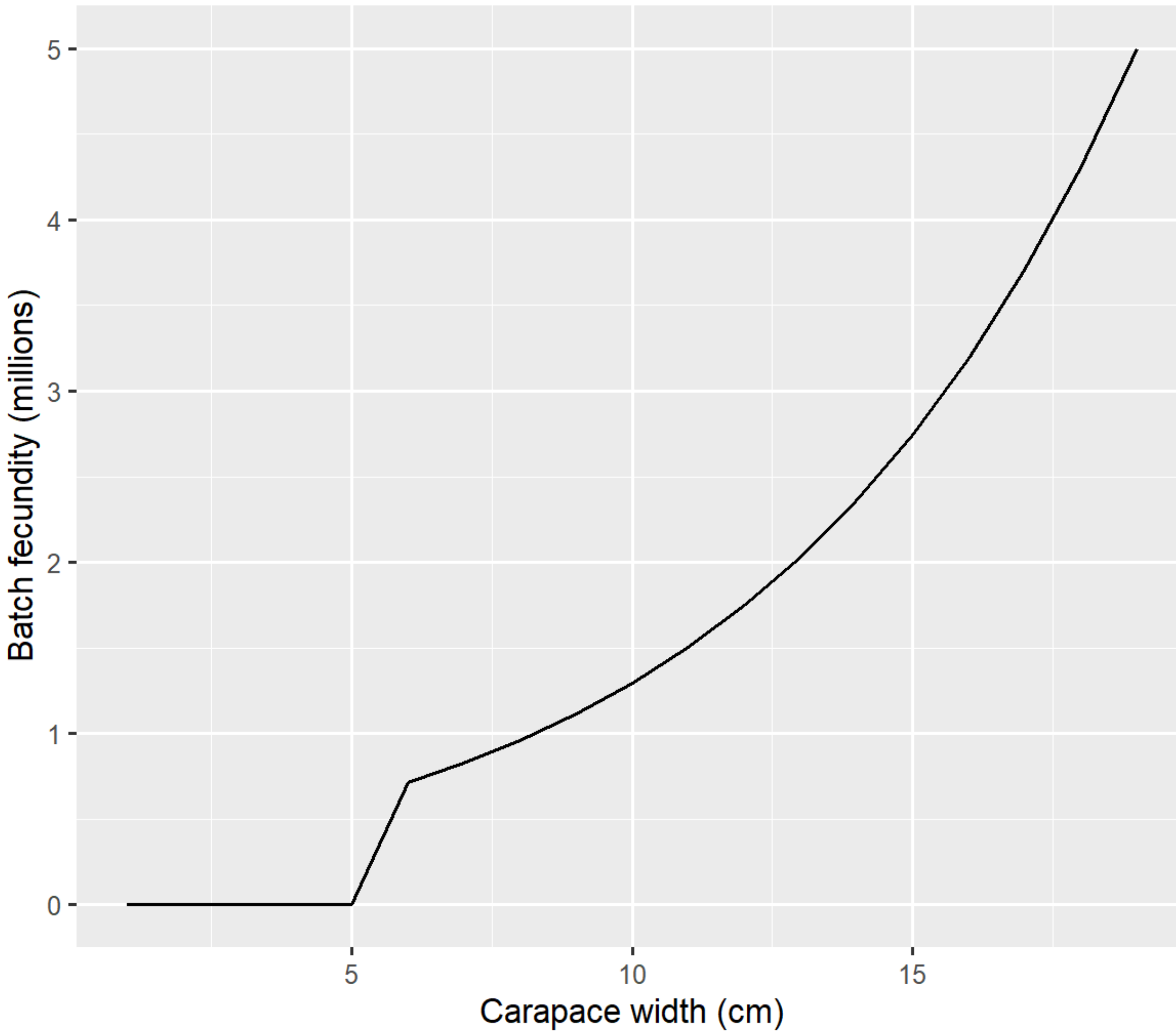

Figure 7.2. Blue crab batch fecundity as a function of carapace width from Schneider et al. (2024) except that mature females 5 cm and smaller were assumed to not be able to reproduce (i.e., batch fecundity was equal to zero).

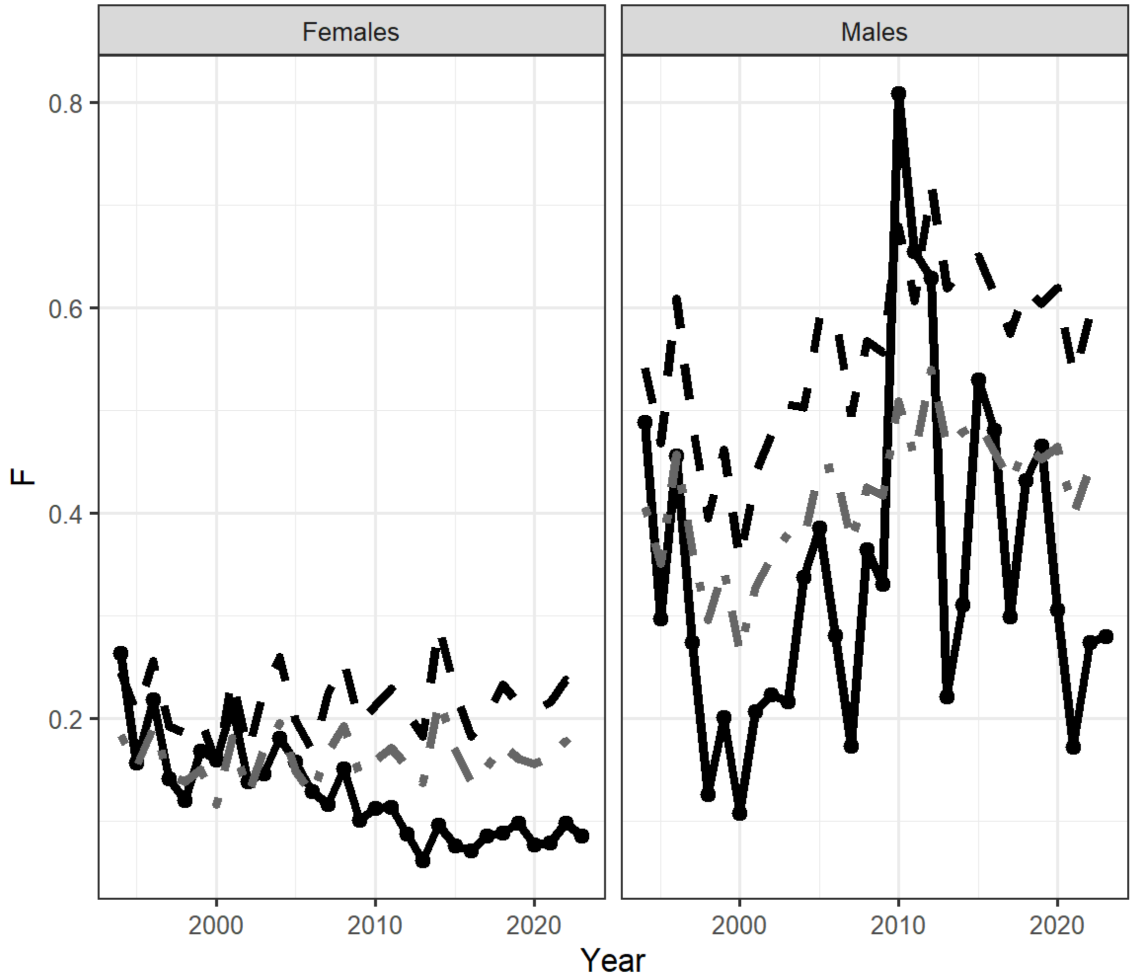

Figure 8.1. Estimated fishing mortality rates that would result in a spawning potential ratio of 40% ($F_{40\%}$; black dashed lines), 75% of $F_{40\%}$ (gray dot-dashed lines), and estimated maximum fishing mortality rates (mo^{-1}; black lines and points) for Chesapeake Bay blue crabs during 1994-2023 by sex.

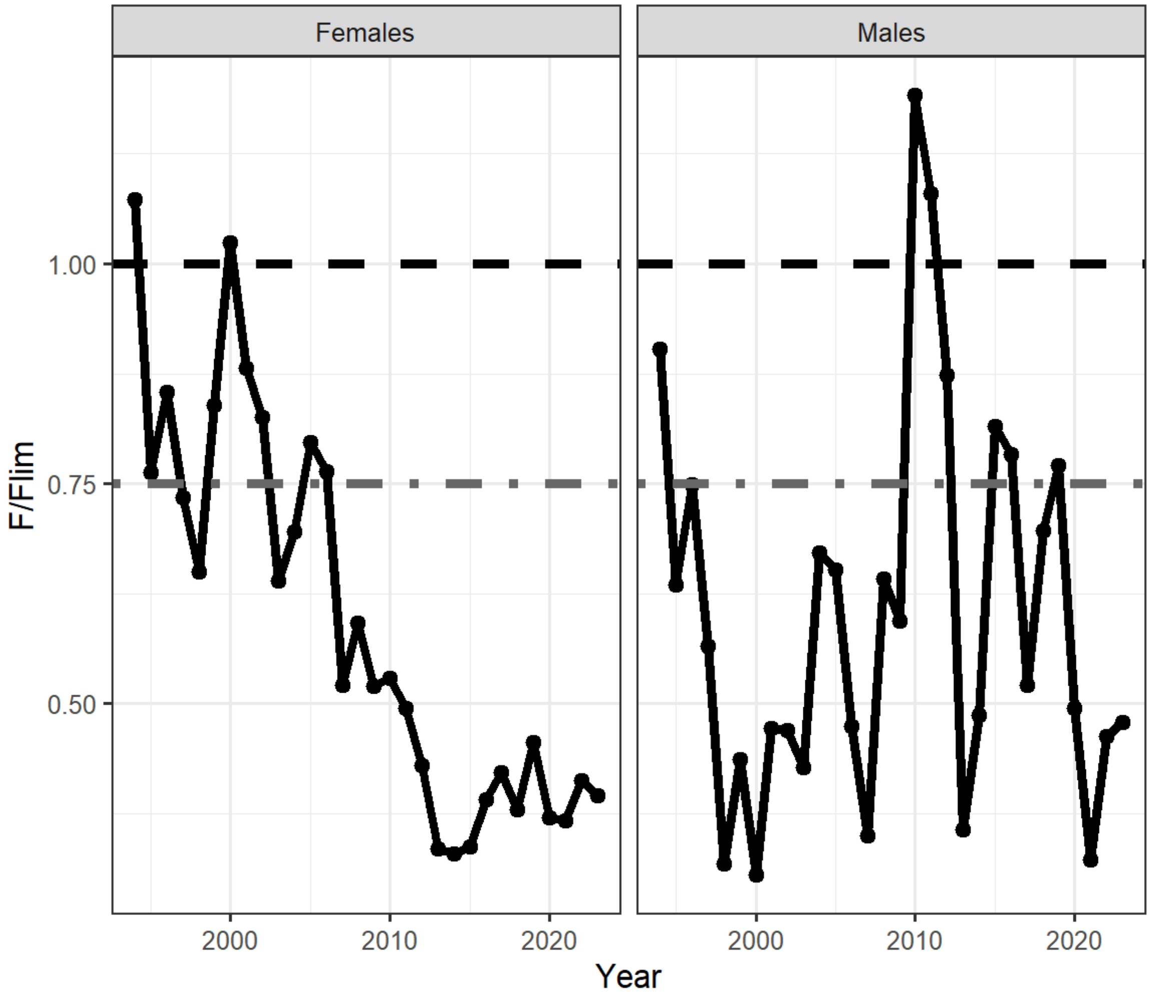

Figure 8.2. Estimated stock status (black line with black points) relative to upper threshold (black dashed line) and target (gray dot-dashed line) fishing mortality rate reference points ($F_{40\%}$) for Chesapeake Bay blue crabs during 1994-2023 by sex.

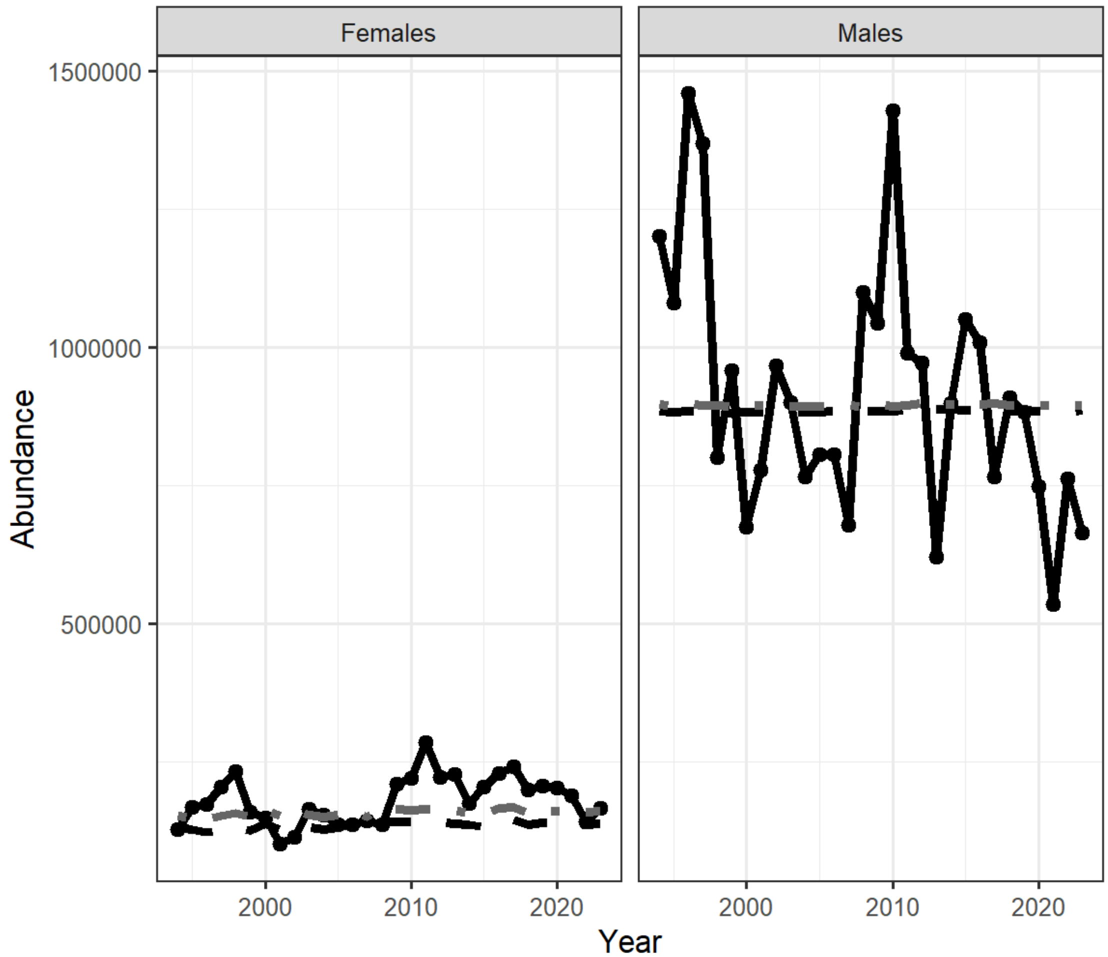

Figure 8.3. Estimated abundance reference points using the median recruitment with the fishing mortality rate at the threshold reference point (black dashed lines), target reference point (gray dot-dashed lines), and estimated abundance (1000s; black lines and points) for females and male blue crabs in Chesapeake Bay during 1994-2023. Abundance is in 1000s of crabs.

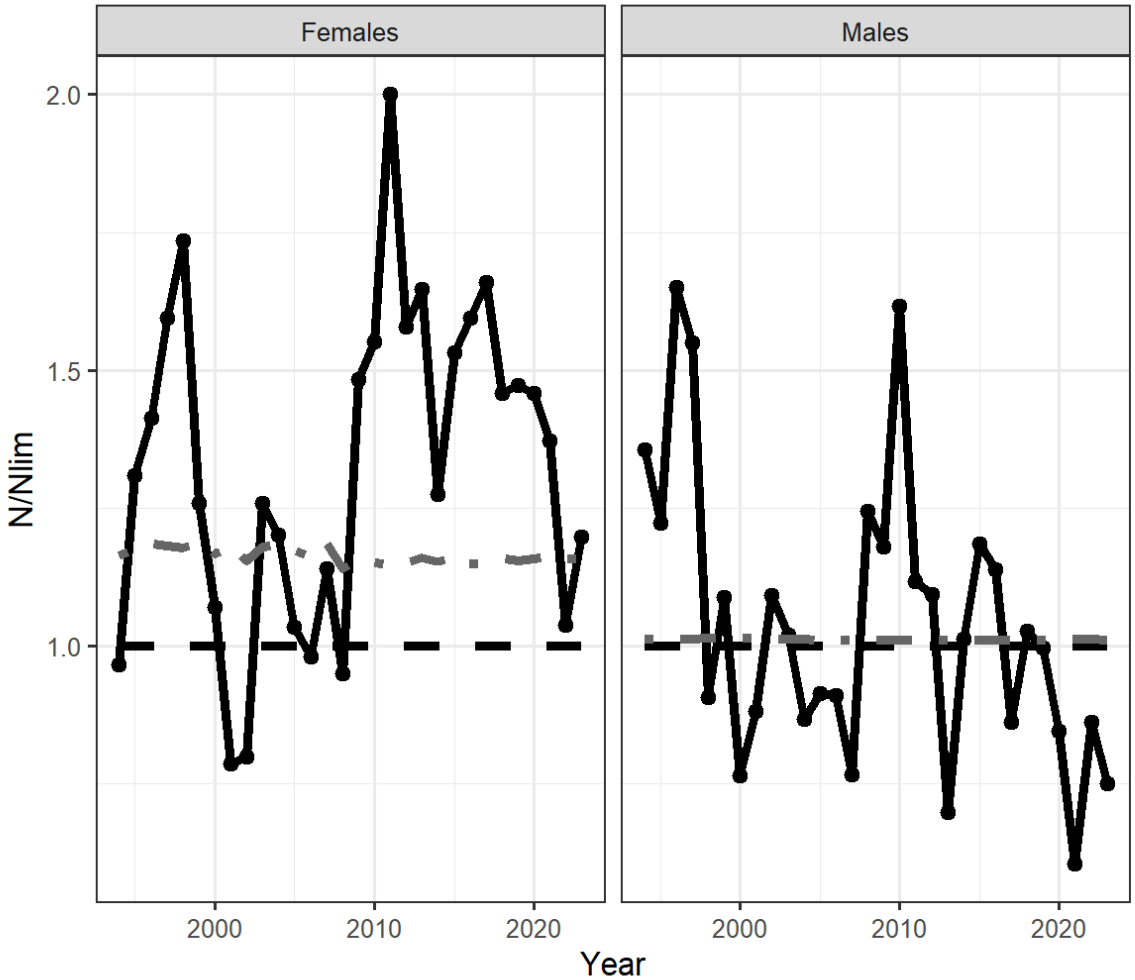

Figure 8.4. Estimated stock status (N/Nlim; solid black line and black points) relative to lower threshold abundance (black dashed line) and target (gray dot-dashed line) reference points for blue crabs in Chesapeake Bay during 1994-2023 by sex.

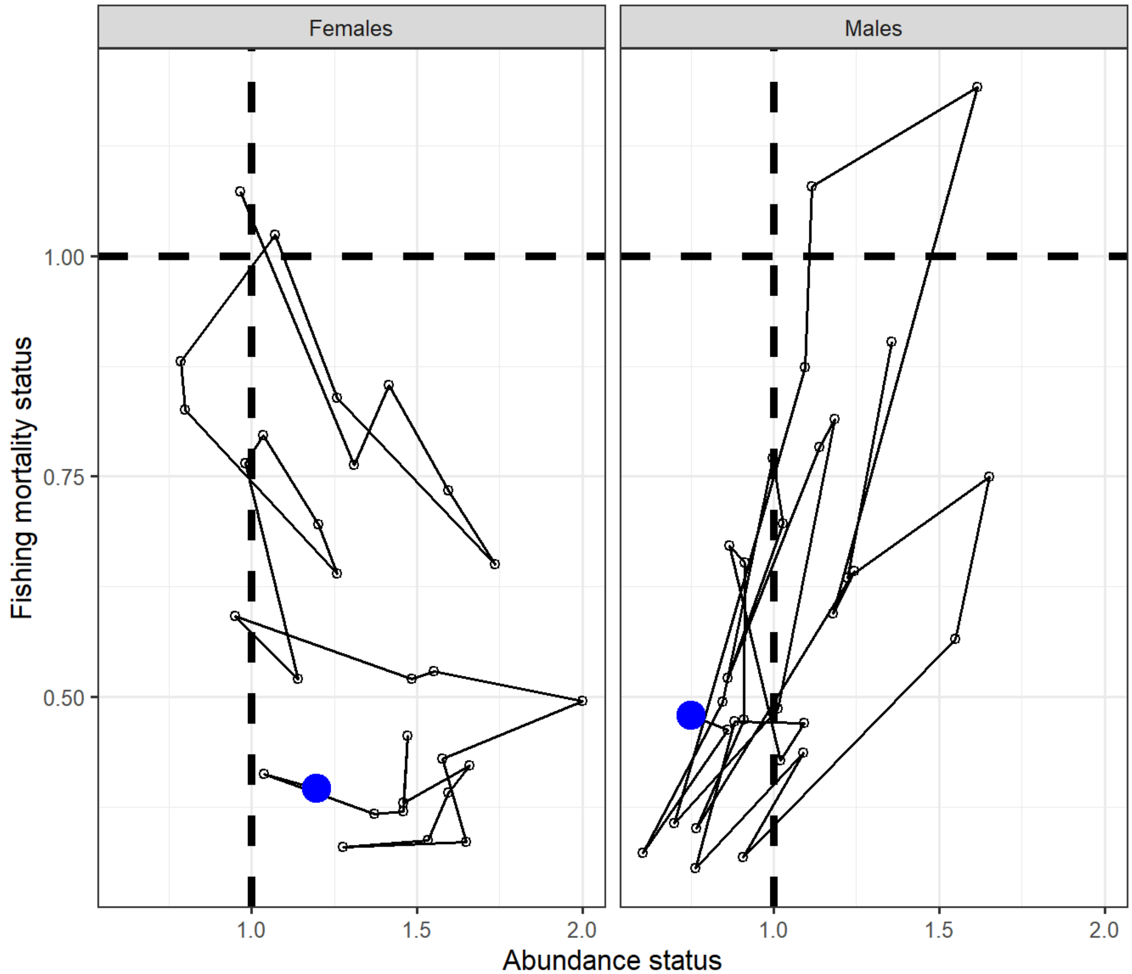

Figure 8.5. Stock status (hollow black points and lines) relative to upper threshold fishing mortality rate and lower threshold abundance reference points (black dashed lines) for Chesapeake Bay blue crabs during 1994-2023 by sex. The value for the most recent year is shown with a large blue point.

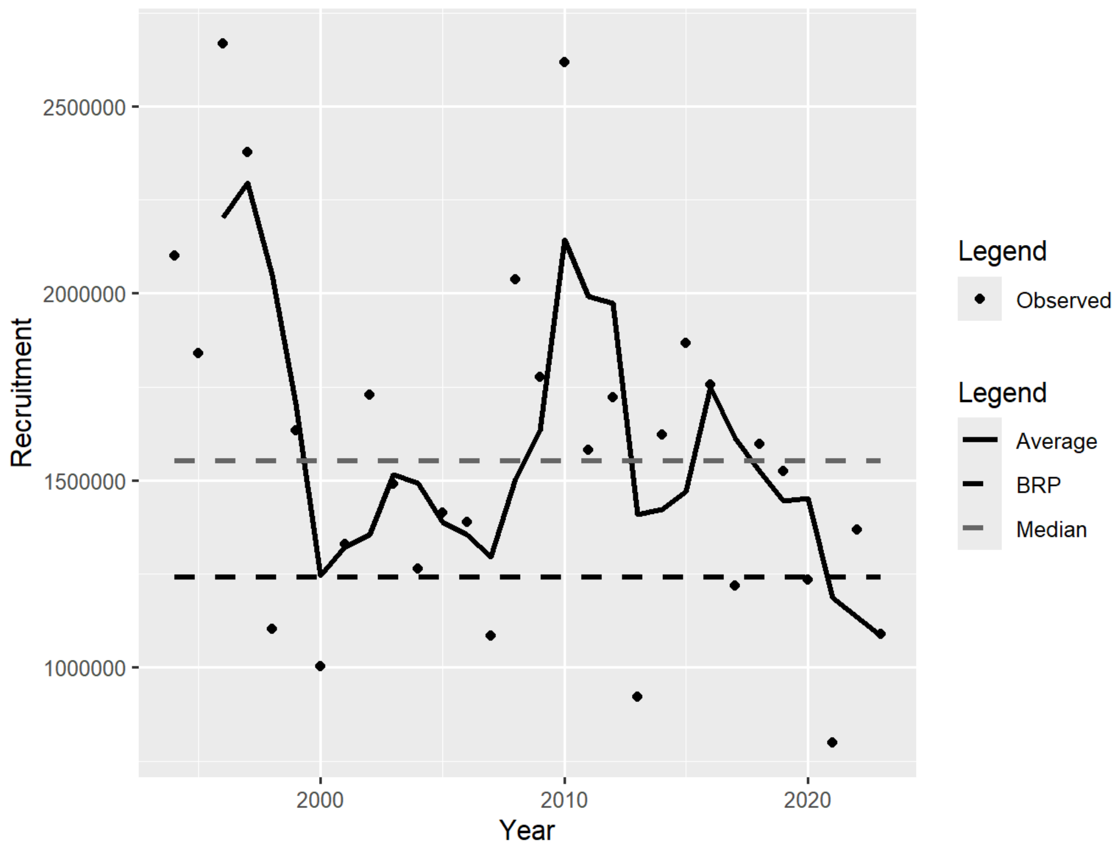

Figure 8.6. Estimated recruitment (black points) and the three-year running average estimated recruitment (solid black line) compared to the lower threshold three-year average recruitment (BRP) of the 25th percentile of estimated recruitment during 1994-2023 (black dashed line). The median recruitment during 1994-2023 is plotted for reference (dashed gray line). Recruitment is in 1000s of crabs.

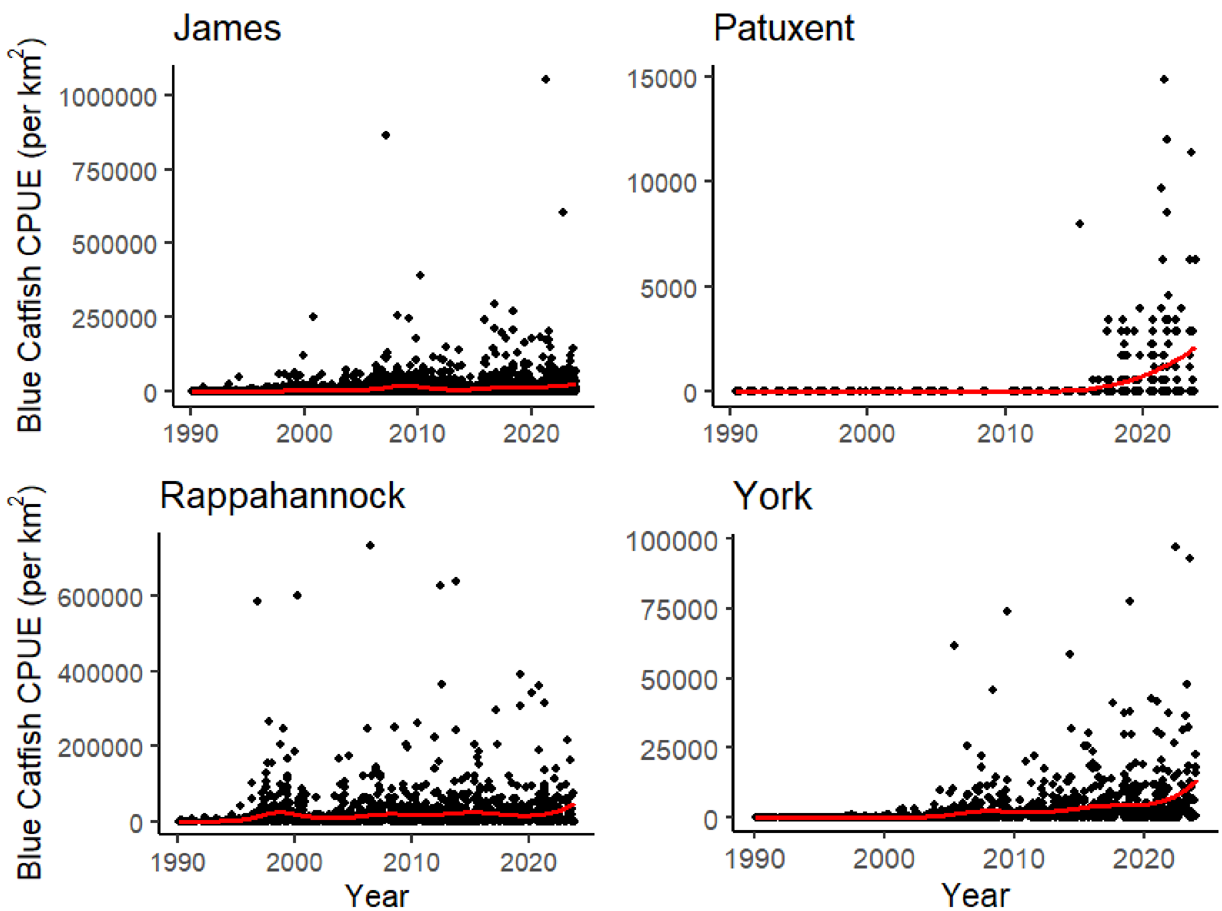

Figure 9.1. Estimated (red line) and observed (black points) Blue Catfish catch per unit effort (CPUE) during 1990-2023. Note scale on Y-axis differs between panels.

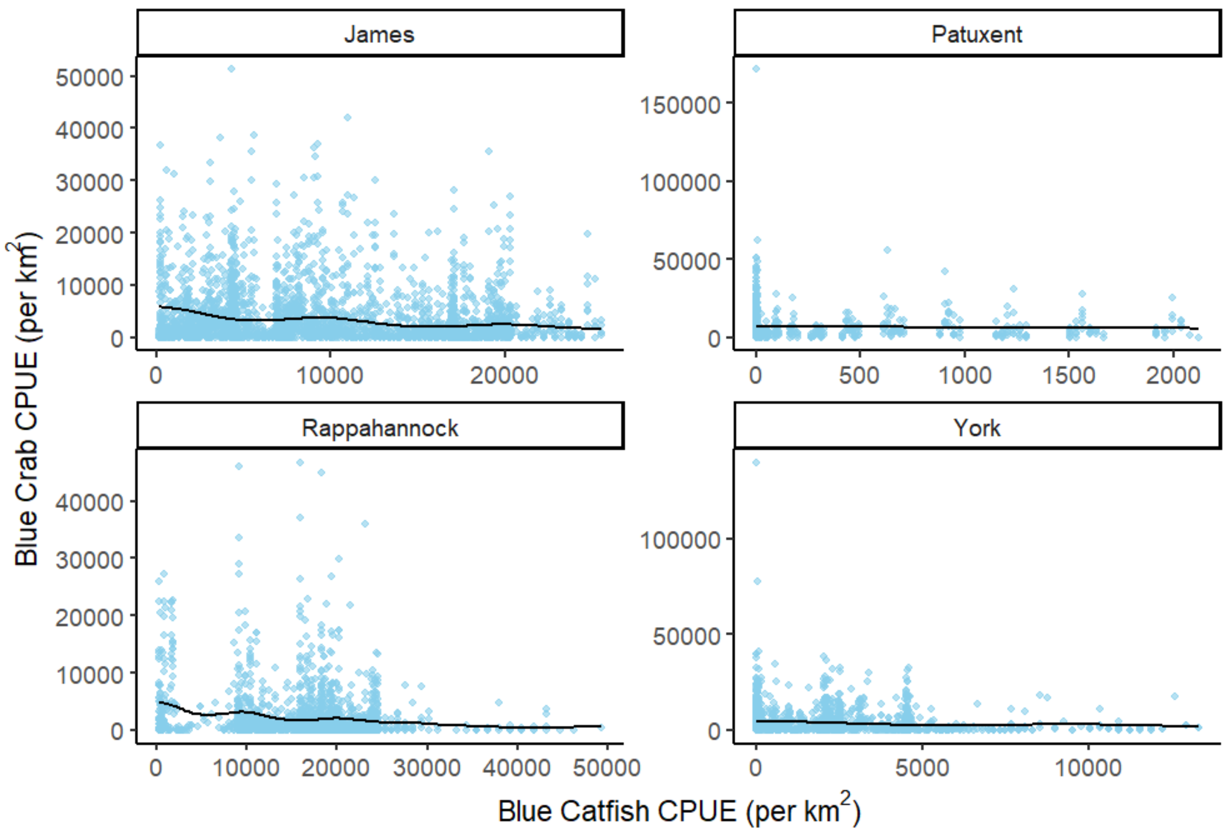

Figure 9.2. Estimated (black line) and observed (blue points) blue crab catch per unit effort (CPUE) versus Blue Catfish CPUE during 1990-2023 for the James, Patuxent, Rappahannock, and York rivers. Note scales on both axes differ among panels.

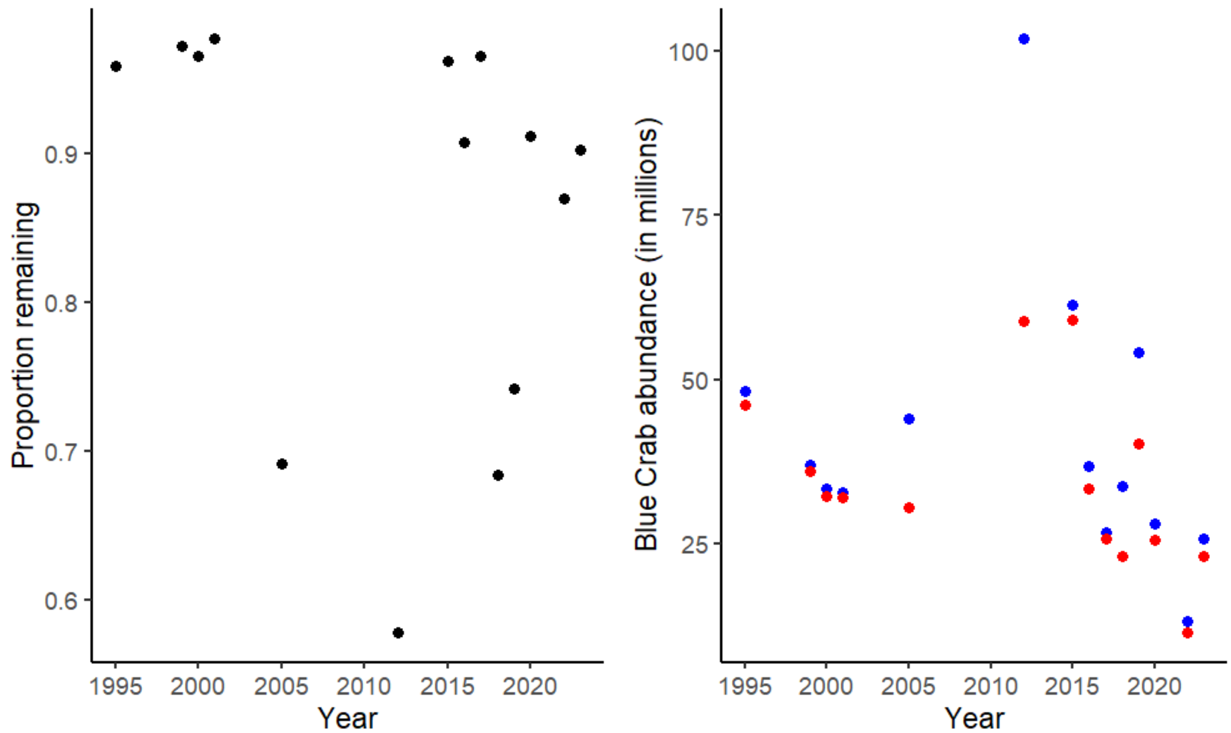

Figure 9.3. Proportion of juvenile blue crab remaining after a potential expansion of Blue Catfish abundance (left) and blue crab abundance with (red) and without (blue) Blue Catfish abundance expansion (right).

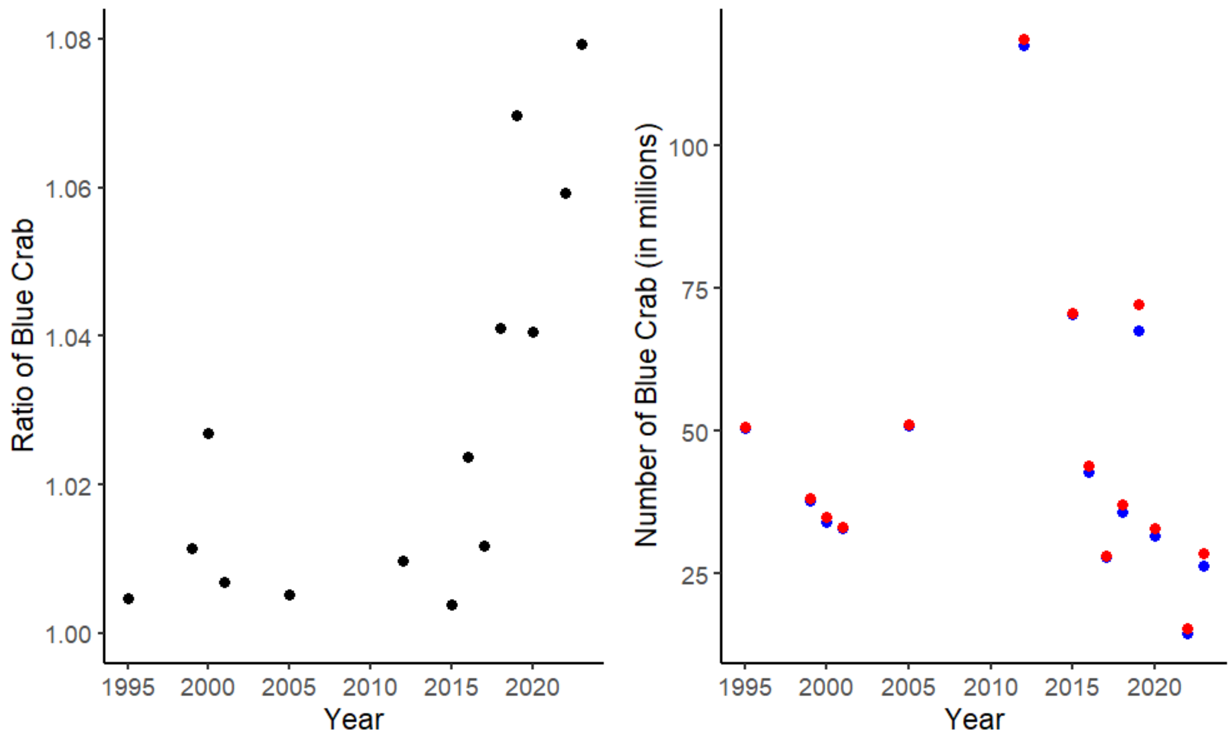

Figure 9.4. Estimated ratio of juvenile blue crab catch per unit effort (CPUE) in the absence of Blue Catfish (left) relative to observed Chesapeake Bay-wide CPUE in the Winter Dredge Survey, and estimated swept area blue crab abundance with (red) and without (blue) the current Blue Catfish effect (right). Note that the ratios on the left reflect the differences between the year-specific values in the panel on the right.

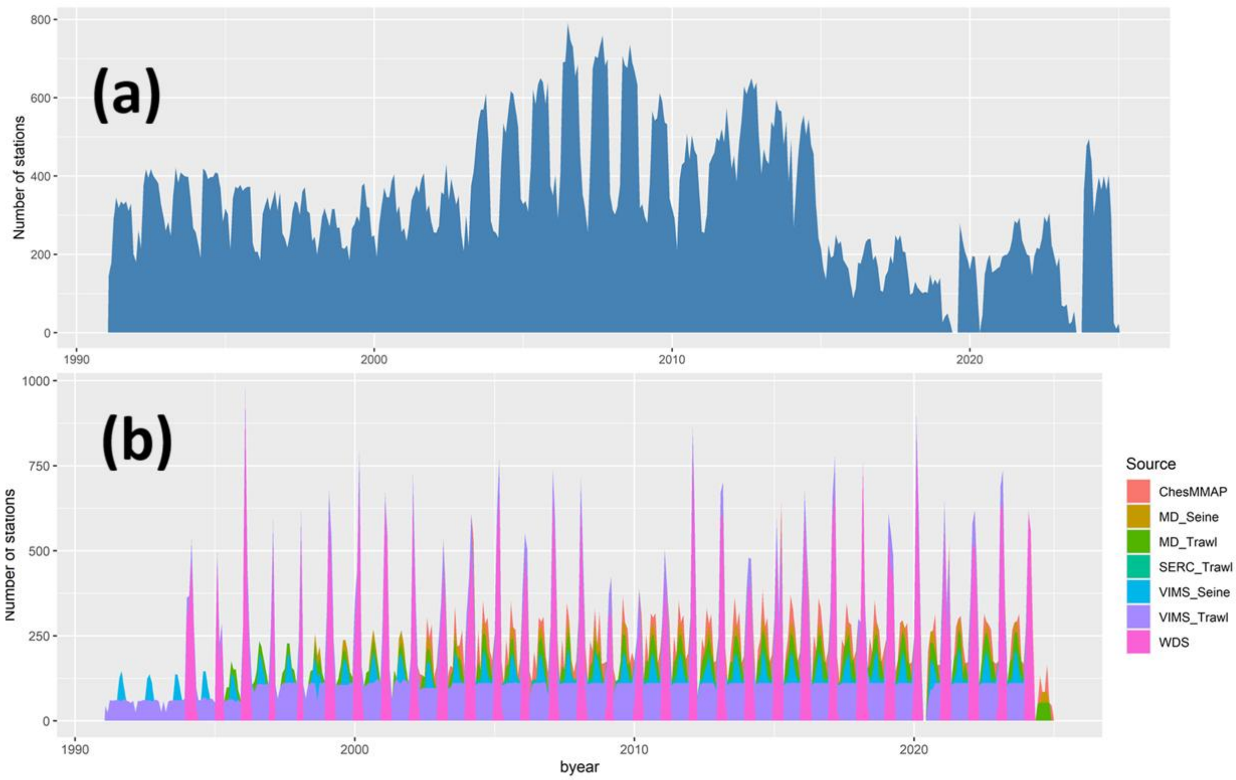

Figure 9.5. Top (a) Bay Program Long-Term Monitoring Data provides a Monthly number of stations recording Water Temperature. Bottom (b) The number of locations from fishery independent surveys recording water temperature.

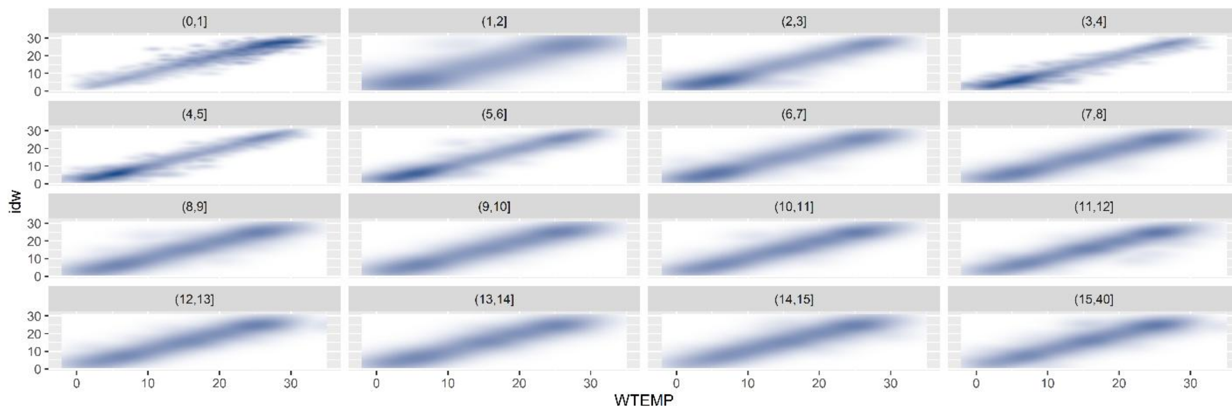

Figure 9.6. Kernel smoothing of scatter plots for water temperature samples collected during the fishery independent surveys and the Inverse-Distance Weighted interpolation from a spatiotemporal neighborhood of long-term fixed station data. Each panel denotes the sampling depth in meters.

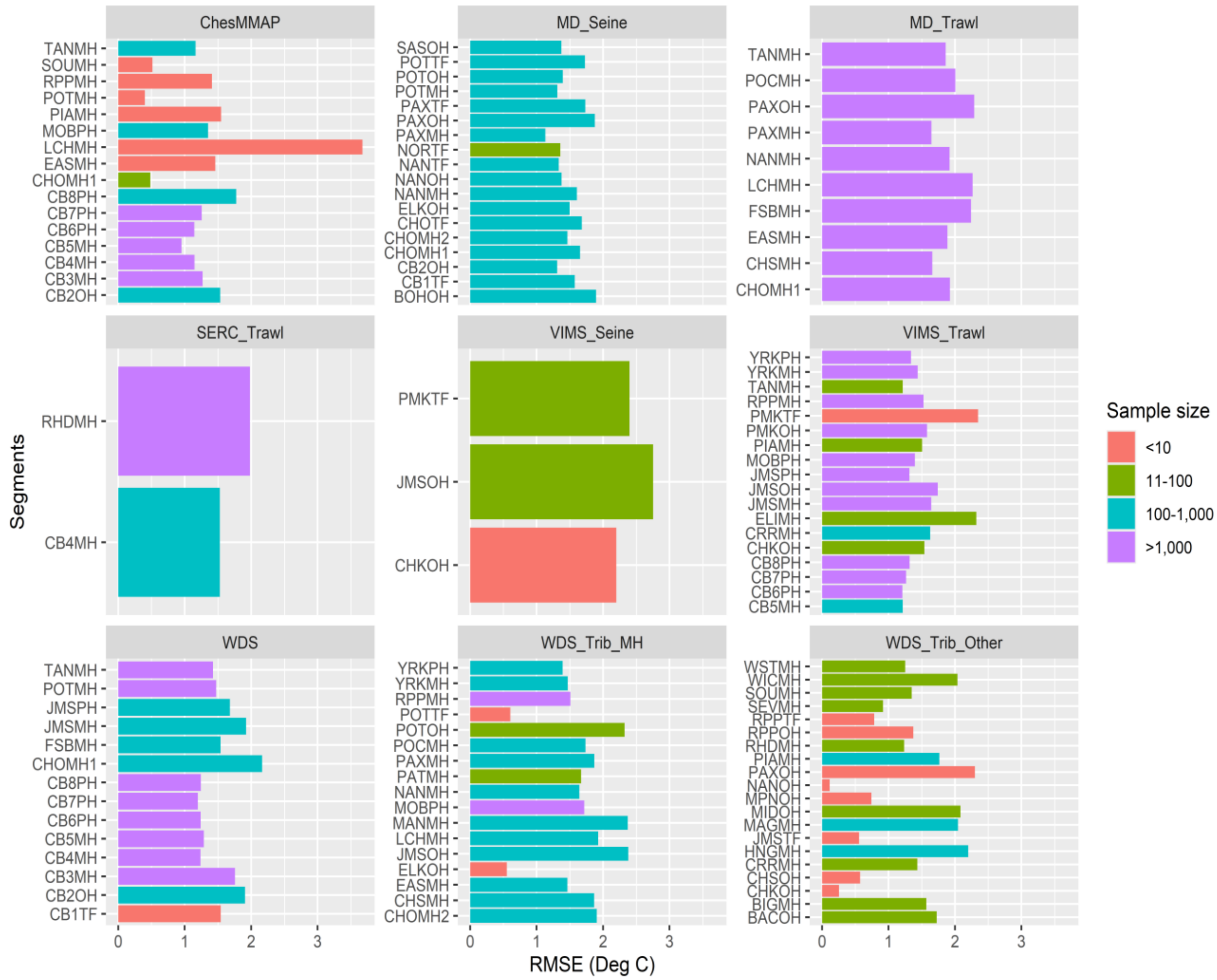

Figure 9.7. Root Mean Square Error of 4D interpolation of water temperature data from fishery independent surveys from the long-term fixed monitoring, presented by the surveys and the management segments of the Chesapeake Bay. Acronym of the segments are defined from the Chesapeake Bay Program website (https://www.chesapeakebay.net/files/documents/chesapeake_bay_program_analytical_segmentation_scheme.pdf).

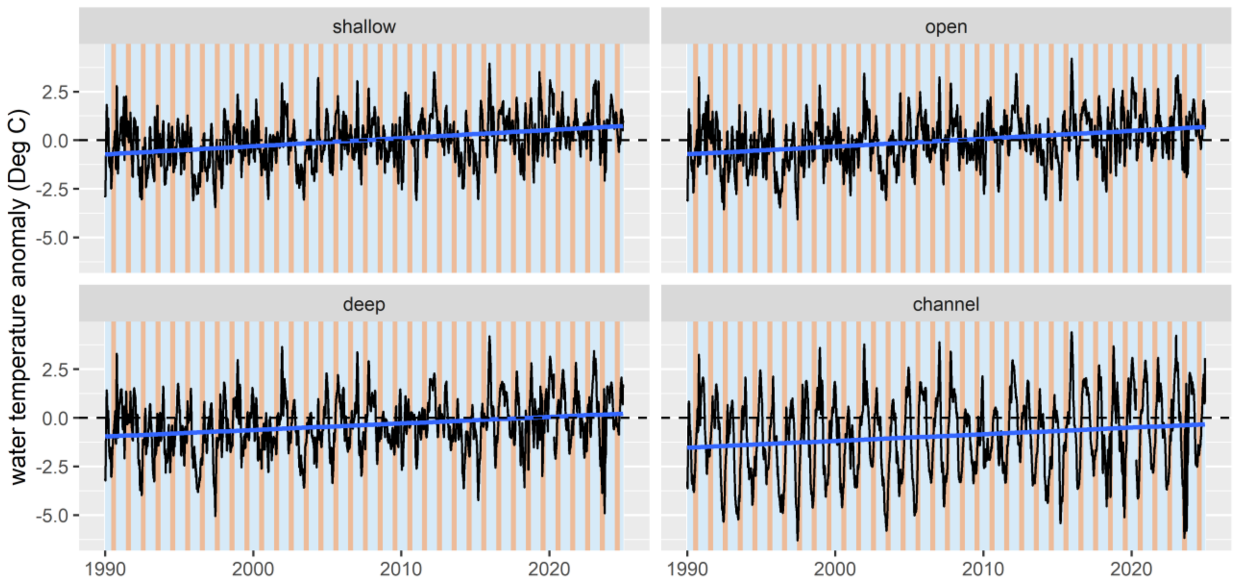

Figure 9.8. Water temperature anomaly from seasonal averages in the shallow habitat estimated from the 4-D interpolator method for each day between 1990 and 2024. The Bay habitat was defined as shallow water, open water, deep water, and deep channel. Shaded regions denote June, July, and August.

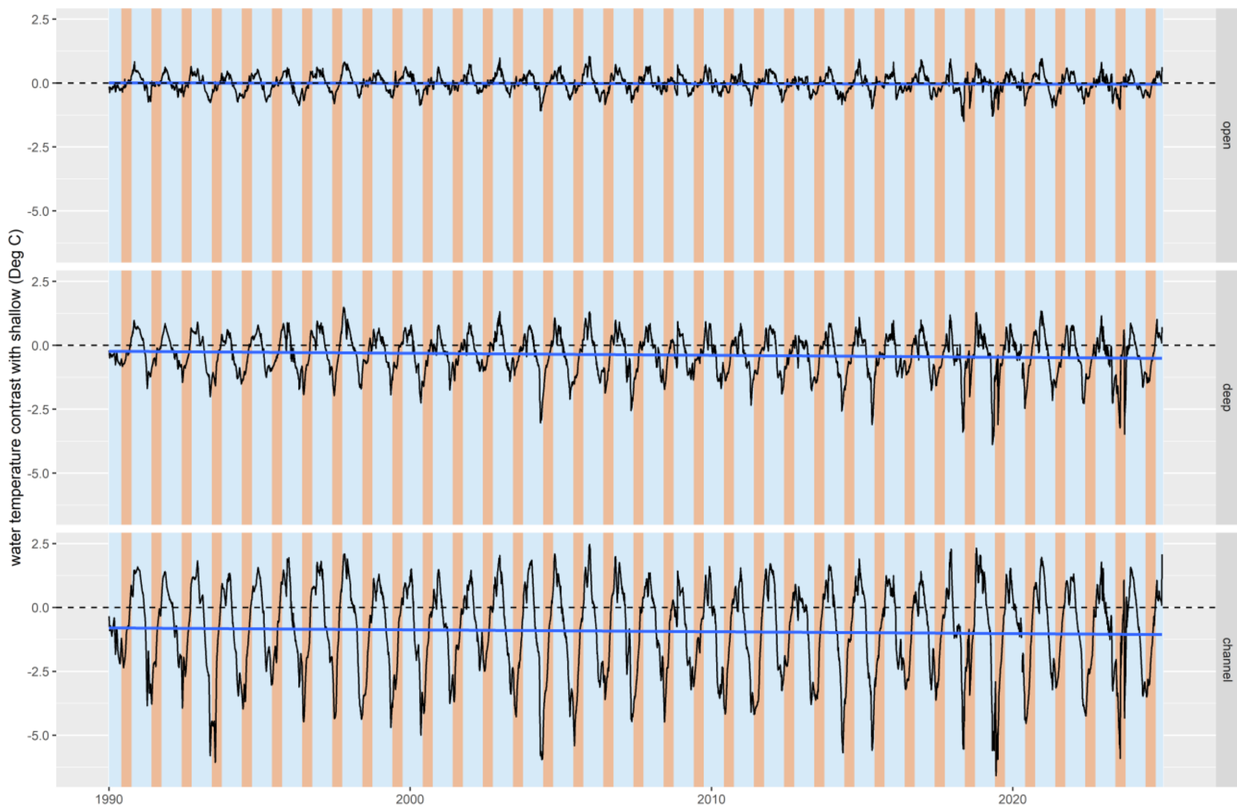

Figure 9.9. Water temperature anomaly from the shallow daily estimated temperature, estimated from the 4-D interpolator method for each day between 1990 and 2024. The Bay habitat was defined as shallow water, open water, deep water, and deep channel. Shaded regions denote June, July, and August.

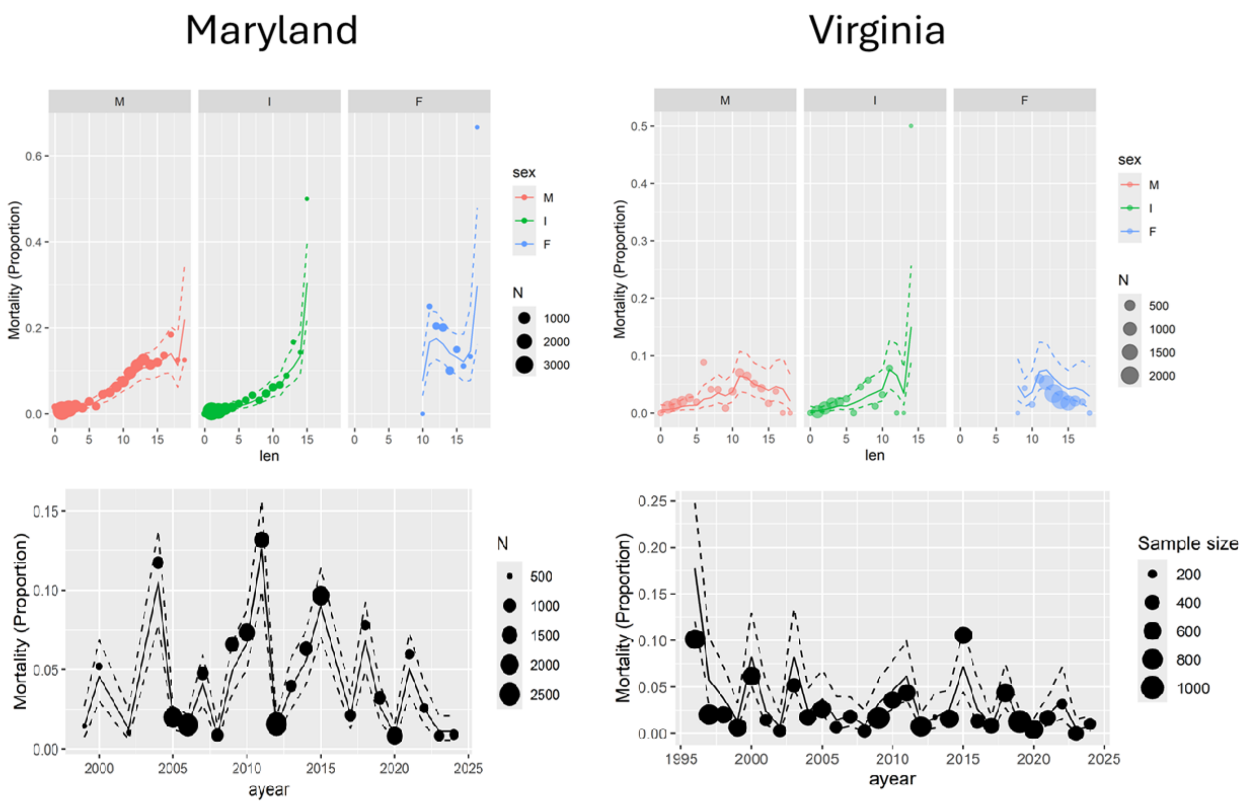

Figure 9.10. Overwinter mortality estimates from Maryland and Virginia portions of the Bay. Top figures are the March mortality rates at length and sex averaged across 1996 and 2024. Bottom figures are the total annual mortality (aggregated for male, female, and across all size classes). Points indicate the aggregation from stations, while the line denotes the estimates from the Bayesian models.

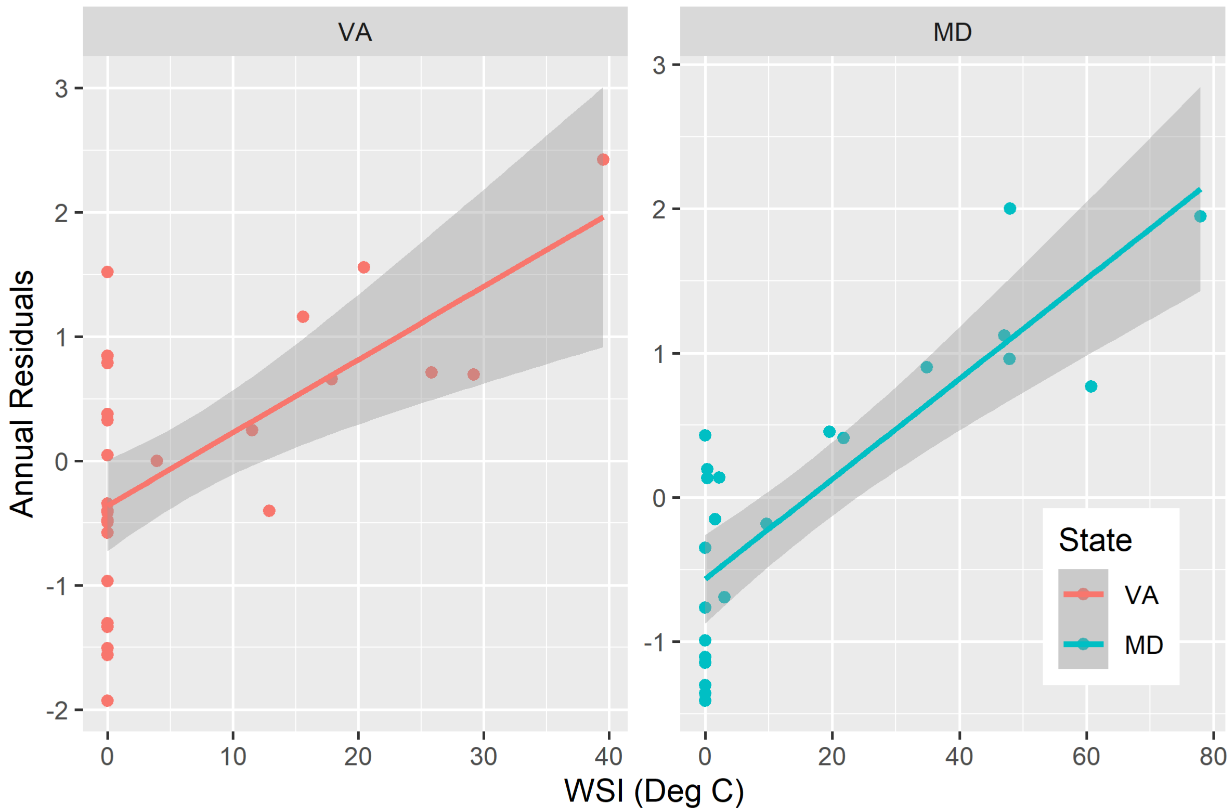

Figure 9.11. Conditional effects of Winter Severity Index on the annual residuals of overwinter mortality from the Bayesian model, after removing the effects of sex, length, and latent spatial process.

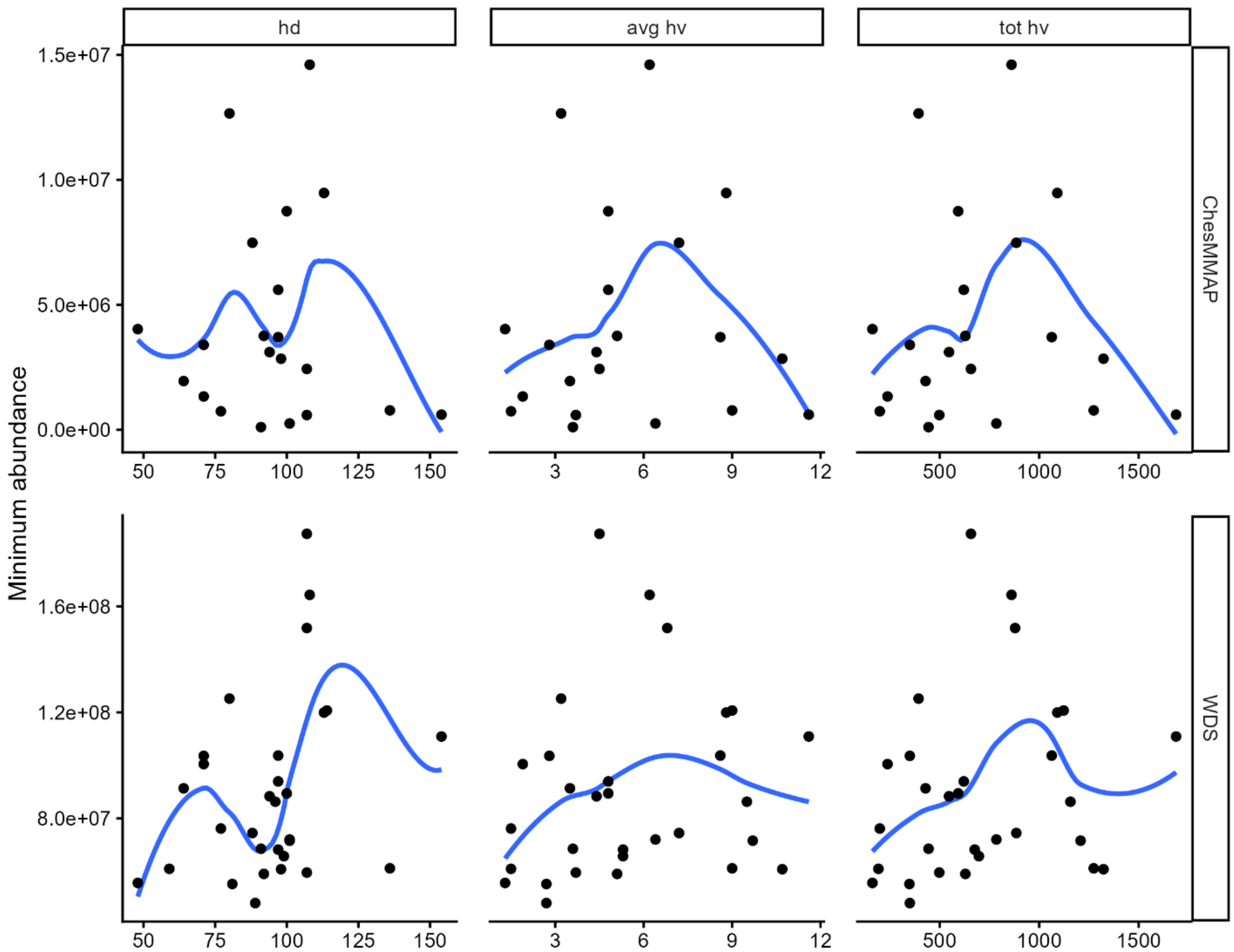

Figure 9.12. Relationship between indices of blue crab abundance (Chesapeake Bay Multispecies Monitoring and Assessment Program September index and Winter Dredge Survey index, lagged by one year) and three annual metrics of hypoxia: hypoxic duration (hd, in days), average daily hypoxic volume (avg hv, in km3), and total annual hypoxic volume (tot hv, km3 days), all based on the Chesapeake Bay Environmental Forecast System (CBEFS), available at: https://www.vims.edu/research/products/cbefs/hypoxic-volume/.