Estimation of Striped Bass Abundance in the Chesapeake Bay and Coastal Ocean: Methods

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Four multi-stock, spatially-explicit statistical catch-at-age models (Fournier and Archibald, 1982; Quinn et al., 1990) were developed for striped bass with alternative assumptions of natural mortality and ageing error (Table 1): the first model assumed stationary natural mortality and did not correct for ageing error (NAE-SM), the second model assumed stationary natural mortality and corrected for ageing error (AE-SM), the third model assumed time-varying natural mortality and did not correct for ageing error (NAE-TVM), and the fourth model assumed time-varying natural mortality and corrected for ageing error (AE-TVM). Each model tracked ages 1-15+, where age 15+ was an aggregate age group representing fish that are age-15 and older. All models included two stocks to partially represent the population complexity of the striped bass multi-stock complex: one for the Chesapeake Bay and another for the remainder of the Atlantic migratory stocks (hereafter referred to as the Atlantic coast stock). The Atlantic coast stock included the Hudson River and Delaware Bay stocks as well as spawning stocks in other smaller systems in the Mid-Atlantic. Each model had two regions that represented the Chesapeake Bay and the “Ocean” (Figure 1). The border of the Chesapeake Bay region extended north from Cape Charles and Cape Henry, Virginia to the head of the Bay in Maryland (NEFSC, 2019). The Ocean region was defined as the area outside of the Chesapeake Bay from Maine to Virginia (including the estuaries), and coastal North Carolina (NEFSC, 2019). Each model included two sub-annual six-month time steps, January-June and July-December, to better represent striped bass migratory behavior and seasonal fishery dynamics. Spatially disaggregated data were available for the period 1982-2017. Each population model was developed in AD Model Builder (Fournier et al., 2012).

Data

We used fishery-independent and fishery-dependent data from Maine to North Carolina in each model. The federally managed portion of the U.S. Exclusive Economic Zone (greater than 5.6 km offshore) is closed to fishing for striped bass and therefore no data is included from this region (NEFSC, 2019). Catches for each region and time step were composed of the commercial harvest obtained from state fishery management agencies, recreational harvest from the U.S. National Oceanic and Atmospheric Administration National Marine Fisheries Service's Marine Recreational Information Program (MRIP), and of the number of fish from each fishery that were assumed to have died from post-release mortality. The proportion of discards assumed to die was gear-dependent and followed the current benchmark assessment (e.g., 9% for hook-and-line; NEFSC, 2019). Catches were aggregated across recreational and commercial fleets to simplify data inputs as has been done in previous striped bass stock assessments (NEFSC, 2019) because disaggregated catch-at-age data were not available from all sources to be able to consider alternative approaches. Catches from the Chesapeake Bay fleet included those from commercial and recreational fisheries within the Chesapeake Bay from Maryland, Virginia, and the Potomac River. The Ocean fleet included catches reported by Maine, New Hampshire, New York, New Jersey, Delaware, coastal Maryland, coastal Virginia, and coastal North Carolina. Stock composition of the catch (i.e., fraction of the catch from each stock) was not routinely collected. Catch proportions-at-age were calculated by applying age-length keys to catch-atlength frequencies from each fishery and state and summarizing them over states within a region for each time step (NEFSC, 2019) When samples of fish from a fishery and time step were insufficient to develop age-length keys, biologists from that state used data from other gears, fisheries, or state samples to inform their age-length keys (NEFSC, 2019). With the exception of Virginia, who aged fish using otoliths, all states used scale ages to estimate the age-composition of their fishery catch (NEFSC, 2019).

Multiple fishery-independent surveys regularly catch striped bass and were used to develop indices of abundance (Table 2; see NEFSC, (2019) for details on survey methods and index estimation). Seven surveys that sampled striped bass age-1 and older were used, while two age-1 surveys and three young-of-the-year surveys were used. Proportions-at-age were developed for each 1+ survey for each six-month time step based on the survey specific age ranges (Table 2).

Sex proportions-at-age and female maturity-at-age were assumed constant over time and regions and were the same as the current benchmark stock assessment model (Table 3; NEFSC, 2019). The proportion female-at-age was calculated using fish with known sex and age determined by otolith ageing (Jiang et al., 2007; NEFSC, 2019). Female maturity-at-age was estimated from a binomial generalized linear model using striped bass sampled in the Chesapeake Bay and Atlantic coast during March-December between 2014 and 2016 (NEFSC, 2019). For Model NAE-SM and Model SE-SM, age-specific natural mortality rates were constant over time and regions and derived from tagging data (NEFSC, 2019). For Models NAE-TVM and AE-TVM, age-specific natural mortality varied by region and time based on natural mortality rate-at-age estimates from a mark-recapture model (Schonfeld et al., in prep). The spatial tag-recovery model was applied to conventional tag and recapture data to track striped bass from three producer regions (Chesapeake Bay, Delaware Bay, and the Hudson River) and recaptures in two recovery regions (Chesapeake Bay and Ocean), which matched the spatial regions and intra-annual time steps of the spatially-explicit model (Schonfeld, 2023). The tag-recovery model estimated age-specific natural mortality rates for ages 2-11+, which were constant during three periods: 1990-1999, 2000-2009, and 2010-2019 (Schonfeld, 2023).

To correct for the extensive use of scales to age striped bass, ageing error matrices were developed to describe the bias and precision of scale ages relative to otolith ages. The ageing error matrix was developed from fish from Massachusetts, Rhode Island, and New Jersey from 1996-2020 that were aged with both scales and otoliths to correct for bias from scale ages (Figure 2). The ageing error matrix was calculated as the proportions of scale ages for fish with a given otolith age, assuming that the otolith age was the true age. Three ageing error matrices were calculated to correspond to the age ranges of each survey (e.g., 1-15+, 2-15+, and 2-13+; Table S1.1). The ageing error matrix was applied in Models AE-SM and AE-TVM to the fishery proportions-at-age and survey proportions-at-age (for surveys that aged fish using scales) to convert between "true" ages in the model and the expected age distribution under scale age reading. Explicitly incorporating ageing errors helps to adjust for potential bias in model estimates for striped bass when age composition is based on scale aged fish (Liao et al., 2013).

General Model Description

Each spatially-explicit model tracked cohorts forward through time, and population dynamics equations were the same for each of the models. The observation models differed depending on whether or not they included ageing error. Abundance in the first year and first time step was estimated to be in equilibrium

$$Nt_{s,\text{y=1,ts=1},a} = Nt_{s,\text{y=1,ts=1},a-1} \times e^{-(M_{a-1}+Feq_{s,a-1})} \qquad (1)$$

where Nt was the abundance of stock s summed over the two spatial regions, M was the instantaneous natural mortality, Feq was the estimated equilibrium instantaneous fishing mortality in the first year, y was the year index, a was the age index, and ts was the time step index. Feq was calculated as

$$Feq_{s,a} = afsel_a \times afeq_s, \qquad (2)$$

where $afsel$ was the fishery selectivity-at-age for both stocks in equilibrium and $afeq$ was the fully selected fishing intensity in equilibrium. Recruitment at age-1 ($Nt_{s,y=1,ts=1,a=1}$) was estimated as normal on the $\log_e$-scale for each year for each stock ($R_{s,y}$),

$$Nt_{s,y=1,ts=1,a=1} = e^{(R_{s,y})}. \qquad (3)$$

The model assumed that movement occurs before mortality, and total abundance for each stock was apportioned to each region based on the occupancy probabilities. Abundance-at-age for each stock was calculated as the sum over regions of the product of total stock abundance and estimated survival in each region in the previous time step,

$$Nt_{s,y,ts,a} = \sum_r N_{s,r,y,ts-1,a} \times e^{-Z_{r,ts-1,a}}, \qquad (4)$$

where r was the region index, Z was the instantaneous total mortality rate and N was the abundance of stock s in a region. Regional abundance-at-age for each stock at the beginning of the time step was calculated as the product of the total stock abundance and the proportion of the stock at age in each region during a given time step,

$$N_{s,r,y,ts,a} = Nt_{s,y,ts,a} \times occ_{s,r,ts,a}, \qquad (5)$$

where occ was the proportion of the stock within a region. For the plus group, abundance for each stock was calculated as the stock-specific sum of the individuals that survived from the previous age, time step, and region and the stock specific abundances that survived from the plus group in the previous time step for a given region,

$$Nt_{s,y,ts,A} = \sum_r N_{s,r,y,ts-1,A-1} \times e^{-Z_{r,ts-1,A-1}} + \sum_r N_{s,r,y,ts-1,A} \times e^{-Z_{r,ts-1,A}}, \qquad (6)$$

where A was age 15+. Spawning stock biomass (SSB) for each stock was estimated as the product of abundance-at-age, the weight-at-age during the spawning season ($w_{y,a}$), the proportion female-at-age (sex), and the proportion of mature females-at-age (mat),

$$SSB_{s,y} = \sum_{a,r} N_{s,r,y,ts=1,a} \times w_{y,a} \times sex_a \times mat_a. \qquad (7)$$

The instantaneous total mortality rate for a given time step, age, and region was calculated as the sum of the instantaneous natural mortality (M) and fishing mortality rates (F),

$$Z_{r,y,ts,a} = M_a + F_{r,y,ts,a}. \qquad (8)$$

The instantaneous fishing mortality rate-at-age was calculated as the product of the fully selected fishing intensity for each region (f) and the age-specific fishery selectivity,

$$F_{r,y,ts,a} = fsel_{r,t,ts,a} \times f_{r,y,ts}, \qquad (9)$$

where t was the index for the fishery selectivity time-block. Fully selected fishing intensity was estimated as normal on the $\log_e$-scale. Fishery selectivity varied over time with four selectivity time-blocks to account for changes in fishing regulations and practices. The first time-block was 1982-1989 to represent regulations prior to and during a fishing moratorium in the Chesapeake Bay and Delaware Bay. The second time-block was 1990-1994 to represent the rebuilding period after the Chesapeake Bay fishery was reopened. The third time-block was during 1995-2014 to represented when the stock was considered recovered and regulations were liberalized. The final time-block was 2015-2017 to represent a period with reductions in daily bag limits. Fishery selectivity was estimated using a logistic function for the Ocean region because large fish are the target of this fishery,

$$fsel = \frac{1}{1+e^{-p_1 \times (a-p_2)}}, \tag{10}$$

where p_1 described the rate of increase, and p_2 was the age at 50% selectivity. A double logistic function was used for the Chesapeake Bay region because older ages of striped bass tend to only be in the Chesapeake for a portion of each six-month time step (Secor et al., 2020),

$$fsel = \frac{1}{1+e^{-p_1 \times (a-p_2)}} \times \frac{1}{1+e^{-p_3 \times (p_4-a)}}, \tag{11}$$

where $p_1$was the slope of the ascending limb, p_2 was the age at 50% selectivity for the ascending limb, $p_3$was the descending slope, and p_4 was the age at 50% selectivity for the descending limb. Selectivity functions differed for each region because regulations vary by region and striped bass are assumed to have different vulnerability to the fishery depending on the region. Our assumptions for selectivity were similar to those made in the current assessment used to inform management (NEFSC, 2019). Parameters for fishery selectivity varied between subannual time steps and fishery time-blocks for a region. Stock-specific average fishing mortality for ages 7+, $Fstock$, was calculated as the weighted average F experienced by each stock by multiplying by the occupancy probability and then taking the weighted average for that F given total abundance of each stock,

$$Fstock_{s,y} = \sum_{ts=1}^{2} (occ_{s,,\mathrm{ts},r,a} \times F_{r,ts,y,a}) \times \frac{Nt_{s,ts,y,a}}{\sum_{a=7}^{a=A} Nt_{s,ts,y,a}}. \tag{12}$$

$Fstock$ was calculated for ages 7-15+ to reflect the ages that were mostly mature.

Catch-at-age (CAA) for a region and time step was estimated using the Baranov catch equation (Ricker, 1975),

$$CAA_{r,y,ts,a} = \frac{F_{r,y,ts}}{Z_{r,y,ts}} \times (1 - e^{-Z_{r,y,ts}}) \times \sum_s N_{s,r,y,ts}. \quad (13)$$

Total catch (C) was estimated by summing the catch-at-age over ages and stocks within a region,

$$C_{y,ts,r} = \sum_a CAA_{r,y,ts,a}. \quad (14)$$

Proportions-at-age (PAA) for each region and time step were calculated by dividing the catch-at-age by the total catch,

$$PAA_{y,ts,r,a} = \frac{CAA_{r,y,ts,a}}{C_{y,ts,r}}. \quad (15)$$

Estimated indices of abundance (I) for the fishery-independent surveys were the product of abundance at age for each time step and region, survey catchability (q), and survey selectivity for each age ($ssel$),

$$I_{v,y} = q_v \times \sum_{s,a} N_{s,r,y,ts,a} \times ssel_{v,a}, \quad (16)$$

for each survey v. The index of abundance was then summed over ages to get a total index for each survey and time step. For each index of abundance, the region was defined as either the Chesapeake Bay or Ocean depending on where the survey was conducted (e.g., region is Ocean for the New Jersey Bottom Trawl (NJBT)). Survey selectivity and catchability were assumed to be constant over years for each survey. For surveys that sampled during both time steps in a year, selectivity and catchability was estimated separately for each time step. Indices of abundance for spawning stock surveys were estimated using the abundance-at-age for their respective stock and region of spawning (e.g., the Chesapeake Bay stock for the Maryland Spawning Stock Survey (MDSSN)),

$$I_{s,v,y} = q_v \times \sum_a N_{s,r,y,ts=1,a} \times ssel_{v,a}. \quad (17)$$

Logistic functions were used to estimate selectivity for the spawning stock surveys and the Chesapeake Bay Multispecies Monitoring and Assessment Program (ChesMMAP; Eq. 10) because these surveys are assumed to sample mature striped bass. Double logistic functions with four parameters were used to estimate selectivity for the remaining fishery-independent surveys (Eq. 11) because older fish may have decreased availability or catchability to these surveys based on the timing, location, or gear. Predicted proportions-at-age in each survey were calculated by dividing the estimated index-at-age during a time step by the sum of the estimated index-at-age over ages during a time step (Eq. 15).

Models NAE-TVM and AE-TVM also included ageing bias in the calculation of the predicted catch-at-age and the proportions-at-age. Catch-at-age for the fisheries were calculated by the Baranov catch equation (13) corrected for ageing error ($CAAerr$) by multiplying CAA by the ageing error matrix ($ageerr$),

$$CAAerr_{r,y,ts,a} = \sum_{j} ageerr_{j,i} \times CAA_{r,y,ts,a=j}, \tag{18}$$

where i is the scale age and j the otolith age. Total catch (C) was then estimated by summing the catch-at-age with ageing error over ages and stocks within a region,

$$C_{y,ts,r} = \sum_{a} CAAerr_{r,y,ts,a}. \tag{19}$$

For the fishery-independent surveys, the predicted proportions-at-age for Models AE-SM and AE-TVM adjusted the “true” proportions-at-age for ageing error in a similar manner as the catch-at-age. Two fishery-independent surveys which used otoliths to inform age composition and an ageing error matrix was not applied to calculate the estimated index-at-age (e.g., ChesMMAP and DE30). The ageing error matrix was applied to the index-at-age calculations for the remaining surveys that used scales to inform age-composition (Eq. 18; Table S1.1).

Models NAE-TVM and AE-TVM assumed spatially- and temporally-varying natural mortality in the Chesapeake Bay and Ocean region based on the results of the spatial tag-recovery model applied to the conventional tagging data (Schonfeld et al., in prep). Specifically, natural mortality during 1982-1999 was set equal to the 1990-1999 tag-recovery estimates while natural mortality during 2000-2009, and 2010-2017 were set equal to the 2000-2009 and 2010-2020 tag-recovery estimates, respectively (Table 3). Natural mortality for age-1 for all years was set equal to the natural mortality for age-1 in the current benchmark assessment (NEFSC, 2019) or equal to age-2, depending on which mortality rate was higher. Natural mortality for ages 12-15+ were set equal to the age-11 estimate for each year.

Parameters for each model were estimated by minimizing the objective function, which was the sum of the negative log likelihood functions representing each data source and penalties on several parameters (see Table 4 for the likelihood components of the objective function and their respective equations). Log-normal observation errors were assumed for total catch ($-ln(L_{catch})$) and indices of abundance ($-ln(L_{Index}$; Eq. 3.1). Similarly, occupancy probabilities were assumed to be normally distributed on the $\log_e$-scale (Eq. 3.1). "Robust multinomial" (Fournier et al., 1990) error distributions were assumed for the age composition of the catch and the survey indices ($-ln(L_{PAA}$; Eq. 3.2). Binomial error distributions were assumed for the stock composition to inform the proportion of the catch for the coastal fishery from each stock for ages 4-15+ in 2010 during July-December, based on stock composition estimated by Kneebone et al. (2014) ($-ln(L_{prop})$; Eq. 3.3). The proportion for the Atlantic coast stock was summed across Delaware and Hudson stocks. Recruitment was assumed to be normally distributed on the $\log_e$ scale with an assumed standard deviation of 1.0 ($-ln(L_{recruitment}$; Eq. 3.4). A log-normal penalty was applied to Feq with a standard deviation of 0.5 to restrict equilibrium fishing mortality to generate initial age compositions ($-ln(Feq$; Eq. 3.5). We applied a weak smoothing penalty to the change in fishing mortality from one year to the next for each time step and region ($-ln(L_{Fdev})$; Eq. 3.6). Log-scale standard deviations (CV) for the surveys and effective sample size (ESS) for the surveys and fishery catches were determined by iterative re-weighting (Francis, 2011; McAllister and Ianelli, 1997). If iterative reweighting produced an estimate <0.2 for a survey CV, the CV was set to equal 0.2. The CVs were held constant across years for each survey. The ESS minimum was set to 15, where if the reweighting process yielded estimates <15, the ESS was set to 15. For the Chesapeake Bay fishery, ESS was allowed to differ between two time-blocks, 1982-1989 and 1990-2017, to account for poor model fits during 1982-1989, potentially as a result of low sample sizes during the Chesapeake Bay moratorium.

Informative priors were placed on the occupancy probabilities ($-ln(L_{occ})$; Eq. 3.7), based on conventional and acoustic tagging data for striped bass. Estimates of occupancy probabilities based on conventional tags were from the spatial tag-recovery model (Schonfeld, 2023). Age-specific occupancy probabilities from the Delaware Bay and Hudson River producer regions were averaged to generate one set of occupancy probabilities for the Atlantic coast stock. This approach implicitly assumed that the Delaware and Hudson River stocks are approximately the same size. Standard deviations used in Eq. 3.7 for each stock were estimated in the spatial tag-recovery model. Acoustic tagging data (Secor et al., 2020) were also used to create informative priors for the occupancy probabilities. Striped bass were fitted with acoustic tags in 2014 and 2016 during the spawning season in the Potomac River and were assumed to represent the Chesapeake Bay stock. Fish that were not tagged during the spawning season in the Chesapeake Bay were excluded from analyses. In total, 78 striped bass were used for these calculations. Acoustic transmissions for each fish were gathered from receivers from Maine to North Carolina. Each transmission was assigned to be in either the Chesapeake Bay or Ocean region based on the location of the receiver. Means for the occupancy probability priors were then calculated as the average proportion of unique months in which a fish was observed in a region out of the total number of months a fish was observed in either region during each time step. Mean occupancy probabilities were calculated for each age that had at least one observation. For ages with more than one individual, standard deviations for each age were calculated as the square root of the squared deviations from the average divided by the total number of observations.

Parameters were estimated by minimizing the objective function (nll_{tot}), that is the sum of the negative log likelihood components, penalties, and priors,

$$nll_{tot} = -ln(L_{Catch}) - ln(L_{Index}) - ln(L_{CatchPAA}) - ln\left(L_{SurveyPAA}\right) - ln\left(L_{prop}\right) - ln(L_{recruitment}) - ln(Feq) - ln(L_{Fdevs}) - ln(L_{occ}) - ln(L_{sel}) - ln\ (p_4). \quad (20)$$

Penalties were included in the model to constrain selectivity parameters ($-ln(L_{sel})$; Eq. 3.8) to reduce correlation among estimated parameters and allow for model convergence. Several selectivity parameters for the Chesapeake Bay fishery in 1982-1989 were penalized because selectivity parameter estimates were unstable for this period. Specifically, the ascending slope parameter in July-December was penalized with a mean of 3 and standard deviation of 0.5. The slopes of the descending limb for January-June and July-December had penalties with a mean of 1 and standard deviation of 0.25. Additionally, the descending limb parameters of double logistic selectivity function were poorly estimated for the Chesapeake Bay fishery and the CTLIST survey when they were not constrained, and penalties were added to prevent the point of inflection of the descending limb from being less than the point of inflection for the ascending limb (Eq. 3.9). Penalties on selectivity were normally distributed with a mean of 0 standard deviation of approximately 0.7. Models NAE-TVM and AE-TVM required additional penalties in the objective function for parameters estimating fishery selectivity across multiple time-blocks for the descending limb inflection point in 1982-1989 during January-June and July-December for the Chesapeake Bay fishery selectivity. Additionally, penalties on the point of inflection for the descending limb of the NYOHS were added (Eq. 3.9). Model fits were evaluated using standardized residuals for fishery-independent indices of abundance,

$$Res_y = \frac{\log(I_y) - \widehat{\log(\hat{I}_y)}}{\sigma_y}, \tag{21}$$

where Res is the standardized residual, I is the observed index, $\hat{I}$ is the estimated index, and σ is the log-scale standard deviation of the index. Residuals for the age-compositions of the fishery and the surveys were evaluated using the one-step ahead approach in R (Thygesen et al., 2017; Trijoulet et al., 2023) and the compResidual package (Trijoulet and Nielsen, 2022). One-step ahead residuals use the Laplace approach (Tierney and Kadane, 1986) and can be used on data that has an assumed multinomial distribution, such as age compositions (Trijoulet et al., 2023).

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Table 1. Assumptions of ageing error and natural mortality for the spatially-explicit models for striped bass. All models had the same assumptions unless otherwise stated in this table. Natural mortality rates for each model are described in Table 3.

Model	Model Name	Ageing error correction	Natural Mortality
1	NAE-SM	No	Constant
2	AE-SM	Yes	Constant
3	NAE-TVM	No	Spatially- and time-varying
4	AE-TVM	Yes	Spatially- and time-varying

Table 2. Fishery-independent data sources used as inputs for the striped bass spatially-explicit population models. The location describes the state and location in which the survey is conducted. The age describes which age classes the survey targets. Years describes the sampling time frame. Time step refers to which sub-annual time step the survey is conducted in (1=January-June, 2=July-December). Region corresponds to the regions of the spatially-explicit models (Oc=Ocean region, CB=Chesapeake Bay region).

Survey Name	Location	Age	Gear	Years	Time step	Spatial Region
Connecticut Long Island Sound Trawl Survey (CTLIST)	Connecticut: Long Island Sound	1-15+	Bottom Trawl	1984-Present	1,2	Oc
New York Ocean Haul Seine Survey (NYOHS)	New York: East of Long Island	2-13+	Ocean Haul Seine	1987-2006	2	Oc
New Jersey Bottom Trawl Survey (NJBT)	New Jersey: Delaware Bay through New York Harbor	2-15+	Bottom Trawl	1989-Present	1	Oc
Delaware Spawning Stock Electrofishing Survey (DESSN)	Delaware: Delaware River	2-13+	Electrofishing	1996-Present	1	Oc
Delaware 30 Foot Trawl Survey (DE30)	Delaware: Delaware Bay	1-15+	9m (30') Bottom Trawl	1990-Present	2	Oc
Maryland Spawning Stock Survey (MDSSN)	Maryland: Chesapeake Bay	2-15+	Multi-panel Drift Gillnet	1985-Present	1	CB
Chesapeake Bay Multispecies Monitoring and Assessment Program (ChesMMAP)	Virginia: Chesapeake Bay	1-15+	Trawl	2002-Present	1,2	CB
New York Yearling Survey (NY1)	New York: Western Long Island	1	Beach Seine	1980-Present	1,2	Oc
Maryland Yearling Survey (MD1)	Maryland: Chesapeake Bay	1	Beach Seine	1954-Present	2	CB
New York YOY Survey (NYYOY)	New York: Western Long Island	YOY	Beach Seine	1979-Present	2	Oc
New Jersey YOY Survey (NJYOY)	New Jersey, Delaware River	YOY	Beach Seine	1980-Present	2	Oc

Survey Name	Location	Age	Gear	Years	Time step	Spatial Region
Chesapeake Bay YOY Index (CBYOY)	Maryland and Virginia: Chesapeake Bay	YOY	Beach Seine	1980-Present	2	CB
Maryland YOY Survey (MDYOY)	Maryland portion of Chesapeake Bay	YOY	Beach Seine	1954-Present	2	CB
Virginia YOY Survey (VAYOY)	Virginia portion of Chesapeake Bay	YOY	Beach Seine	1980-Present	2	CB

Table 3. A) Assumed natural mortality rates-at-age per six-month period ($6mo^{-1}$), proportion female-at-age, and female maturity-at-age used in the spatially-explicit models. Estimates were similar to those used in the benchmark stock assessment for striped bass (NEFSC, 2019). Natural mortality was assumed constant in Model NAE-SM and AE-SM (Table 1). B) Natural mortality rates-at-age ($6mo^{-1}$) for each region in Model NAE-TVM and Model AE-TVM that evaluated time-varying natural mortality estimated. Natural mortality was assumed to be the same for each time step. Region corresponds to the regions of the spatially-explicit models (Oc=Ocean region, CB=Chesapeake Bay region).

A)

Parameter	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15+
Natural mortality	0.565	0.34	0.225	0.165	0.125	0.095	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075
Proportion female-at-age	0.530	0.56	0.560	0.520	0.570	0.650	0.730	0.810	0.880	0.920	0.950	0.970	1.000	1.000	1.000
Female maturity-at-age	0.000	0.00	0.000	0.090	0.320	0.450	0.840	0.890	1.000	1.000	1.000	1.000	1.000	1.000	1.000

B

Region	Years	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15+
Oc	1982-1999	0.565	0.265	0.142	0.166	0.084	0.072	0.056	0.078	0.022	0.033	0.061	0.061	0.061	0.061	0.061
Oc	2000-2009	0.565	0.375	0.140	0.179	0.102	0.112	0.070	0.071	0.021	0.066	0.051	0.051	0.051	0.051	0.051
Oc	2010-2017	0.565	0.489	0.112	0.234	0.103	0.175	0.057	0.078	0.047	0.081	0.059	0.059	0.059	0.059	0.059
CB	1982-1999	0.565	0.276	0.148	0.145	0.126	0.098	0.138	0.058	0.166	0.121	0.040	0.040	0.040	0.040	0.040
CB	2000-2009	0.833	0.833	0.208	0.180	0.229	0.211	0.168	0.203	0.226	0.219	0.035	0.035	0.035	0.035	0.035
CB	2010-2017	0.715	0.715	0.324	0.191	0.289	0.138	0.319	0.288	0.351	0.307	0.131	0.131	0.131	0.131	0.131

Table 4. Negative log likelihood components for each of the two-stock, spatially-explicit striped bass models. Additive constants are not included in the equations.

Num.	Equation	Description
3. 1	$$-ln(L_{Catch/Index}) = \sum_{y} \frac{\left(ln(X) - ln(\hat{X})\right)^2}{2\sigma^2}$$	Lognormal
3. 2	$$-ln(L_{Catch/SurveyPAA}) = \sum - ln\left(e^{\frac{0.5\times(-PAA-\widehat{PAA})^2}{\sigma^2}+0.01}\right)$$	Robust multinomial
3. 3	$$-ln(L_{prop}) = -ESS \times (prop_{s=1,r} \times ln\left(0.1 + \frac{\sum_{a=4:lage} CAA_{s=1,r}}{\sum_{s,a=4:lage} CAA_r}\right) + (1 - prop_{s=1,r}) \times ln\left(0.1 + \frac{\sum_{a=4:lage} CAA_{s=2,r}}{\sum_{s,a=4:lage} CAA_r}\right))$$	Binomial for stock composition
3. 4	$$-ln(L_{recruitment}) = \sum_{y} ln(Rdev_{s=ac,y}) + ln(Rdev_{s=cb,y})$$	Normal for log-scale recruitment deviations with mean of 0 and standard deviation of 1
3. 5	$$-ln(L_{Feq}) = \frac{1}{2}\left(\frac{Feq_{r,ts} - 0.3}{0.1}\right)^2$$	Normal negative log-likelihood for Feq with standard deviation of 0.1
3. 6	$$-ln(L_{Fdev}) = \frac{1}{0.5^2}\left(Fdev_{r,y,ts} - Fdev_{r,y-1,ts}\right)^2$$	Normal negative log-likelihood for F deviations with standard deviation of approximately 0.35
3. 7	$$-ln(L_{occ}) = \sum_{s,r,a} \frac{\left(prop_{s,r,ts,a} - \widehat{prop}_{s,r,ts,a}\right)^2}{2\times\sigma^2_{s,r,ts,a}}$$	Normal informative priors of occupancy probability
3. 8	$$-ln(L_{sel}) = \left(ln(\hat{p}_{1,r,a}) - X\right)^2$$	Lognormal penalty on selectivity parameters
3. 9	$$-ln(L_{p_4}) = 10 \times \left(ln(p_{4_{ts}}) - ln(p_{2_{ts}})\right)^2$$	Lognormal penalty on descending point of inflection for double logistic function

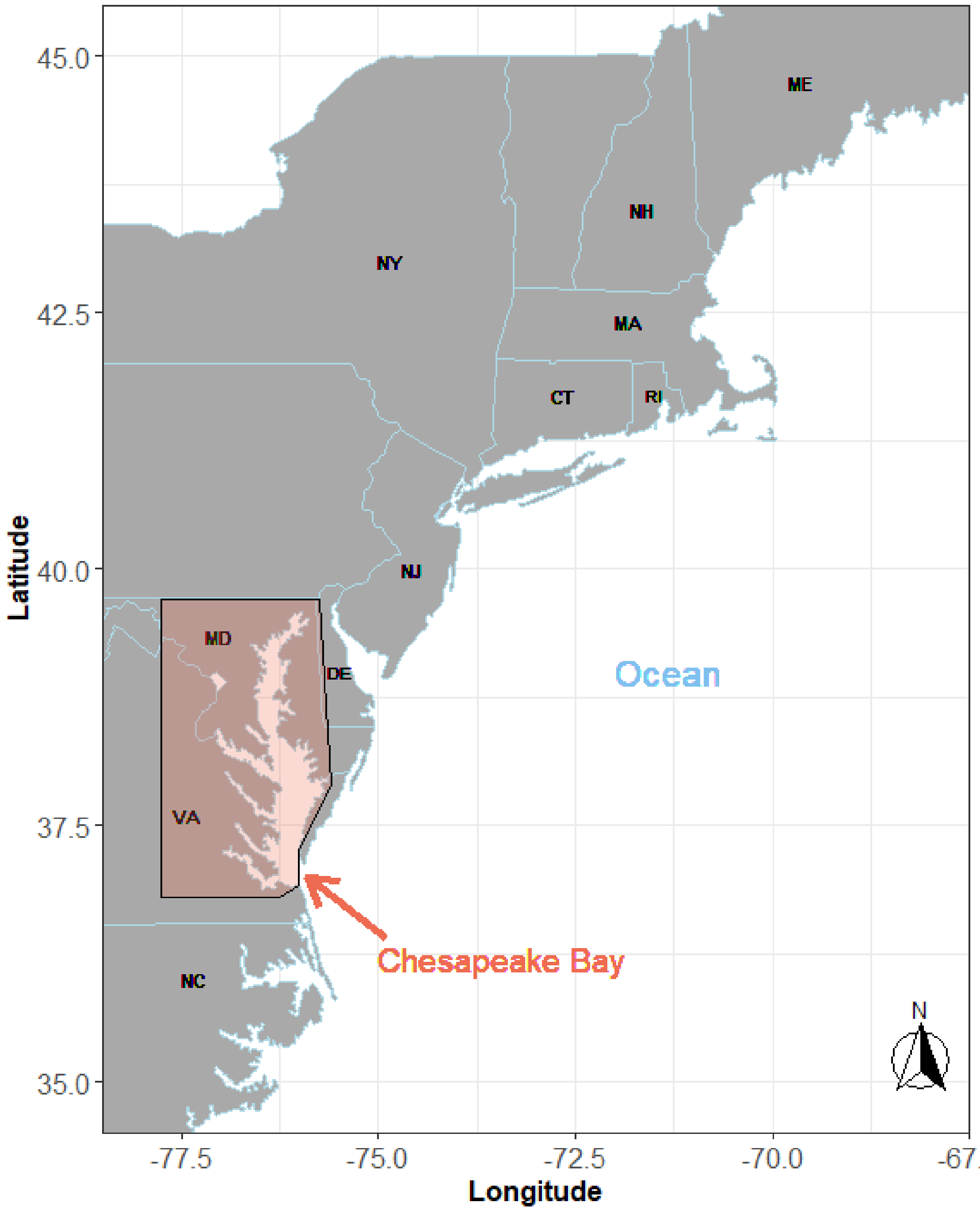

Figure 1. Study region of spatially-explicit population models for striped bass. The red box represents the Chesapeake Bay region. The white area outside of the red box represents the Ocean region, excluding waters inside of Albemarle Sound and the Roanoke River. ME, NH,

MA, RI, CT, NY, NJ, DE, MD, VA, and NC represent Maine, New Hampshire, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Delaware, Maryland, Virginia, and North Carolina, respectively.

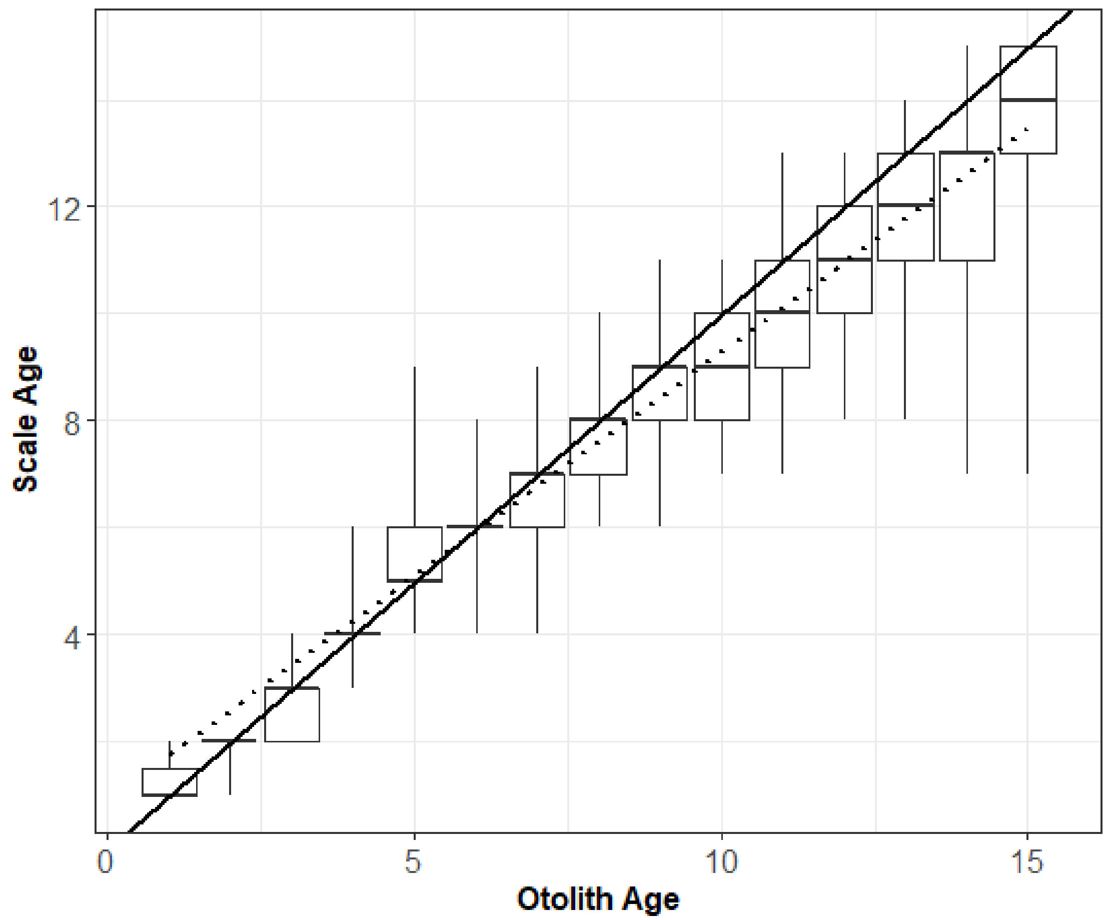

Figure 2. Comparison age classification of striped bass aged with scales and otolith. Striped bass were aged from Rhode Island, Massachusetts, and New Jersey between 1996 and 2017. The solid line represents the 1:1 line when scale ages would equal the otolith age. The dashed black line represents the linear regression through the observed age comparisons. The lower and upper hinge of the box represents the 25th and 75th percentiles. The middle line represents the median. The whiskers extend to the minimum and maximum values.