# Estimating Abundance of Chesapeake Bay Species: Spot

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We developed a statistical catch at age (SCAA) model that was spatially structured to model spot in two regions: the Chesapeake Bay and the remainder of the U.S. Atlantic Coast from New Jersey to Florida. We modeled ages-0-3+, where 3+ was an aggregate age group that included all spot age-3 and older. The model operated on an annual time step because the fishery largely occurs in the late summer and fall and data are sparse in the winter and early spring. We modeled spot during 2002-2019. Although spot ageing data in some states goes as far back as 1989, we did not have an index of abundance to inform the Chesapeake Bay region prior to 2002. To avoid dealing with missing data caused by COVID-19 sampling disruptions in 2020, we ended our model in 2019. The model included three fleets, commercial, recreational, and shrimp trawl bycatch. Recreational and commercial fishing occurred in both regions, but shrimp trawling did not occur in the Chesapeake Bay. Our base model allowed for spatially-varying mortality (referred to as the SVM model) by fixing the occupancy probabilities to be constant over time but allowing fishing mortality rate to vary over time between regions. We adapted this model into a time-varying occupancy model (referred to as the TVO model) that allowed the occupancy probabilities to change over time, but annually varying fishing mortality rates for commercial and recreational fisheries were the same across regions. Our model was developed using Template Model Builder (TMB: Kristensen et al., 2016). During the development process, we tested our estimation model using data simulated with minimal error, and found it was able to estimate simulated values.

*Data*

*Fishery Catch*

Fishery removals (landed catch and estimated dead discards) were summarized by gear and region. Daily commercial catch reports for spot were obtained from the Atlantic Coastal Cooperative Statistics Program (ACCSP) for all states from New Jersey to Florida during 1982-2022. Fishing trips that originated in Maryland or Virginia were further subdivided into trips that occurred within the Chesapeake Bay or the Atlantic Ocean based on landing location. Catch was recorded in live pounds (whole weight) and converted to kilograms. We compiled commercial catch into yearly summaries for each region. Discards from commercial fisheries were estimated by ASMFC (2017) using observer data from the Northeast Fisheries Observer program. Gillnets discarded a median of 2,769 fish and trawls discarded a median of 58,682 fish (ASMFC, 2017). Discards were higher in Mid-Atlantic trawl fisheries, but both sources made up less than 10% of all coastwide fishery removals combined in a given year. These data were not available to us, so commercial discards were assumed to be zero. We considered using North Carolina and Virginia "scrap" fishery landings as a source of commercial mortality, but they made up a very small proportion of non-shrimp trawl commercial removals (<0.1%) and were not used in the model.

Recreational catch data were obtained through the Marine Recreational Information Program (MRIP) online query tool (NOAA, 2023). Recreational data for the Chesapeake Bay had an average percent standard error (PSE) of 74.3% across years and categories of catch, and recreational data for the coast had an average of 77.5%. Total recreational catch in each region was the sum of observed harvest, reported harvest, and dead discards. We calculated dead discards from estimated discards assuming a 15% recreational release mortality rate (ASMFC, 2017).

Because large numbers of spot are caught as bycatch in shrimp trawl fisheries on the U.S. Atlantic coast, we used estimates of bycatch from this fishery as another source of fishing mortality. The average number of spot discarded in the shrimp trawl fishery per year were calculated using observer coverage data from the Southeast Shrimp Trawl Observer Program (SESTOP) for 2008-2019. Years prior to 2008 were hindcasted using catch rate data for spot from the Southeast Area Monitoring and Assessment Program (SEAMAP) survey, which uses a shrimp trawl. Discard rate estimates were then applied to reported effort data to estimate total shrimp trawl discards. Bycatch discards in numbers were modelled with a negative binomial generalized linear model (J. Kipp, ASMFC, personal communication; ASMFC 2017). All shrimp trawl bycatch was assumed to be age-0 (ASMFC, 2017).

*Fishery-Independent Indices*

Data from multiple surveys were used to develop regional indices of abundance for spot (Table 2.1). To inform abundance in the Chesapeake Bay we used the Chesapeake Bay Multispecies Monitoring and Assessment Program (ChesMMAP) survey and the Virginia Institute of Marine Science (VIMS) Juvenile Finfish Trawl Survey. ChesMMAP is a bottom trawl survey that began in 2002 and samples up to 80 stations in the mainstem of the Chesapeake Bay every March, June, September, and November using a stratified random design (Bonzek et al., 2022; VIMS, 2023a). Indices of abundance from ChesMMAP were developed using generalized linear models in the glmmTMB R package (Brooks et al., 2017). We built a model for summer (June and July) and fall (September and November) to allow for differences in variances. Models were tested for zero inflation, and zero inflation factors were included when necessary. The equation described the natural logarithm of the expected value of catch-per-unit-effort (CPUE) as a linear function of year with effort as an offset,

$$log(CPUE) = Intercept + Year_y + log\ (Effort) \quad ,$$

where CPUE followed a negative binomial distribution CPUE~NB($\mu$,$\theta$). The unit of effort used was area swept in $m^2$.

Since 1955, the VIMS Juvenile Finfish Trawl Survey conducted monthly sampling (excluding January and March) of juvenile fishes in the Virginia portion of the Chesapeake Bay and its tributaries (Tuckey and Fabrizio, 2023). All spot from this survey were considered to be age-0. The VIMS juvenile trawl survey was standardized using a weighted geometric mean catch-per-tow using data from July to October (Tuckey and Fabrizio, 2023).

To inform abundance along the Atlantic coast, we used the Northeast Area Monitoring and Assessment program (NEAMAP) survey and a coastal aggregate index. NEAMAP is a bottom trawl survey in the mid-Atlantic Bight in near shore waters to a depth of 18 meters that has been conducted since fall 2007. It was implemented to maintain coverage of shallow strata following a change in the Northeast Fishery Science Center bottom trawl survey (Latour et al., 2021). We used the spring survey (April and May). The NEAMAP spring index was calculated as the weighted geometric mean of catch per standard area swept weighted by the strata area (Bonzek et al., 2017; VIMS, 2023b). Data from 2013 and 2017 were dropped because of unusually high catch numbers (6 and 21 times the time series average). This was likely the result of a small number of tows with high catches, which may not reflect true trends in abundance (Bonzek et al., 2017).

A fall coastal aggregate index was developed to estimate biomass by combining several trawl surveys using a Vector Autoregressive Spatio-Temporal Model (VAST; R. Mestav, VIMS, personal communication). The surveys included the SEAMAP coastal trawl, NEAMAP, the New Jersey Ocean Stock Assessment Program Trawl Survey, and the Northeast Fisheries Science Center Bottom Trawl Survey. Combined, these bottom trawl surveys covered the region of the Atlantic coast from Cape Hatteras, NC to Canada during the fall (September – November). The coastal aggregate represented the estimated biomass over the area covered by the combined surveys (Cape Canaveral, Florida to Nova Scotia).

*Age Data*

Age and length frequency data from commercial fisheries were available from Virginia, North Carolina, and Maryland. All spot were aged using otoliths. Ageing workshops have been conducted for other sciaenid species (Atlantic Croaker and Red Drum) to develop ageing protocols. Because these closely related species were straightforward to age, the same protocols also work well for spot (ASMFC, 2008; ASMFC, 2017). The Virginia Marine Resources Commission (VMRC) randomly sampled commercial spot from fish houses and docks in the Chesapeake Bay and coastal Virginia annually. The majority of samples came from gill nets (38%), pound nets (36%), and haul seines (25%). The North Carolina Department of Marine Fisheries (NC DMF) sampled spot from fish houses for ageing. Gear was not known for 86% of aged fish from commercial fisheries, and the remaining NC DMF samples came from gill nets, haul seines, pound nets, or trawls. NC DMF subsampled 30 fish per market grade, which were measured and aged (ASMFC, 2017). The Maryland Department of Natural Resources (MD DNR) sampled spot from the commercial pound net fishery in the Chesapeake Bay (ASMFC, 2017) with ageing beginning in 2012. No age data were available from the recreational fishery, but length composition data were available from MRIP (NOAA, 2023). Fishery-independent ageing data were available from ChesMMAP and NEAMAP. For both ChesMMAP and

NEAMAP, individuals selected for ageing were sampled using a length-stratified random sampling approach (ASMFC, 2017).

For commercial data, sufficient age or length data were not available to create state-specific age compositions. Therefore, we developed regional age-length keys (ALKs) for the Chesapeake Bay and the Atlantic coast by aggregating the available age data from North Carolina, Virginia, and Maryland. Age-length data from Virginia were assigned to the coast or Chesapeake Bay based on whether the catch occurred outside or inside of the Chesapeake Bay. All age data from Maryland were from catches inside the Chesapeake Bay, and all data from North Carolina were from outside the Chesapeake Bay. ALKs were calculated as the proportion of spot at age in each 1 cm length bin for each year and region.

Proportions-at-age for commercial and recreational catches in each region were calculated by applying the ALKs to regional length frequencies. Regional length frequencies for the commercial fishery were weighted based on the amount of catch from each state. Length frequency data were available from the same commercial data sources specified above. Approximately 86% of the commercial ages for the Chesapeake Bay region came from Virginia and 14% from Maryland. Approximately 78% of the commercial ages for the coastal region came from North Carolina and 22% from Virginia. Lengths were reported differently by state with most states reporting total length except for North Carolina, which reported a combination of total length and fork length. Using the individual length data from North Carolina for samples that had total and fork length, fork length was converted to total length using a linear regression,

$$Total\ Length = 0.57 + 1.07 \times Fork\ Length.$$

This linear regression was used to convert all fork length records without associated total length. Estimated total lengths were combined with measured total length data to build the length composition for North Carolina. Lengths for the ALKs and length compositions were condensed into 1-cm length bins from a minimum bin of 13- cm (length <14 cm) to maximum bin of 31+ cm (length ≥ 31 cm) groups, which were determined based on length bins that represented 1-2% of cumulative length distribution. To get proportions-at-age for each region, the length frequency vector was multiplied by the ALK matrix,

$$\begin{bmatrix} N_{a=0} \\ N_{a=1} \\ N_{a=2} \\ N_{a=3+} \end{bmatrix} = \begin{bmatrix} P_{a=0,L=13-} & P_{a=0,L=14} & \cdots & P_{a=0,L=31+} \\ P_{a=1,L=13-} & P_{a=01L=14} & \cdots & P_{a=1,L=31+} \\ P_{a=2,L=13-} & P_{a=2,L=14} & \cdots & P_{a=2,L=31+} \\ P_{a=3+,L=13-} & P_{a=3+,L=14} & \cdots & P_{a=3+,L=31+} \end{bmatrix} \times \begin{bmatrix} N_{L=13} \\ N_{L=14} \\ \vdots \\ N_{L=31+} \end{bmatrix},$$

where $N_a$ was the number of fish of age $a$, $P$ was the proportion of fish age $a$ within each length bin, $L$, and $N_L$ was the number of fish in a given length bin. Ages were not available from the recreational fishery, so we applied the commercial ALK to the recreational length composition data to calculate the recreational age compositions. This application of the commercial data ALKs to the recreational length frequencies assumed that growth was the same between fish caught by both fleets. The recreational length composition were aggregated over states and compiled into two regions using data collected by MRIP (J. Kipp, ASMFC, personal communication).

For each survey (NEAMAP and ChesMMAP) and season, we compiled ALKs, length compositions, and proportions at age using the same methods as for the fishery-dependent data. Because NEAMAP was one of the surveys used in the aggregate index, we assumed that age data from the NEAMAP fall survey represented the age composition of the aggregate index.

*Model Description*

The model tracked abundance-at-age of spot over time within each region.  Movement of spot was modeled as a pulse at the beginning of each year, such that a proportion of total abundance at each age was allocated to each region. Total abundance (*TN*) at the beginning of year *y* for age *a*, was calculated as the sum of abundance at the beginning of the year ($\widetilde{N}$) across regions for ages > 0,

$$TN_{y,a} = \sum_r \widetilde{N}_{r,y,a}.$$

For age-0, total abundance at the beginning of the year was equal to estimated recruitment (*R*),

$$TN_{y,0} = R_y,$$

where R in year, *y*, was an estimated parameter. Abundance for each region at the beginning of the year after movement (*N*) was calculated as the product of total abundance and the region and age-specific occupancy probability (*P*),

$$N_{r,y,a} = TN_{y,a}P_{r,y,a}.$$

The occupancy probability (*P*) was an estimated parameter that represented the proportion of fish at a given age in each region at the beginning of the year. Abundance in region *r*, at the beginning of the next year before movement followed the exponential mortality model,

$$\widetilde{N}_{r,y+1,a+1} = N_{r,y,a} \times e^{-Z_{r,y,a}},$$

where *Z* was the total instantaneous mortality rate. For age-3+, abundance in region *r* at the beginning of the next year before movement was the sum of the survivors of age-2 individuals to age-3 and the survivors of the age-3+ individuals,

$$N_{r,y+1,a=3+} = N_{r,y,a=2} \times e^{-Z_{r,y,a=2}} + N_{r,y,a=3+} \times e^{-Z_{r,y,a=3+}}.$$

The 3+ age group for the first year was assumed to be in equilibrium where *N* in region, *r,* was equal to the product of the occupancy probability (*P*) and total abundance,

$$N_{r,1,3} = P_{r,3} \times TN_{1,3}.$$

Equilibrium abundance for the remaining ages, *a,* for the first year was,

$$N_{r,1,a} = P_{r,a} \times TN_{1,a}.$$

TN by age and region in the first year was assumed to be in equilibrium

$$TN_{1,3} = \frac{TN_{1,3}}{1-S_{eq}},$$

where $S_{eq}$ was the weighted survival rate with weights equal to the sum of the proportion, *P*, in region *r*, times the survival rate in region *r* for age-3+,

$$S_{eq} = \sum P_{r,3} \times e^{-Z_{r,3}}.$$

The occupancy probabilities-at-age for the Chesapeake Bay were estimated on the logit scale, and the occupancy probabilities for the coast were calculated as,

$$P_{r=2,a} = 1 - P_{r=1,a}.$$

The total instantaneous mortality rate was calculated as the sum of fishing mortality (*F*) over fleets and the age-specific natural mortality rate (*M*),

$$Z_{r,y,a} = M_a + \sum_f F_{r,y,a}.$$

M at age was estimated using a mortality-length model developed by Lorenzen (2005) and rescaled with a constant (0.145) to approximately match the age-constant natural mortality value estimate, 0.91, calculated using the approach of Then et al. (2014) with a maximum age of 6 (Table S2).

Fishing mortality rate ($\tilde{F}$) for fully selected ages was estimated as an individual parameter for each fleet (commercial, recreational, and shrimp; *f*) and year (*y*). The age-specific fishing mortality rate (*F*) for a given fleet, year, and age (*a*) was the product of fully selected fishing mortality rate and the fleet-, region-, and age-specific selectivity (*Sel*),

$$F_{f,r,y,a} = \tilde{F}_{f,r,y} \times Sel_{f,r,a}.$$

Selectivity for the recreational and commercial fisheries was specified equal to one for some ages and was estimated for the other ages (Table 2.2). Shrimp trawl fishery was assumed to select only age-0 spot, so selectivity was specified as one for age-0 and zero for all other ages.

Fishing for spot primarily occurs in the late summer through the fall. Therefore, we modified the catch equation to allow for natural mortality outside of the fishing season and both fishing and natural mortality during the fishing season. Catch at age (*CAA*) for fleet *f*, region *r,* year *y,* and age *a*, was estimated as the product of the proportion of mortality during the fishing season due to fishing by fleet *f*, the fraction of individuals that died during the fishing season, and the abundance at the beginning of the fishing season,

$$CAA_{f,r,y,a} = \frac{F_{f,y,r,a}}{\sum_f F_{f,r,y,a} \quad + M \times Dur_M} \times \left(1 - e^{-\left(\sum_f F_{f,r,y,a} F_{total} + M \times Dur_M\right)}\right) \times N_{r,y,a} \times e^{-M \times Bef_M},$$

where $Dur_M$ was the fraction of natural mortality that happened during the fishery and $Bef_M$ was the fraction of natural mortality that happened before the fishery began.

Indices of abundance were calculated in a similar manner to catch by allowing for some mortality before the survey occurred. Specifically, the index of abundance at age (IAA) for index *i*, region *r*, year *y*, and age *a*, was estimated as the product of catchability (*q*), abundance, survey selectivity, and modified by the fraction of natural and fishing mortality that occurred prior to the survey,

$$IAA_{i,r,y,a} = q_i \times N_{r,y,a} \times Sel_{i,r,a} \times e^{-(M \times Frac_M + F \times Frac_F)},$$

where $Sel_{i,r,a}$ was the selectivity at age parameter for index *i*, and $q_i$ was the catchability parameter for index *i*. $Frac_M$ was the fraction of natural mortality that occurred before the survey and $Frac_F$ was the fraction of fishing mortality that occurred before the survey. $Frac_M$ and $Frac_F$ depended on the timing of the survey in relation to the fishery (Table 2.3).

Proportions-at-age for fishery catches were calculated for each region and fleet as:

$$PAA_{f,r,y,a} = \frac{CAA_{f,r,y,a}}{\sum_a CAA_{f,r,y,a}}.$$

Proportions-at-age for each survey used the same equation with IAA replacing CAA.

Parameters were estimated by minimizing the objective function ($NLL_{Obj}$), which was the sum of the negative log likelihood functions for each data source and penalties on some of the estimated parameters,

$$NLL_{Obj} = -ln(L_{Catch}) - ln(L_{Index}) - ln(L_{CatchPAA}) - ln(L_{SurveyPAA}) - ln(L_{Penalties}),$$

where $L_{Penalties}$ was the sum of all penalties described in Table 2.4.

Lognormal errors were assumed for the survey indices ($-ln(L_{Index})$) and the fishery catch ($-ln(L_{Catch})$), and the negative log likelihood for the proportions-at-age ($-ln(L_{CatchPAA}); -ln(L_{SurveyPAA})$) used a robust multinomial distribution (Fournier et al., 1990; Fisch et al., 2021). Model fit was assessed using Pearson residuals for catch and surveys and standardized residuals for proportions at age. Coefficient of variations (i.e., log-scale standard deviations; CV) for the lognormal distributions and effective sample sizes (Neff) for the robust multinomial distributions were determined by iterative re-weighting for each survey (Francis, 2011). Neff describes the information in the proportions-at-age if sampling is random, and it cannot be larger than the number of fish aged in a year. Typically, higher Neff values indicate more confidence in ageing data. Neff values were restricted to a minimum value of 5-10, but values in the 10-20 range were considered to be better because they reflected the low samples size and lower confidence in the proportions at age relative to the survey indices. We were less concerned with ageing error because spot are considered easy to age, however, we were more concerned that our ageing data was not a representative sample of the population. To reflect that uncertainty, we used lower Neff values. Because no fish were aged from the recreational fishery, we restricted Neff for this fleet to be lower than that for the commercial fishery. CV values represented our confidence in the reliability of a data set. Smaller CV values indicate less error in the data (relative to the true unknown values) and will force the model to fit better. The commercial catch had a lower CV than the recreational or shrimp bycatch fleets because we believed that the commercial catch summaries were more reliable than the other fleets. CV and Neff were constant over time. Final values of the CVs and Neffs are presented in Table S1.

We used several penalties to constrain parameters such that they were estimable and to ensure that the model produced biologically plausible estimates. Therefore, we implemented several penalties that were in three categories: 1) parameter estimates should be similar to other related parameter estimates, 2) fishing mortality rates are unlikely to be extremely high or low, and 3) the spatial distribution of spot recruitment should be somewhat similar to estuarine primary productivity and the proportions of recreational and commercial catch. Penalized likelihood components of the objective function and their respective equations, means, and standard deviations are described in Table 2.4. Normal distributions were assumed for all penalties, but for some parameters the penalty was applied to a transformed value. The occupancy probability parameters ($P$) had several penalties because we did not have data to inform these values. Instead, we used an estimate of the proportion of primary production in the Chesapeake Bay relative to other estuaries on the U.S. East Coast to penalize the occupancy probability for age-0. ASMFC (2004) calculated the weighted average of primary productivity and estimated that 69% of the estuarine primary production occurred in the Chesapeake Bay. The average occupancy probability for age-0 spot in the Chesapeake Bay over years was penalized to match productivity levels ($-ln(L_{P0})$, Eq. 4.1). Spot are estuarine dependent as juveniles (Odell et al., 2017), and primary productivity should positively relate to their prey. Additionally, proportions for ages 1-3+ were penalized using a mean value of 0.5 ($-ln(L_{Psplit})$, Eq. 4.2) because commercial and recreational fishery catches were similar between the Chesapeake Bay and coastal regions. P was additionally penalized to minimize differences between ages ($-ln(L_{Pagediff})$, Eq. 4.3). These penalties were included because we do not expect large proportions of the population to be concentrated in one region for a given age based on fishery catches, and we do not expect the occupancy probabilities to vary substantially from one age to the next. Fishing mortality rates for spot are not likely to undergo large jumps from one year to the next because fishing effort in likely not highly variable year-to-year. Therefore, we constrained $\tilde{F}$ to penalize year-to-year changes for each fleet within a region ($-ln(L_{F-cdiff})$, Eq. 4.4; ($-ln(L_{F-rdiff})$, Eq. 4.5; ($-ln(L_{F-sdiff})$, Eq. 4.6). Similarly, the models included penalties on between-age differences in the occupancy probabilities in both regions. These penalties on the differences between parameters do not provide information on the scale of the parameter estimates and should be relatively uninformative for estimates of abundance or fishing mortality rates. $\tilde{F}$ for the recreational fishery in the Chesapeake Bay and shrimp trawl bycatch were additionally penalized to avoid extremely high (e.g., 20 $yr^{-1}$) values that were estimated in preliminary model runs ($-ln(L_{Frecbay})$, Eq. 4.7, ($-ln(L_{Fshrimp})$, Eq. 4.8) by including a normal penalty on the $\log(\tilde{F})$ with a mean of 0.5 and an SD of 0.2. The purpose of this penalty was to inform the model that very high or low values of $\tilde{F}$ were unlikely. Finally, recreational selectivity patterns for commercial and recreational fisheries were penalized to minimize differences between the Chesapeake Bay and the coast because we assumed that age-specific fishing selectivity patterns would be similar between regions ($-ln(L_{sel})$, Eq. 4.9).

We implemented two versions of the model that differed in estimated parameters and penalties. The SVM model assumed that occupancy probabilities-at-age were constant over time while fishing mortality rates for each fleet and fishery selectivity differed between regions. The TVO model allowed occupancy probability parameters, $P$, to vary over time while holding fishing mortality rates and selectivity patterns constant between regions for the recreational and commercial fleets. Time-varying occupancy probabilities were estimated by modeling P for each age as a random walk on the logit scale,

$$logit(P_{y+1,a}) = logit(P_{y,a}) + Pdevs_{y,a},$$

where the annual deviations in the occupancy probabilities ($Pdevs_{y,a}$) were penalized using a normal distribution ($-ln(L_{pdevs})$, Eq. 4.10). Except for the changes specified, the structure of the TVO model was the same as the SVM model (all other penalties were the same).

The SVM and TVO models were compared using a set of qualitative plausibility criteria related to biological plausibility and model fit (Table 2.5). We deemed a model to be biologically plausible if spot were not extremely concentrated in one region. Also, occupancy probabilities within a region should be similar between ages because it is unlikely that fish close in age have drastically different movement patterns. Additionally, selectivity patterns should not have inexplicable patterns and fishing mortality rates should not exceed 2 $yr^{-1}$ for a single fleet because it is unlikely that spot fishing mortality rates were that high during the study period. We believe this is realistic because spot are a low value fish that is usually not the target species. Because they are so widely distributed, it would be difficult to concentrate fishing effort to remove large quantities of the population. Lastly, the model should be able to fit catch and indices relatively well and avoid any major patterning in age composition residuals.

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## Tables

*Table 2.1: Description of fisheries independent data sources including the survey name, area sampled, ages of spot caught, gear, years sampled, months sampled, and region applied in the model. Young-of-the-year (i.e., age-0) surveys are indicated as YOY.*

| Survey Name | Location | Age | Gear | Years | Season | Region in model |
|---|---|---|---|---|---|---|
| Chesapeake Bay Multispecies Monitoring and Assessment Program (ChesMMAP) | Mainstem of the Chesapeake Bay | 0-3+ (Very few age-3) | Trawl | 2002-2019 | March, June, September, and November | Chesapeake Bay |
| Northeast Area Monitoring and Assessment Program (NEAMAP) | Mid-Atlantic | 0-3+ (very few age 3) | Trawl | 2008-2019 | Spring, Fall | Coast |
| Virginia Institute of Marine Science (VIMS) Juvenile Finfish Trawl Survey (YOY) | Virginia portion of the Chesapeake Bay | 0 | Trawl | 1989-2019 | Fall | Chesapeake Bay |
| Aggregate Coast Index | Atlantic Coast | 0-3+ | Trawl | 2002-2019 | Fall | Coast |

*Table 2.2*: *Description of estimated and fixed selectivity-at-age parameters for each fleet or survey, where 1 indicates ages that had selectivity specified at 1, 0 indicates ages that had selectivity specified at 0, and "estimated" refers to parameters that are estimated by the model.*

| Fishery or Survey | Age 0 | Age 1 | Age 2 | Age 3+ |
|---|---|---|---|---|
| Commercial Bay and Coast | estimated | 1 | 1 | 1 |
| Recreational Bay and Coast | estimated | 1 | estimated | estimated |
| ChesMMAP Summer | 1 | estimated | estimated | 0 |
| ChesMMAP Fall | 1 | estimated | estimated | 0 |
| NEAMAP Spring | 0 | 1 | estimated | 0 |
| Aggregate | 1 | estimated | estimated | 0 |

*Table 2.3: Seasonal timing of surveys represented by the fraction of fishing mortality (F) and natural mortality (M) that occurred before the survey. The commercial and recreational fisheries were assumed to occur during August-November. Survey abbreviations are defined in Table 2.1.*

| Survey | Timing of survey | Parameter value F | Parameter value M |
|---|---|---|---|
| ChesMMAP Summer | June-July | 0 | 6/12 |
| NEAMAP Spring | April-May | 0 | 4/12 |
| ChesMMAP Fall | September-November | 6/12 | 9/12 |
| Aggregate | Fall (September-October) | 6/12 | 9/12 |

*Table 2.4*: *Penalties for model parameters including the occupancy probabilities (P) and fishing mortality rate (F) with their means and standard deviations. Parameters were penalized using normal distributions. X indicates the value that was used to calculate the penalty including any transformations.*

| Number | Penalties | Equation | Mean | Standard Deviation |
|---|---|---|---|---|
| 4.1 | Penalize average of P0 (P for age 0) in the Chesapeake Bay $(-ln(L_{P0}))$ | $X = \sum_{y} \frac{P_{y,Chesapeake\ Bay}}{18}$ | 0.69 | 0.1 |
| 4.2 | Keep P for ages 1-3+ close to 0.5 $(-ln(L_{Psplit}))$ | $X = P_{y,a}$ | 0.5 | 0.2 |
| 4.3 | Minimize differences in P between ages $(-ln(L_{Pagediff}))$ | $X = P_{y,a} - P_{y,a+1}$ | 0 | 0.05 |
| 4.4 | Minimize year to year differences in commercial F $(-ln(L_{F-cdiff}))$ | $X = \log(\tilde{F}_{commercial,r,y}) - \log(\tilde{F}_{commercial,r,y+1})$ | 0 | 0.2 |
| 4.5 | Minimize year to year differences in recreational F $(-ln(L_{F-rdiff}))$ | $X = \log(\tilde{F}_{recreational,r,y}) - \log(\tilde{F}_{recreational,r,y+1})$ | 0 | 0.2 |
| 4.6 | Minimize year to year differences in shrimp F $(-ln(L_{F-sdiff}))$ | $X = \log(\tilde{F}_{shrimp,r,y}) - \log(\tilde{F}_{shrimp,r,y+1})$ | 0 | 0.2 |
| 4.7 | Minimize recreational bay F $(-ln(L_{Frecbay}))$ | $X = \log(\tilde{F}_{recreational,r,y})$ | -0.69 | 1 |
| 4.8 | Minimize Shrimp F $(-ln(L_{Fshrimp}))$ | $X = \tilde{F}_{shrimp,r,y}$ | 0.5 | 1 |
| 4.9 | Minimize difference between coast and bay recreational selectivity $(-ln(L_{Sel}))$ | $X = \log(Sel_{a,r}) - \log(Sel_{a,r+1})$ | 0 | 0.2 |
| 4.10 | Random walk for P to vary over time $(-ln(L_{Pdevs}))$ | $X = logit(P_{devs})$ | 0 | 0.2 |

*Table 2.5*: *Qualitative plausibility table used to evaluate and compare the spatially-varying mortality (SVM) model and the time-varying occupancy model (TVO).*

| Criteria | SVM | TVO |
|---|---|---|
| **Biological Plausibility** | | |
| Occupancy probabilities not very high or low | Low proportion in the Chesapeake Bay relative to the coast | Yes |
| Occupancy probabilities for neighboring ages should be similar | Yes | Yes |
| Selectivity pattern with implausible jumps between ages | Yes | Yes |
| Fishing mortality rate (F) should not be too high (F>2 kills the majority of fish in a region) | Very high F for the recreational fishery in the Chesapeake Bay and shrimp trawl bycatch | F is reasonable |
| **Model Fit** | | |
| Good fit to catch | Commercial good | Commercial good; Better fit to recreational and shrimp trawl bycatch than SVM |
| Reasonable fit to indices | Cannot match extremes in all surveys | Cannot match extremes in all surveys; Better fit to most surveys than SVM; Much better fit to aggregate than SVM |
| Avoid major patterns in age composition residuals (avoid standardized residuals >4, runs, many outliers) | Issues discussed in results section, largely the same for both models. SVM slightly larger residuals for several data sources | |
| Pearson residual plots should appear random without extreme values (> 4) | ChesMMAP trending, outliers in aggregate and YOY | ChesMMAP trending, outliers in aggregate and YOY |

## Supplemental Tables

*Table S1. Effective sample sizes (Neff) and log-scale standard deviations (CV) used to weight the data sources in the negative log likelihood functions. The same values were used in both the spatially-varying mortality and time-varying occupancy models.*

| Data Source | Neff | CV |
|---|---|---|
| Commercial | 20 | 0.05 |
| Recreational | 10 | 0.2 |
| Shrimp Trawl | | 0.2 |
| ChesMMAP Summer | 20 | 0.4 |
| ChesMMAP Fall | 20 | 0.4 |
| NEAMAP | 10 | 0.4 |
| Aggregate | 20 | 0.2 |
| YOY | | 0.7 |

*Table S2. Natural mortality (M) values-at-age ($yr^{-1}$) for the base model runs and sensitivity analyses. The low and high values for the sensitivity analyses were calculated as the base value ± 0.145.*

| **Run** | **Age 0** | **Age 1** | **Age 2** | **Age 3+** |
|---|---|---|---|---|
| Base | 1.00 | 0.925 | 0.8 | 0.83 |
| Low M (Lorenzen (2005) values) | 0.86 | 0.78 | 0.73 | 0.69 |
| High M | 1.15 | 1.07 | 1.02 | 0.98 |