Evaluating the impact of plus group definition on the Atlantic and Gulf menhaden stock assessments

August 6, 2022

Technical Report TS-783-22 of the University of Maryland Center for Environmental Science

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UMCES Grant #07-4-31786

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Rationale

The Gulf menhaden (*Brevoortia patronus*) and Atlantic menhaden (*Brevoortia tyrannus*) stocks support the largest commercial fisheries on the Gulf and East Coasts, respectively (NMFS 2022). Given a lack of targeted fishery-independent data collection for menhadens, particularly for older fish, the assessments used to manage these stocks are poorly informed about older fish in the population. This could impact our ability to estimate fishery and abundance index selectivities, stock abundance or biomass, and fishing mortality. The 2019 Atlantic Menhaden Benchmark Stock Assessment Peer Review Panel highlighted the lack of data collection on older Atlantic menhaden in the population as a primary area of concern for the assessment, stating that "existing data do not provide good information on the relative abundance of larger, older fish" (SEDAR 2019). In addition, previous SCEMFIS-funded research indicated that Gulf menhaden abundance for ages 4+ may be poorly estimated given reduction fishery encounters with age 4+ fish are relatively rare (Nesslage et al. 2020).

When older fish are rarely intercepted in the fishery and fishery-independent surveys, statistical catch-at-age assessment models may perform poorly due to there being too little information in the data. In such situations, the assessment model is often configured such that the terminal age class represents a suite of older age classes, and data associated with those older ages is pooled. This pooled terminal age class is smaller than the maximum observed age in the population and is commonly called a "plus group". For example, if a species is thought to have a maximum age of 50, but little data are available to inform the model about fish age-26 and older, the assessment model may be configured to have a plus group of "age-25+" that tracks fish ages 25 and older together in one age class. Abundance of fish in the plus group is calculated by assuming the same mortality rate applies across all ages in the pooled age class (Quinn and Deriso 1999).

The selection of an appropriate plus group for a given stock assessment is often based on expert judgement of the assessment team after taking into consideration the life history of the species, quantity and quality of the available data for older fish in the population, as well as the way in which age composition is estimated in the model (e.g., likelihood function; Fisch et al. 2021). Decisions regarding plus group definition are important in that they may affect model performance (Smith et al. 2012); in other words, plus group definition may affect the ability of the model to converge on a solution and produce accurate and precise estimates. The choice of ages to include in a plus group may also interact with other modeling decisions to impact model performance. For example, the shape and estimability of selectivity-at-age is determined in part by other parameters being estimated (e.g., natural mortality) and the number of age classes that can be modeled given the available data (Privitera-Johnson et al. 2022; Punt et al. 2014).

Due to lack of data collection on older menhaden of both species, a plus group is utilized in the Gulf and Atlantic menhaden assessment models (SEDAR 2018; SEDAR 2019). Gulf menhaden can live to approximately age 6, but few older fish are encountered in the fishery or in fishery-independent data collection programs; therefore, a plus group of age-4+ is used, which pools information and calculations associated with fish ages 4 and older. Atlantic menhaden can live to age 8 or older, but few older fish are encountered in the fishery or in fishery-independent data collection programs; therefore, a plus group of age-6+ is used, which pools information and calculations associated with fish ages 6 and older.

Of particular concern for Gulf and Atlantic menhaden is the dependency of the plus group definition with the functional form of selectivity for both the abundance indices and the fishery. Surveys used to generate abundance indices for both Gulf and Atlantic menhaden are deployed in estuaries and nearshore waters where few older menhaden are encountered, making the decision to model age-specific selectivity with a logistic function a major source of uncertainty in these models. Use of an inappropriate plus group could introduce bias, but definition of an appropriate plus group could reduce model error (e.g., if the plus group is set at a low age relative to the age at which uncertainty in selectivity is highest). In addition, both menhaden assessment models assume fishery selectivity is dome-shaped to account for lack of spatial overlap between fisheries and older fish in the population. Parameters describing the shape of the descending limb of these selectivity curves can be particularly difficult to estimate when presented with little information about older aged fish. Of particular concern is the Gulf menhaden assessment, which estimates selectivity for age-1 and specifies selectivity for age-0 and ages-2+. Specifying selectivity-at-age is a strong assumption that, if violated, could result in biased model results; definition of the plus group in such situations could influence the amount of bias in model estimates. Also, the degree of doming in the Atlantic menhaden assessment is poorly informed due to lack of data collection on larger older fish that are typically not encountered by the fishery or current fishery-independent surveys.

However, the consequences of plus group definition on statistical catch-at-age model performance have not been thoroughly evaluated by the Gulf or Atlantic menhaden stock assessment teams and the broader issue of how to properly evaluate plus group selection has not been formally addressed in the scientific literature. In the absence of expansion of menhaden data collection programs aimed at providing additional information about the proportion of older fish, it is critical that the impact of defining the plus group in Gulf and Atlantic menhaden statistical catch-at-age models be explored. Thus, we conducted two simulation studies, one for each stock, that quantified the impact of including a suite of different ages in the plus group. We assessed model accuracy and precision for quantities of interest to menhaden management, namely age-1+ abundance, spawning stock biomass, recruitment, and fishery exploitation rate. This study will provide the stock assessment teams on both coasts with information about how the performance of these assessment models might be impacted by current or potential future configuration decisions, including changes in plus group definition, model misspecification, and the addition of new data sources.

Goals and objectives

The goal of this study was to evaluate the impact of plus group definition on the performance of both the Gulf and Atlantic menhaden stock assessment models. The objectives of our study were to:

1. Build a simulation modeling tool for both stocks based on the estimation (BAM) models used in Gulf and Atlantic menhaden management.
2. Quantify the potential impact of plus group definition on accuracy and precision of BAM estimates under both ideal conditions and conditions in which the model is misspecified.
3. Assess the impact of adding new fishery-independent data to the Gulf and Atlantic menhaden assessments using the current plus group definition for both stocks.

Methods

We conducted a simulation study for both the Gulf and Atlantic menhaden stocks that characterized the impact of plus group definition on accuracy and precision of BAM estimates of adult abundance, spawning stock biomass, recruitment, and fishery exploitation under a range of different scenarios, including model misspecification and the addition of new data sources. Overall simulation study design is presented first in this section, followed by stock-specific details.

Study design

Simulation modeling frameworks for both Gulf and Atlantic menhaden were developed by converting the BAM statistical catch-at-age model (Williams and Shertzer 2015) into a simulation model that generated stochastic menhaden dynamics projected forward from terminal year conditions estimated for each stock (SEDAR 2018; SEDAR 2019) over a period of 50 years. Stock dynamics were driven by one of three trends in fleet-specific fishing mortality (F). The trend in F varied by scenario (Tables 1 and 2) and was specified as either: 1) constant fleet-specific Fs set at the estimated Fs from the terminal year of the most recent assessment, 2) linear peaked trend in fleet-specific Fs (beginning and ending at the minimum estimated Fs with a peak at the maximum estimated F in the middle of the time series), or 3) a constant low fishing mortality equal to half the Fs estimated in the terminal year of the most recent assessment. Simulated data were used to create input data sets for the estimation model (BAM). Each scenario was simulated 1,000 times and estimation models were determined to have converged if the maximum gradient was < 0.001.

Model input parameters and model configuration were maintained as in the base model with the following exceptions:

1. Stochasticity was incorporated in the generation of annual recruitment, landings, and initial abundance at age by multiplying the simulated values by a random number drawn

from a normal distribution with a mean of zero and standard deviations (SDs) of 0.5, 0.04, and 0.05, respectively.

2. Observation error in the simulated indices of abundance was calculated similarly using estimated SDs for each index from the most recent stock assessments (SEDAR 2018; SEDAR 2019).
3. To simplify the Atlantic menhaden study, only the Northern Adult (NAD) index of abundance and Juvenile Abundance Index (JAI) were retained from the base model as fishery-independent data sources along with the simulated new age-structured index in certain scenarios.
4. Observation errors for catch-at-age, index catch-at-length or catch-at-age were drawn from a multinomial distribution using sample sizes equal to the effective sample sizes estimated for each quantity in the most recent stock assessments (SEDAR 2018; SEDAR 2019).
5. For some model scenarios (see Tables 1 and 2), the estimation model was modified to accept an additional data source in the form of a new age-structured survey with observation error (as described in #3 above assuming a sample size of 200) following the index and catch-at-age fitting methodology utilized in the base model.
6. For some model scenarios, the estimation model was modified to be able to fit terminal year age-1+ biomass to a survey-based estimate of age-1+ biomass with an SD of either 0.2 or 0.5 using the following likelihood equation:

$$L_B = 0.5 * \left(\frac{\ln(\hat{B})/B_{est}}{SD_{est}}\right)^2,$$

where L_B is the likelihood component for fitting terminal year age-1+ biomass to a survey-based estimate B_{est}, $\hat{B}$ is the model estimate of terminal year age-1+ biomass, and SD_{est} is the SD associated with B_{est}.

7. The robust multinomial likelihood option available in the estimation model was used in place of the Dirichlet multinomial likelihood because the associated parameters tended to be difficult to estimate well in a large simulation framework.

Unless otherwise noted for specific scenarios in Tables 1 and 2 or in the next section, the estimation model was provided the starting values for all estimated parameters from the most recent assessments for each stock (SEDAR 2018; SEDAR 2019) or accurate starting values based on stochastically simulated data (e.g., initial recruitment).

Scenarios

Gulf menhaden

For Gulf menhaden, we began by evaluating the impact of plus group definition on estimation model performance under ideal conditions (no model misspecification). To accomplish this, we simulated a complete set of 20 plus group scenarios ranging from age-3+ to age-6+ across a range of population maximum ages from age-3+ to age-6+ under both constant and peaked F patterns (Table 1; Scenarios 1-20).

Next, we explored the interaction between plus group definition and estimation model misspecification in two ways. First, we simulated dome-shaped selectivity for the Louisiana Gill Net index of abundance (LAGN index) while estimating selectivity in the BAM using a logistic selectivity curve (as in the current stock assessment) to explore the potential impact of assuming all ages of Gulf menhaden are vulnerable to this estuarine/inshore survey. We simulated both constant and peaked F patterns (Table 1; Scenarios 21-24). For brevity, we compared only two plus group configurations which spanned the extremes of the range of plus groups explored (age-6+ and age-3+ with a population maximum age class of age-6). We also explored the impact of estimation model misspecification by simulating a higher degree of doming in commercial reduction fishery selectivity (0.73 for ages-3+) using alternative selectivity values for older ages from likelihood profiles conducted during the most recent stock assessment (SEDAR 2018; Table 1; Scenarios 25-28). We explored this scenario to examine the potential impact of uncertainty in the degree of doming, which is a major source of uncertainty in the assessment (SEDAR 2018). We then estimated age-1 selectivity in the BAM using the same starting values as in the current stock assessment to explore the potential impact of incorrectly specifying values for selectivity of ages-3+. We simulated both constant and peaked F patterns (Table 1; Scenarios 25-28). Here also we compared only two plus group configurations which spanned the extremes of the range of plus groups explored (age-6+ and age-3+ with a population maximum age class of age-6) for brevity.

Lastly, we explored the impact of adding new fishery-independent data to the Gulf menhaden assessment using the plus group definition from the current assessment (age-4+) in two ways. We began by simulating a well-sampled, age-structured survey with logistic selectivity across all 50 years of simulation (Table 1; Scenarios 30-31). The estimation model was provided with starting values for selectivity and catchability from the simulation model. Next, we simulated incorporation of a single fishery-independent survey-based estimate of age-1+ biomass in the estimation model (Table 1; Scenarios 32-33). For both scenarios, the estimation model was provided with starting values for selectivity and catchability from the simulation model and two levels of survey observation error generated using coefficients of variation (CV) of 0.2 and 0.5. For both types of new data sources simulated, we also explored scenarios in which these data sources were incorporated in the estimation model when commercial reduction fishery selectivity was misspecified as described above (Table 1; Scenarios 35-38); this allowed us to determine the degree to which these new data sources might improve BAM performance in situations where it was seriously challenged by incorrect assumptions about the degree of doming. For all of scenarios that incorporated new data sources, we applied a constant low F pattern to demonstrate how these new data might impact estimation model performance in situations with little available fishery-dependent information.

Atlantic menhaden

For Atlantic menhaden, we began by evaluating the impact of plus group definition on estimation model performance under ideal conditions (no model misspecification). To accomplish this, we simulated a set of 10 plus group scenarios ranging from age-4+ to age-8+ assuming a maximum population age of eight under both constant and peaked F patterns (Table 1; Scenarios 1-10).

Next, we explored the interaction between plus group definition and estimation model misspecification in three ways. First, we simulated dome-shaped selectivity for the Northern Adult index of abundance (NAD index) while estimating selectivity in the BAM using a logistic selectivity curve (as in the current stock assessment) to explore the potential impact of assuming all ages of Atlantic menhaden are vulnerable to this estuarine/inshore survey (Table 2; Scenarios 11-20). We also explored the impact of estimation model misspecification by simulating logistic selectivity for the northern commercial bait and reduction fleets while assuming dome-shaped selectivity in the estimation model as in the most recent stock assessment (SEDAR 2019; Table 2; Scenarios 21-30). Finally, we explored the impact on model performance of poor starting values for selectivity of the southern commercial reduction fishery by simulating a lower degree of doming but retaining starting values from the base assessment model (Table 2; Scenarios 31-40). For all of these scenarios, we simulated both constant and peaked F patterns across all 10 plus group definitions.

Lastly, we explored the impact of adding new fishery-independent data to the Atlantic menhaden assessment in two ways, similar to Gulf menhaden as described above. We began by simulating a well-sampled, age-structured survey with logistic selectivity across all 50 years of the simulation (Table 2; Scenarios 41-50). The estimation model was provided with starting values for selectivity and catchability from the simulation model, and we examined scenarios with plus group definitions of age-3+ to age-8+. We also explored scenarios in which either a new age-structured survey or a single fishery-independent survey-based estimate of age-1+ biomass were incorporated in the estimation model when NAD abundance index selectivity was misspecified, as described above, using the plus group definition from the current assessment (age-6+; Table 2; Scenarios 52-55); this allowed us to determine the degree to which these new data sources might improve assessment model performance in situations where it was seriously challenged by incorrect assumptions about the shape of the adult index selectivity curve. For these scenarios, two levels of survey observation error were explored (CVs of 0.2 and 0.5). Results generated using a constant current and a constant low F pattern were compared for scenarios that incorporated the new index of abundance to demonstrate how these new data might impact estimation model performance in situations with little available fishery-dependent information. A constant low F pattern was applied to scenarios that incorporated a single fishery-independent survey-based estimate of age-1+ biomass to demonstrate how this new information might impact estimation model performance in situations with little available fishery-dependent information.

Performance evaluation

We evaluated performance of the estimation model for each scenario by examining the difference between simulated and estimated terminal year values for four primary metrics of interest in fisheries management: 1) total age-1+ abundance, 2) recruitment (i.e., total age-0 abundance), 3) spawning stock biomass, and 4) exploitation rate, which was defined as fishery catch divided by stock biomass. Model performance was characterized in three ways. First, percent convergence was used to represent model stability and was calculated as the proportion of 1,000 runs that converged multiplied by 100%. Model precision was characterized by calculating Median Absolute Relative Error (MARE) for all four metrics in the terminal year as follows:

$$MARE = \frac{median(absolute\ value(estimated\ value - simulated\ value))}{simulated\ value}.$$

Model accuracy was characterized by Median Relative Error (MRE) for all four metrics in the terminal year as follows:

$$MRE = \frac{median(estimated\ value - simulated\ value)}{simulated\ value}.$$

Results

Across all simulations in this study, MARE ranged from 0.09-0.6 for Gulf menhaden and 0.07-0.26 for Atlantic menhaden, and MRE ranged from 0.001-0.54 for Gulf menhaden and 0-0.097 for Atlantic menhaden. For both stocks, the magnitude of these precision and accuracy metrics was generally small when the model was not misspecified, but model error increased substantially with model misspecification in either fishery or survey selectivity. Even when the magnitude of error produced was small, the relative difference in error across plus group definitions and scenarios indicated that the definition of a plus group can impact model performance. The impact of plus group definition was often more evident in the presence of model misspecification, both survey or fishery selectivity, and with the addition of new data sources as described below.

Gulf menhaden

The Gulf menhaden BAM estimation model was highly stable as indicated by the rate of convergence ranging from 99-100% across all scenarios (Table 1). Relative model accuracy and precision depended on plus group definition and F pattern, and greater differences were observed among plus group definitions when more ages were present in the simulated population. For Gulf menhaden Scenarios 1-20 (Table 1), MARE was not clearly impacted by F pattern (Figs. 1-4). Bias (MRE) in model estimates was more heavily influenced by plus group definition for scenarios in which population maximum age was 5 or 6 (Figs. 5-8). In most cases, bias decreased with increasing plus group age for estimates of age 1+ abundance and spawning stock biomass. In contrast, bias in recruitment and exploitation rate was reduced when the plus group was set at a lower age, particularly age-3+. Thus, our simulations suggest that the older the plus group age, the more likely the model is to produce underestimates of recruitment and overestimates exploitation rate.

When selectivity of the adult index of abundance (LAGN) was misspecified (Scenarios 21-24), MARE was similar across plus group definitions and F pattern scenarios (Table 1; Fig. 9); however, MRE was reduced when the estimation model was configured with a lower max age in the plus group (Table 1; Fig. 10). For scenarios in which selectivity of the commercial fishery was misspecified (Scenarios 25-28), the model performed better (both accuracy and precision) when the F pattern was constant. Both MARE and MRE were reduced slightly with a lower plus group maximum age for all metrics but recruitment (Table 1; Figs. 11-12).

With incorporation of a new age-structured index of abundance generated using a CV of 0.2 (Scenario 30), MARE did not improve, and MRE worsened (Table 1; Figs. 13-14). With incorporation of a new age-structured index of abundance generated using a CV of 0.5 (Scenario 31), both MARE and MRE increased, resulting in lower accuracy and higher bias in terminal year estimates despite good overall time series fits (Table 1 and Figs. 13-14). Similarly, model improvement was minimal or worsened with the inclusion of an age-structured index when commercial fishery selectivity was misspecified (Scenarios 35-36; Table 1; Figs. 15-16).

In contrast, incorporation of a survey-based terminal year estimate of biomass in a model that was not misspecified (Scenarios 32-33) improved model precision slightly for abundance and biomass, particularly when the new data source was simulated with relatively low error (CV=0.2 vs 0.5) (Table 1; Figs. 17-18). However, pronounced improvements in performance were observed when the new survey was incorporated in a model for which commercial selectivity was misspecified (Scenarios 37-38; Table 1; Figs. 19-20).

Atlantic menhaden

The Atlantic menhaden BAM estimation model was highly stable across a wide range of scenarios, but exhibited markedly poorer performance (86-91% convergence) when challenged by misspecification in selectivity of the NAD abundance index (Table 2). A peaked F pattern generally resulted in higher precision (lower MARE) and lower bias (lower MRE) for abundance of age-1+, spawning stock biomass, and exploitation rate, but not recruitment. For Atlantic menhaden Scenarios 1-20 (Table 2), plus group definition had minimal impact on MARE (Table 2; Figs. 21-22; Scenarios 1-10). However, MRE was generally lower for plus groups of age-5+ and age-6+ (the current base model configuration).

When selectivity of the adult index of abundance (NAD) was misspecified (Scenarios 11-20), MARE was largely similar across plus group definitions (Table 2; Fig. 23); however, MRE was reduced when a plus group definition of age-5+ was used (Table 2; Fig. 24). For scenarios in which selectivities for the northern commercial fisheries were misspecified (Scenarios 21-30), MARE was largely similar across plus group definitions (Table 2; Fig. 25); however, MRE was lowest when a plus group definition of age-6+ was used (Table 2; Fig. 26). For scenarios in which selectivity of the southern commercial reduction fishery was misspecified (Scenarios 31-40), MARE was again largely similar across plus group definitions (Table 2; Fig. 27); however, MRE was lowest when a plus group definition of age-6+ was used (Table 2; Fig. 28).

With incorporation of a new age-structured index of abundance (Scenarios 41-50), MARE was lowered, particularly when a low constant F pattern was applied and when the plus group was defined as age-6+ (Table 2; Fig. 29). However, MRE worsened slightly with the addition of a new age-structured index of abundance under a constant F pattern, and MRE generally increased with older plus group definitions (Table 2; Figs. 30). Similarly, when the NAD index of abundance was misspecified, model improvements in MARE were observed with the inclusion of a new age-structured index of abundance (Scenarios 52-53), but MRE worsened slightly (Table 2; Figs. 31-32). In contrast, incorporation of a survey-based terminal year estimate of biomass in a misspecified model (Scenarios 51-55) improved model performance, particularly when the new data source was simulated with relatively low error (CV=0.2 vs 0.5) (Table 2; Figs. 33-34).

Discussion

In this simulation study, we demonstrated the ways in which the definition of a plus group interacts with model parameterization in a statistical catch-at-age model to influence model error, highlighting the importance of understanding the interplay between the number of age classes included in the estimation model, model misspecification, and configuration of fishery and abundance index selectivity. Although the magnitude of error in model estimates across plus group definitions was often small (because the estimation model was provided with data generated under moderate levels of observation error and good starting values), the relative difference in error across plus group definitions and scenarios indicated that the definition of a plus group can impact model performance. The potential benefits of selecting the most appropriate plus group definition are likely to be gained when the model is misspecified.

Plus group definition

The Gulf menhaden assessment model demonstrated a trade-off in improved model performance between the estimation of terminal year stock size (abundance and spawning stock biomass) and the estimation of recruitment and exploitation rate, which are often poorly informed by available data toward the end of a time series. The current plus group definition of age-4+ is likely to provide a reasonable balance between these two estimation challenges and in many circumstances produced a better estimate of stock size to inform the overfished stock status than the use of a plus group that included fewer age classes. Use of an age-3+ plus group definition frequently resulted in the worst model performance under ideal conditions (Scenarios 1-20), but it did result in slightly improved model performance when the model was misspecified, likely because it does not rely so heavily on characterizing appropriately the degree of selectivity doming (Scenarios 21-28). Given the fact that reduction fishery selectivity parameters for all ages except age-1 are specified in the Gulf menhaden assessment model used for management, and there is considerable uncertainty in the degree of doming for these selectivity functions, the assessment team may wish to consider exploring alternative model configurations that reduce the plus group definition to age 3+. This work may also be supported by a previous simulation study that indicated the proportion of age-4+ in the catch is not well estimated (Nesslage et al. 2020). Before any future changes to assessment model plus group definition are made, the simulation modeling tools built for this study should be used to explore the potential impacts of the exact changes proposed. The deliverables from this project should prove to be a valuable resource for assessment teams to explore this and other alternative model configurations and modeling assumptions during future benchmarks.

Our study also indicated that performance of the Atlantic menhaden assessment model can be influenced by plus group definition, and that the current definition of age-6+ is the least likely to be biased given the available data, current model configuration, and the assumption that there are eight age classes in the population. In the presence of model misspecification, the best-performing plus group definition was often age-6+, or age-5+ in some circumstances. Thus, the current model configuration of age-6+ is likely the most appropriate and need not be reconsidered unless new information about maximum age or natural mortality becomes available, or major model configuration changes are considered.

Incorporation of new data sources

A persistent research recommendation for both stocks is the collection of more targeted, fishery-independent data to support menhaden assessment. A frequent research recommendation, particularly for the Atlantic menhaden assessment, is the development of a coastwide survey which could generate either an age-structured index of abundance (if conducted over 7+ year), or a single estimate of total biomass for one year (if conducted as a one-off or infrequent study). Here we demonstrated that the inclusion of an additional index of abundance may not help and may actually hinder model performance if the other indices of abundance currently included in the assessment are retained and all are assumed to be accurate. Increased model error in the terminal year with inclusion of an additional index of abundance is likely due to tension between the new age-structured index and other indices in the model. In a real assessment situation, it may be possible to improve model performance in light of the addition of a new age-structured survey with more careful attention paid to the likelihood weights applied to each data source. However, such fine-tuning of an individual assessment model was beyond the scope of this large simulation study.

In contrast, we also demonstrated that the incorporation of a single fishery-independent estimate of coastwide biomass has the potential to improve assessment model performance, particularly in situations where the model is misspecified. However, uncertainty surrounding this survey-based estimate of biomass must be relatively low; for example, an estimate with a CV of 0.2 resulted in improved model performance in this study, but an estimate with a CV of 0.5 often resulted in poorer model performance than the current models. We also found that the benefits of such a survey are more likely to be realized for the Atlantic menhaden stock than the Gulf menhaden stock. This is likely due to the fact that Gulf menhaden have fewer age classes and high natural mortality and thus is less likely to benefit from the addition of age data as compared with Atlantic menhaden, which can live twice as long.

Should development of a new fishery-independent survey be considered on either coast, a complete set of simulations exploring the frequency and placement of that survey estimate in the time series (e.g., terminal year only, 5- to 10-year frequency), as well as the inclusion of associated age structure information should be explored. In the Gulf of Mexico and the Southeastern US, one-off surveys aimed at generating a single annual estimate of total abundance or biomass have been implemented for several reef fish. However, the way in which these new data sources are incorporated in stock assessments has proven controversial. Our simulation study and modeling framework could be used to explore best practices for incorporating estimates derived from such surveys before they are implemented and added to a benchmark stock assessment model.

Assessment error

The magnitude of precision and accuracy across plus group definitions in our study was generally small when the model was not misspecified, and model error increased substantially with model misspecification in fishery or survey selectivity. The errors reported here are similar in magnitude to those summarized from the literature by Ralston et al. 2011, who reported an average CV of terminal year biomass of 18% without model misspecification and 37% with model misspecification. However, our estimates of assessment error are underestimates given our simulation study design; the estimation (BAM) model was generally very well-informed with data generated using moderate to low observation error, good parameter starting values, and only one source of model misspecification per scenario. Thus, our simulations represent nearly ideal or excellent conditions in which to conduct an assessment and our estimates of model error should be viewed as minimums. Error in actual stock assessments is likely much higher due to higher observation error and the potential for greater model misspecification.

It is worth noting that the F pattern applied to the simulated population had an impact on Atlantic menhaden assessment model such that the model performed worse when a constant F pattern (estimated in the terminal year of the last assessment) was projected forward. Across our simulations, a constant F pattern generally resulted in higher precision (lower MARE) and lower bias (lower MRE) for abundance of age-1+, spawning stock biomass, and exploitation rate, but not recruitment. The magnitude of the increase in bias was often more prominent for scenarios with fewer ages in the plus group. Thus, our study indicates that continued low F could result in increased bias in terminal year estimates of recruitment as the length of the time series grows if landings of Atlantic menhaden continue at their current relatively low level.

Summary

Our study demonstrated that plus group definition can impact model performance, in particular bias in model estimates of important quantities used in fisheries management such as stock size and fishing mortality. Thus, careful consideration should be given to selection of the maximum age in the model when a new assessment is being constructed or when model configuration changes are being considered. The interaction between selectivity and plus group definition is rarely explored thoroughly, yet our study showed that these combined decisions could have large impacts on model performance. Our study also indicated that the current plus group definitions for Gulf and Atlantic menhaden are appropriate, but that Gulf menhaden might benefit from a slight change to a lower maximum model age (age-3+); such a change might help ameliorate issues that may arise from specified selectivity for older ages. Also, our study indicated that the incorporation of a fishery-independent terminal year estimate of biomass with a low CV could improve model performance, particularly for the Atlantic menhaden assessment, if the model is misspecified.

Acknowledgments

This project was funded by the National Science Foundation Science Center for Marine Fisheries (SCEMFIS) under NSF award 1266057 (UMCES grant # 07-4-31786) and through membership fees provided by the SCEMFIS Industry Advisory Board. Special thanks to all who provided data and advice in support of this project, including Greg DiDomenico, Peter Himchak, Jeff Kaelin, Ben Landry, Michael Wilberg, and the SCEMFIS Industry Advisory Board and SCEMFIS researchers. This is UMCES Technical Report Ref. No. [UMCES] CBL 2023-001.

References

Fisch, N., Camp, E., Shertzer, K., Ahrens, R., 2021. Assessing likelihoods for fitting composition data within stock assessments, with emphasis on different degrees of process and observation error. Fisheries Research. 243, 106069.

Nesslage, G.M., Leaf, R.T., Wilberg, M.J., Mroch III, R.M., Schueller, A.M., 2020. A Simulation-Based Evaluation of Commercial Port Sampling Programs for the Gulf and Atlantic Menhaden Fisheries. N Am J Fish Manage. 40, 995-1006.

NMFS, 2022. Fisheries of the United States, 2020. U.S. Department of Commerce, NOAA Current Fishery Statistics No. 2020 Available at: https://www.fisheries.noaa.gov/national/sustainable-fisheries/fisheries-united-states,

Privitera-Johnson, K.M., Methot, R.D., Punt, A.E., 2022. Towards best practice for specifying selectivity in age-structured integrated stock assessments. Fisheries Research. 249, 106247.

Punt, A.E., Hurtado-Ferro, F., Whitten, A.R., 2014. Model selection for selectivity in fisheries stock assessments. Fisheries Research. 158, 124-134.

Quinn, T.J., Deriso, R.B., 1999. Quantitative fish dynamics. Oxford University Press, Oxford, pp. 560.

Ralston, S., Punt, A.E., Hamel, O.S., DeVore, J.D., Conser, R.J., 2011. A meta-analytic approach to quantifying scientific uncertainty in stock assessments. Fish Bull. 109,

SEDAR, 2018. Gulf Menhaden Stock Assessment Report available online at: https://sedarweb.org/sedar-63. SEDAR, North Charleston, SC, pp. 333.
SEDAR, 2019. SEDAR 69 – Atlantic Menhaden Stock Assessment Report. SEDAR, North Charleston SC. 691 pp. available online at: http://sedarweb.org/sedar-69. North Charleston, SC
Smith, M.W., Then, A.Y., Wor, C., Ralph, G., Pollock, K.H., Hoenig, J.M., 2012. Recommendations for catch-curve analysis. N Am J Fish Manage. 32, 956-967.
Williams, E.H., Shertzer, K.W., 2015. Technical documentation of the Beaufort Assessment Model (BAM).

Tables

Table 1. Scenarios explored in the Gulf menhaden simulation study. PopMaxAge is the maximum age in the simulated population, F Pattern is the trend in fishing mortality, R is recruitment, SSB is spawning stock biomass, U is exploitation rate, MARE is median absolute relative error, and MRE is median relative error.

						Age 1+ Abundance		R		SSB		U	
Scenario	Scenario description	PopMaxAge	PlusGroup	F Pattern	%Convergence	MARE	MRE	MARE	MRE	MARE	MRE	MARE	MRE
1	No model misspecification	6	6	Constant	100	0.140	-0.001	0.261	-0.040	0.135	-0.004	0.170	0.029
2	No model misspecification	6	5	Constant	100	0.142	0.005	0.260	-0.044	0.137	-0.001	0.171	0.031
3	No model misspecification	6	4	Constant	100	0.142	0.004	0.260	-0.041	0.137	-0.003	0.171	0.028
4	No model misspecification	6	3	Constant	100	0.145	0.016	0.264	-0.028	0.138	0.003	0.170	0.012
5	No model misspecification	5	5	Constant	100	0.149	-0.009	0.261	-0.020	0.141	-0.011	0.164	0.032
6	No model misspecification	5	4	Constant	100	0.149	-0.009	0.263	-0.016	0.141	-0.016	0.162	0.032
7	No model misspecification	5	3	Constant	100	0.148	0.011	0.259	-0.007	0.144	-0.006	0.176	0.011
8	No model misspecification	4	4	Constant	100	0.145	-0.010	0.254	-0.005	0.139	-0.015	0.162	0.024
9	No model misspecification	4	3	Constant	100	0.148	0.005	0.257	0.003	0.142	-0.001	0.163	0.010
10	No model misspecification	3	3	Constant	100	0.147	-0.002	0.260	-0.022	0.142	-0.006	0.161	0.027
11	No model misspecification	6	6	Peaked	100	0.144	0.006	0.258	-0.041	0.139	0.005	0.169	0.028
12	No model misspecification	6	5	Peaked	100	0.144	0.006	0.262	-0.040	0.138	0.004	0.172	0.030
13	No model misspecification	6	4	Peaked	100	0.144	0.010	0.257	-0.042	0.138	0.006	0.171	0.030
14	No model misspecification	6	3	Peaked	100	0.147	0.030	0.259	-0.022	0.145	0.016	0.164	0.004
15	No model misspecification	5	5	Peaked	100	0.146	-0.013	0.264	-0.021	0.142	-0.017	0.158	0.031
16	No model misspecification	5	4	Peaked	100	0.148	-0.012	0.262	-0.019	0.142	-0.011	0.160	0.029
17	No model misspecification	5	3	Peaked	100	0.150	0.008	0.259	0.001	0.140	0.001	0.163	0.008
18	No model misspecification	4	4	Peaked	100	0.144	-0.012	0.252	-0.008	0.138	-0.011	0.162	0.028
19	No model misspecification	4	3	Peaked	100	0.148	0.010	0.257	0.011	0.138	0.005	0.162	0.006
20	No model misspecification	3	3	Peaked	100	0.150	-0.001	0.258	-0.017	0.144	0.000	0.162	0.024
21	LAGN index selectivity misspecified	6	6	Constant	100	0.121	-0.027	0.178	-0.029	0.117	-0.032	0.141	0.026
22	LAGN index selectivity misspecified	6	3	Constant	100	0.121	-0.007	0.177	-0.006	0.116	-0.018	0.136	0.004
23	LAGN index selectivity misspecified	6	6	Peaked	100	0.120	-0.040	0.186	-0.047	0.114	-0.044	0.143	0.037
24	LAGN index selectivity misspecified	6	3	Peaked	100	0.122	-0.007	0.177	-0.017	0.115	-0.021	0.141	0.008
25	Comm. reduction selectivity misspecified	6	6	Constant	100	0.155	-0.108	0.270	-0.122	0.151	-0.123	0.203	0.141
26	Comm. reduction selectivity misspecified	6	3	Constant	100	0.148	-0.076	0.273	-0.118	0.144	-0.102	0.200	0.117
27	Comm. reduction selectivity misspecified	6	6	Peaked	100	0.169	-0.142	0.278	-0.158	0.172	-0.158	0.234	0.188
28	Comm. reduction selectivity misspecified	6	3	Peaked	100	0.154	-0.110	0.277	-0.144	0.160	-0.131	0.212	0.158
29	No model misspecification	6	4	Constant low	100	0.130	-0.009	0.263	-0.045	0.127	-0.018	0.166	0.037
30	Fishery-indep. age-structured index (CV=0.2)	6	4	Constant low	99.6	0.121	-0.098	0.282	-0.130	0.126	-0.115	0.189	0.137
31	Fishery-indep. age-structured index (CV=0.5)	6	4	Constant low	99.7	0.178	-0.082	0.272	-0.112	0.175	-0.097	0.189	0.112
32	Fishery-indep. B Estimate (CV=0.2)	6	4	Constant low	100	0.094	-0.006	0.270	-0.048	0.094	-0.016	0.159	0.032
33	Fishery-indep. B Estimate (CV=0.5)	6	4	Constant low	100	0.121	-0.008	0.265	-0.044	0.121	-0.018	0.164	0.038
34	Comm. reduction selectivity misspecified	6	4	Constant low	100	0.304	-0.303	0.349	-0.304	0.325	-0.325	0.461	0.461
35	Comm. reduction selectivity misspecified, Fishery-indep. age-structured index (CV=0.2)	6	4	Constant low	98.1	0.335	-0.335	0.381	-0.351	0.361	-0.361	0.544	0.544
36	Comm. reduction selectivity misspecified, Fishery-indep. age-structured index (CV=0.5)	6	4	Constant low	98.9	0.331	-0.330	0.376	-0.346	0.356	-0.355	0.522	0.522
37	Comm. reduction selectivity misspecified, Fishery-indep. B Estimate (CV=0.2)	6	4	Constant low	100	0.178	-0.177	0.341	-0.294	0.204	-0.203	0.326	0.326
38	Comm. reduction selectivity misspecified, Fishery-indep. B Estimate (CV=0.5)	6	4	Constant low	100	0.274	-0.272	0.347	-0.302	0.297	-0.297	0.429	0.429

Table 2. Scenarios explored in the Atlantic menhaden simulation study. PopMaxAge is the maximum age in the simulated population, F Pattern is the trend in fishing mortality, R is recruitment, SSB is spawning stock biomass, U is exploitation rate, MARE is median absolute relative error, and MRE is median relative error.

						Age 1+ Abundance		R		SSB		U	
Scenario	Scenario description	PopMaxAge	PlusGroup	F Pattern	%Convergence	MARE	MRE	MARE	MRE	MARE	MRE	MARE	MRE
1	No model misspecification	8	8	Constant	97	0.146	0.019	0.227	0.025	0.136	0.010	0.157	-0.014
2	No model misspecification	8	7	Constant	97	0.146	0.018	0.226	0.019	0.136	0.012	0.159	-0.012
3	No model misspecification	8	6	Constant	97	0.145	0.011	0.226	0.015	0.134	0.004	0.159	-0.004
4	No model misspecification	8	5	Constant	95	0.144	0.003	0.227	0.006	0.135	-0.006	0.162	0.005
5	No model misspecification	8	4	Constant	98	0.155	0.033	0.223	0.044	0.137	0.019	0.161	-0.027
6	No model misspecification	8	8	Peaked	97	0.134	0.011	0.238	0.033	0.129	0.015	0.163	-0.018
7	No model misspecification	8	7	Peaked	97	0.132	0.011	0.233	0.032	0.128	0.014	0.164	-0.013
8	No model misspecification	8	6	Peaked	96	0.131	0.002	0.235	0.031	0.127	0.000	0.161	-0.007
9	No model misspecification	8	5	Peaked	95	0.132	-0.003	0.236	0.030	0.126	-0.005	0.160	-0.004
10	No model misspecification	8	4	Peaked	99	0.135	0.007	0.238	0.039	0.119	-0.009	0.159	-0.013
11	NAD index selectivity misspecified	8	8	Constant	89	0.167	0.096	0.233	0.079	0.145	0.076	0.160	-0.069
12	NAD index selectivity misspecified	8	7	Constant	90	0.167	0.097	0.231	0.077	0.147	0.077	0.160	-0.069
13	NAD index selectivity misspecified	8	6	Constant	90	0.163	0.082	0.227	0.058	0.137	0.055	0.157	-0.055
14	NAD index selectivity misspecified	8	5	Constant	89	0.158	0.053	0.230	0.042	0.130	0.027	0.160	-0.035
15	NAD index selectivity misspecified	8	4	Constant	88	0.161	0.085	0.236	0.074	0.139	0.052	0.168	-0.062
16	NAD index selectivity misspecified	8	8	Peaked	88	0.150	0.088	0.240	0.050	0.138	0.071	0.159	-0.058
17	NAD index selectivity misspecified	8	7	Peaked	86	0.147	0.086	0.239	0.054	0.138	0.070	0.160	-0.056
18	NAD index selectivity misspecified	8	6	Peaked	89	0.140	0.066	0.239	0.037	0.129	0.053	0.158	-0.039
19	NAD index selectivity misspecified	8	5	Peaked	88	0.147	0.052	0.240	0.026	0.129	0.037	0.158	-0.025
20	NAD index selectivity misspecified	8	4	Peaked	91	0.143	0.057	0.241	0.037	0.129	0.027	0.161	-0.033
21	N. comm. selectivities misspecified	8	8	Constant	95	0.151	-0.019	0.246	0.000	0.148	-0.016	0.175	0.012
22	N. comm. selectivities misspecified	8	6	Constant	97	0.151	-0.018	0.245	0.004	0.146	-0.018	0.176	0.014
23	N. comm. selectivities misspecified	8	7	Constant	96	0.156	-0.025	0.241	-0.018	0.149	-0.026	0.174	0.025
24	N. comm. selectivities misspecified	8	5	Constant	96	0.159	-0.044	0.241	-0.025	0.153	-0.040	0.176	0.045
25	N. comm. selectivities misspecified	8	4	Constant	96	0.176	-0.063	0.259	-0.053	0.164	-0.063	0.188	0.069
26	N. comm. selectivities misspecified	8	8	Peaked	97	0.151	0.022	0.257	0.044	0.151	0.025	0.176	-0.031
27	N. comm. selectivities misspecified	8	6	Peaked	98	0.151	0.019	0.252	0.037	0.151	0.019	0.173	-0.028
28	N. comm. selectivities misspecified	8	7	Peaked	98	0.149	-0.004	0.249	0.049	0.141	0.001	0.174	-0.020
29	N. comm. selectivities misspecified	8	5	Peaked	97	0.151	-0.017	0.250	0.019	0.146	-0.013	0.177	0.009
30	N. comm. selectivities misspecified	8	4	Peaked	98	0.157	-0.045	0.252	-0.020	0.155	-0.051	0.178	0.033
31	Comm. reduction selectivity misspecified	8	8	Constant	97	0.148	0.018	0.227	0.024	0.136	0.011	0.158	-0.012
32	Comm. reduction selectivity misspecified	8	6	Constant	97	0.145	0.018	0.227	0.020	0.136	0.011	0.157	-0.015
33	Comm. reduction selectivity misspecified	8	7	Constant	97	0.145	0.011	0.228	0.014	0.134	0.004	0.160	-0.003
34	Comm. reduction selectivity misspecified	8	5	Constant	98	0.155	0.033	0.223	0.040	0.138	0.019	0.161	-0.026
35	Comm. reduction selectivity misspecified	8	4	Constant	98	0.153	0.033	0.224	0.041	0.136	0.017	0.160	-0.027
36	Comm. reduction selectivity misspecified	8	8	Peaked	97	0.133	0.010	0.237	0.033	0.128	0.014	0.164	-0.016
37	Comm. reduction selectivity misspecified	8	6	Peaked	97	0.133	0.009	0.235	0.032	0.129	0.013	0.164	-0.013
38	Comm. reduction selectivity misspecified	8	7	Peaked	96	0.130	0.001	0.235	0.030	0.128	0.000	0.161	-0.007
39	Comm. reduction selectivity misspecified	8	5	Peaked	99	0.134	0.007	0.241	0.037	0.121	-0.007	0.160	-0.013
40	Comm. reduction selectivity misspecified	8	4	Peaked	99	0.134	0.007	0.240	0.037	0.120	-0.009	0.160	-0.012
41	Fishery-indep. age-structured index (CV=0.2)	8	8	Constant	98	0.099	0.044	0.152	0.075	0.101	0.032	0.114	-0.053
42	Fishery-indep. age-structured index (CV=0.2)	8	6	Constant	97	0.150	0.049	0.212	0.068	0.147	0.036	0.177	-0.058
43	Fishery-indep. age-structured index (CV=0.2)	8	7	Constant	98	0.097	0.033	0.146	0.062	0.099	0.021	0.111	-0.040
44	Fishery-indep. age-structured index (CV=0.2)	8	5	Constant	96	0.145	0.035	0.212	0.051	0.142	0.016	0.173	-0.041
45	Fishery-indep. age-structured index (CV=0.2)	8	4	Constant	96	0.147	0.031	0.218	0.055	0.139	0.010	0.175	-0.042
46	Fishery-indep. age-structured index (CV=0.2)	8	8	Constant low	100	0.080	0.011	0.131	0.030	0.072	0.015	0.090	-0.020
47	Fishery-indep. age-structured index (CV=0.2)	8	6	Constant low	99	0.080	0.007	0.133	0.023	0.073	0.005	0.094	-0.016
48	Fishery-indep. age-structured index (CV=0.2)	8	7	Constant low	100	0.094	0.025	0.151	0.040	0.086	0.021	0.111	-0.024
49	Fishery-indep. age-structured index (CV=0.2)	8	5	Constant low	100	0.092	0.014	0.150	0.030	0.085	0.001	0.111	-0.013
50	Fishery-indep. age-structured index (CV=0.2)	8	4	Constant low	99	0.095	0.007	0.154	0.021	0.087	-0.015	0.113	-0.005
51	NAD Index selectivity misspecified	8	6	Constant low	99	0.130	0.028	0.238	0.001	0.111	0.020	0.155	-0.001
52	NAD index selectivity misspecified + Index (CV=0.2)	8	6	Constant low	99	0.082	0.015	0.131	0.027	0.071	0.010	0.093	-0.022
53	NAD index selectivity misspecified + Index (CV=0.5)	8	6	Constant low	99	0.102	0.033	0.151	0.052	0.097	0.031	0.114	-0.041
54	NAD index selectivity misspecified + B Est (CV=0.2)	8	6	Constant low	100	0.102	0.018	0.239	0.004	0.092	0.008	0.143	-0.005
55	NAD index selectivity misspecified + B Est (CV=0.5)	8	6	Constant low	99	0.126	0.025	0.237	0.002	0.111	0.013	0.154	0.000

Figures

Figure 1. Median absolute relative error in model estimates of age-1+ Gulf menhaden abundance generated under scenarios with alternative plus group definitions (model maximum age) relative to the maximum age in the population of ages three to six (panels) and two fishing mortality (F) patterns.

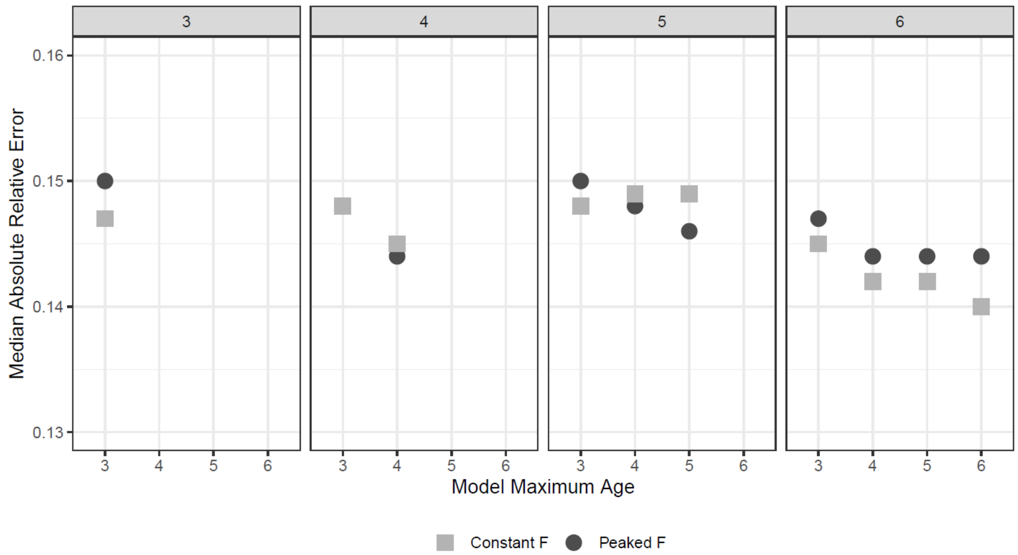

Figure 2. Median absolute relative error in model estimates of Gulf menhaden recruitment generated under scenarios with alternative plus group definitions (model maximum age) relative to the maximum age in the population of ages three to six (panels) and two fishing mortality (F) patterns.

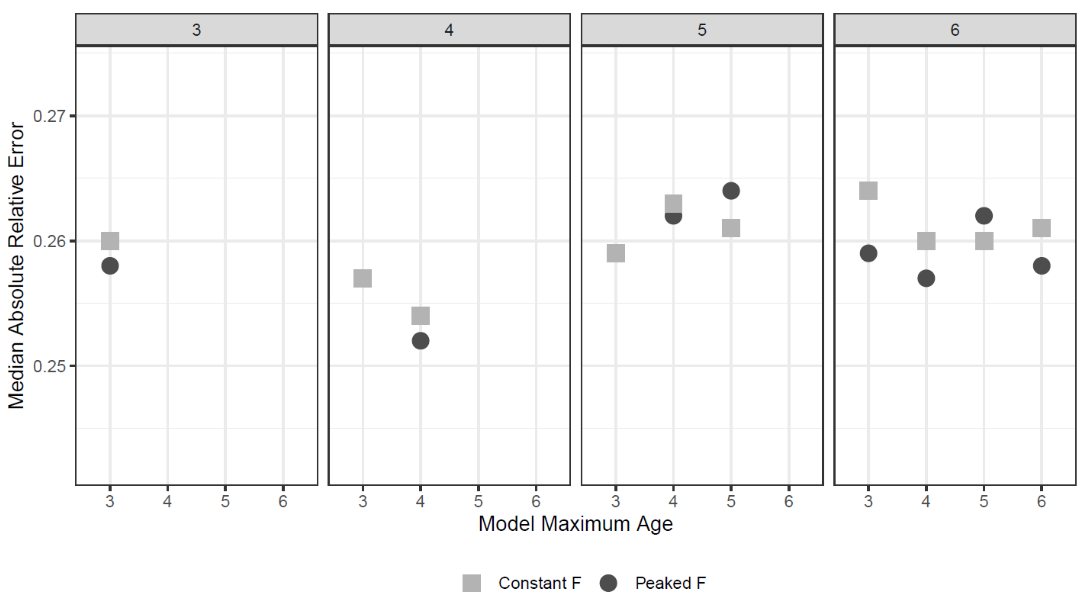

Figure 3. Median absolute relative error in model estimates of Gulf menhaden spawning stock biomass generated under scenarios with alternative plus group definitions (model maximum age) relative to the maximum age in the population of ages three to six (panels) and two fishing mortality (F) patterns.

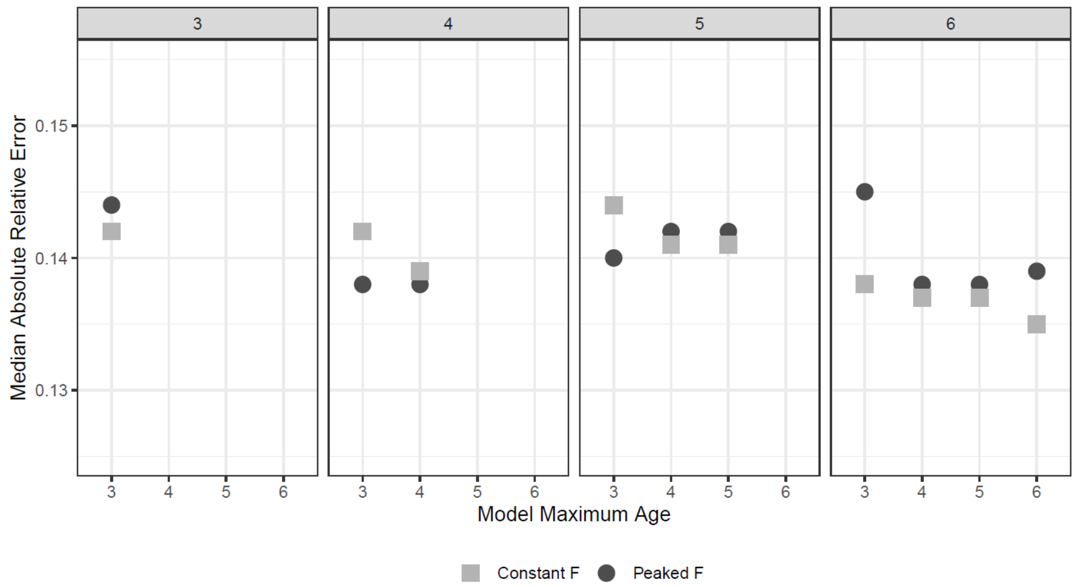

Figure 4. Median absolute relative error in model estimates of Gulf menhaden exploitation rate generated under scenarios with alternative plus group definitions (model maximum age) relative to the maximum age in the population of ages three to six (panels) and two fishing mortality (F) patterns.

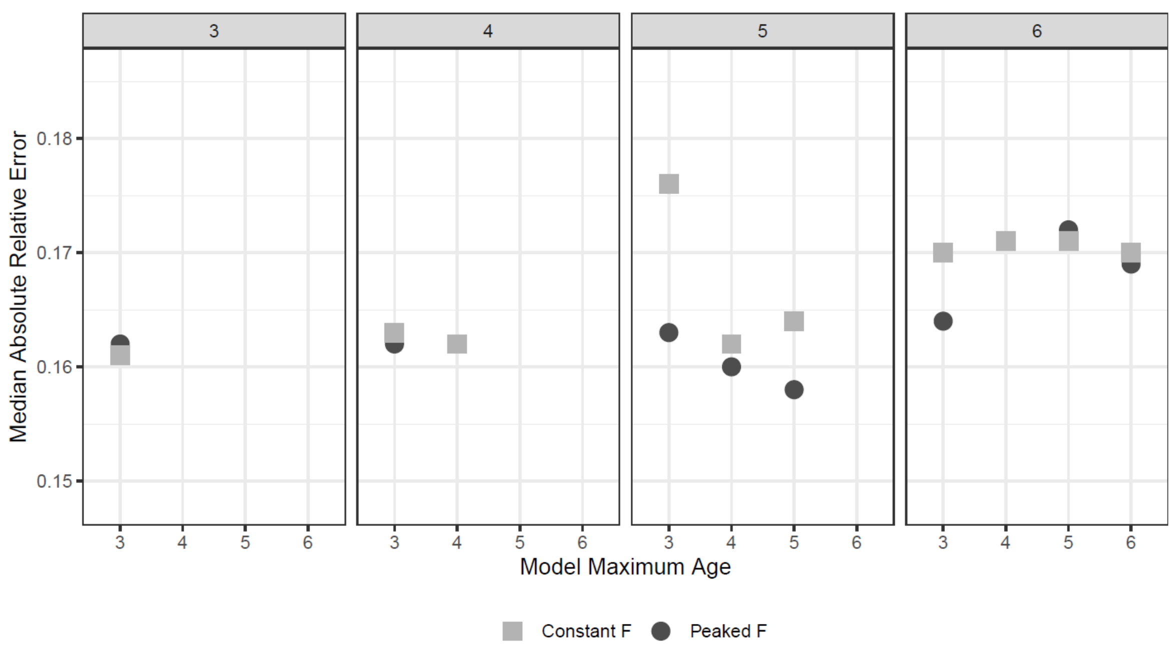

Figure 5. Median relative error in model estimates of age-1+ Gulf menhaden abundance generated under scenarios with alternative plus group definitions (model maximum age) relative to the maximum age in the population of ages three to six (panels) and two fishing mortality (F) patterns.

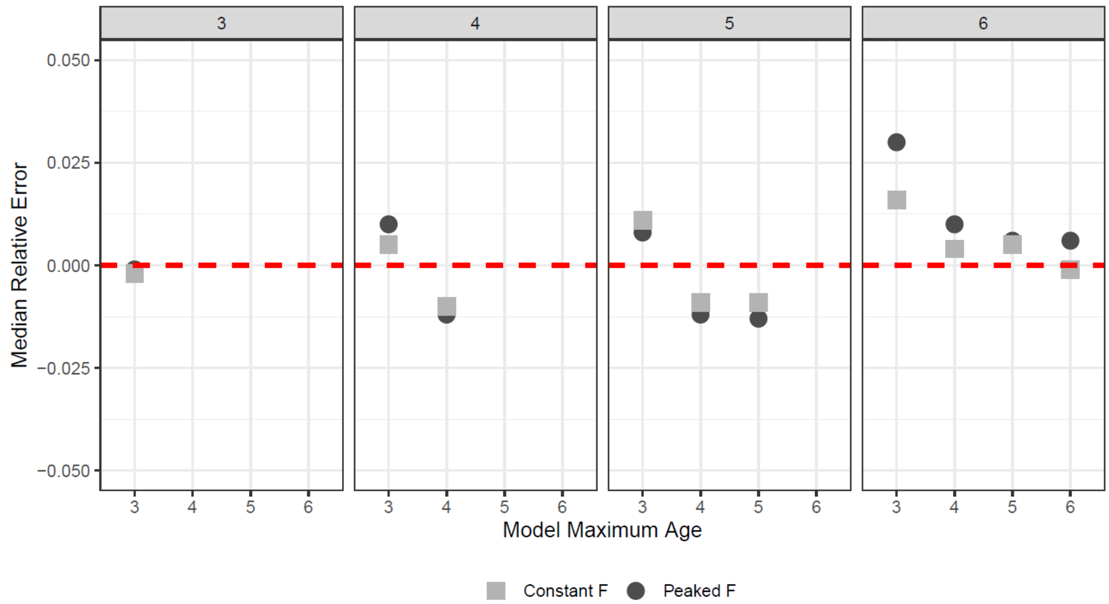

Figure 6. Median relative error in model estimates of Gulf menhaden recruitment generated under scenarios with alternative plus group definitions (model maximum age) relative to the maximum age in the population of ages three to six (panels) and two fishing mortality (F) patterns.

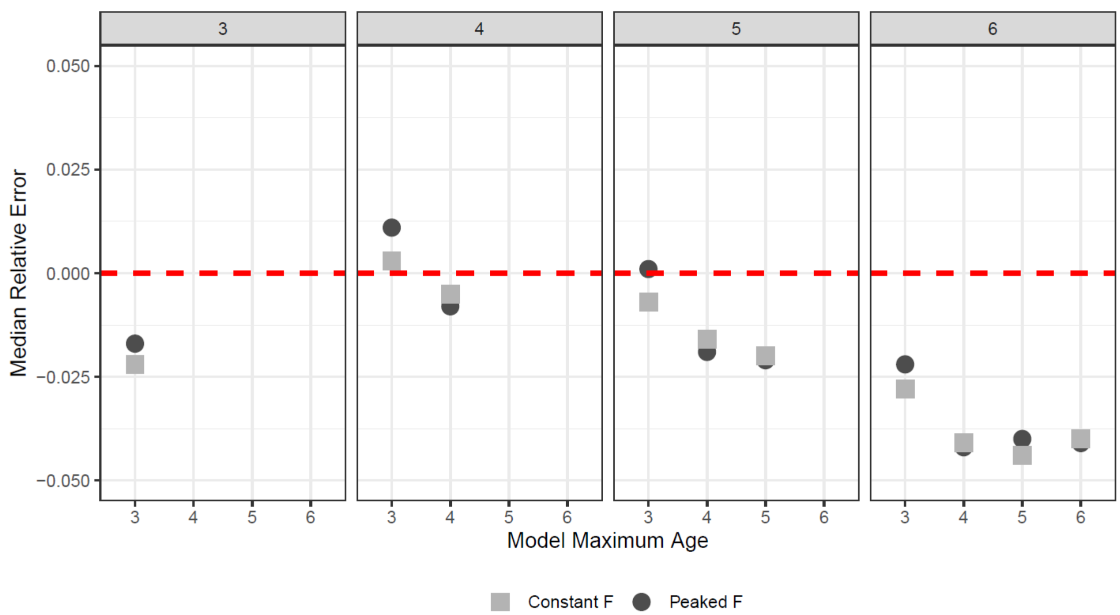

Figure 7. Median relative error in model estimates of Gulf menhaden spawning stock biomass generated under scenarios with alternative plus group definitions (model maximum age) relative to the maximum age in the population of ages three to six (panels) and two fishing mortality (F) patterns.

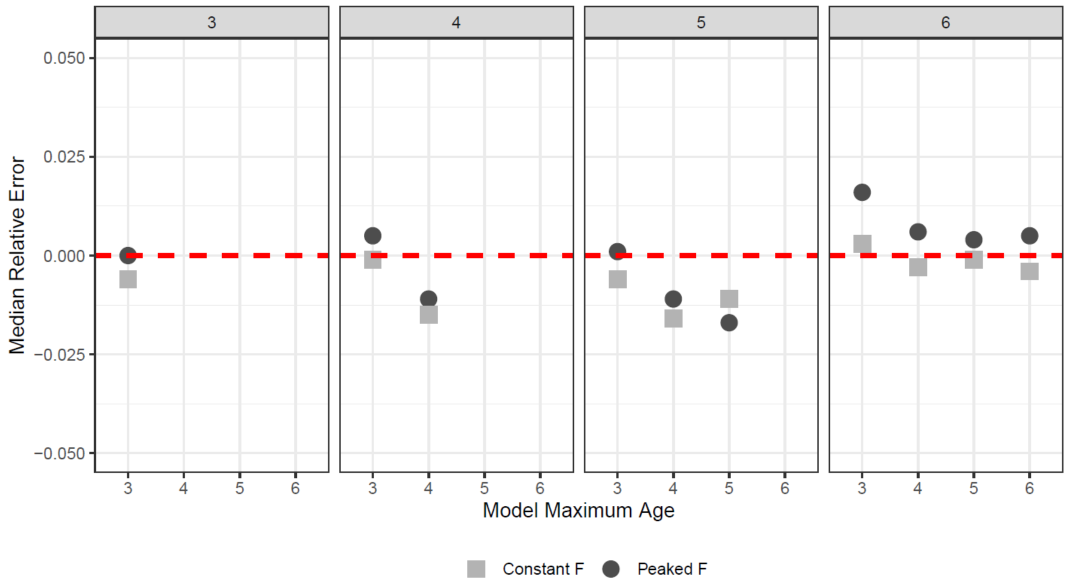

Figure 8. Median relative error in model estimates of Gulf menhaden exploitation rate generated under scenarios with alternative plus group definitions (model maximum age) relative to the maximum age in the population of ages three to six (panels) and two fishing mortality (F) patterns.

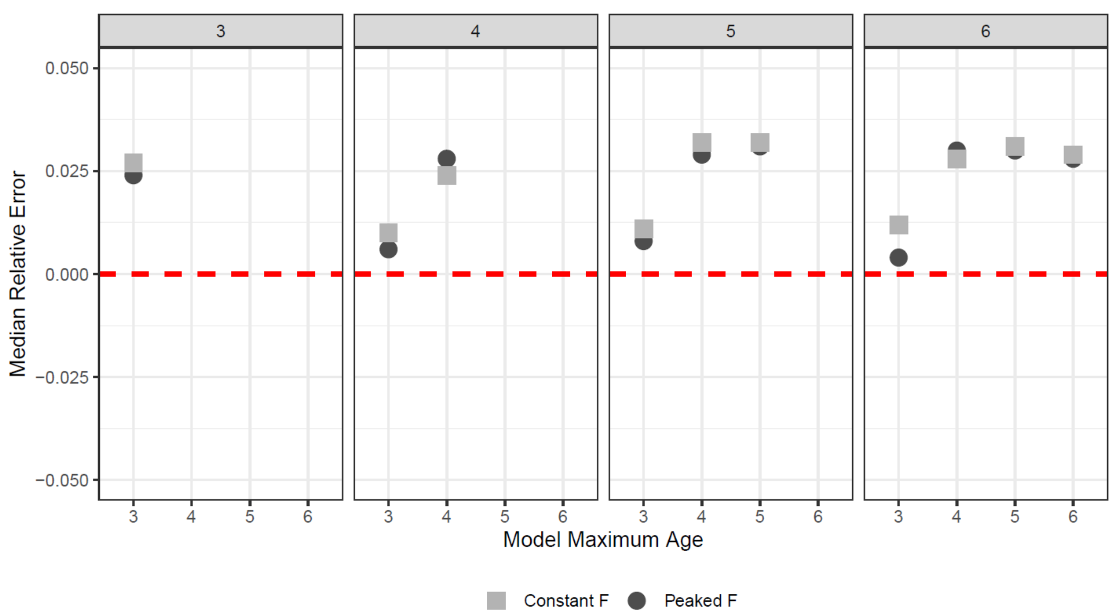

Figure 9. Median absolute relative error in model estimates of Gulf menhaden age-1+ abundance, recruitment, spawning stock biomass, and exploitation rate generated under scenarios with two alternative plus group definitions (model maximum age) for a population with a max age of six, two fishing mortality (F) patterns, and misspecification of selectivity for the adult index of abundance.

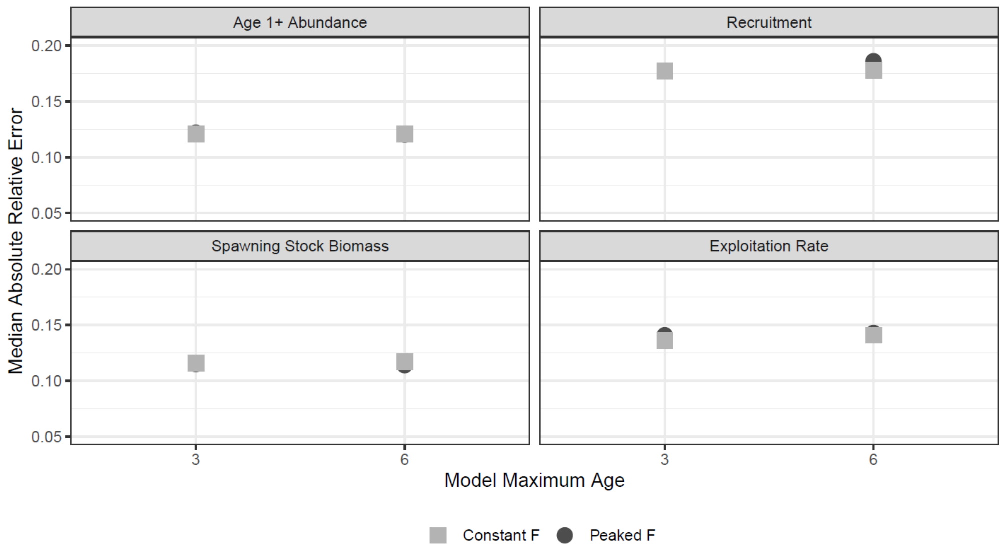

Figure 10. Median relative error in model estimates of Gulf menhaden age-1+ abundance, recruitment, spawning stock biomass, and exploitation rate generated under scenarios with alternative two plus group definitions (model maximum age) for a population with a max age of six, two fishing mortality (F) patterns, and misspecification of selectivity for the adult index of abundance.

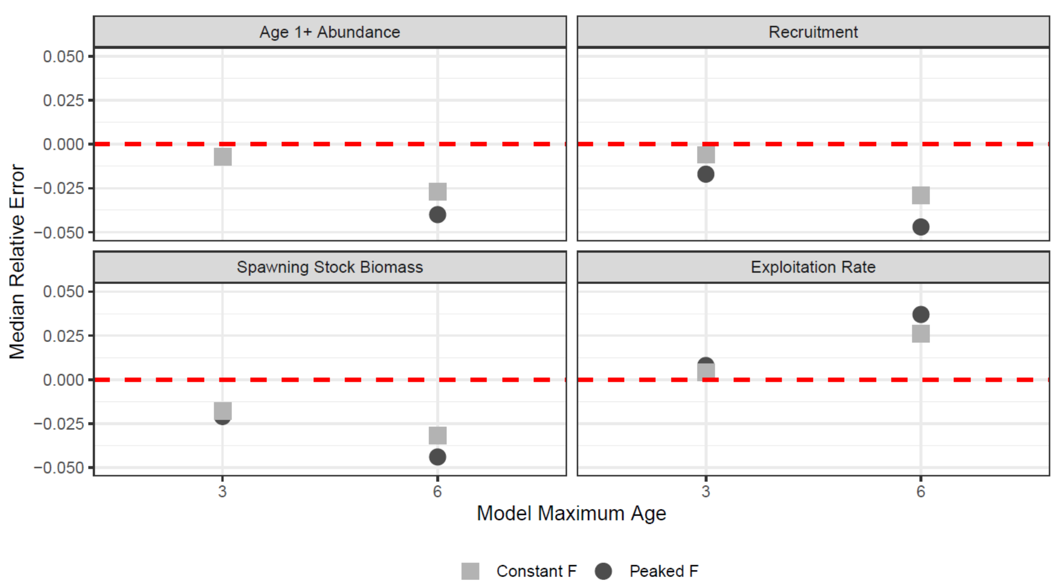

Figure 11. Median absolute relative error in model estimates of Gulf menhaden age-1+ abundance, recruitment, spawning stock biomass, and exploitation rate generated under scenarios with two alternative plus group definitions (model maximum age) for a population with a max age of six, two fishing mortality (F) patterns, and misspecification of selectivity for the reduction fishery.

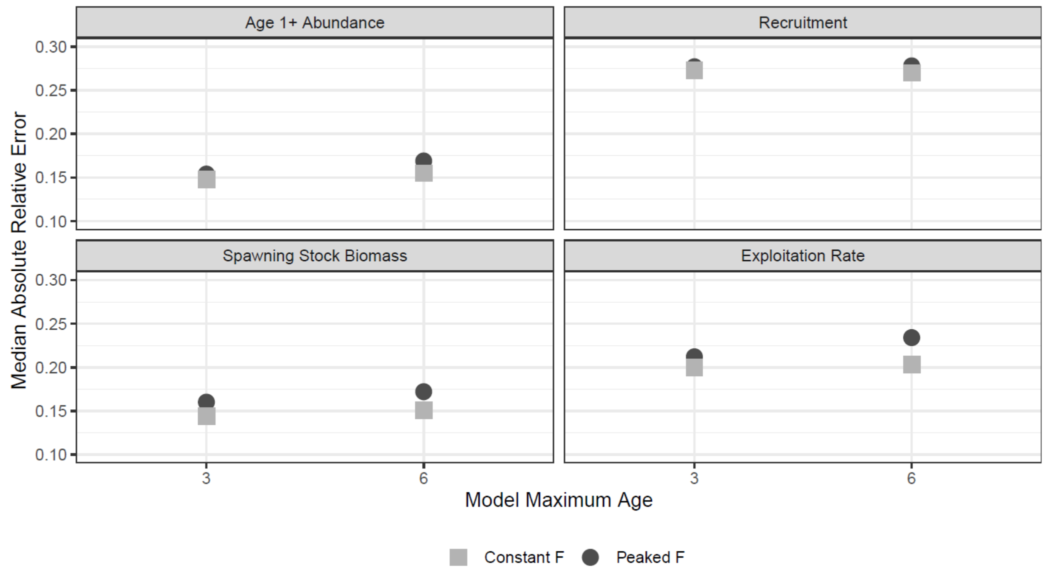

Figure 12. Median relative error in model estimates of Gulf menhaden age-1+ abundance, recruitment, spawning stock biomass, and exploitation rate generated under scenarios with two alternative plus group definitions (model maximum age) for a population with a max age of six, two fishing mortality (F) patterns, and misspecification of selectivity for the reduction fishery.

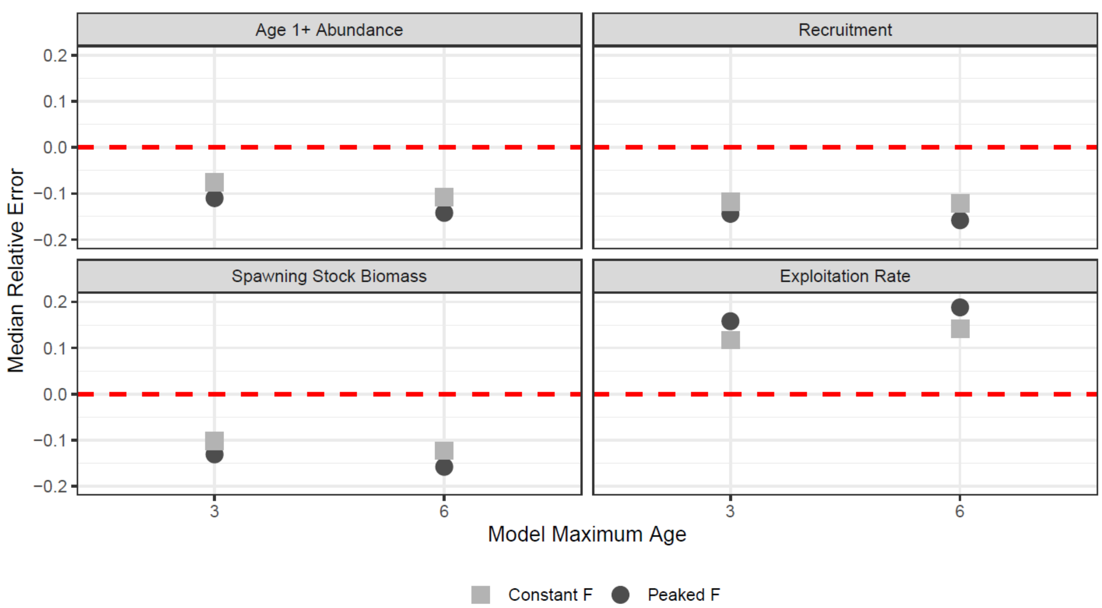

Figure 13. Median absolute relative error in model estimates of Gulf menhaden age-1+ abundance, recruitment, spawning stock biomass, and exploitation rate generated under scenarios with a plus group definition (model maximum age) of four for a population with a max age of six, a constant low fishing mortality (F) patterns, and addition of an age-structured index of abundance generated using two alternative coefficients of variation (CV).

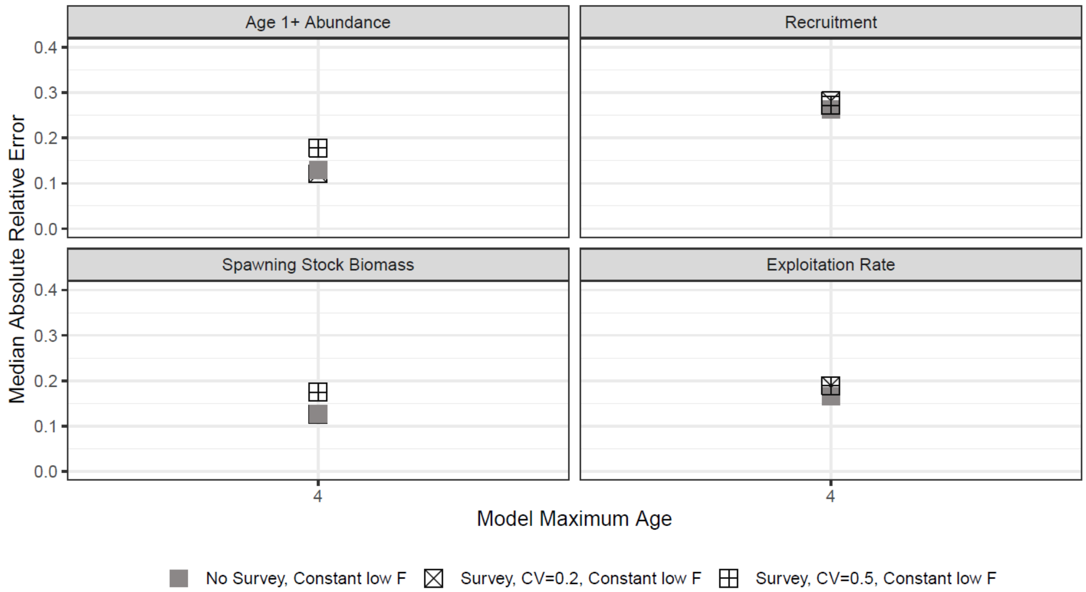

Figure 14. Median relative error in model estimates of Gulf menhaden age-1+ abundance, recruitment, spawning stock biomass, and exploitation rate generated under scenarios with a plus group definition (model maximum age) of four for a population with a max age of six, a constant low fishing mortality (F) patterns, and addition of an age-structured index of abundance generated using two alternative coefficients of variation (CV).

Figure 15. Median absolute relative error in model estimates of Gulf menhaden age-1+ abundance, recruitment, spawning stock biomass, and exploitation rate generated under scenarios with a plus group definition (model maximum age) of four for a population with a max age of six, a constant low fishing mortality (F) patterns, and addition of an age-structured index of abundance generated using two alternative coefficients of variation (CV) with misspecified fishery selectivity.

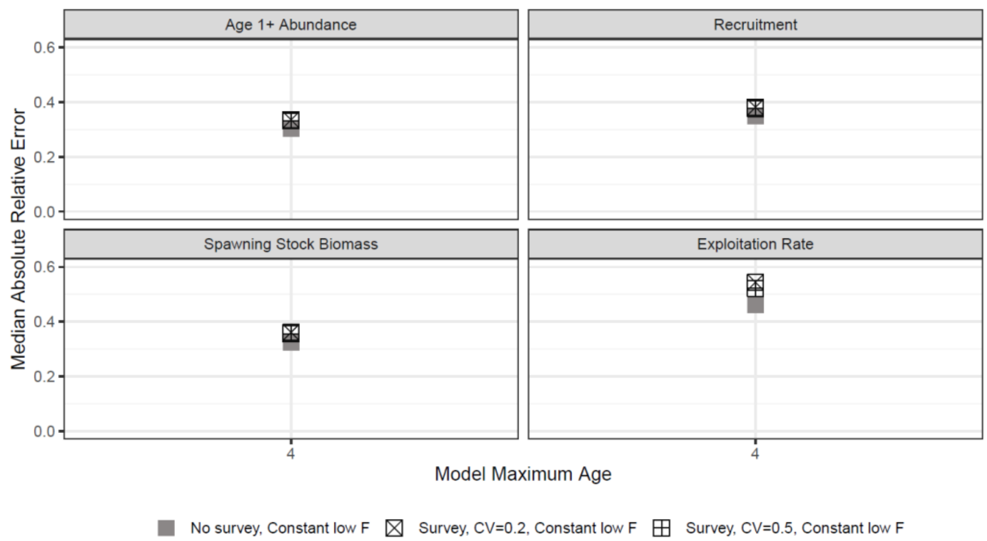

Figure 16. Median relative error in model estimates of Gulf menhaden age-1+ abundance, recruitment, spawning stock biomass, and exploitation rate generated under scenarios with a plus group definition (model maximum age) of four for a population with a max age of six, a constant low fishing mortality (F) patterns, and addition of an age-structured index of abundance generated using two alternative coefficients of variation (CV) with misspecified fishery selectivity.

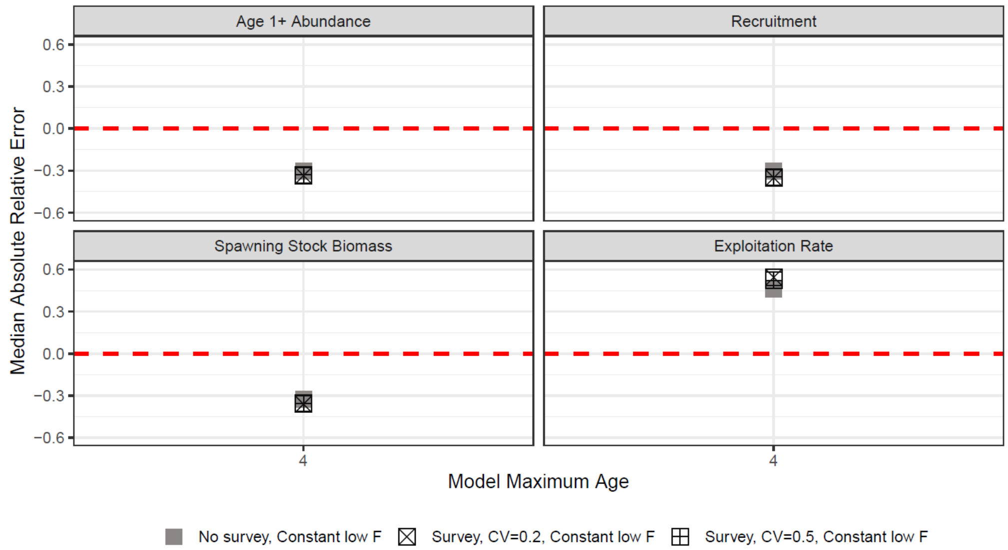

Figure 17. Median absolute relative error in model estimates of Gulf menhaden age-1+ abundance, recruitment, spawning stock biomass, and exploitation rate generated under scenarios with a plus group definition (model maximum age) of four for a population with a max age of six, a constant low fishing mortality (F) patterns, and addition of a terminal year estimate of age-1+ biomass generated using two alternative coefficients of variation (CV).

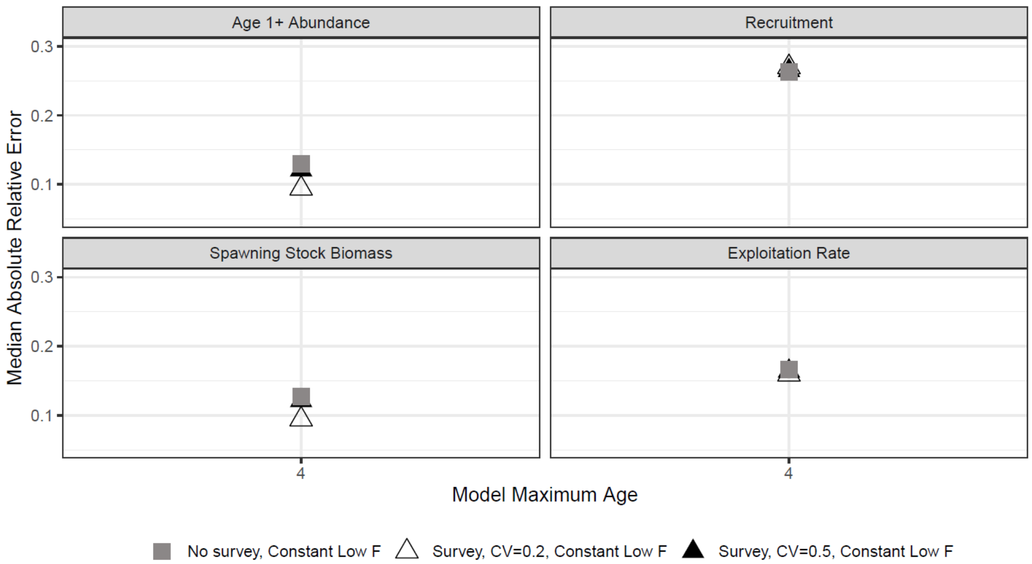

Figure 18. Median relative error in model estimates of Gulf menhaden age-1+ abundance, recruitment, spawning stock biomass, and exploitation rate generated under scenarios with a plus group definition (model maximum age) of four for a population with a max age of six, a constant low fishing mortality (F) patterns, and addition of a terminal year estimate of age-1+ biomass generated using two alternative coefficients of variation (CV).

Figure 19. Median absolute relative error in model estimates of Gulf menhaden age-1+ abundance, recruitment, spawning stock biomass, and exploitation rate generated under scenarios with a plus group definition (model maximum age) of four for a population with a max age of six, a constant low fishing mortality (F) patterns, and addition of a terminal year estimate of age-1+ biomass generated using two alternative coefficients of variation (CV) with misspecified fishery selectivity.

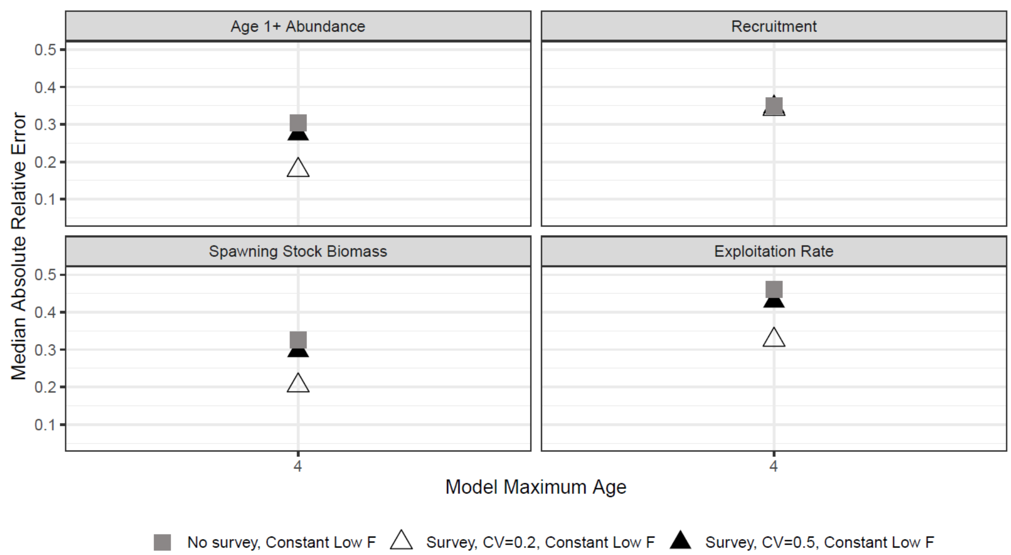

Figure 20. Median relative error in model estimates of Gulf menhaden age-1+ abundance, recruitment, spawning stock biomass, and exploitation rate generated under scenarios with a plus group definition (model maximum age) of four for a population with a max age of six, a constant low fishing mortality (F) patterns, and addition of a terminal year estimate of age-1+ biomass generated using two alternative coefficients of variation (CV) with misspecified fishery selectivity.

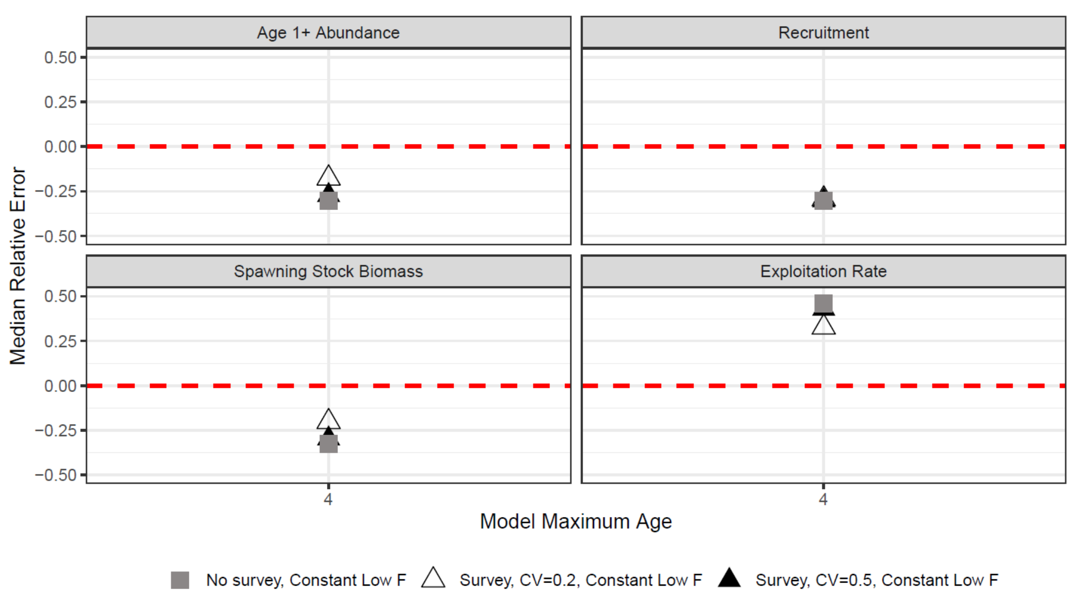

Figure 21. Median absolute relative error in model estimates of age-1+ Atlantic menhaden abundance generated under scenarios with alternative plus group definitions (model maximum age) relative to the maximum age in the population of age of eight and two fishing mortality (F) patterns.

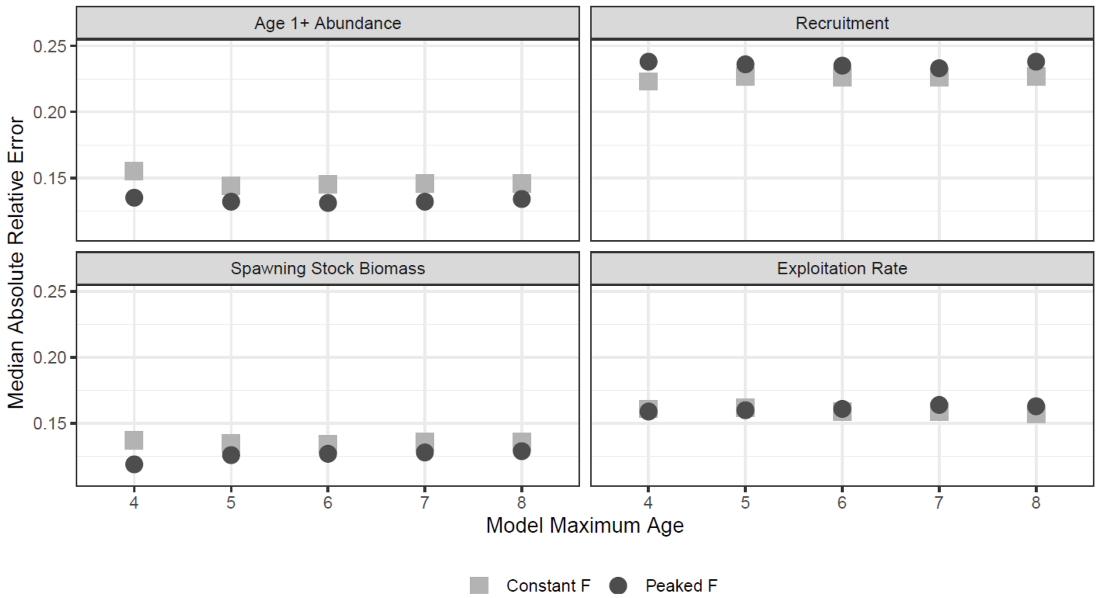

Figure 22. Median absolute relative error in model estimates of age-1+ Atlantic menhaden abundance generated under scenarios with alternative plus group definitions (model maximum age) relative to the maximum age in the population of age of eight and two fishing mortality (F) patterns.

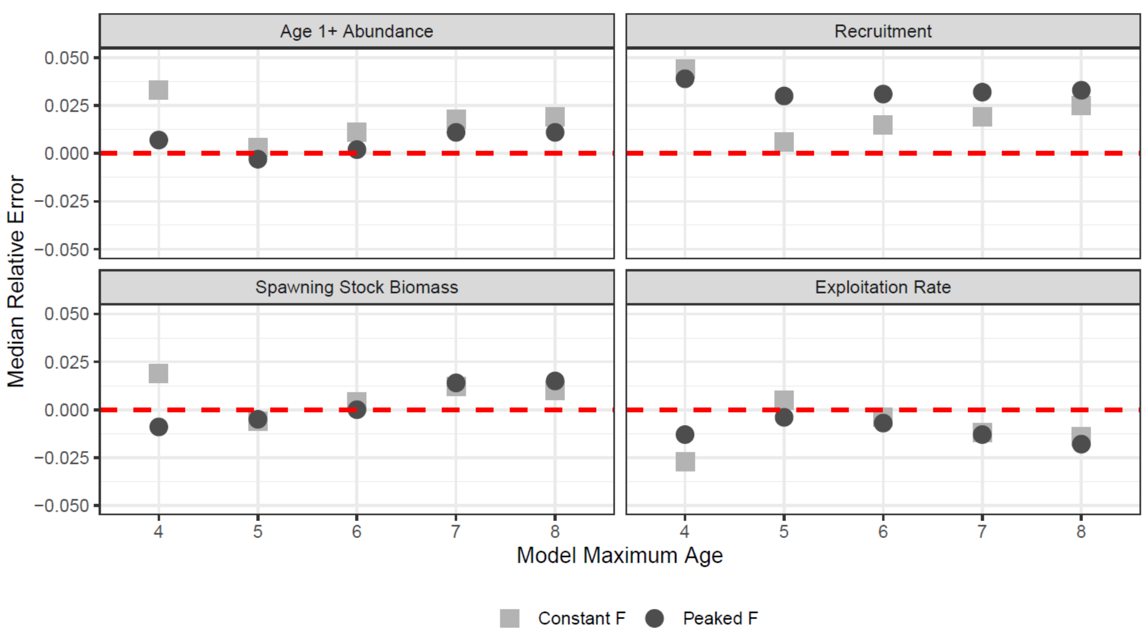

Figure 23. Median absolute relative error in model estimates of age-1+ Atlantic menhaden abundance generated under scenarios with alternative plus group definitions (model maximum age) relative to the maximum age in the population of age of eight, two fishing mortality (F) patterns, and misspecified selectivity for the adult index of abundance.

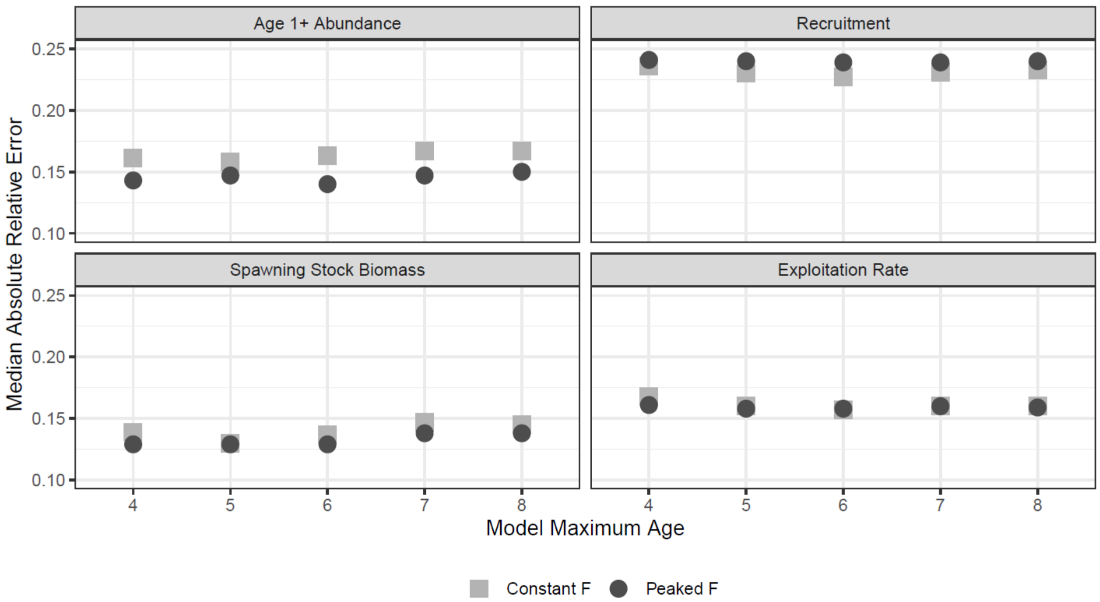

Figure 24. Median relative error in model estimates of age-1+ Atlantic menhaden abundance generated under scenarios with alternative plus group definitions (model maximum age) relative to the maximum age in the population of age of eight, two fishing mortality (F) patterns, and misspecified selectivity for the adult index of abundance.

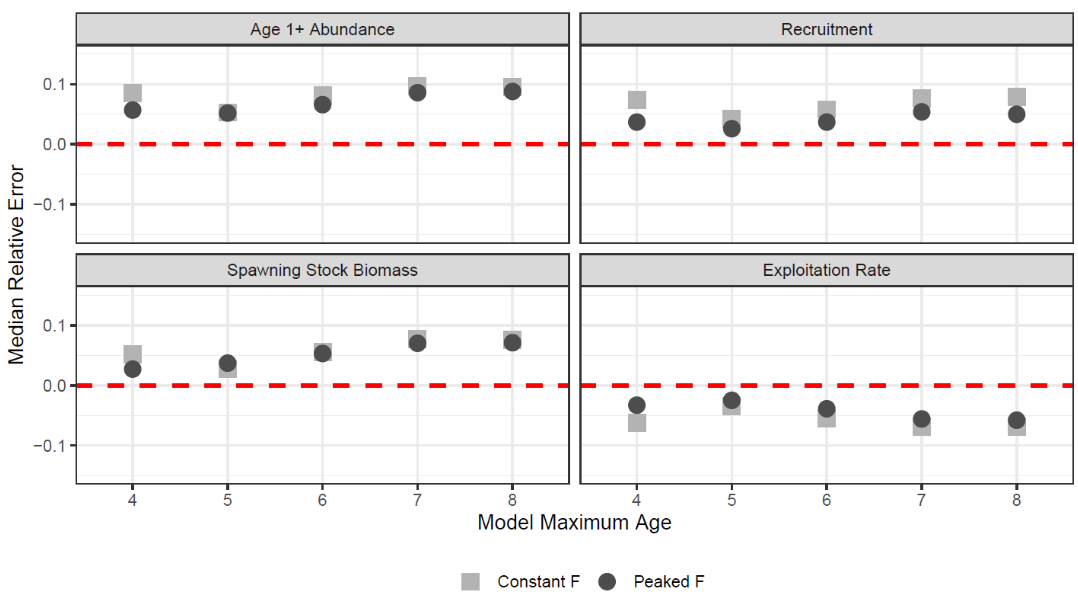

Figure 25. Median absolute relative error in model estimates of age-1+ Atlantic menhaden abundance generated under scenarios with alternative plus group definitions (model maximum age) relative to the maximum age in the population of age of eight, two fishing mortality (F) patterns, and misspecified northern commercial fleet fishery selectivity.

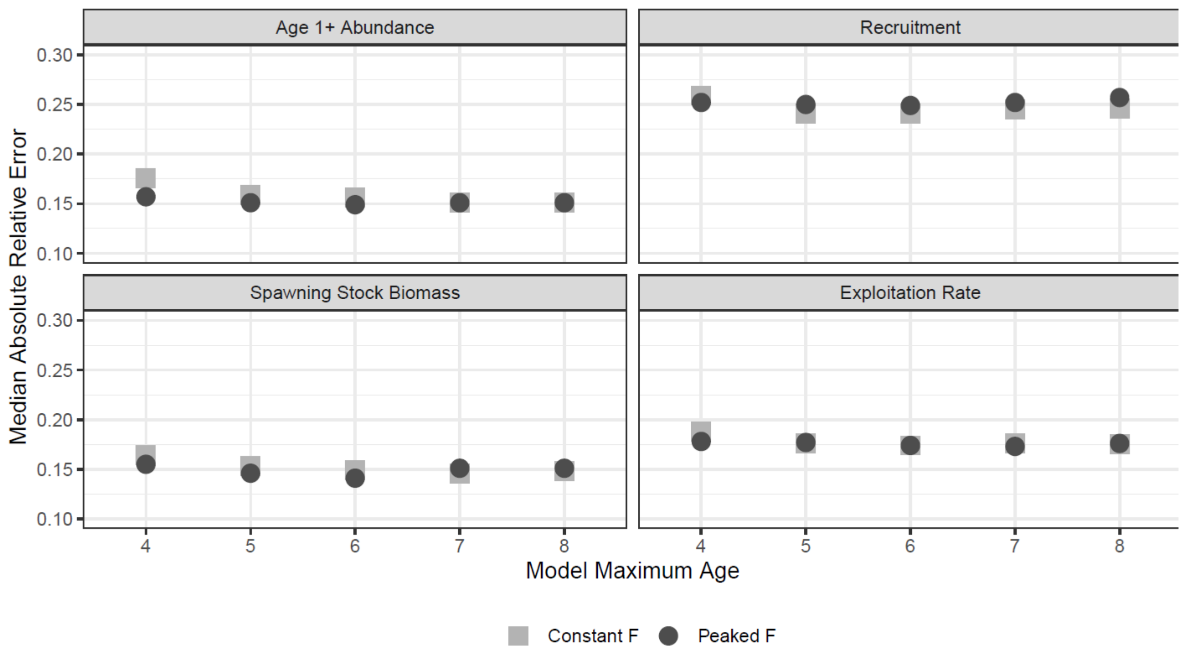

Figure 26. Median relative error in model estimates of age-1+ Atlantic menhaden abundance generated under scenarios with alternative plus group definitions (model maximum age) relative to the maximum age in the population of age of eight, two fishing mortality (F) patterns, and misspecified northern commercial fleet fishery selectivity.

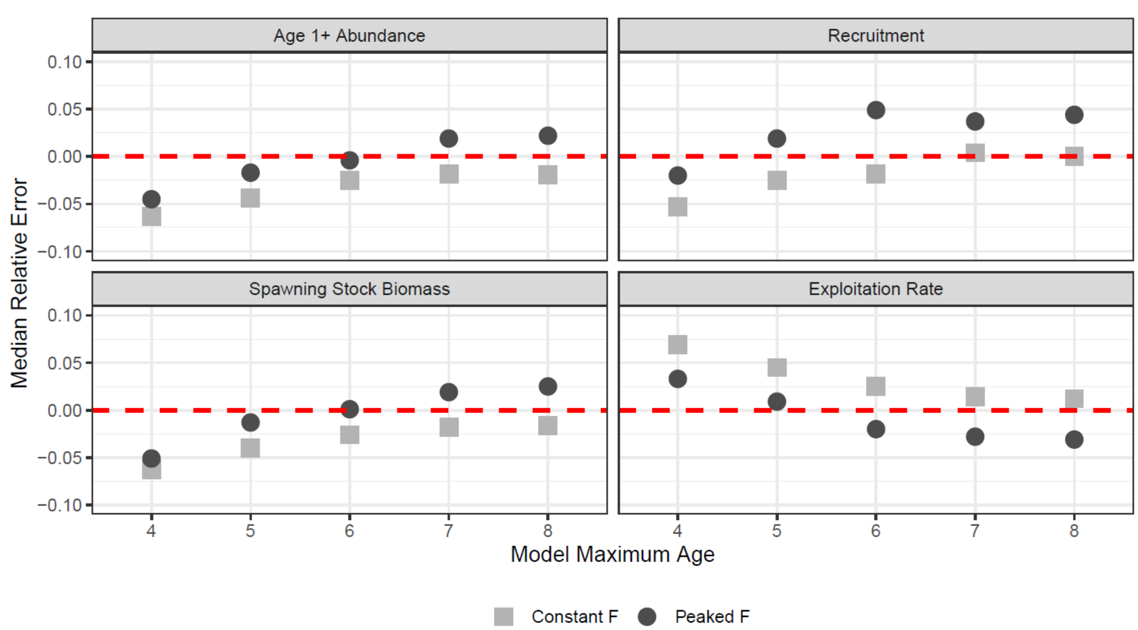

Figure 27. Median absolute relative error in model estimates of age-1+ Atlantic menhaden abundance generated under scenarios with alternative plus group definitions (model maximum age) relative to the maximum age in the population of age of eight, two fishing mortality (F) patterns, and misspecified commercial reduction south fishery selectivity.

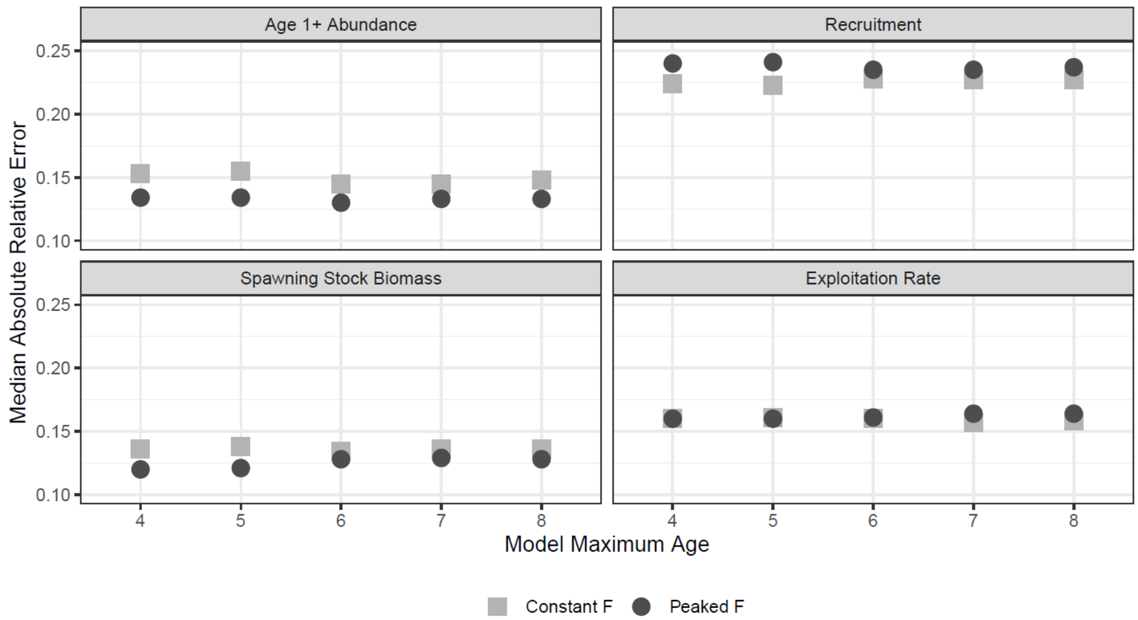

Figure 28. Median absolute relative error in model estimates of age-1+ Atlantic menhaden abundance generated under scenarios with alternative plus group definitions (model maximum age) relative to the maximum age in the population of age of eight, two fishing mortality (F) patterns, and misspecified commercial reduction south fishery selectivity.

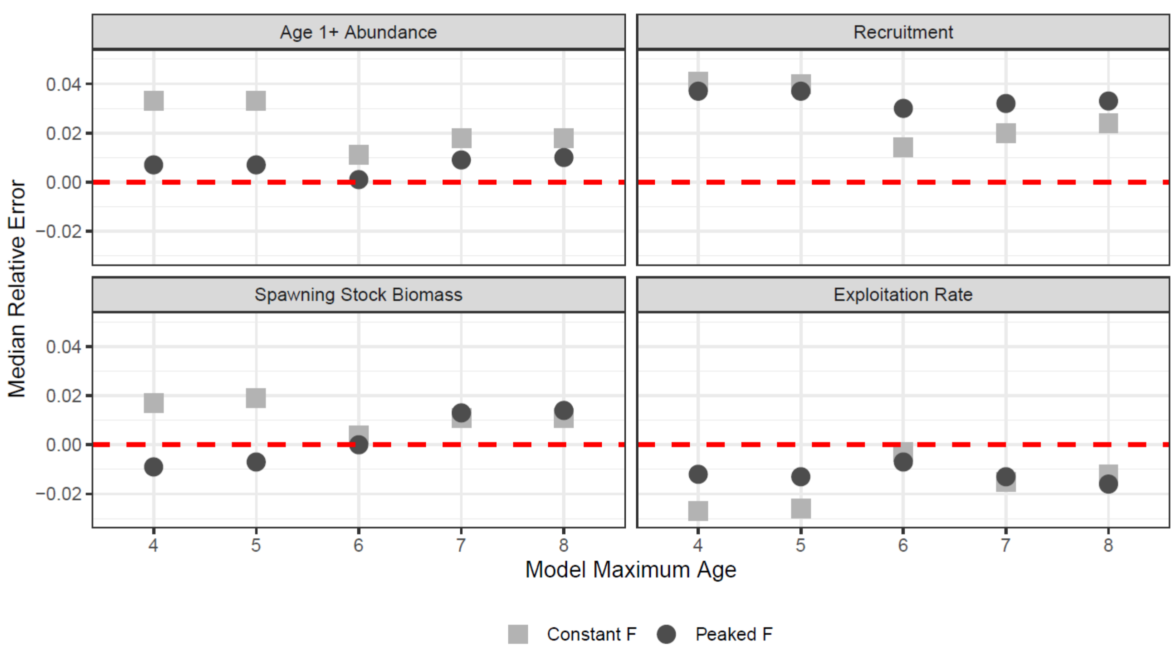

Figure 29. Median absolute relative error in model estimates of Atlantic menhaden age-1+ abundance, recruitment, spawning stock biomass, and exploitation rate generated under alternative plus group scenarios (model maximum age) with a population with a max age of eight, either constant current fishing mortality (F) or constant low F patterns, and the addition of an age-structured index of abundance.

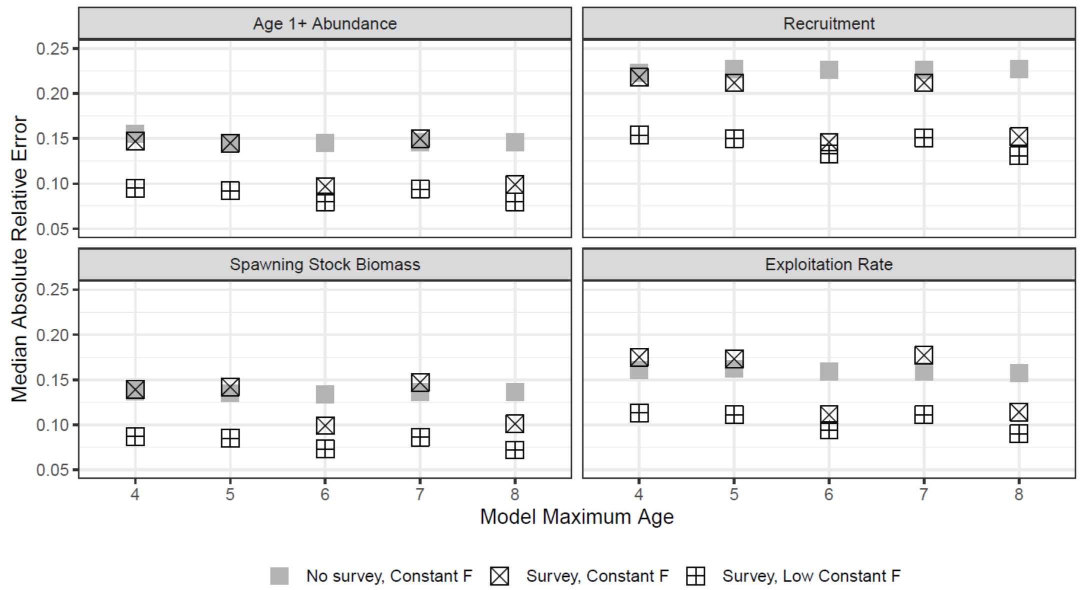

Figure 30. Median relative error in model estimates of Atlantic menhaden age-1+ abundance, recruitment, spawning stock biomass, and exploitation rate generated under alternative plus group scenarios (model maximum age) with a population with a max age of eight, either constant current fishing mortality (F) or constant low F patterns, and the addition of an age-structured index of abundance.

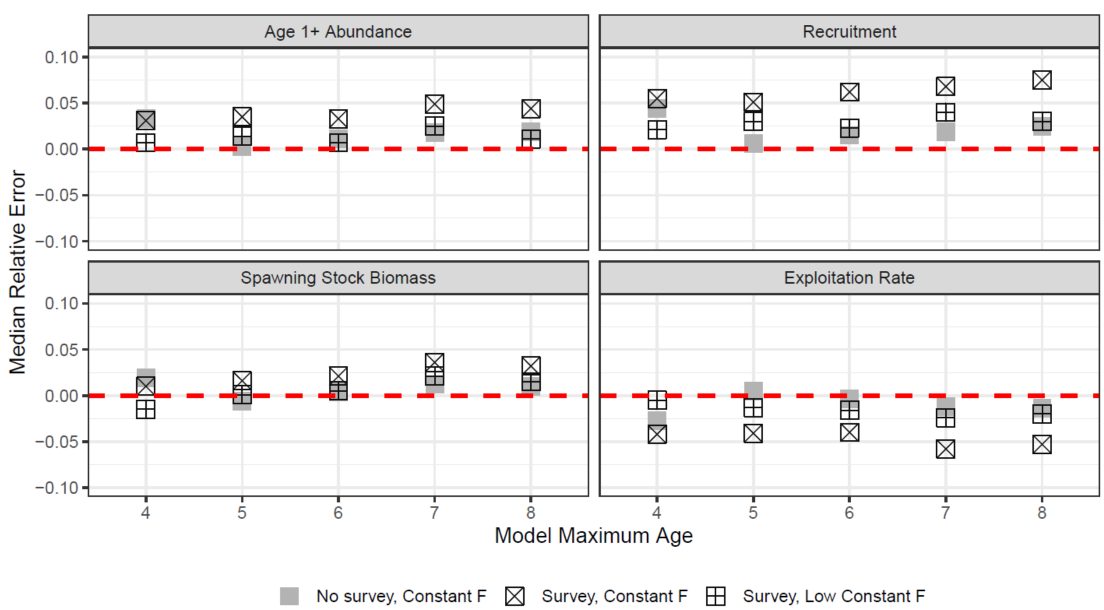

Figure 31. Median absolute relative error in model estimates of Atlantic menhaden age-1+ abundance, recruitment, spawning stock biomass, and exploitation rate generated under alternative plus group scenarios (model maximum age) with a population with a max age of eight, a constant low fishing mortality (F) pattern, the addition of an age-structured index of abundance, and misspecified selectivity for the adult index of abundance.

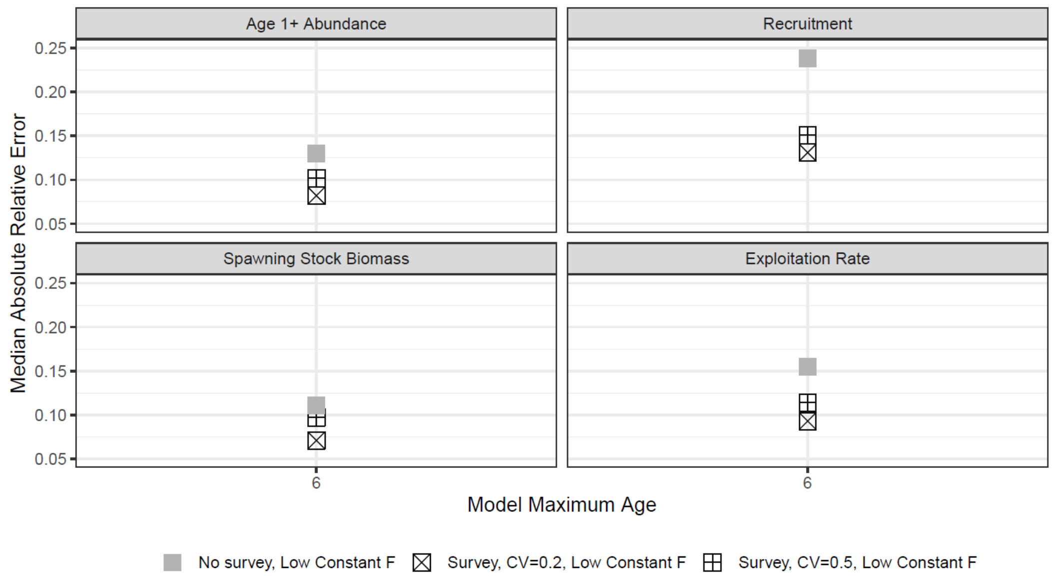

Figure 32. Median relative error in model estimates of Atlantic menhaden age-1+ abundance, recruitment, spawning stock biomass, and exploitation rate generated under alternative plus group scenarios (model maximum age) with a population with a max age of eight, a constant low fishing mortality (F) pattern, the addition of an age-structured index of abundance, and misspecified selectivity for the adult index of abundance.

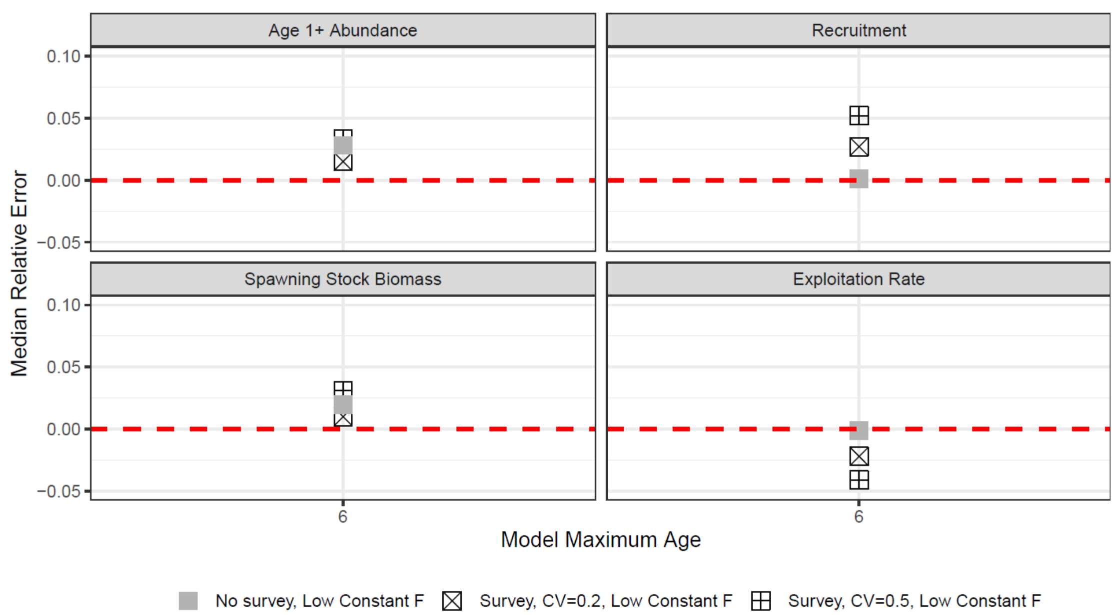

Figure 33. Median absolute relative error in model estimates of Atlantic menhaden age-1+ abundance, recruitment, spawning stock biomass, and exploitation rate generated under alternative plus group scenarios (model maximum age) with a population with a max age of eight, a constant low fishing mortality (F) pattern, misspecified adult index selectivity, and addition of a terminal year estimate of age-1+ biomass generated using two alternative coefficients of variation (CV).

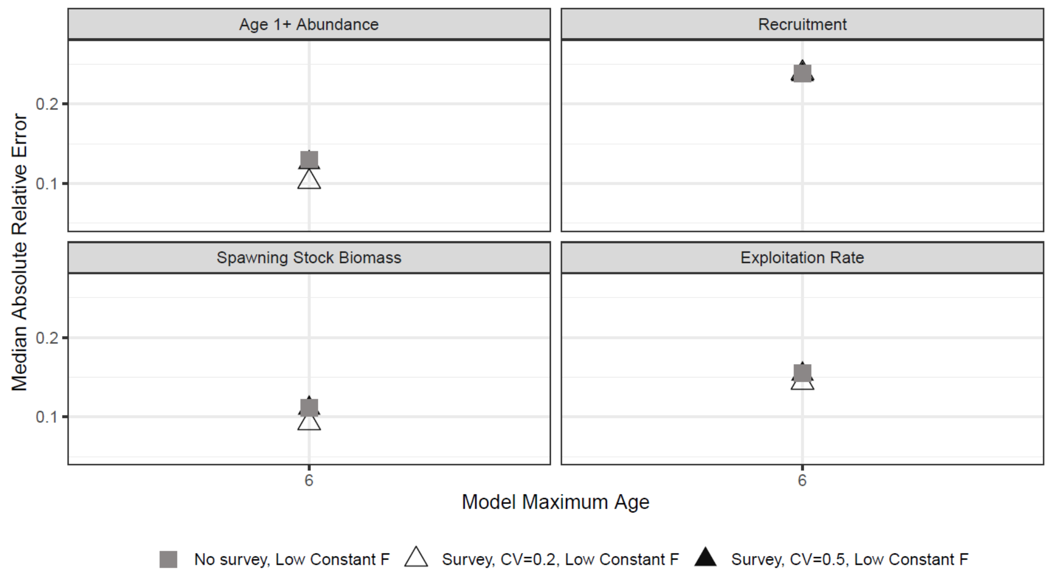

Figure 34. Median relative error in model estimates of Atlantic menhaden age-1+ abundance, recruitment, spawning stock biomass, and exploitation rate generated under alternative plus group scenarios (model maximum age) with a population with a max age of eight, a constant low fishing mortality (F) pattern, misspecified adult index selectivity, and addition of a terminal year estimate of age-1+ biomass generated using two alternative coefficients of variation (CV).