ABSTRACT

Title of Thesis:	EVALUATING THE CONSEQUENCES OF ALTERNATIVE ATLANTIC STRIPED BASS HARVEST CONTROL RULES ON THEIR PREY, ATLANTIC MENHADEN
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Harvest control rules (HCRs) are automatic fishery management procedures that are agreed upon in advance and that dictate the rate of fishing that can take place. I evaluated a suite of single species and dynamic multispecies HCRs to evaluate their relative performance in achieving management goals for the striped bass (*Morone saxatilis*) and Atlantic menhaden (*Brevoortia tyrannus*) stocks using a linked, age-structured predator-prey simulation model. First, simulation model inputs were updated using the most recent stock assessment information, and striped bass length- and weight-at-age estimates were updated using otolith-based ageing data. Linear models evaluating change in striped bass length- and weight-at-age over time and between sexes identified an increase in size of as much as 30% between 1998 and 2019. Additionally, striped bass continued to grow past age-15, indicating that future striped bass stock assessments should consider expanding the number of ages included in the model. The updated predator-prey simulation model was then used to compare performance of a suite of 27 HCRs. The most influential factor determining performance of striped bass HCRs was striped bass fishing

mortality (F). Atlantic menhaden had little effect on striped bass spawning stock biomass (SSB) at both high and low percent composition of Atlantic menhaden in striped bass diets. Traditional single species HCRs performed well, specifically those for which striped bass are managed at or below their target F. Although there was no single HCR that performed well for both stocks given their current reference points, both single species and dynamic multispecies HCRs that involved the “40-10 rule” for striped bass (lower threshold at 10% of unfished SSB and upper threshold at 40% unfished SSB) performed best across all striped bass performance metrics.

EVALUATING THE CONSEQUENCES OF ALTERNATIVE ATLANTIC STRIPED BASS HARVEST CONTROL RULES ON THEIR PREY, ATLANTIC MENHADEN

by

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Introduction

Evaluations of fish growth are essential components of stock assessments used in fisheries management. Estimates of length- and weight-at-age are used to calculate stock biomass and can inform estimation of annual fishing and natural mortality rates (Flinn & Midway, 2021; Houde, 1997). Length- and weight-at-age can influence our understanding of stock structure and status (Ahti et al., 2020) as well as inform management decisions such as gear mesh size limits or minimum size regulations (Gislason et al., 2010), which affect the potential rate of harvest a stock can undergo (King & McFarlane, 2003; Liang et al., 2014). Even in some frequently assessed species, length- and weight-at-age evaluations may not be routinely updated despite their importance in generating accurate stock assessment estimates.

One such species that has not been recently evaluated is striped bass (*Morone saxatilis*). Striped bass are one of the most economically important fish species on the U.S. east coast. The stock supports one of the nation's largest recreational fisheries (NMFS, 2020). Striped bass have been an important resource dating back to the mid-1600s, and concerns about stock sustainability arose as early as the late 1700s (Richards & Rago, 1999). More recently, the stock has been a priority for management since it experienced severe declines in the 1970s due to a combination of poor recruitment and overfishing. In 1981, an interstate management plan for striped bass was developed by the Atlantic States Marine Fisheries Commission

(ASMFC) to better manage the stock (NEFSC, 2019). A fishery moratorium was implemented in 1985 to aid in the recovery of the stock (ASFMC, 2016). Strong recruitment of striped bass occurred in the years following the implementation of the interstate fishery management plan and fishery moratorium, and the stock was declared recovered in 1995 (Hartman & Margraf, 2003). Restrictions on commercial and recreational fisheries were liberalized after 1995, and fishing pressure and landings continued to increase through the early 2000s (ASFMC, 2016). The striped bass stock declined again in the mid-2000s (ASFMC, 2016; ASMFC, 2013). The stock has been declared overfished and is experiencing overfishing, according to the 2019 stock assessment (NEFSC, 2019). Much of the stock's decline can be attributed to effects of recreational fishing, which has increased from 264,000 fish landed in 1984 to 5.4 million fish in 2010 (ASMFC, 2021). Recreational catch leveled out after 2010 and decreased during 2015-2017 (ASMFC, 2021).

Accurate length- and weight-at-age information is essential for striped bass management. Regulations for striped bass include minimum or maximum recreational and commercial size limits, which vary by state. Length-at-age information can be used to identify the need for changing size limits to possibly protect future spawning age classes or preserve the stock size structure. Annual weight-at-age is used in the calculation of spawning stock biomass in the stock assessment, and is a key component determining management reference points (NEFSC, 2019). Differences in weight-at-age or length-at-age can lead to inaccurate estimates of spawning stock biomass, which could impact stock status (Morgan, 1999).

Concerns about declines in striped bass weight-at-age (Uphoff & Sharov, 2018) highlight the need to reevaluate potential trends in length- and weight-at-age. The most recent synthesis of weight- and length-at-age for the coastal migratory stock of striped bass was in 2013 (ASMFC, 2013). The goal of this chapter was to update striped bass length- and weight-at-age estimates using data for 1998-2019. My objectives were to 1) estimate the average length- and weight-at-age of striped bass, and 2) determine if there were trends in striped bass growth in the U.S. Mid-Atlantic during 1998-2019.

Methods

Data

Length- and weight-at-age data were collected from multiple fishery-dependent and fishery-independent monitoring programs within the coastal migratory stock's range along the east coast of the US from Massachusetts to Virginia (Figure 1.1). Common data elements included state from which the data were collected or collection program, year, month, fishery or survey, gear, striped bass weight- and length-at-age, sex, and ageing structure (otolith vs scale). I only used otolith-derived ages for these analyses because scale-based age determination methods tend to have a positive bias for intermediate ages and a negative bias for older ages compared with otolith-based methods, and otolith ageing methods have been validated on known-age striped bass (Abecasis et al., 2008; Liao et al., 2013; Secor et al., 1995). The available otolith data spanned 1998-2019, but each data provider varied in temporal coverage. Although most fishery-independent monitoring of striped bass is conducted by state fishery management agencies, I also included samples collected by Virginia Institute of Marine Science (VIMS) through their Chesapeake Bay Multispecies Monitoring and Assessment Program (ChesMMAP). All data were compiled and analyses conducted in RStudio version 2022.2.3.492 (RStudio Team, 2020).

Massachusetts

The Massachusetts Division of Marine Fisheries age and growth lab provided length-at-age data for striped bass collected from May through October during 2002-2019. All 1,837 samples were from recreationally caught fish. Weights were not collected.

Rhode Island

Length- and weight-at-age data from Rhode Island were provided by the age and growth lab at the Rhode Island Department of Environmental Management (RIDEM) and were collected during April-October in 2015, 2016, and 2017. Both fishery-dependent and fishery-independent samples were collected from a variety of monitoring programs including commercial dealers, state-based recreational sampling programs, state trawl surveys, and a fish pot survey. The total sample size was 133.

New Jersey

New Jersey Department of Natural Resources provided striped bass length- and weight-at-age samples during 1998-2010. The data included samples from two fishery independent sampling programs. Both surveys were conducted within the

Delaware Bay twice a year in March through May and October from 1998 through 2008 and 2010. Limited ageing using otolith-based methods within the timeframe of this study resulted in 54 total samples.

ChesMMAP

VIMS ChesMMAP uses a large mesh bottom trawl to survey the mainstem of the both Maryland and Virginia waters of the Chesapeake Bay during March-November. Length- and weight-at-age data were available for 2003-2019 (Bonzek et al., 2022). This survey made up a large portion of the otolith samples for this study (6,153 samples).

Virginia

Length- and weight-at-age samples from Virginia were collected from commercial and recreational catches by the Virginia Marine Resources Commission and commercial catches by the Potomac River Fisheries Commission. Recreational catches were sampled from fishing tournaments in 2000, 2003, 2004, and 2006. Additional recreational samples were collected during the Marine Recreational Information Program during 2003 to 2019. Commercial samples made up the majority of the data and were collected throughout the year from 1998 to 2019 from multiple surveys using pound nets, seines, and gill nets for a total sample size of 6,517. There were an additional 469 samples sourced from recreational data in Virginia.

Mean Length- and Weight-at-age

Four options for calculating mean length- and weight-at-age were considered (Table 1.1). For option 1, annual mean length- and weight-at-age were calculated as stratified mean length- and weight-at-age with state as strata. This option accounts for unequal sample sizes among states and is correct if equal proportions of the stock are within each sampling program's area. For option 2, mean length- and weight-at-age was calculated as an unstratified mean, but young fish from fishery-dependent data sources were excluded to reduce potential bias of size-selective sampling due to minimum length limits. The largest differences in mean length- or weight-at-age between fishery-dependent and fishery-independent sources were found at young ages. Three age thresholds (age-5, age-7, and age-9) were implemented to determine the effect of the threshold age of inclusion on mean length- or weight-at-age. This option is appropriate if fishery regulations cause a bias in the mean length- and weight-at-age due to fisheries selectively harvesting the largest fish of the younger age classes. For option 3, mean length- and weight-at-age was calculated using an unstratified mean with no censoring of the base data set. This option assumes that the population is well mixed and all data sources have equal size selectivity. Finally, for option 4, the impact of size differences due to sexually dimorphic growth between male and female striped bass were accounted for by calculating mean length- and weight-at-age using sex as strata. These resulting sex-specific mean length- and weight-at-age values were averaged to calculate sex-aggregated mean length- and weight-at-age of striped bass. Option 4 assumes that the sex ratio of the population is 50:50 for all ages and that all data sources are sampling the same well-mixed population. The results of these analyses were compared to the current striped bass stock assessment, Uphoff and Sharov (2018), and Garrison et. al. (2010) by comparing length-at-age over time, and Mansueti (1961) comparing average weight-at-age by sex.

Temporal Trends in Striped Bass Size-at-Age

I used general linear models of length-at-age or weight-at-age over time to test for linear temporal trends in striped bass size for ages 1-24. These models allowed for sexually dimorphic growth by including a sex and a year*sex interaction term. The models were applied separately for each age of striped bass where size (length or weight) was calculated as a function of year, sex, and a year*sex interaction term,

$$size = intercept + b_1(year) + b_2(sex) + b_3(year{:}\,sex), \qquad (1)$$

where size is defined as either the expected mean length or weight, b_1 was the average change in mean length-at-age per year, b_2 was the difference in the intercept between female and male striped bass, and b_3 was an interaction term that described the difference in the slope of the relationship over time between females and males. The same model was generated for weight, where weight replaced the length terms in the equation above. Applying the models separately for each age allows for the variance of length- or weight-at-age to vary with age. To account for multiple comparisons, a

Bonferroni correction was used to determine p-values associated with an alpha-level of 0.05 (p-value < 0.002).

Percent and magnitude of change were calculated to quantify the importance of the trends in length- and weight-at-age by sex over time. The change in length- or weight-at-age was calculated as the difference between the estimated mean in the last and first year,

$$Magnitude = size(2019) - size(1998). \tag{2}$$

Percent change was calculated as the magnitude of change divided by the mean length or weight in the first year multiplied by 100.

Striped Bass Length-Weight Relationship

A linear model in the package 'lme4' was used to estimate changes over time in the striped bass length-weight relationship (Bates et al., 2015). The relationship between striped bass length and weight was estimated by modeling weight as a log-transformed power function of length,

$$\log(W) = (\log(intercept) + b_s) + (b_y + b_s) \bullet \log(L), \tag{3}$$

where weight (W), was calculated as a function of length, L, year effects, b_y, and sex, b_s. A step-wise process was used to determine whether to include the effects of sex and year on striped bass weight as a function of length. First a model was fitted that included sex. The relationship between length and weight was significantly different for males and females (b_s=0.10, standard error=0.02, p<0.001), but the differences in estimated weight-at-length were less than 2%. Therefore, I did not include sex as a parameter in the final models. Mean weights were calculated for a striped bass at 100 cm length to determine the amount of change in mean weight-at-age, and the expected weight of a 100 cm fish was also plotted to examine changes in time-varying striped bass weight.

Results

Mean length- and weight-at-age

Male striped bass asymptotic mean length (80 cm) was smaller than that of females (120 cm; Figure 1.2). Most of the data above age-15, however, were dominated by female samples. Sexual dimorphism in mean length-at-age was evident as early as age-3.

Striped bass mean weights-at-age were similar between males and females for ages 1-4 but for age-5 and older, sexually dimorphic growth became apparent as females displayed higher mean weight-at-age than males (Figure 1.3). Similar to length, males had a lower asymptotic weight (around 8 kg) compared to the average and to females. Female striped bass did not reach their asymptote as early as male striped bass, but after age-24 exhibited an estimated asymptotic weight of about 20 kg (Figure 1.3).

When sexes were combined, striped bass displayed an average asymptotic length of 117 cm and an average asymptotic weight of 19 kg (Figures 1.4 and 1.5).

Sex-aggregated mean size at age was similar among alternative mean length- and weight-at-age calculation options 1, 2, and 3 with two exceptions. One exception was that the mean length-at-age in Option 2, with age data truncated at ages 7 and 9, was smaller on average than the other options between ages 5 and 9 (Figure 1.5). Option 4 resulted in lower length- and weight-at-age at older ages (19-24) due to a higher weighting of male samples in these older age categories.

Trends in Striped Bass Size-at-Age

Length

The magnitude and direction of changes in mean length-at-age over time varied by sex and age (Tables 1.2-1.3). Most ages did not show significant trends in mean length-at-age over time. However, mean length-at-age of females ages 10-15 increased significantly during 1998-2019 (Figure 1.6). Male mean length-at-age increased significantly for ages 10-14 and decreased significantly for age-15 (Figure 1.7). Males also had a significant difference in the interaction between sex and year than females for ages 3, 8, and 9 (Table 1.2). Female striped bass were significantly larger, on average, than males except for ages 1 and 19.

The amount of change in mean length-at-age differed by age and sex (Table 1.4). Male striped bass ages 10-14 averaged an 11% increase in mean length during 1998-2019, whereas female striped bass ages 10-15 averaged an 8% increase in mean length over the same period. Among significant models, changes in mean length-at-age for male striped bass age 10-14 ranged in magnitude from 0.9 cm to 15 cm during 1998-2019 (Table 1.4). Male striped bass length-at-age increased as much as 19.5 cm (age-9) and 35.4 cm (age-20) and decreased up to 31.2 cm (age-19). Female striped bass showed 7.0 cm to 8.4 cm increases in mean length-at-age for ages 10-15. Striped bass under age-6 had mostly negative changes in mean length-at-age over time, but these changes were not significant. Changes in mean length-at-age were highly variable for striped bass ages 21 to 24, likely due to low sample sizes.

Weight

Trends in weight-at-age of striped bass during 1998-2019 showed similar patterns to that of length-at-age (Figures 1.8 and 1.9). Sixteen of the 24 models identified trends in striped bass weight-at-age by sex, whereas five models identified statistically significant trends in striped bass weight-at-age over time (Tables 1.5-1.6). Similar to length-at-age, significant linear trends were identified in weight-at-age of striped bass for ages 10-14.

On average, over ages 10-14 and for both male and female striped bass, there was an almost 3 kg (± 0.94) increase in mean weight across the time series (Table 1.7). Overall percent change in male mean weight was positive and much higher in magnitude than for female striped bass. Male striped bass also displayed more variability in mean weight than females. Age-14 males displayed a much lower magnitude of change compared to age-10 through age-13 (0.661 kg). Age-9 male striped bass displayed the largest change in weight (approximately 4 kg) compared with other ages at 159.1% during 1998-2019.

Length-Weight

Striped bass weight increased as a function of length (estimate=2.97, standard error=0.002, $p<0.001$). The effect of length on weight changed significantly during 1998-2019 (Figure A.1). In the beginning of the time series, striped bass displayed a steeper length-weight relationship than at the end of the time series (Figure 1.10). The estimated weight of a 100 cm striped bass (approximately age-15) was predicted to increase by 2 kg during 1998-2019 (Figure 1.11). However, the change over time in predicted weight-at-age was monotonic (Figure A.1). Despite slight interannual variation in predicted weight-at-age, the overall trend over the period was increasing for a 100cm striped bass.

Discussion

I estimated mean length- and weight-at-age for the Atlantic migratory stock of striped bass. Striped bass displayed sexually dimorphic growth with females growing larger than males as has been found in other studies (Mansueti, 1961; Pearson, 1938). I also found that mean length- and weight-at-age have increased substantially for intermediate ages of striped bass during 1998-2019. Increasing trends in mean weight-at-age over time were somewhat driven by increases in mean length-at-age. The change in striped bass length- and weight-at-age could be due to a variety of factors including density dependence, adequate prey availability, fishery selectivity effects, and data collection inconsistencies among data sources.

No other studies have characterized size-at-age for striped bass beyond age 15. The few who have explored striped bass size-at-age have acknowledged the presence of age-15 and older striped bass, but limited sample availability at older ages and concern about ageing accuracy of scale-based aging methods have restricted the age structure explored in these studies (Goodyear, 2002; Mansueti, 1961; Merriman, 1941; Secor, 2000). The current striped bass stock assessment has an aggregate age 15+ for its oldest age class, which implicitly assumes that striped bass mean length and weight asymptote at age-15 which is only supported in this analysis for male striped bass (Figures 1.2-1.3) (NEFSC, 2019). Female striped bass do not begin to asymptote until age-24, which does not support the assumption made in the striped bass stock assessment.

Causes of changes over time

Mean length- and weight-at-age of striped bass changed during 1998-2019, particularly increasing for intermediate ages 10-15. Although trends in length- and weight-at-age were not consistent across all ages, both sexes generally displayed increasing mean length- and weight-at-age for ages 10-14 during 1998-2019. Males tended to exhibit larger increases in length- and weight-at-age than females, but both sexes saw high increases in both length and weight. Density dependent growth, in which growth increases as abundance decreases, may explain the increase in length- and weight-at-age over time (Eikeset et al., 2016).

The availability of adequate prey for striped bass has been identified as a management concern (Buchheister et al., 2017; Chagaris et al., 2020; Howell et al., 2021). Biomass of Atlantic menhaden, a large component of striped bass diet (Hartman & Brandt, 1995; Overton et al., 2009; Walter & Austin, 2003), has been relatively stable during 1998-2019 (SEDAR, 2020b). The consistent biomass of Atlantic menhaden coupled with a declining biomass of striped bass could have led to an increase in striped bass weight-at-age for ages 10-14 striped bass, which are most likely to consume age-1 Atlantic menhaden (Anstead et al., 2021; Overton et al., 2009). Bay anchovy is another prey species that comprises a large portion of striped bass diet (Overton et al., 2009). The VIMS random stratified index of bay anchovy abundance was highly variable with below average abundance in the early 2000s and a large peak in abundance in 2010 (Tuckey & Fabrizio, 2011). This additional prey source for striped bass in conjunction with declining striped bass biomass could have created conditions that led to increased striped bass length- and weight-at-age.

Changes in striped bass mean length- and weight-at-age were not likely due to changes in sampling over time. The majority of the samples originated from Virginia (sample size=6,986) and ChesMMAP in the Chesapeake Bay (sample size=6,153) and there is more limited sampling in other regions (total sample size=2,024). The large sample sizes from Virginia and the Chesapeake Bay could result in an underestimate of mean length or weight because younger striped bass tend to reside longer within and outside of the Chesapeake Bay, while older, larger striped bass spend the majority of their time in the coastal ocean (Able et al., 2012; Mansueti, 1961; Secor et al., 2020). However, data sources from outside the Chesapeake Bay that were included in this study were consistently sampled throughout the time series, and were within the size ranges of samples from within the Chesapeake Bay (Figure A.2). Thus, migratory fish were represented in this study.

Comparisons with previous studies

I used only otolith samples for this study, but most previous studies used scales (Garrison et al., 2010; Mansueti, 1961; Uphoff & Sharov, 2018) or a combination of scales and otoliths (Goodyear, 1998; NEFSC, 2019). Otolith-based ageing methods have much higher agreement among readers than scale-ageing and have been validated with known-age fish (Liao et al., 2013; Secor et al., 1995). Scale-based ageing tends to over-predict younger age and under-predict older age fish which leads to inaccurate estimates of biomass (Liao et al., 2013; Secor et al., 1995). Because of the unreliability of scale ages, I recommend the use of otolith-based ages for characterization of striped bass length- and weight-at-age.

My estimates of mean length-at-age were similar to those from the striped bass Multispecies Virtual Population Analysis (MSVPA) (Figure 1.12) (Garrison et al., 2010). However, my striped bass mean weight-at-age estimates were lower than previous estimates published by Mansueti (1961) (Figure 1.13), Uphoff and Sharov (2018) and the benchmark stock assessment (NEFSC, 2019) (Figure 1.14). Mansueti (1961) used scale ages during 1957-1958 in the Chesapeake Bay, whereas, in this study, I used otolith-based ages for 1998-2019. Although different ageing methods are known to affect estimates of length- and weight-at-age (Secor et al., 1995), striped bass mean length-at-age could have changed since the 1950s. Also, Mansueti's samples were collected using commercial gill nets potentially biasing his estimates along with the use of scale-based ageing methods (Mansueti, 1961), whereas the data used in my study spanned a variety of gears. With the exception of a few ages, Uphoff and Sharov (2018) estimated a higher mean weight-at-age most likely due to their use of scale ages (Figure 1.14). The stock assessment also estimates higher striped bass mean weights-at-age (Figure 1.14). Although the assessment uses a combination of scale- and otolith-base ageing methods, it only incorporates fishery-dependent data which could affect the estimated length- and weight-at-age, particularly for younger ages (NEFSC, 2019).

There were some inconsistencies in length- and weight-at-age over time that may have affected the resulting mean size-at-age estimates, such as decreased average size between ages when tracking a cohort. Specifically, mean length- and weight-at-age often decreased the next year for the next older age striped bass greater than age-12 (Figure 1.14). This was most likely due to the low sample sizes at older age striped bass rather than a true size decrease between ages.

Efforts to correct for potential non-random sampling in my analysis included multiple approaches for calculating mean length- and weight-at-age. Mean length- and weight-at-age of striped bass was slightly influenced by the calculation method. Fishery-dependent data sources had higher mean length- and weight-at-age than fishery independent ones, which was likely due to selectivity and minimum size limits (Figure A.2). However, not including fishery-dependent data for younger ages generated length- and weight-at-age patterns that were similar overall to the unweighted average of the data (Figures 1.4 and 1.5). Therefore, I recommend using an unweighted average of the entire data set to incorporate as much of the available data as possible (Option 3). This approach assumes that the stock was randomly sampled and thus the data represent the true variability in length- and weight-at-age across the stock's range. This analysis was highly reliant on samples from ChesMMAP, which concentrates sampling in the Chesapeake Bay, yet provided the largest range of lengths and weights.

I do not recommend Option 4 (assuming a population sex ratio of 50:50 males to females) because it was strongly affected by sexually dimorphic growth. The most strongly affected ages were 11-24, which displayed substantially lower mean lengths and weights because males were upweighted in calculations. Above age-24, the samples were all female, which explains why option 4 was almost exactly the same as the other options when calculated over these ages. Although Option 4 assumes a 50:50 male to female sex ratio, multiple reports in the literature are not consistent with the assumption that the majority of the older ages and younger migrants are dominated by females (Dorazio et al., 1994; Merriman, 1941; Trent & Hassler, 1968).

Conclusions

Overall, striped bass mean weight-at-age has changed over time. I estimated about a 30% increase in weight-at-age from 1998 to 2019 for some ages of striped bass that is only partially accounted for in the current stock assessment. There are increases of weight-at-age over time in the stock assessment that mimic the trends I identified, but they are often less extreme. Although the assessment includes time-varying mean weights-at-age (NEFSC, 2019), the majority of ageing data collected and used is still from scale ages, which is likely the main cause of differences between my results and the stock assessment. An increase in striped bass weight-at-age over time could lead to different conclusions about stock status given the current reference points are based on current spawning stock biomass relative to that in 1995. Also, the increase in mean weight-at-age identified in this study would indicate that available prey is not negatively impacting striped bass growth, which has been a major concern raised by managers and stakeholders in recent years.

I also demonstrated that striped bass continue to grow after age-15 (the plus group in the assessment) and begin to asymptote around age-20; however, when separated by sex, male striped bass asymptote at age-15 while female striped bass asymptote by age-22. The striped bass stock assessment could benefit from using updated, otolith-based estimates of length- and weight-at-age, even though this would limit the spatial extent of the samples currently available. Given the importance of this stock and the well-documented bias in scale-based ages that is likely impacting accuracy of the stock assessment (Henriquez et al., 2016; Reeves, 2003), the development of a coastwide otolith-based sampling should be prioritized.

Tables

Table 1.1: Methods for calculating mean length- and weight-at-age of striped bass.

Option	Description	Pros	Cons
1	Stratified coastwide mean of length- and weight-at-age with state as strata	Accounts for unequal sample sizes among states	Data sources equally weighted across stock range
2	Mean length- and weight-at-age after truncation of fishery-dependent data below minimum legal size. Truncation was assessed using cutoffs of <5, 7, and 9 years of age.	Helps to reduce bias from fishery-dependent minimum size regulations and angler preference	Removes young individuals caught by the fishery at the upper end of their size range for truncated ages
3	Unstratified mean length- and weight-at-age	Equal weight placed on all available data	May be biased by data sources with larger sample sizes
4	Sex-stratified mean length- and weight-at-age averaged across all sexes	Reduces impact of a higher proportion of females sampled at older ages	Population sex ratio may not be 50:50

Table 1.2: P-values resulting from 24 linear models testing for trends over time in striped bass mean length-at-age during 1998-2019 by sex. The p-values were compared to a Bonferroni adjusted threshold where p≤0.002 is equivalent to an overall alpha level of 0.5. Displayed are the p-values for the intercept (P(int)), the year term (P(year)), the male sex term (difference from females; P(sexM)), and the interaction term between year and sex (P(year:sexM)). Significant values are bolded.

Age	P(int)	P(year)	P(sexM)	P(year:sexM)	R-Squared	F statistic
1	**<0.001**	0.554	0.727	0.061	0.009	2.539
2	**<0.001**	0.096	**<0.001**	0.655	0.012	7.206
3	**<0.001**	0.190	**<0.001**	**<0.001**	0.015	9.214
4	**<0.001**	0.039	**<0.001**	0.006	0.092	45.454
5	**<0.001**	0.453	**<0.001**	0.805	0.225	106.171
6	**<0.001**	0.022	**<0.001**	0.016	0.281	143.500
7	**<0.001**	0.013	**<0.001**	0.278	0.340	201.844
8	**<0.001**	0.020	**<0.001**	**<0.001**	0.398	190.212
9	**<0.001**	0.196	**<0.001**	**<0.001**	0.497	273.107
10	**<0.001**	**<0.001**	**<0.001**	0.042	0.484	237.491
11	**<0.001**	**<0.001**	**<0.001**	0.009	0.533	248.067
12	**<0.001**	**<0.001**	**<0.001**	0.999	0.532	192.042
13	**<0.001**	**<0.001**	**<0.001**	0.768	0.521	129.949
14	**<0.001**	**<0.001**	**<0.001**	0.082	0.457	80.863
15	**<0.001**	**0.002**	**<0.001**	0.015	0.437	50.697
16	**<0.001**	0.050	**<0.001**	0.580	0.514	46.462
17	**<0.001**	0.057	**<0.001**	0.280	0.540	39.522
18	**<0.001**	0.841	**<0.001**	0.250	0.449	20.382
19	**<0.001**	0.605	0.019	0.468	0.242	8.398
20	**<0.001**	0.035	**<0.001**	0.118	0.458	15.764
21	**<0.001**	0.256	**<0.001**	0.628	0.366	10.953
22	**<0.001**	0.056			0.063	3.819
23	**<0.001**	0.685	**<0.001**	0.687	0.394	8.672
24	**<0.001**	0.728			0.009	0.126

Table 1.3: The estimates (values) and standard errors (in parentheses) of the coefficients resulting from the linear models analyzing the trends striped bass length-at-age by year and sex. Models for age-2 through age-18, age-20, age-21, and age-23 identified significant differences in length between sexes, models for age-10 through age-14 identified significant differences in length over time, and models for age-3, age-8, and age-9 identified a significant interaction between year and sex.

Age	***Intercept***	***Year***	***Sex***	***Year:Sex***
1	0.19 (0.01)	0 (0)	0.01 (0.01)	0.12 (0.06)
2	0.34 (0.01)	0 (0)	0.05 (0.01)	-0.02 (0.06)
3	0.65 (0.02)	0 (0)	0.04 (0.02)	-0.24 (0.08)
4	1.59 (0.03)	0.01 (0.01)	-0.42 (0.04)	-0.25 (0.09)
5	2.52 (0.05)	0 (0.01)	-0.89 (0.06)	0.02 (0.09)
6	3.3 (0.07)	0.02 (0.01)	-1.16 (0.08)	-0.21 (0.08)
7	4.44 (0.08)	0.02 (0.01)	-1.63 (0.1)	0.09 (0.09)
8	5.75 (0.11)	0.03 (0.02)	-2.07 (0.13)	0.46 (0.1)
9	7.32 (0.1)	0.05 (0.02)	-2.97 (0.15)	0.81 (0.11)
10	8.47 (0.1)	0.13 (0.02)	-3.37 (0.16)	0.24 (0.12)
11	9.53 (0.12)	0.14 (0.02)	-4.06 (0.19)	0.34 (0.13)
12	10.29 (0.14)	0.16 (0.03)	-4.04 (0.24)	0 (0.13)
13	10.57 (0.18)	0.12 (0.03)	-4.06 (0.29)	-0.05 (0.17)
14	12.21 (0.23)	0.18 (0.04)	-4.29 (0.42)	-0.32 (0.18)
15	12.79 (0.31)	0.16 (0.05)	-3.98 (0.56)	-0.65 (0.27)
16	14.69 (0.4)	0.07 (0.06)	-6.52 (0.79)	0.14 (0.26)
17	14.24 (0.36)	0.17 (0.06)	-6.84 (0.79)	-0.38 (0.35)
18	16.29 (0.58)	0.04 (0.09)	-6.98 (1.21)	0.45 (0.38)
19	18.98 (0.83)	-0.25 (0.15)	-10.05 (3.8)	-1.3 (1.78)
20	15.1 (0.9)	0.37 (0.15)	-5.72 (1.77)	1.14 (0.72)
21	17.49 (1.33)	0.1 (0.2)	-10.88 (3.15)	-0.33 (0.67)
22	22.41 (1.5)	-0.34 (0.2)	-18.4 (4.82)	
23	21.4 (1.99)	-0.15 (0.25)	-11.8 (3.98)	0.45 (1.12)
24	20.05 (1.55)	-0.05 (0.19)	-12.3 (2.35)	

Table 1.4: Percent and magnitude (cm) of change in female and male striped bass length-at-age during 1998-2019.

	Length			
	Female		Male	
Age	Percent Change	Magnitude	Percent Change	Magnitude
1	-2.1	-0.6	8.0	2.0
2	-4.8	-1.5	-6.2	-2.1
3	4.9	1.9	-8.3	-3.5
4	6.7	3.5	-3.9	-1.9
5	-2.0	-1.3	-1.5	-0.8
6	4.6	3.2	-2.1	-1.3
7	4.2	3.2	8.3	5.2
8	4.2	3.5	21.3	13.7
9	2.0	1.8	29.9	19.5
10	8.7	7.9	18.4	13.2
11	7.7	7.3	20.2	14.9
12	8.6	8.4	10.5	8.4
13	8.2	8.2	8.5	7.1
14	7.7	7.9	1.0	0.9
15	6.6	7.0	-7.6	-7.4
16	4.5	4.9	9.1	8.1
17	5.1	5.6	-3.0	-2.9
18	-0.6	-0.7	9.9	9.1
19	-2.2	-2.7	-26.5	-31.2
20	9.2	10.3	46.1	35.4
21	5.6	6.5	-0.7	-0.7
22	-8.8	-11.7	-13.4	-11.7
23	-2.7	-3.4	6.9	6.6
24	-5.9	-7.5	-7.5	-7.5

Table 1.5: P-values resulting from 24 linear models testing for trends over time in striped bass mean weight-at-age during 1998-2019 by sex. The p-values were compared to a Bonferroni adjusted threshold where p≤0.002 is equivalent to an overall alpha level of 0.5. Displayed is the p-values for the intercept (P(int)), the year term (P(year)), the male sex term (difference from females) (P(sexM)), and the interaction term between year and sex (P(year:sexM)). Displayed is the p-values for the intercept (P(int)), the year term (P(year)), the male sex term (difference from females) (P(sexM)), and the interaction term between year and sex (P(year:sexM)). Significant values are bolded.

Age	P(int)	P(year)	P(sexM)	P(year:sexM)	R-Squared	F statistic
1	**<0.001**	0.730	0.417	0.233	0.008	2.441
2	**<0.001**	0.004	**<0.001**	0.342	0.023	14.541
3	**<0.001**	0.587	0.031	0.082	0.006	3.772
4	**<0.001**	0.053	**<0.001**	0.144	0.091	44.489
5	**<0.001**	0.983	**<0.001**	0.380	0.184	78.727
6	**<0.001**	0.057	**<0.001**	0.166	0.182	69.535
7	**<0.001**	0.160	**<0.001**	0.347	0.253	99.685
8	**<0.001**	0.073	**<0.001**	0.002	0.323	108.411
9	**<0.001**	0.004	**<0.001**	**<0.001**	0.490	200.224
10	**<0.001**	**<0.001**	**<0.001**	0.955	0.490	204.302
11	**<0.001**	**<0.001**	**<0.001**	0.239	0.532	199.444
12	**<0.001**	**<0.001**	**<0.001**	0.545	0.472	121.189
13	**<0.001**	**<0.001**	**<0.001**	0.528	0.467	81.058
14	**<0.001**	**<0.001**	**<0.001**	0.070	0.444	46.264
15	**<0.001**	0.003	**<0.001**	0.056	0.376	26.163
16	**<0.001**	0.264	**<0.001**	0.375	0.497	27.655
17	**<0.001**	0.006	**<0.001**	0.745	0.559	31.724
18	**<0.001**	0.624	**<0.001**	0.407	0.429	12.775
19	**<0.001**	0.108			0.045	2.666
20	**<0.001**	0.017	0.003	0.971	0.442	9.762
21	**<0.001**	0.628			0.006	0.239
22	**<0.001**	0.100			0.075	2.856
23	**<0.001**	0.556	0.006	0.729	0.287	3.889
24	**<0.001**	0.786			0.013	0.081

Table 1.6: Estimates (values) and standard errors (in parentheses) of the coefficients resulting from the linear models analyzing the trends striped bass weight-at-age by year and sex. Age-2 and age-4 through age-18 all found significant differences in length between sex, age-10 through age-14 models found significant differences in length over time, and age-9 had a significant interaction between year and sex.

Age	***Intercept***	***Year***	***Sex***	***Year:Sex***
1	0.19 (0.01)	0 (0)	0.01 (0.01)	0.12 (0.06)
2	0.34 (0.01)	0 (0)	0.05 (0.01)	-0.02 (0.06)
3	0.65 (0.02)	0 (0)	0.04 (0.02)	-0.24 (0.08)
4	1.59 (0.03)	0.01 (0.01)	-0.42 (0.04)	-0.25 (0.09)
5	2.52 (0.05)	0 (0.01)	-0.89 (0.06)	0.02 (0.09)
6	3.3 (0.07)	0.02 (0.01)	-1.16 (0.08)	-0.21 (0.08)
7	4.44 (0.08)	0.02 (0.01)	-1.63 (0.1)	0.09 (0.09)
8	5.75 (0.11)	0.03 (0.02)	-2.07 (0.13)	0.46 (0.1)
9	7.32 (0.1)	0.05 (0.02)	-2.97 (0.15)	0.81 (0.11)
10	8.47 (0.1)	0.13 (0.02)	-3.37 (0.16)	0.24 (0.12)
11	9.53 (0.12)	0.14 (0.02)	-4.06 (0.19)	0.34 (0.13)
12	10.29 (0.14)	0.16 (0.03)	-4.04 (0.24)	0 (0.13)
13	10.57 (0.18)	0.12 (0.03)	-4.06 (0.29)	-0.05 (0.17)
14	12.21 (0.23)	0.18 (0.04)	-4.29 (0.42)	-0.32 (0.18)
15	12.79 (0.31)	0.16 (0.05)	-3.98 (0.56)	-0.65 (0.27)
16	14.69 (0.4)	0.07 (0.06)	-6.52 (0.79)	0.14 (0.26)
17	14.24 (0.36)	0.17 (0.06)	-6.84 (0.79)	-0.38 (0.35)
18	16.29 (0.58)	0.04 (0.09)	-6.98 (1.21)	0.45 (0.38)
19	18.98 (0.83)	-0.25 (0.15)	-10.05 (3.8)	-1.3 (1.78)
20	15.1 (0.9)	0.37 (0.15)	-5.72 (1.77)	1.14 (0.72)
21	17.49 (1.33)	0.1 (0.2)	-10.88 (3.15)	-0.33 (0.67)
22	22.41 (1.5)	-0.34 (0.2)	-18.4 (4.82)	
23	21.4 (1.99)	-0.15 (0.25)	-11.8 (3.98)	0.45 (1.12)
24	20.05 (1.55)	-0.05 (0.19)	-12.3 (2.35)	

Table 1.7: Percent and magnitude of change (kg) in female and male striped bass weight-at-age during 1998-2019.

	Weight			
	Female		Male	
Age	Percent Change	Magnitude	Percent Change	Magnitude
1	3.73	0.01	23.99	0.04
2	-25.78	-0.11	-31.57	-0.15
3	6.48	0.04	-15.20	-0.12
4	17.05	0.26	2.63	0.03
5	0.16	0.00	12.44	0.20
6	13.55	0.44	2.02	0.04
7	9.52	0.42	30.90	0.78
8	12.00	0.68	78.41	2.15
9	15.66	1.11	159.17	3.96
10	38.65	2.85	72.79	2.81
11	36.53	3.06	112.23	4.05
12	39.27	3.51	58.20	2.92
13	28.02	2.71	71.19	3.54
14	35.97	3.87	8.31	0.66
15	30.24	3.50	-10.51	-1.03
16	9.80	1.43	57.37	3.78
17	28.94	3.75	40.07	2.57
18	5.78	0.96	61.38	4.53
19	-23.96	-5.45	-23.96	-5.45
20	70.39	8.13	154.85	8.40
21	12.29	2.12	12.29	2.12
22	-27.39	-7.51	-27.39	-7.51
23	-13.39	-3.23	25.63	2.27
24	-5.50	-1.19	-5.50	-1.19

Figures

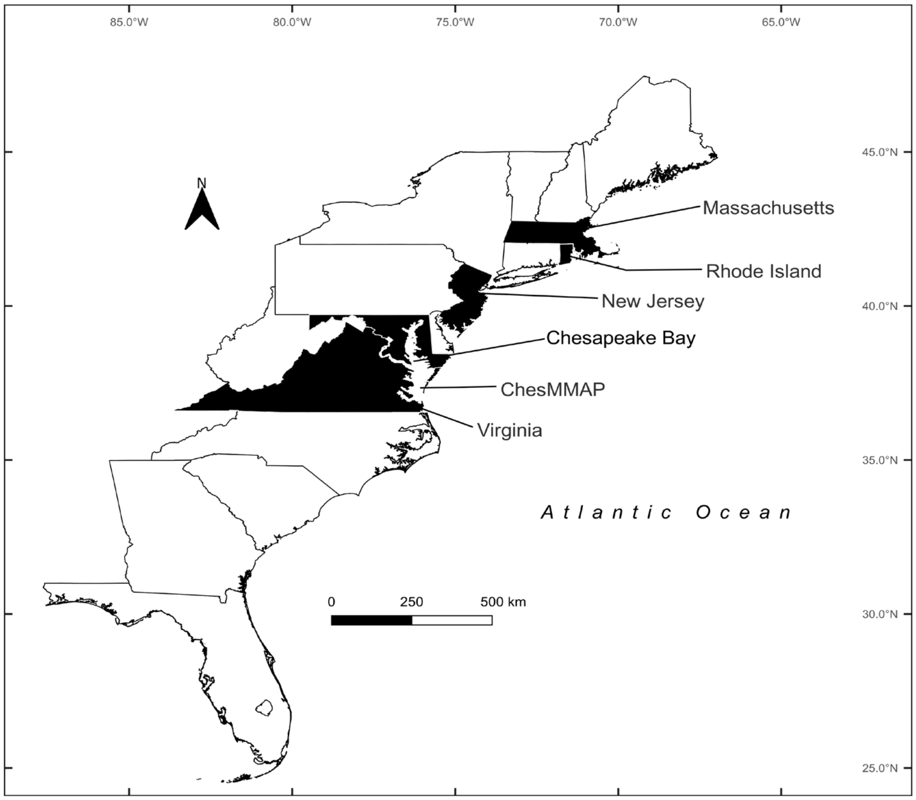

Figure 1.1: Map of the U.S. Atlantic coast with locations of striped bass age, length, and weight data used in this study.

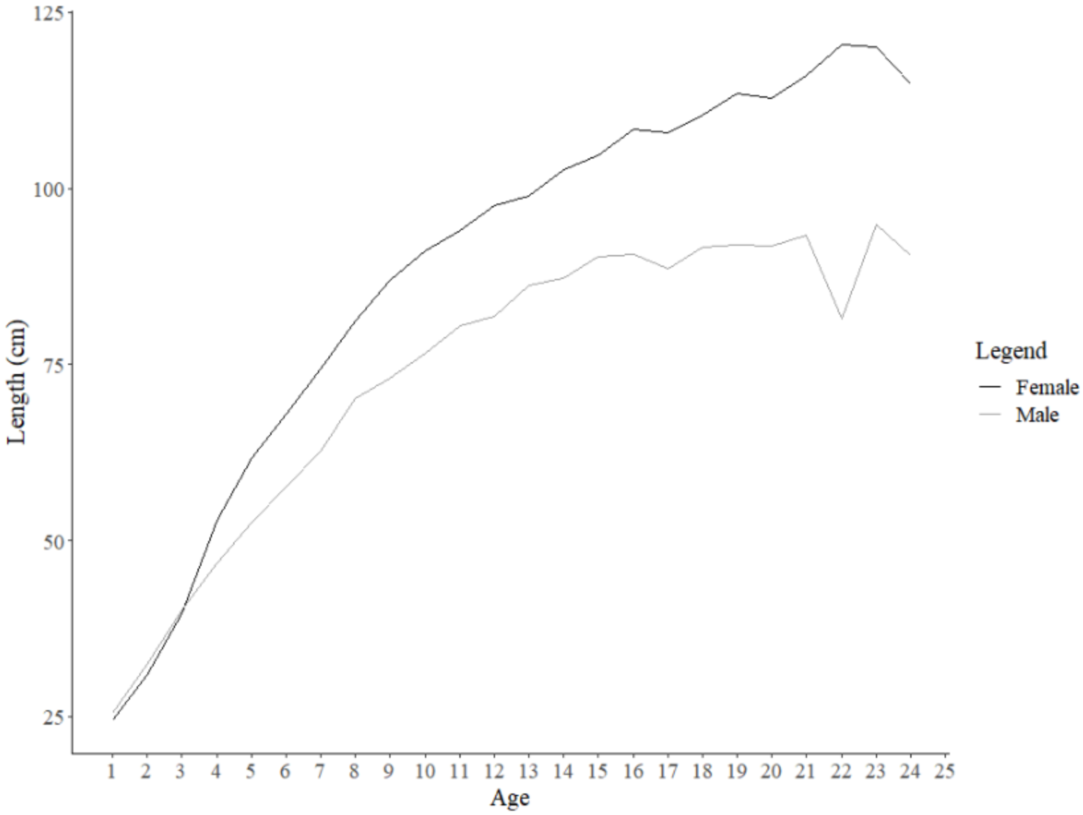

Figure 1.2: Mean length-at-age by sex for striped bass during 1998-2019) using calculation option 3 (Table 1.1).

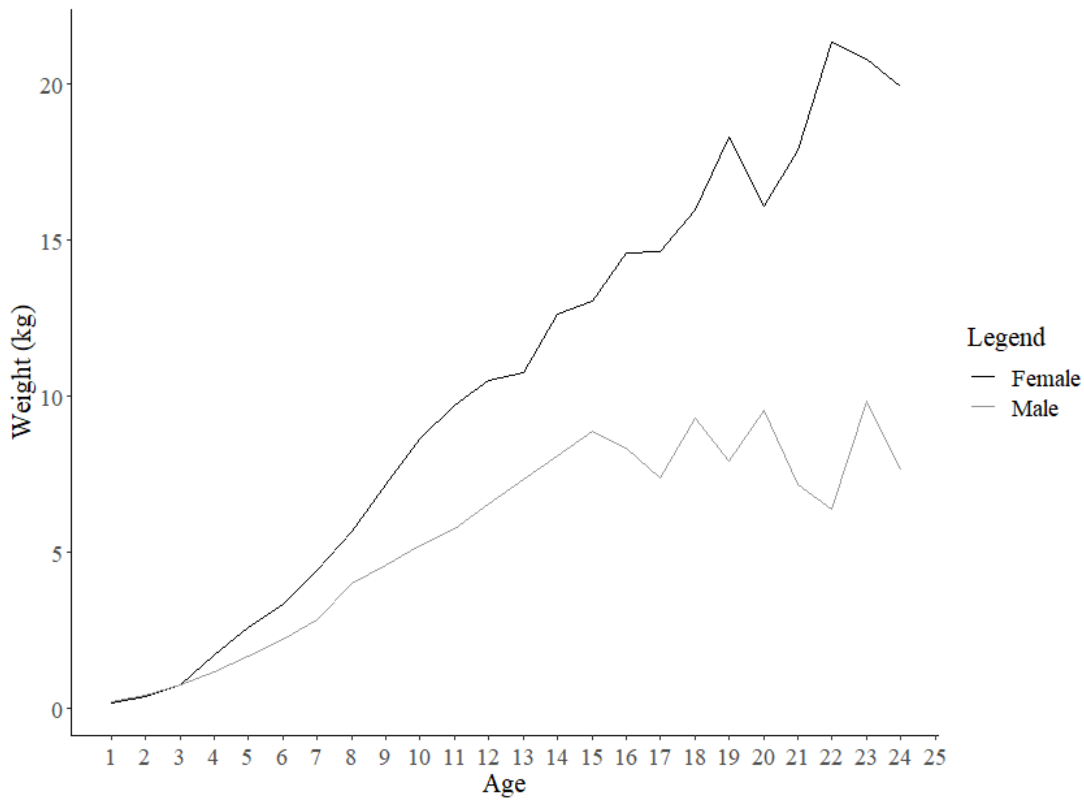

Figure 1.3: Mean weight-at-age by sex for striped bass during 1998-2019 using calculation option 3 (Table 1.1).

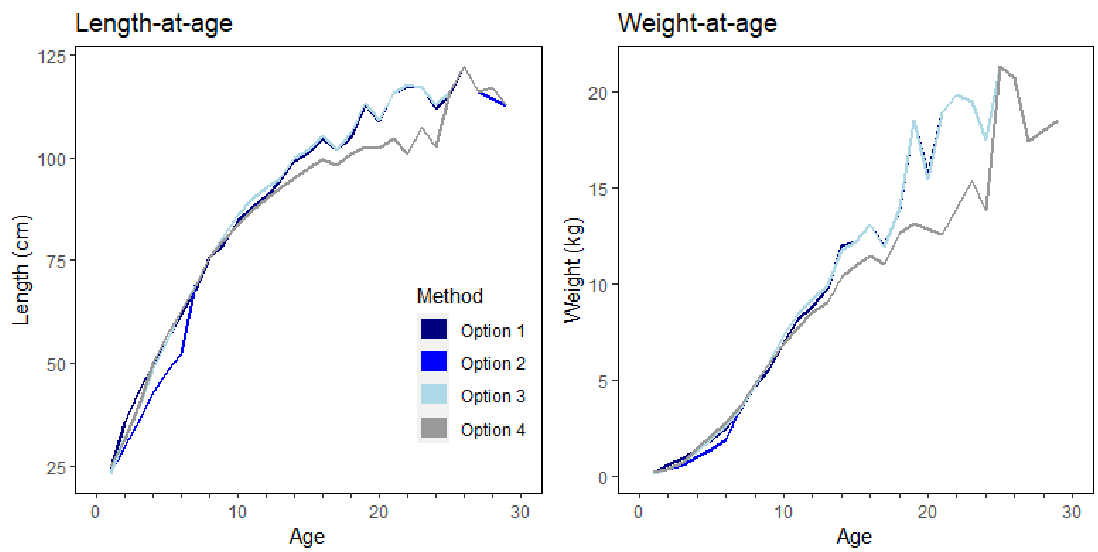

Figure 1.4: Estimated mean length-at-age (left) and mean weight-at-age (right) for four options for calculating length- and weight-at-age of striped bass during 1998-2019. Option 1 (black) is a stratified mean length- and weight-at-age using source as strata. Option 2 (dark gray) depicts truncation of fishery dependent data for age-7 and under. Option 3 (medium gray) is an unstratified mean using all of the data. Option 4 (light gray) is a stratified mean with sex as strata in which the population is assumed to have a 50:50 sex ratio.

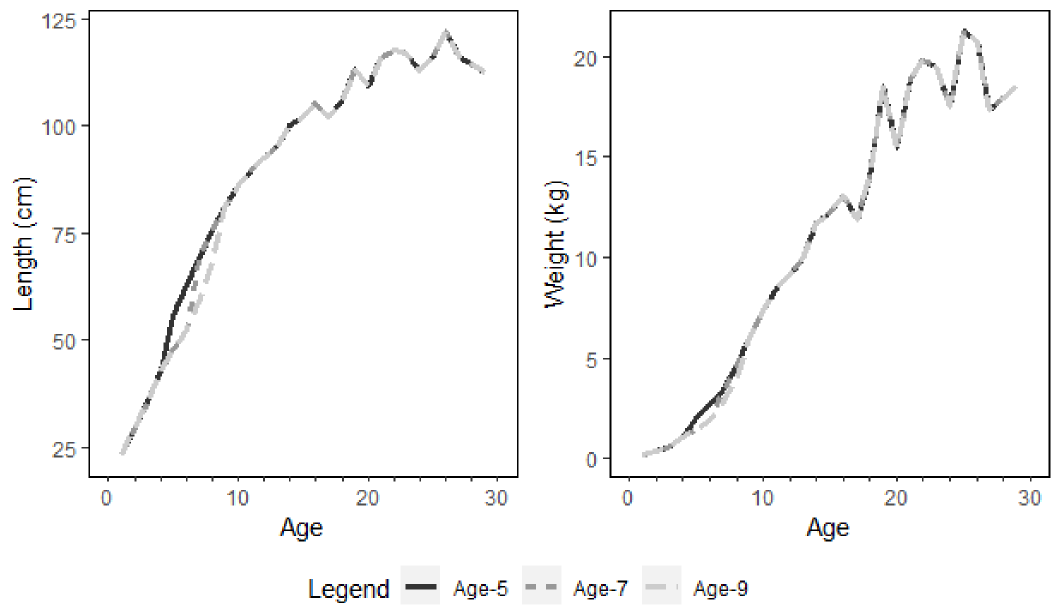

Figure 1.5: Mean length-at-age (left panel) and mean weight-at-age (right panel) estimated using three variations for Option 2 in which fishery-dependent data were excluded for calculating the mean below a specific age. The solid black line represents the mean when fishery-dependent data were excluded for ages < 5. The dark gray short dashed line indicates exclusion of fishery dependent data for ages < 7. The long-dashed light grey line indicates exclusion of fishery dependent for calculating the mean for ages < 9.

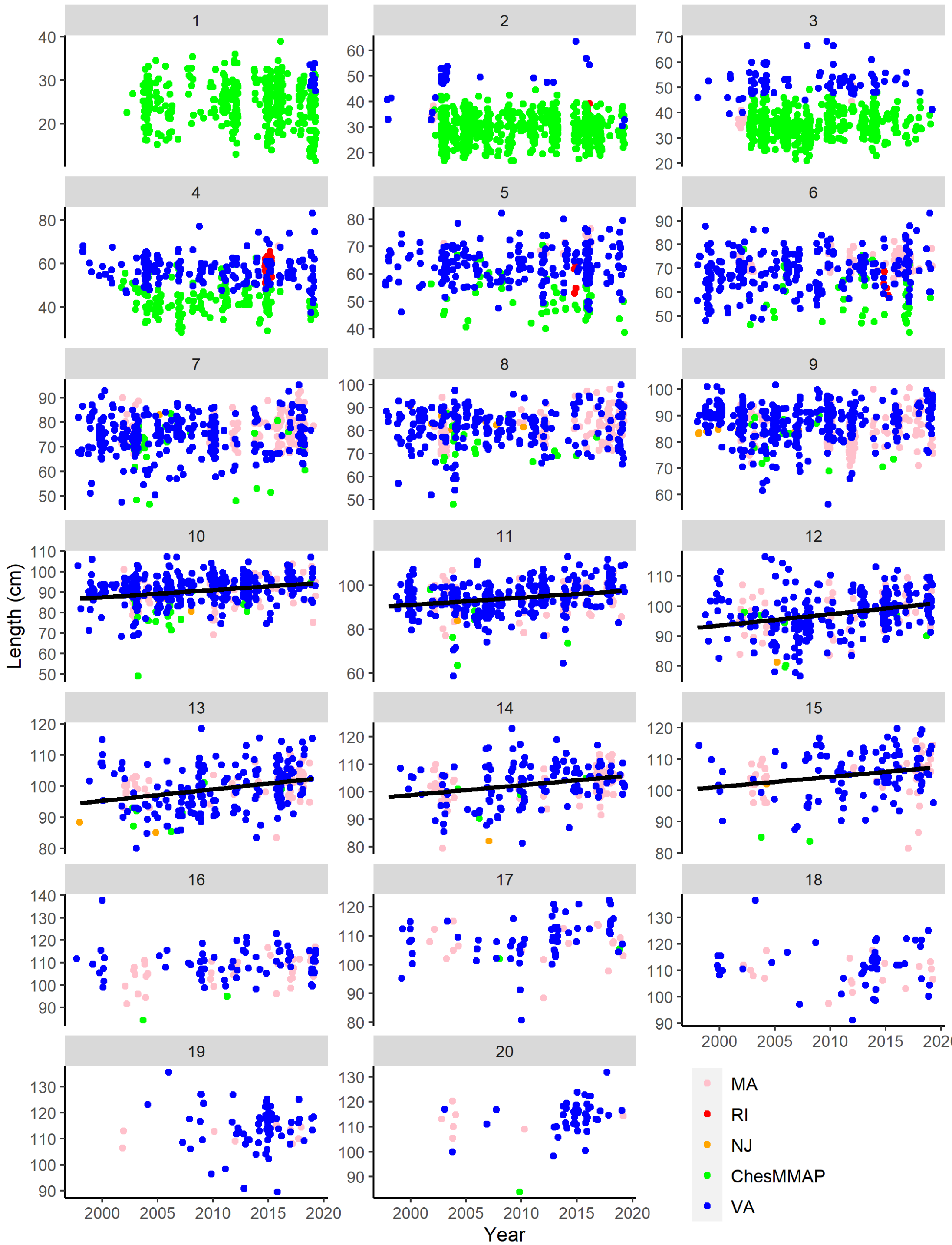

Figure 1.6: Length-at-age data for female striped bass during 1998-2019. Colors indicate sampling programs: Massachusetts (MA; pink), Rhode Island (RI; red), New Jersey (NJ; orange), ChesMMAP (green), and Virginia (VA; blue). ChesMMAP data encompass samples from the Chesapeake Bay in both Maryland and Virginia. Regression lines are included for ages that had significant trends in mean length-at-age over time. Ages are indicated by the numbers at the top of each panel.

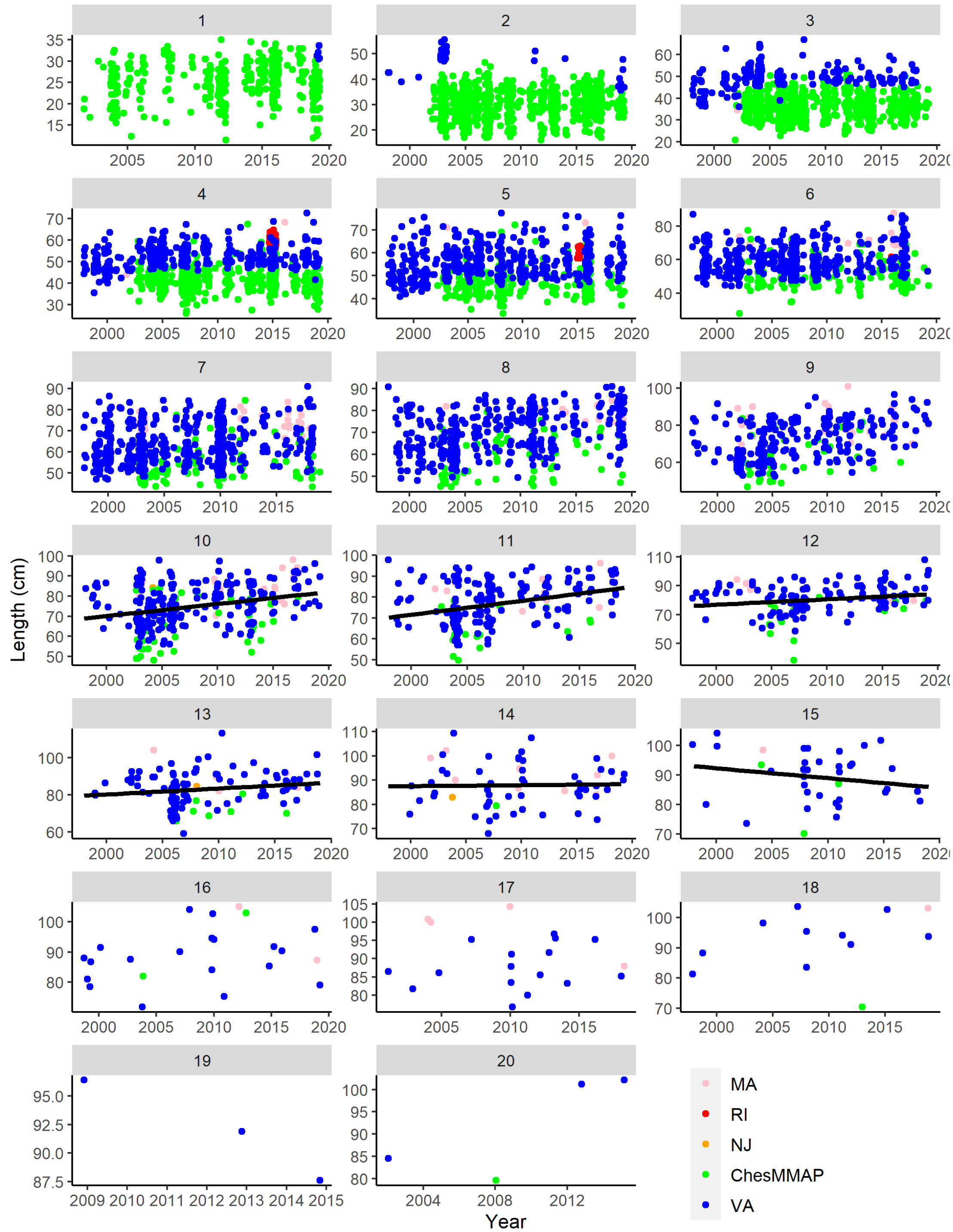

Figure 1.7: Length-at-age data for male striped bass during 1998-2019. Colors indicate sampling programs: Massachusetts (MA; pink), Rhode Island (RI; red), New Jersey (NJ; orange), ChesMMAP (green), and Virginia (VA; blue). ChesMMAP data encompass samples from the Chesapeake Bay in both Maryland and Virginia. Regression lines are included for ages that had significant trends in mean length-at-age over time. Ages are indicated by the numbers at the top of each panel.

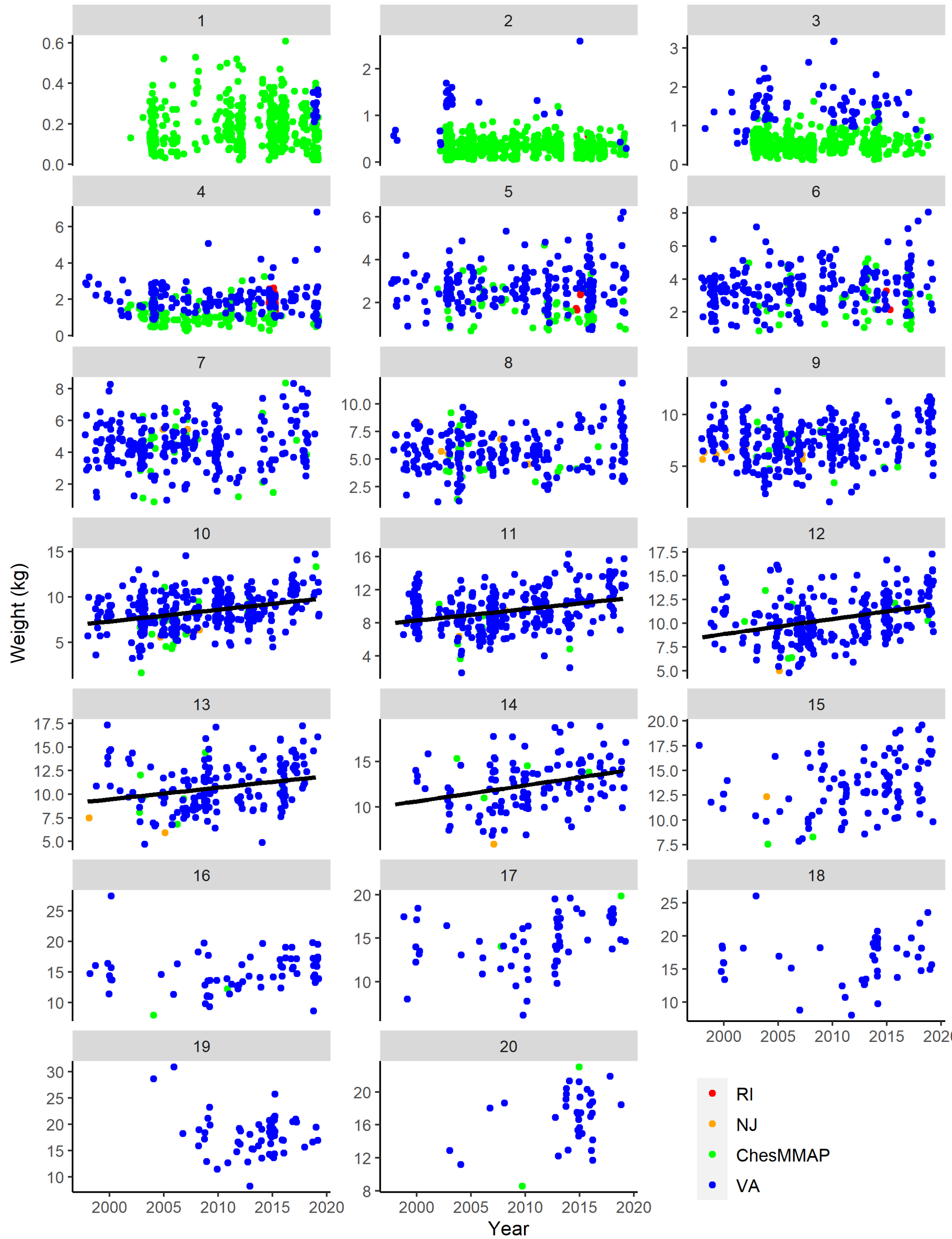

Figure 1.8: Weight-at-age data for female striped bass during 1998-2019. Colors indicate sampling programs: Rhode Island (RI; red), New Jersey (NJ; orange), ChesMMAP (green), and Virginia (VA; blue). ChesMMAP samples include data in the Chesapeake Bay from Maryland and Virginia. Weight-at-age was not sampled for Massachusetts. Regression lines are included for ages that had significant trends in mean weight-at-age over time. Ages are indicated by the numbers at the top of each panel.

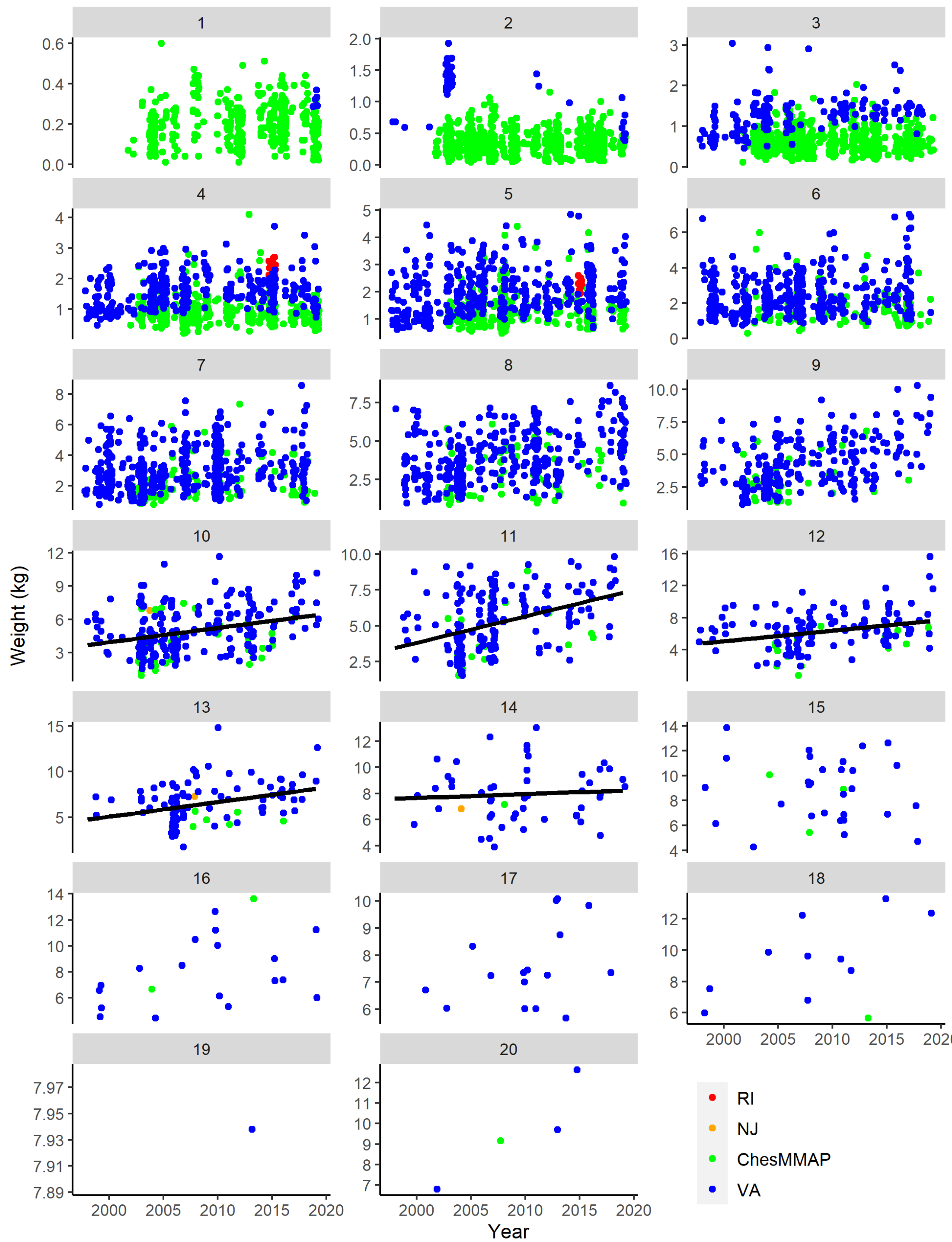

Figure 1.9: Weight-at-age data for male striped bass during 1998-2019. Colors indicate sampling programs: Rhode Island (RI; red), New Jersey (NJ; orange), ChesMMAP (green), and Virginia (VA; blue). ChesMMAP samples include data in the Chesapeake Bay from Maryland and Virginia. Weight-at-age was not samples for Massachusetts. Regression lines are included for ages that had significant trends in mean weight-at-age over time. Ages are indicated by the numbers at the top of each panel.

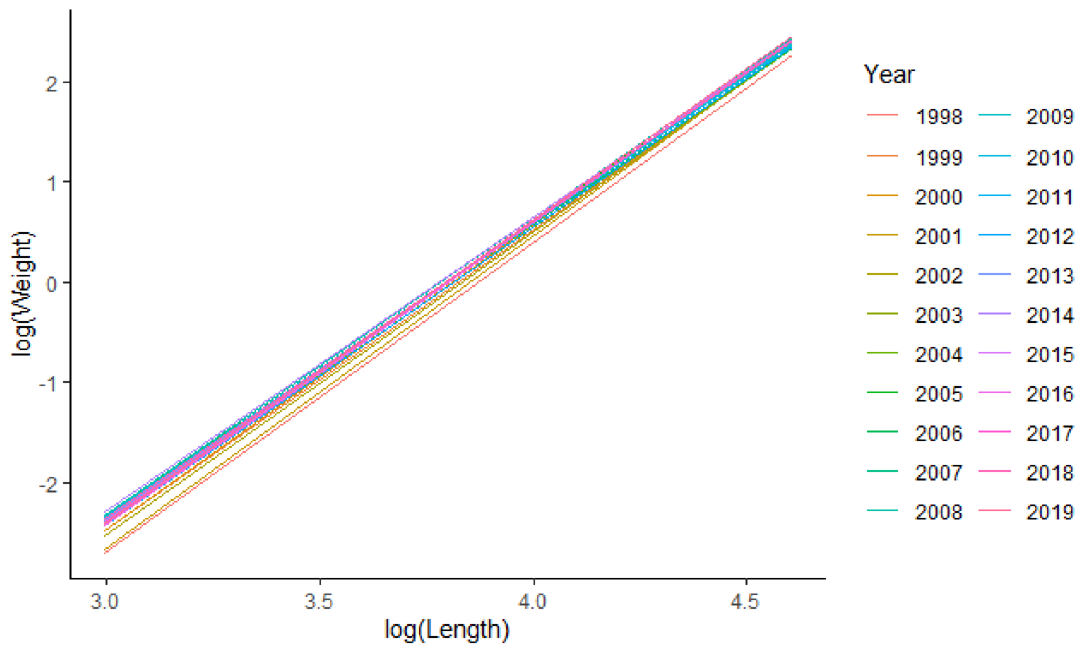

Figure 1.100: Estimated relationship between log(length) and log(weight) of striped bass during 1998-2019 from a random effects model with a random year effect on the slope and intercept.

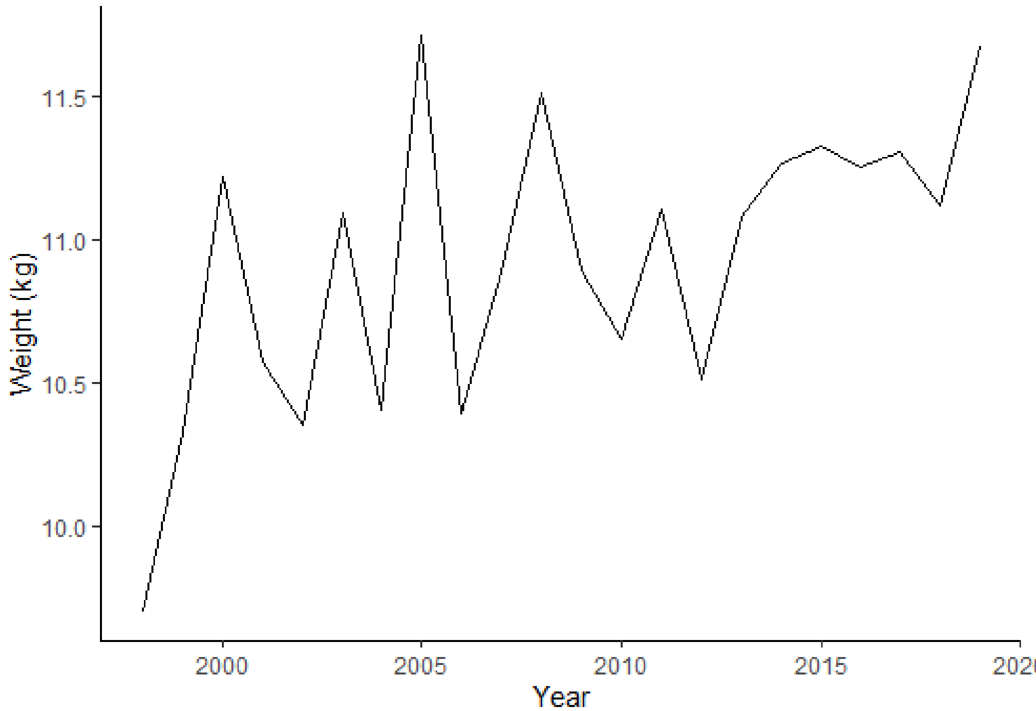

Figure 1.111: The predicted change in weight over time for a 100 cm striped bass (approximately age-15). The model reflected the variability year to year of striped bass weight, but also the increase in size over the entire time series.

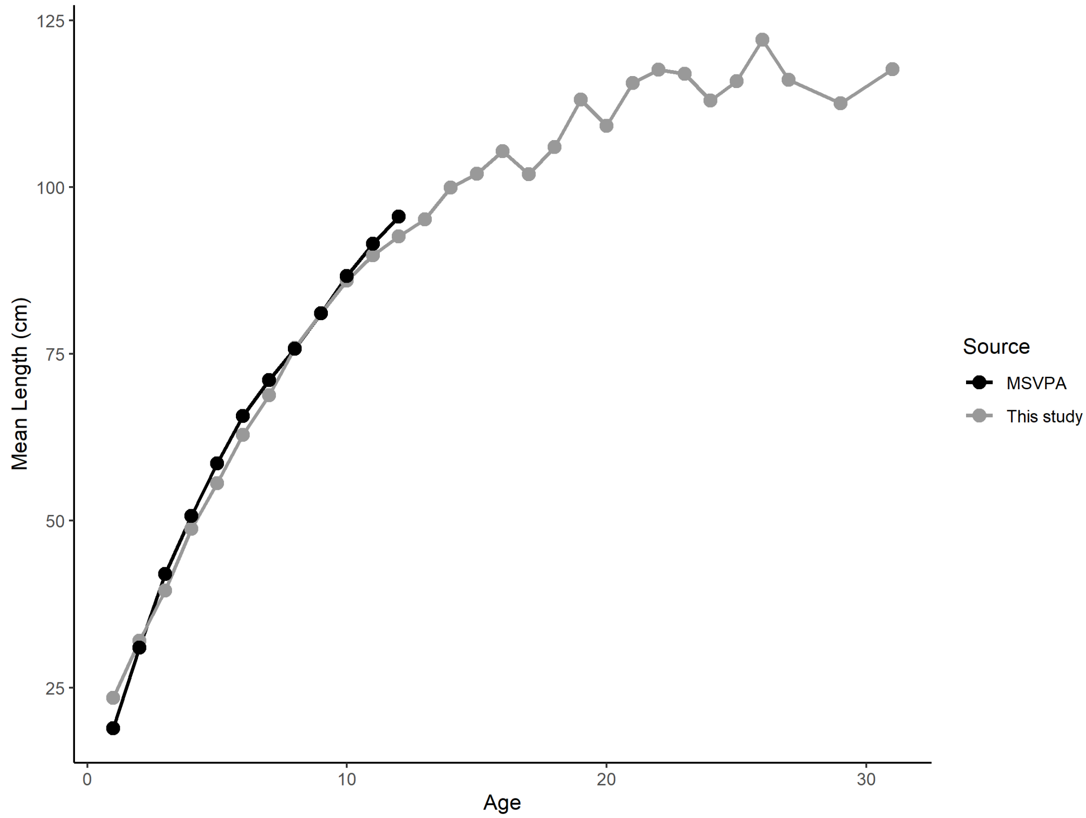

Figure 1.122: Comparisons of mean length-at-age of striped bass during 1998-2019 with mean length-at-age estimated in the Multispecies Virtual Population Analysis (Garrison et al., 2010).

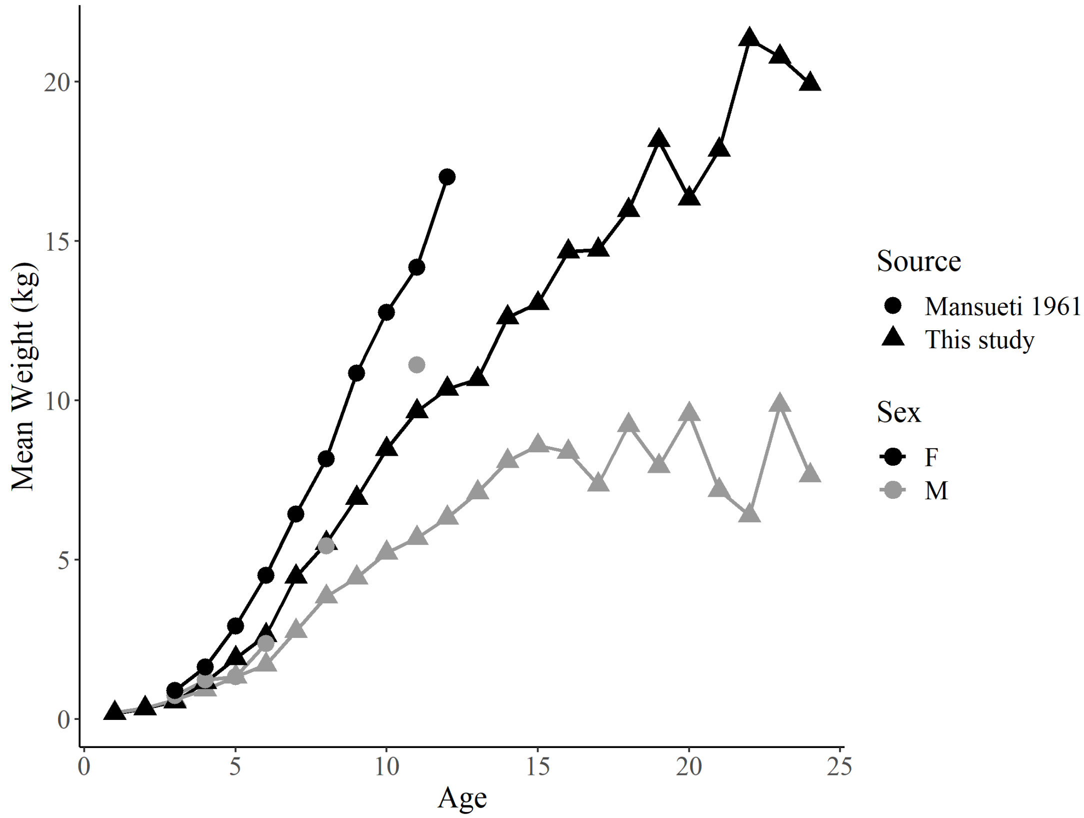

Figure 1.133: Comparison of estimated female (black) and male (gray) weight-at-age of striped bass with Mansueti (1961) estimates.

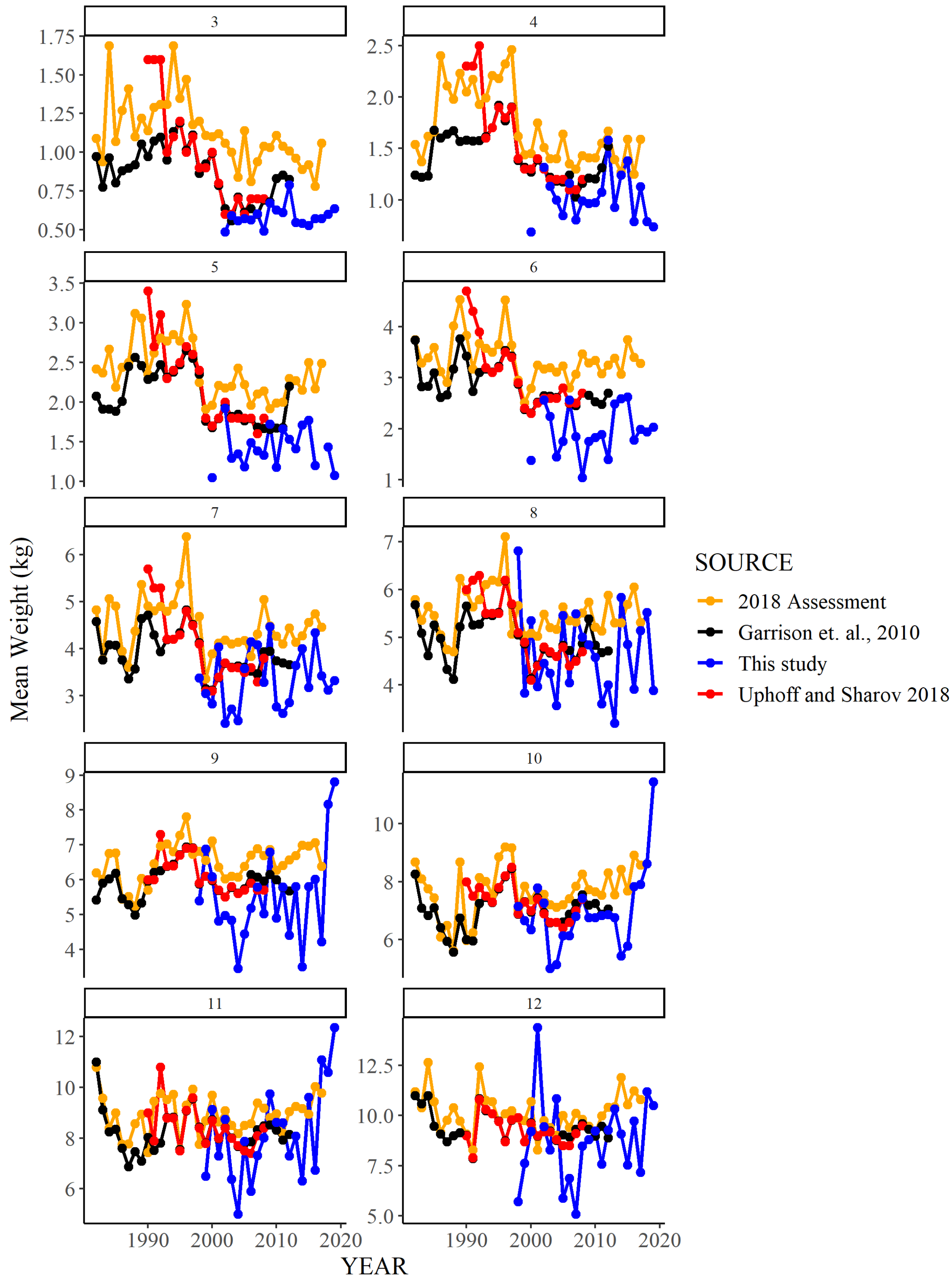

Figure 1.144: Additional comparisons of the estimated weight-at-age of striped bass from this study (blue) over time compared with the current striped bass benchmark stock assessment (2018 Assessment; orange), Garrison et. al. (2010) (black), and Uphoff and Sharov (2018) (red). All studies overlapped in age structure from age-3 through age-12.

Chapter 2: Evaluation of Alternative Harvest Policies for Striped Bass and their Prey, Atlantic Menhaden

Introduction

Ecosystem Approach to Fisheries Management

Ecosystem based fisheries management (EBFM) is an approach to managing fisheries that extends beyond a single species management mindset and incorporates all aspects of the ecosystem including social, economic, and human interactions to better manage the ecosystem as a whole (Dickey-Collas et al., 2022; Link & Browman, 2014). An ecosystem approach to fisheries management (EAFM), as opposed to EBFM, focuses on a single or select group of fisheries and specific processes that link them (Patrick & Link, 2015). EAFM recognizes the interworking of the ecosystem while remaining similar to traditional fisheries management by focusing on individual stocks. EAFM has begun to emerge throughout managing bodies around the East Coast of the U.S. (Gaichas et al., 2018; Koen-Alonso et al., 2019; Muffley et al., 2021). While the concept of EAFM is not new, some misconceptions about and complexities of these approaches have impeded implementation in management such as lack of a management structure that can incorporate EAFM and limited data availability to develop models that encompass the entire ecosystem (Patrick & Link, 2015). Despite these challenges, agencies like the Mid-Atlantic Fisheries Management Council and the Atlantic States Marine Fisheries Commission (ASMFC) have shifted towards goals and objectives incorporating ecosystem aspects such as predator-prey and multispecies interactions (Drew et al., 2021; Gaichas et al., 2018).

Although fish stocks have traditionally been managed on a single species basis, applications of EAFM are growing (Drew et al., 2021; Garrison et al., 2010; McGowan et al., 2011). Yet even within these contexts, many species are still managed at a single species level without adding in considerations for the ecosystem. While managing on a single species basis can be highly useful and a better alternative to limited or no management (Hilborn & Ovando, 2014), taking an EAFM approach makes it possible to better understand the effects of fishing on ecosystem interactions such as predator-prey relationships (Mace, 2001). Studying a limited set of interactions makes for more tractable models to provide management advice for more than a single species (Mace, 2001). Barriers to implementing EAFM such as lack of data, expenses in the long term, and competing interests among single species fisheries, can cause difficulties for the application of the science and the adoption of reasonable EAFM actions (Koen-Alonso et al., 2019; Safiq et al., 2021). The interconnected nature of EAFM requires strong and clear communication among scientists, managers, and stakeholders, as well as willingness from management bodies to implement this approach consistently over the long-term (Koen-Alonso et al., 2019; Safiq et al., 2021).

Predator-Prey Dynamics

Predator-prey systems are an area where EAFM is actively being applied. Predator-prey dynamics are important to consider when managing fish stocks because predators and prey affect each other’s population structures through metrics like predation mortality and predator relative weight (Bailey et al., 2010). In predator-prey models, predation mortality (M_2) is the mortality of a prey species resulting from predation by one or more predators (Curti et al., 2013). In a strong predator-prey system, predation mortality can heavily influence the natural mortality (M) of the prey and in response affect the biomass of the prey available for harvest. Predation can vary depending on the rate at which a prey is consumed by a predator as a function of the prey's density (i.e., functional response) and abundance of the predators (Abrams & Ginzburg, 2000).

Previous studies have investigated multispecies predator-prey interactions and explored the effects on their fisheries. For example, Multispecies Virtual Population Analysis (MSVPA) has been applied to multiple predator-prey based fisheries in the U.S. and Europe (Gislason & Helgason, 1985; Helgason & Gislason, 1979). This type of analysis has allowed scientists to evaluate the effects of fishing on stocks that are connected through multiple trophic interactions (Garrison et al., 2010). The Lenfest Forage Fish Task Force also evaluated multiple predator-prey interactions within several ecosystems (Pikitch et al., 2012). The task force specifically evaluated the reliance of piscivorous predators in multiple ecosystems on their forage fish prey, and came to the conclusion that piscivorous predator conservation is a part of forage fish management that should be considered (Pikitch et al., 2012; Pikitch et al., 2014). Predator-prey interactions have also been explored along the U.S. East Coast by Buchheister et al. (2017) by taking an ecosystem approach to developing reference points for Atlantic menhaden (*Brevoortia tyrranus*). In their study, an Ecopath with Ecosim model was used to evaluate the impacts of Atlantic menhaden management on multiple key predator species. Atlantic menhaden stock reference points were developed relative to striped bass (*Morone saxatilis*), the predator that had the greatest response to changes in Atlantic menhaden biomass (Chagaris et al., 2020). Incorporating predator-prey interactions within management can support predator stocks by ensuring adequate prey supply and help evaluate trade-offs that may occur when fishing forage fish stocks (Pikitch et al., 2012)

Harvest Control Rules

To achieve their goals and objectives, fishery managers must determine how often and how much harvest to allow. Historically, much of fisheries management has been reactive, only changing harvest or fishing mortality rates when biomass levels are declining or critical (Nelson, 2018; Richards & Rago, 1999). This method of management revolves around a short-term mindset (Mardle & Pascoe, 2002). To break the cycle of short-term management focus and rebuild or avoid having to rebuild stocks, explicit guidelines should be set to responsibly manage harvest in the long term (Deroba & Bence, 2008). Harvest control rules (HCRs) are automatic management procedures that are agreed upon in advance and that dictate the rate of fishing that can take place. Fishing mortality (F) is commonly used as a control variable to determine harvest levels in traditional HCRs by setting catch as a proportion of the stock relative to the stock size (Punt, 2014). HCRs take a top-down management approach that can help formalize catch limit-setting decisions and help prevent or prepare a response to an overfishing and overfished stock status (Kvamsdal et al., 2016). HCRs are rule-based rather than model-based management which allow for management responses to be predetermined by establishing how the fishery responds as stock size or another metric changes (Kvamsdal et al., 2016; Thompson, 1999).

There are many different variants of HCRs. HCRs range from simple, one-parameter approaches to complex, multi-parameter control rules (Thompson, 1999). Many HCRs approach management from a single species standpoint by controlling harvest or F in relation to the biomass of a single species. Some examples of single species HCRs include constant F and biomass-based HCRs (Deroba & Bence, 2008) (Figure 2.1). Constant F control rules are less complex compared to other HCRs because harvest is based on a single target F regardless of the stock's biomass. Constant F HCRs exhibit satisfactory performance in some management scenarios and have low implementation costs (Deroba & Bence, 2008). However, a constant F HCR can lead to poor management outcomes if it results in high F at low biomass. Therefore, biomass-based HCRs that decrease F as stock biomass declines have increasingly been adopted (Deroba & Bence, 2008). Such harvest control rules can take a 'hockey-stick' form in which F decreases linearly as spawning stock biomass (SSB) decreases below a specified level (Figure 2.1).

Dynamic multispecies HCRs (DMSHCR), in which the target F rate of one species depends at least partially on the status of another species, have been considered in the literature (Pérez-Rodríguez et al., 2022). In the case of Pérez-Rodríguez et al (2022), it was not possible to balance DMSHCRs among a three species predator-prey system, demonstrating the difficulty in managing three fisheries simultaneously. If DMSHCRs are not properly tuned, they may result in significant reduction in one of the stocks. Their study references "two-staged" HCRs which operate as two hockey-stick HCRs stacked where two slopes of increasing F change based on SSB thresholds. “Two-staged” HCRs may provide a better balance of the ecosystem and fisheries (Pérez-Rodríguez et al., 2022). They also found that susceptibility of fish stocks to fishing and predation pressure are also factors that impact the success of DMSHCRs (Pérez-Rodríguez et al., 2022).

Target Species

Striped Bass

Striped bass support one of the largest recreational fisheries on the U.S. East Coast, but is currently overfished and experiencing overfishing (NEFSC, 2019). The management goal for the stock is to maintain the age-structure of the stock in the long term through cooperative, interstate fishery management (ASMFC, 2022). The coastal migratory stock is managed using a constant F HCR that is intended to achieve a target SSB (SSB_{TARGET}=125% of female SSB estimate from 1995 when the stock was declared recovered from an overfished state). This HCR is implemented through a complex set of state-specific regulations intended to achieve the target F. Despite this goal, F in recent years has exceeded target levels. Therefore, ASMFC recently implemented management measures that are designed to bring the stock above its target SSB and below its target F (ASMFC, 2022). The ASMFC also aims to adopt effective long-term management that will avoid annual responsive actions (ASMFC, 2022). Striped bass management continues to operate on a single species basis. However, striped bass biomass may be highly influenced by key prey species, such as Atlantic menhaden (Chagaris et al., 2020), and that ecosystem perspective is not currently incorporated in the striped bass fishery management plan.

Atlantic Menhaden

Atlantic menhaden is a key forage fish for many piscivorous predators along the U.S. Atlantic Coast, including striped bass (Buchheister et al., 2017). The Atlantic menhaden fishery is the largest commercial fishery by volume on the U.S. East Coast (NMFS, 2020) and is primarily used for reduction into fish oil and fish meal as well as for bait (Smith, 1991). Similar to striped bass, Atlantic menhaden fisheries operate under an ASMFC interstate fishery management plan. The stock is neither overfished nor experiencing overfishing (SEDAR, 2020b). However, concerns about the availability of Atlantic menhaden to support striped bass have caused ASMFC to move towards a more holistic management approach that takes into account the predator-prey relationship between these species. Atlantic menhaden are managed with a multispecies focus by selecting an F target and threshold for Atlantic menhaden that achieves the biomass target and threshold of their predator, striped bass, while fishing the predator at their target F (Chagaris et al., 2020; Drew et al., 2021). The management goals for Atlantic menhaden include sustaining biomass to provide for both its fisheries and its predators, minimizing risk of stock collapse, and ensuring an adequate supply of menhaden for predators (ASMFC, 2015).

There is a desire among management agencies to incorporate EAFM in their decisions in order to better account for the impact of fisheries on the ecosystem as a whole. While ASMFC has implemented management of Atlantic menhaden based on its most reliant predator, striped bass, the HCRs for Atlantic menhaden and striped bass are still single species constant F HCRs. The important, high-profile predator-prey relationship of Atlantic menhaden and striped bass in the mid-Atlantic makes them a strong candidate for evaluating impacts of single species and multispecies HCRs on their respective stocks and fisheries. Previous studies have yet to test dynamic single species HCRs and multispecies HCRs for Atlantic menhaden and striped bass. The goal of this chapter was to evaluate the performance of a suite of harvest control rules on the Atlantic menhaden and striped bass stocks and fisheries. My objectives were to 1) quantify the ability of single and multispecies HCRs to meet ASMFC's goals for the Atlantic menhaden and striped bass fisheries, and 2) explore the trade-offs among HCRs for striped bass.

Methods

Predator Prey Simulation Model

I conducted a harvest policy evaluation using an updated age-structured, linked, predator-prey simulation model (Nesslage & Wilberg, 2019) to test a suite of new and existing HCRs on striped bass and Atlantic menhaden. The predator-prey simulation model simulated the age-structured population dynamics for striped bass ages 1-20+ and Atlantic menhaden ages 0-6+. The model reached steady states (with differences due to stochastic variation) by 100 years, so I ran the simulations out to 100 years for all HCRs. I incorporated life history data and abundance estimates from the most recent stock assessments as inputs into the model. I also reviewed the striped bass diet literature and generated prey importance scenarios for the range of observed dependence of striped bass on Atlantic menhaden. The model used a multiple predator and multiple prey type II functional response to model the consumption dynamics of multiple ages of striped bass and Atlantic menhaden. The model also included a static set of eight alternative prey sources that differed in their size and biomass to supplement the remainder of the striped bass diet. Striped bass weight-at-age varied over time based on their consumption. Consumption of Atlantic menhaden by striped bass influenced M_2 and total M of Atlantic menhaden. In turn, striped bass M was influenced by its weight-at-age, which was a function of consumption.

I generated a suite of both single species HCRs and DMSHCRs and I evaluated how well each HCR met the objectives for each stock set by ASMFC. The modeling was conducted in AD Model Builder (Fournier et al, 2012) and the harvest control rules and analyses were conducted in R (RStudio team, 2020). Parameter and variable definitions are provided in Table 2.1, model dynamics equations are provided in Table 2.2, and equations defining the HCRs are provided in Table 2.3. For each HCR, 100 stochastic simulations were run.

Predator-Prey Model

The predator-prey simulation model used age-structured population dynamics models for striped bass and Atlantic menhaden that were based on Tsehaye et al. (2014). The model included four intra-annual time steps (season 1: January to March, season 2: April to June, season 3: July to September, season 4: October to December). Parameter values for the model were estimated from outside analyses including the most recent stock assessments (NEFSC, 2019; SEDAR, 2020b). Appendix B describes stock recruitment and consumption analyses that were performed outside the operating model in order to develop sets of plausible parameters.

Recruitment and abundance-at-age were calculated using similar equations for striped bass and Atlantic menhaden. Initial abundance-at-age for each species was the estimated abundance-at-age from the most recent year in their respective stock assessments. Recruits were calculated for the first season of each year following a Beverton-Holt stock-recruitment function (Eqn. T.2.2.1). Recruitment of striped bass was calculated based on SSB of the previous year (Eqn. T.2.2.1) while Atlantic menhaden recruitment did not include a lag (Eqn. T.2.2.2). Recruitment included a multiplicative lognormal error that followed a first order autoregressive process over time (Eqn. T.2.2.3; Atlantic menhaden autocorrelation = 0.31, striped bass autocorrelation = 0.22) that also included correlation between the recruitment deviations of two species (-0.11). Stock-recruitment parameters were estimated by conducting stock-recruitment analyses that used the SSB and recruitment from the respective stock assessments. Stock size for the stock-recruitment models was calculated in terms of female SSB. Recruitment represented age-1 for striped bass and age-0 for Atlantic menhaden. After the first age, abundance of a cohort throughout each season declined following the exponential mortality model (Eqn. T.2.2.4). The abundance in the first season was calculated using the abundance in the previous age and season 4 of the previous year (Eqn. T.2.2.5). Abundance of age 20+ in the first season was calculated similarly to equation T.2.2.5, but the abundance in the last season of the previous age was added to abundance of survivors age-20+ (Eqn. T.2.2.6).

Total instantaneous mortality for striped bass and Atlantic menhaden was calculated as the sum of F and M for a given time step and age (Eqn. T.2.2.7, Eqn.

T.2.2.8). The proportion of F in each season was specified based on historical averages of the annual catch in each season. The F in the first year was set at the status quo values: 0.307 yr^{-1} for striped bass and 0.157 yr^{-1} for Atlantic menhaden. In subsequent years, the value for F depended on the HCR applied (Table 2.4). The background natural morality for each age was constant and divided evenly among the four seasons. Striped bass M was higher when their relative weight was low (M_c) to include starvation mortality for striped bass that could not consume enough prey (Hoenig et al 2017). M_c was calculated such that if an estimated fraction of striped bass at an age were below a threshold relative weight (Eqn. T.2.2.9), the striped bass in that age class experienced higher M (Eqn. T.2.2.11). Relative weight at age was calculated based on the relative weight in the previous season (Eqn. T.2.2.12). Striped bass standard relative weight was calculated as a function of their length, as input from a smoothed geometric mean calculated in Chapter 1, and parameters extracted from Hoenig et al. (2017) (Eqn. T.2.2.10). The estimated weight at length 0 cm was $10^{-4.924}$ and the shape parameter for striped bass was estimated at 3.007 for the denominator of the relative weight equation. Appendix B includes additional description of the striped bass length-weight relationship.

The threshold for striped bass low relative weight was designed to represent the results of Hoenig et al. (2017) who estimated that striped bass with poor relative weight experienced higher mortality rates than striped bass with good relative weight (See Appendix B). For Atlantic menhaden, M_2 was a function of consumption by striped bass (Eqn. T.2.2.13). The M for a given season for Atlantic menhaden was a combination of M_2 and M_1, where M_1 was a proportion of constant M-at-age in a given season sourced from the most recent Atlantic menhaden stock assessment (Eqn. T.2.2.14). M_1 values for striped bass and Atlantic menhaden were chosen such that the M in the status quo scenario was approximately equal to the M-at-age vectors specified in their respective stock assessments. By holding Atlantic menhaden M_1 constant, a Type 1 functional response was assumed for all Atlantic menhaden predators other than striped bass.

Striped bass weight-at-age was the product of their maximum potential growth (*Gmax*) at a given age and their consumption relative to their maximum potential consumption (*Cmax*) (Eqn. T.2.2.15). The *Gmax* and *Cmax* parameters were calculated outside of the predator-prey simulation model using approximate changes in mean weight-at-age of striped bass in Chapter 1, assuming equal growth rates throughout the year (See Appendix B). *Gmax* was estimated by assuming that striped bass achieved 90% of their maximum potential consumption in 2017. *Cmax* was calculated using *Gmax* and the conversion efficiency of striped bass from Hartman and Brandt (1995) for age-1 and age-2 and Nelson et al. (2006) for ages 3 -12. I used smoothed geometric mean striped bass length- and weight-at-age as calculated in Chapter 1 for the sizes-at-age in the first time step of the simulation.

Striped bass consumption was based on a normally distributed size preference function of prey length and optimum prey size (Eqn. T.2.2.16). The optimum prey size was based on Ruderhausen et al. (2005). The total consumption of prey (Eqn. T.2.2.17) by striped bass was calculated as the product of an instantaneous consumption rate (Eqn. T.2.2.18) and instantaneous attack rate (Eqn. T.2.2.19) of each prey type for each age of striped bass. The instantaneous consumption rate was a function of prey abundance, weight, and the instantaneous attack rate, while the instantaneous attack rate was a function of length and size preference. While Atlantic menhaden ages-0 to 6+ were modelled dynamically, the consumption model included an additional eight static alternative prey categories based on size. The alternative prey pool provided striped bass an additional prey source that influenced their growth. Alternative prey categories 2-8 were assumed to have the same mean length and weight as Atlantic menhaden ages 0-6+. Alternative prey category 1 had a mean length of 59 mm and weight of 0.01 kg to represent prey smaller than an age-0 Atlantic menhaden (e.g., bay anchovy (*Anchoa mitchilli*)).

Harvest Control Rules

Reference points for both striped bass and Atlantic menhaden were developed by running a suite of constant F HCRs as in Chagaris et al. (2020). A total of 336 single species, constant F HCRs were run ranging in F rate from 0 to 1.49 yr^{-1} for Atlantic menhaden and 0 to 0.47 yr^{-1} for striped bass. I estimated unfished SSB (SSB_0) of striped bass and Atlantic menhaden as the geometric mean of striped bass and Atlantic menhaden SSB when F was 0 yr^{-1}. I also plotted yield curves in order to estimate the F that achieved maximum sustainable yield (F_{MSY}) and the SSB at F_{MSY} (SSB_{MSY}) for both striped bass and Atlantic menhaden. Lastly, I used these constant F HCRs to compare model performance and predator-prey dynamics with that of the Northwest Atlantic Continental Shelf (NWACS) Model of Ecosystem Complexity for Ecosystem Assessment (MICE) used in Atlantic menhaden management (Chagaris et al. 2020).

A suite of 27 HCRs was evaluated to assess their relative performance (Table 2.4). I considered three classes of HCRs: Type 1 – traditional single species HCRs for both striped bass and Atlantic menhaden (Figures 2.2-2.3); Type 2 – HCRs in which F on one species was a linear function of relative SSB for the other (Figures 2.4-2.5); and Type 3 – traditional single species HCRs for striped bass and threshold-based cessation of fishing for Atlantic menhaden when striped bass fall below a relative SSB threshold (Figures 2.6-2.7). Each HCR determined the annual F of either striped bass or Atlantic menhaden in response to relative SSB from the previous year. Relative SSB was calculated by dividing SSB in the previous year by either the striped bass SSB target (114 million kg; NEFSC, 2019) or Atlantic menhaden SSB target (843 million kg). The current Atlantic menhaden SSB target is in number of eggs (SEDAR, 2020b). Therefore, it was converted into weight (millions of kg) by finding the SSB that achieved the target fecundity using a spawning potential ratio model. Type 1 HCRs included both constant F HCRs and biomass-based HCRs, specifically the "hockey stick" shaped HCR (Deroba & Bence, 2008; Pikitch et al., 2012).

Type 1 HCRs were single-species rules in which the status of the other species was not considered in determining the target F. All type 1 HCRs were calculated such that if all parameters other than the upper F were 0, the HCR would be a constant F at the upper F. When the HCR was biomass-based, F was calculated based on the SSB of the previous year and SSB upper and lower thresholds and the lower and higher F (Eqn. T.2.3.1; Table 2.4).

Type 2 HCRs were DMSHCRs in which the state of another species guides F on the target species (Figures 2.3-2.4). In this predator-prey system, type 2 HCRs dictated that F for striped bass changed in response to the SSB of Atlantic menhaden and vice versa (Eqn. T.2.3.2). To my knowledge, this type of HCR has not been considered in management. This type of HCR was created based on a study by Pérez-Rodríguez (2022) which used multispecies 'one' or 'two-stage' HCRs that take a hockey-stick shape and function in a stepwise manner. In my study, the HCR is applied to a predator-prey system with an unspecified alternative prey and there is no stepwise function, but a singular slope relating SSB to F.

Type 3 HCRs involved a threshold-based cessation of fishing for the prey species when predator biomass was below a predetermined level (Figures 2.5-2.6). This type of HCR was only applied to Atlantic menhaden where their F was determined by striped bass relative SSB. If striped bass SSB was under a specified threshold, then F was 0 yr^{-1} otherwise F was at the designated rate (Eqn. T.2.3.3).

In the suite of HCRs I developed, there were 18 Type 1, six Type 2, and three Type 3 HCRs. Of the 18 Type 1 HCRs, ten were constant F HCRs and eight were biomass-based harvest control rules (Table 2.4). HCR 1 implemented the status quo constant F rates for both species and was used as a reference control rule for comparison with the others. HCR 1 was referred to as the baseline run. HCR 2 operated under the target F rate for both fisheries (F of 0.204 yr^{-1} for striped bass and 0.157 yr^{-1} for Atlantic menhaden). This scenario was designed to understand the response of the stocks if management was achieving its targets. HCR 3 represented fishing at the mean F of striped bass or Atlantic menhaden during 1998-2017 (F of

0.258 yr^{-1} for striped bass and 0.18 yr^{-1} for Atlantic menhaden). This time frame was used to describe recent average fishing pressure of striped bass and Atlantic menhaden. HCRs 4-10 were developed to test model dynamics and performance under various scenarios. These HCRs used either an F of 0 yr^{-1} or a high F that collapsed the stock. In HCR 4, both stocks were unfished (F=0 yr^{-1}). This HCR was used to develop reference points of SSB_0, SSB_{MSY}, and F_{MSY} which were used in HCRs 12-14, 16-18, and 27. Although these HCRs were useful for testing model performance and examining stock dynamics, they were not considered viable options that would achieve management goals, and thus were not included in the HCR comparison for management performance.

HCRs 12-14 represented the low, intermediate, and high information tier scenarios of recommended forage fish HCRs from the Lenfest Forage Fish report (Pikitch et al. 2012). All three scenarios used a Type 1 biomass-based HCR with varying proportions of SSB_0 of Atlantic menhaden as their upper and lower SSB thresholds. HCR 12 and 13 were threshold-based cessation HCRs for Atlantic menhaden. HCR 12 operated at a threshold such that Atlantic menhaden F was 0 yr^{-1} if Atlantic menhaden SSB was less than 0.8 SSB_0. Above this threshold, F was at Atlantic menhaden status quo. In HCR 13, F was 0.5 of F_{MSY} when SSB was above 40% of SSB_0, and F was 0 yr^{-1} if SSB was less than 40% SSB_0. HCR 14 followed a hockey-stick shape in which the lower SSB threshold was 25% of Atlantic menhaden SSB_0 and the upper threshold was at 85% of SSB_0. The lower F for this HCR was 0 yr^{-1} and the upper F was 75% of Atlantic menhaden F_{MSY}. In all three of these HCRs, striped bass operated under a constant F Type 1 HCR with the striped bass target F of

0.204 yr^{-1}. HCR 15, similar to HCRs 12-14, attempted to mimic suggestions for forage fish retention for their predators proposed by Cury et al. (2011) in order to sustain one third of Atlantic menhaden unfished biomass to provide for predators (“1/3 for the birds” rule).

HCR 16 tested a constant F HCR on striped bass and a biomass-based HCR for Atlantic menhaden. This HCR was intended to manage striped bass using the current ASMFC target F, but use a higher target F for Atlantic menhaden the current reference point. HCRs 17 and 18 were used to test dynamics of two biomass-based HCRs. HCR 18 focused on the traditional 40-10 rule (Pacific Fishery Managment Council, 2012) where F is 0 yr^{-1} when a stock is below 10% of SSB_0, F is the stock-specific target (0.204 yr^{-1} for striped bass and 0.157 yr^{-1} for Atlantic menhaden) when a stock is above 40% of SSB_0, and between the two thresholds F increased linearly between 0 yr^{-1} and the target F.

A smaller number of Type 2 and Type 3 HCRs was tested. HCRs 19-24 were developed to test a suite of Type 2 HCRs. Three of the six Type 2 HCRs had positive slopes for both species, two had one positive and one negative slope, and one HCR had 2 negative slopes. HCR 25 was developed to maintain striped bass at status quo F while ceasing Atlantic menhaden fishing when striped bass SSB was below their threshold (91,625.66 thousand kg). HCR 26 operated so that Atlantic menhaden fishing ceased when striped bass SSB was lower than the threshold. HCR 27 had striped bass operating under a biomass-based HCR while Atlantic menhaden were fished at almost double status quo rate (0.3 yr^{-1}) if striped bass SSB was double the SSB_{TARGET} otherwise fishing on Atlantic menhaden was 0 yr^{-1}.

Performance metrics

Performance metrics were used to evaluate the ability of the suite of HCRs to achieve ASMFC management goals (Table 2.5) for the striped bass stock and fishery. HCRs were ranked based on performance metrics where high SSB or catch and low average annual variation (AAV) of catch were considered best performing. There were four objectives for the striped bass stock that were addressed by 6 performance metrics relating to SSB, catch, or abundance (Table 2.5). Metrics were summarized using results from the last 10 years of each simulation to reflect long-term performance of each HCR. Biomass for both striped bass and Atlantic menhaden were calculated as a product of the abundance-at-age and weight-at-age summed over ages in the first season (Eqn. T.2.2.20). Annual SSB for Atlantic menhaden was calculated as the product of abundance-at-age, weight-at-age, and maturity-at-age summed over ages in the first season (Eqn. T.2.2.21). Striped bass SSB was calculated in the same manner except abundance-at-age was multiplied by the proportion female-at-age to calculate female SSB which reflects the metric used in the striped bass stock assessment (Eqn. T.2.2.22). Striped bass and Atlantic menhaden catch in weight were calculated following the Baranov catch equation (Eqn. T.2.2.23; Quinn & Deriso, 1999). Additionally, striped bass catch in numbers used the Baranov catch equation, but disregarded weight (Eqn. T.2.2.24). Catch, either in weight or numbers, was then used to calculate the AAV of catch by taking the absolute value of the change in catch in one year from the previous year (Eqn. T.2.2.25).

Alternative Scenarios

There were many uncertainties that were not fully captured within the base predator-prey simulation model. Two main uncertainties that were not fully addressed were the fraction of Atlantic menhaden in the diet of striped bass and the prey size preference of striped bass. In the base simulation model configuration, the fraction of Atlantic menhaden in the striped bass diet was 4% for age-1, 15.7% for age-2 through age-5, and 30.4% for ages 6 and older striped bass and the operating model assumed a symmetric prey preference function. This meant that older aged-striped bass consumed a greater proportion of Atlantic menhaden than younger aged striped bass. Previous studies have estimated the percentage of Atlantic menhaden in striped bass diets may be as low as 10% and as high as 72% (Hartman & Brandt, 1995; Overton et al., 2009). Each of these studies were conducted under relatively short time frames and in relatively small locations within the Atlantic Ocean and the Chesapeake Bay (Austin & Walter, 2001; Griffin & Margraf, 2003; Overton et al., 2008; Walter et al., 2003). Due to the wide range of estimates of striped bass consumption, there was high uncertainty in the true percent consumption of Atlantic menhaden. Additionally, a study by Overton et al. (2009) estimated that large striped bass consumed both more smaller sized prey and a wider range of prey sizes than assumed in the base predator-prey simulation model.

To determine whether these uncertainties affected the relative performance of the HCRs evaluated, I developed two alternative operating models that differed from the base predator-prey simulation model (hereafter referred to as NC30) in the consumption dynamics between striped bass and Atlantic menhaden. NC30 assumed that Atlantic menhaden made up 30% of the diet of age-6 and older striped bass (Hartman & Brandt, 1995; Walter & Austin, 2003). The two alternative operating models bracketed the uncertainty around the importance of Atlantic menhaden in the diet of striped bass and the shape of the prey size preference function for striped bass. The first alternative operating model assumed that striped bass are much more reliant on Atlantic menhaden than NC30. Specifically, the alternative operating model (NC70) included modified consumption model parameters that resulted in Atlantic menhaden comprising approximately 70% of striped bass diets (Griffin & Margraf, 2003; Hartman & Brandt, 1995), which represents the highest published estimates from striped bass diet studies. In NC70, alternative prey abundance is much lower than in NC30 so that Atlantic menhaden comprise up to 70% of striped bass diet. In NC70, consumption of Atlantic menhaden was 24% of age-1, 59.2% of age-2, and 71.1% of the age-3 and older striped bass diet. Similar to NC30, NC70 also assumed a symmetrical prey size preference function. The second alternative scenario (LNC30) used an asymmetric prey size preference function (Eqn. T.2.2.26), namely an unscaled lognormal distribution. The parameters of this prey size preference function were set to match the observed prey sizes of striped bass from Overton et al. (2009). In LNC30, alternative prey abundance was specified such that Atlantic menhaden comprised about 30% of the diet of ages 6 and older striped bass, similarly to NC30.

Results

Model Performance

Several HCRs (4-10) tested the bounds of the stock and the overall dynamics of the model. Current striped bass SSB was approximately equal to the levels found when fishing at the status quo F (HCR 1), but the stock could reach more than quadruple its current levels in an unfished condition (Figure 2.8). Under unfished conditions for both species, striped bass SSB was 665% higher than status quo SSB and 360% higher than the striped bass SSB target. SSB_0 was estimated to be 553,192 thousand kg for striped bass and 0.596 billion kg for Atlantic menhaden. In HCRs 8 and 10 (high F on Atlantic menhaden), the Atlantic menhaden stock collapsed, and, in HCRs 9 and 10 (high F on striped bass), the striped bass stock collapsed.

When fished at the status quo constant F of 0.307 yr^{-1}, striped bass median SSB dropped below their threshold in all scenarios (Figure 2.8). Striped bass constant F HCRs at or below the target F of 0.204 yr^{-1} resulted in median SSBs at or above the target striped bass SSB under all Atlantic menhaden constant F HCRs. There was little effect of a constant F HCR for Atlantic menhaden on striped bass SSB (Figure 2.8 and 2.9).

Striped bass SSB declined with increasing striped bass F (Figure 2.9). Increasing Atlantic menhaden F resulted in a small decline in striped bass SSB, but had considerably less effect on striped bass SSB than striped bass F (Figure 2.9). SSB_{MSY} for striped bass was estimated to be 139,254 thousand kg when Atlantic menhaden was unfished. In contrast, Atlantic menhaden SSB was strongly affected by striped bass (Figure 2.10). Atlantic menhaden SSB was at its highest when

Atlantic menhaden F was 0 yr^{-1} and striped bass were heavily fished (Figure 2.10). In this unfished scenario, Atlantic menhaden SSB increased by 20%. Unlike striped bass, unfished conditions for both species did not result in the highest Atlantic menhaden SSB. In these conditions, SSB_{MSY} was 0.257 billion kg, substantially lower than the current SSB target. Under status quo F, Atlantic menhaden was also only able to achieve target SSB when striped bass F was high (Figure 2.10).

Median striped bass catch had a small range across Atlantic menhaden Fs and displayed a negative parabolic shape of catch with increasing striped bass F (Figure 2.11), indicating Atlantic menhaden constant F HCRs had little effect on variation in striped bass catch. F_{MSY} for striped bass when F was 0 yr^{-1} for Atlantic menhaden was 0.186 yr^{-1} (Figure 2.11). Under status quo F (0.307 yr^{-1}), median striped bass catch was lower than at the target F (0.204 yr^{-1}) and at F_{MSY}. Atlantic menhaden catch also showed a negative parabolic shape in which catch eventually reached 0 often for F above 1.0 yr^{-1} (Figure 2.12). F_{MSY} for Atlantic menhaden when F was 0 yr^{-1} for striped bass was 0.236 yr^{-1} (Figure 2.12). Additionally, there was a wide variation in median Atlantic menhaden catch in response to indirect effects of the striped bass F (Figure 2.12).

All three scenarios, NC30, NC70, and LNC30, had similar results. The main difference among scenarios was that NC70 and LNC30 had wider ranges of median catch and SSB for striped bass than NC30 under the range of Atlantic menhaden Fs evaluated. Therefore, the results section focuses on results from NC30. Results for the other two scenarios can be found in Appendix C (Figures C.3-C.64).

HCR Performance

SSB

No HCR resulted in median SSB above the targets for both species (Figure 2.13). The response of striped bass median SSB varied among HCRs (Figure 2.14). HCRs 11-18 resulted in median striped bass SSB above their target with the exception of HCR 15 ("1/3 for the birds" rule) (Figure 2.14). HCRs 11, 18, 19, 22, and 27 achieved a median SSB above SSB_{MSY}. Additionally, median SSB under those 5 HCRs and HCRs 2, 12-14, and 16 were above the SSB_{TARGET}. HCRs 21, 23, 24, and 26 had a median relative SSB below the target but an F higher than the target (Figure 2.15). HCR 19 (Type 2 DMSHCR) resulted in the highest striped bass SSB, but the lowest F (Figure 2.15). HCRs 11, 18-20, 22, and 27 resulted in striped bass SSB higher than the SSB_{TARGET} and F lower than the F_{TARGET} (Figure 2.15). Similar to the constant F HCRs, the main driver of striped bass SSB was striped bass F (Figure 2.15).

For Atlantic menhaden, most of the HCRs achieved median SSB of 40-90% of the target (Figure 2.16). HCR 23 was the only HCR within the suite tested that reached a median SSB above SSB_{TARGET}; HCR 23 also had an F lower than status quo (Figure 2.17). HCRs 13, 15, and 23 resulted in median SSBs at or higher than status quo. HCR 23 had 19% higher median SSB than HCR 1 (status quo). HCRs 19 and 20 (Type 2 DMSHCRs) resulted in the lowest median SSBs for Atlantic menhaden at 0.02 and 0.03 billion kg, respectively, compared to all 27 HCRs (Figure 2.16). HCRs 12-14, designed to implement the "precautionary approach to the management of forage fish" developed by the Lenfest Forage Fish Task Force (Pikitch et al., 2012), on average were below the target Atlantic menhaden SSB by 14%, 8%, and 15%, respectively. Although these HCRs were under the Atlantic menhaden SSB_{TARGET}, they resulted in median SSBs that were around 90% of the target.

Few HCRs resulted in striped bass and Atlantic menhaden median biomasses near their targets (Figure 2.13). For example, HCR 23 resulted in a median Atlantic menhaden SSB 6% higher than the target, but also in a median striped bass SSB 72% below its target. Median SSBs for HCRs 11-13, 16, 18, 22, 24, and 27 were above 0.5 of the Atlantic menhaden SSB_{TARGET} while also staying under striped bass F_{TARGET} (Figure 2.18). HCRs 11 and 18 resulted in median SSBs above the target for striped bass and were among the highest SSBs for Atlantic menhaden (Figure 2.13). HCRs 11-13 and 18 resulted in median striped bass SSBs above the target while maintaining both striped bass and Atlantic menhaden F below their targets (Figures 2.18 and 2.19).

Catch

Similar to SSB, no single HCR resulted in the highest catch for both striped bass and Atlantic menhaden. For striped bass, HCRs 15 and 25 were the only HCRs to result in a median catch in numbers at or above the catches under the status quo (Figure 2.20). HCR 19 and 24 had the lowest striped bass median catches in numbers at 79% and 28% lower than catch at status quo. While most of the HCRs resulted in catch lower than status quo, there was a small difference for nine HCRs 12-14, 16, 17, 21, 23, 25, and 26, where catch was at or below 10% lower than the median catch at status quo (Figure 2.20). HCRs 11, 18, 20, and 27 resulted in the highest combination of median catch in weight and median SSB among all HCRs (Figure 2.21). There was a substantial difference between striped bass median catches in weight and numbers. Catch in weight was higher than status quo catch (HCR 1) for all HCRs except for HCR 19-21, 23, 24, and 26 (Figure C.1), as opposed to catch in numbers which resulted in most HCRs (other than HCR 15 and 25) below status quo (Figure 2.20).

Atlantic menhaden did not result in average catch (in weight) lower than status quo as often as striped bass. HCRs 26, 22, and 24 resulted in the highest median catches, ranking at first, second, and third, respectively (Figure 2.22). HCRs 3, 16, 17, 21, 22, and 24-27 all resulted in median catches higher than status quo (Figure 2.22). HCRs 19 and 20 resulted in almost no catch for Atlantic menhaden (Figure 2.22). There was a cluster of HCRs that resulted in similar tradeoffs between Atlantic menhaden SSB and catch, including HCR 13, 21, 25, 15, and 3 (Figure 2.23).

Although HCRs that had a high SSB for Atlantic menhaden resulted in a low SSB for striped bass more often than not, the same was not true for catch. HCRs that had the highest median catches in numbers for striped bass, 15 and 25, resulted in median catches (in weight) for Atlantic menhaden near status quo for HCR 15 and 18% higher than status quo for HCR 25 (Figure 2.22). HCR 19 for both species resulted in the lowest median catch among HCRs. (Figures 2.20 and 2.22).

Catch was much more variable among HCRs than SSB. HCRs 1-3, 12, 13, 16 and 24-26 had low median AAV in catch for both striped bass and Atlantic menhaden (Figures 2.24 and 2.25). Additionally, HCRs 14 and 20 for striped bass and 11, 15, 18, and 27 for Atlantic menhaden also had very low median AAV in catch (Figures

2.24 and 2.25). For striped bass, HCR 27 had some of the highest median AAV in catch among HCRs followed by HCR 22, 11, and 18 (Figure 2.24). For Atlantic menhaden, HCR 22 had the highest median AAV in catch, as well as the highest range of AAV compared to all other HCRs (Figure 2.25). Atlantic menhaden had a higher AAV for all HCRs compared with striped bass, but both followed similar trends in AAV.

Additional Metrics

Some of the metrics most highly influenced by the striped bass and Atlantic menhaden HCRs were consumption of Atlantic menhaden (Figures 2.26 and 2.27), M (Figures 2.28, 2.29, 2.30, and 2.31), and striped bass weight (Figures 2.32 and 2.33). Under most HCR scenarios, age-3 striped bass did not reach their status quo level of consumption of 15.7% Atlantic menhaden with the exception of HCR 23 (Figure 2.26). However, seven HCRs (1-3 and 12-15) had less than 6% difference from the status quo consumption of Atlantic menhaden by age-3 striped bass (Figure 2.26). Age-15 striped bass were more consistent at reaching the status quo proportion of Atlantic menhaden in their diet and in some cases surpassed it when Atlantic menhaden abundance was high (Figure 2.27). In HCRs 1-3, 11-15, 21, 22, and 24, age-15 striped bass reached a maximum consumption of Atlantic menhaden above 30.4% (Figure 2.27). Under HCR 19 and 20, Atlantic menhaden only comprised 1% of striped bass age-15 diet.

Both striped bass and Atlantic menhaden M-at-age were affected by the other's biomass. Striped bass M at age 3 differed little from the M in the stock assessment in the last 10 years of the simulation (Figure 2.28). All HCRs had a striped bass M at age 3 that was less than 1% different than the stock assessment M at age 3. Higher striped bass M occurred in the same HCR scenarios in which Atlantic menhaden SSB experienced substantial declines (HCRs 19, 20, and 24). Striped bass M at age 15 showed higher variability among HCRs than age-3 striped bass M (Figure 2.29). The largest changes in M at age 15 were again seen under HCR scenarios when Atlantic menhaden were under high fishing pressure such as HCRs 19, 20, and 24. The majority of HCRs resulted in less than a 2% change in striped bass M at age 15 from the status quo. Atlantic menhaden M at age 1 was larger than M at age 4 (Figures 2.30 and 2.31). The HCR with the lowest Ms at age 1 for Atlantic menhaden were HCRs 9, 21, 23, and 24. Under HCR 19, age-1 Atlantic menhaden experienced up to an 7.5% difference from the status quo M at age-1. HCRs 1, 3, 15, 21, and 23-26 had lower M at age 1 than the status quo. Age-4 Atlantic menhaden showed patterns consistent with those seen in Atlantic menhaden M-at-age-1 such that the same HCRs that were lower than the status quo M at age 1 were also lower than the status quo M at age 4 (Figure 2.31). Change in Atlantic menhaden M at age 4 was overall lower than M at age 1. HCR 19 had the largest change in M at age 4 from the status quo.

Striped bass weight-at-age and abundance of age-15 and older were the last metrics I evaluated to determine performance of the suite of HCRs. Generally, striped bass age-3 had little variability in median weight among HCRs and had a similar median weight to input values (Figures 2.32, C.27, and C.58). Age-3 striped bass had a small increase in weight over all HCRs, but there was very little variation among

HCRs (Figure 2.32). In all HCRs, striped bass weight-at-age 15 declined (Figure 2.33). On average, age-15 striped bass declined in weight among HCRs by 2% or 0.3 kg (Figure 2.33). HCRs 19 and 20 had highest decline in weight at age 15 at approximately 10%.

Median abundance of striped bass age-15 and older was higher than the status quo for most HCRs (Figure 2.34). The highest increase in median abundance of age-15 and older striped bass was in HCRs 18, 27, and 22 (Figure 2.34). These HCRs also resulted in the highest variability in abundance (Figure 2.34). HCRs 21, 23, and 24 resulted in abundance of age-15 and older striped bass lower than that of status quo (HCR 1). Fishing under HCRs 15, 25, and 16 resulted in a median abundance of 15 and older striped bass at status quo (Figure 2.34).

HCR Performance Across Operating Models

I evaluated the robustness of each HCR to consumption model assumptions by comparing their performance among 3 alternative operating model scenarios, NC30, NC70, and LNC30. In most cases, differences in striped bass and Atlantic menhaden SSB, abundance, and catch were small among scenarios for individual HCRs. Most HCRs were highly robust to model assumptions with the exception of HCRs 3 and 20. The most robust and well performing HCRs for striped bass were HCR 18 and 27. In these two HCRs, relative SSB for both species was about the same such that striped bass SSB was above its target (Figure 2.14) and Atlantic menhaden SSB was below the target, but above SSB_{MSY} (Figure 2.16). Atlantic menhaden median SSB under LNC30 was lower for all HCRs compared with the other scenarios. More

HCRs in LNC30 performed worse than in the other two model scenarios and there were no HCRs in the most ideal range when comparing striped bass SSB and Atlantic menhaden SSB (Figure 2.13). The last notable difference in LNC30 compared to NC30 and NC70 was that the striped bass SSB_0 was not as high as in the other scenarios.

The largest differences among HCRs were for metrics associated with striped bass consumption such as maximum proportion consumption of Atlantic menhaden, striped bass weight-at-age, and M for both species. It was expected that the maximum proportion of consumption between NC30 and NC70 would change because the parameters were chosen to have different percent Atlantic menhaden in the striped bass diet. However, a 71% proportion of Atlantic menhaden in the striped bass diet was difficult to achieve at all ages. For LNC30, the proportion consumption of Atlantic menhaden was consistent with model assumptions except at lower ages where proportion consumption was on average 30% rather than 15.7%. The variability and change in weight-at-age among HCRs in NC70 was wider than what was found in NC30 and LNC30 for striped bass older than age-9. Weight-at-age 9 and under striped bass was relatively consistent among HCRs and operating models.

M had the most noticeable differences in responses for all three model scenarios. NC70 and LNC30 resulted in larger average striped bass M-at-age 3 and 15 than NC30 among all HCRs. NC70 striped bass M-at-age-3 was on average 0.5% and LNC30 striped bass M at the same age was on average 3%, whereas striped bass M-at-age 3 for NC30 was on average 0.4 % (Figures 2.28, C.23, and C.54). Striped bass M-at-age-15 for NC70 and LNC30 were similar to each other, 15% and 17%, respectively, but were much higher than NC30, 2% (Figures 2.29, C.24, and C.55). Between NC70 and LNC30, NC70 resulted in higher variation in median M among HCRs than LNC30. The patterns of M generated by different HCRs among scenarios were consistent. This trend continued where M at age-15 striped bass was much higher in NC70 and LNC30 than with NC30, but NC70 had the largest M at age-15 striped bass than any other HCR (Figure C.24). There was on average a 15% change in age-15 striped bass M and up to 45% in extreme HCR scenarios such as HCR 3. Atlantic menhaden M followed similar trends to that of striped bass. Age-1 Atlantic menhaden M was higher for all HCRs in NC70 and LNC30 than with NC30 (Figures 2.26, C.25, and C.56). Atlantic menhaden M at age-4 was the highest in LNC30 compared with NC30 and NC70, but the general trends between HCRs stayed consistent. Generally, M increased when assumptions from NC30 were changed such that either consumption increased as with NC70 or prey preference was different as with LNC30. Lastly, AAV of catch differed by operating model. AAV of catch for NC70 was lower compared with NC30 (Figures 2.24, 2.25, C.19, and C.20) and AAV of catch for all HCRs tested in LNC30 were much higher than compared with both NC70 and NC30.

Discussion

I evaluated a suite of HCRs for both striped bass and Atlantic menhaden by modifying an existing predator-prey simulation model to examine the tradeoffs among a suite of HCRs in attaining ASMFC's goals for the striped bass stock. I was able to model the range of observed consumption of Atlantic menhaden by striped bass found in the literature (30% and 70%; Hartman & Brandt, 1995; Walter et al., 2003). Atlantic menhaden were sensitive to directed fishing mortality and M_2 when an HCR (18, 19, 22, and 27) resulted in high striped bass SSB indicating that Atlantic menhaden were responsive to both fishing mortality and predation (Figures 2.17 and 2.19). However, striped bass were not highly influenced by Atlantic menhaden, and the main driver affecting the stock was fishing (Figure 2.15). There was no single HCR that performed well for both stocks, which follows similar conclusions for achieving targets for interacting species from other studies (Kaplan et al., 2020; Pérez-Rodríguez et al., 2022).

Most of the HCRs performed consistently among alternative operating models. HCRs 18 and 27 resulted in SSB above the target with relatively high median catches for striped bass across operating model scenarios. Additionally, these two HCRs had median Fs lower than F target (Figure 2.15). These control rules also performed fairly well for Atlantic menhaden, but resulted in average SSB lower than the target and catches around status quo. HCR 27 performed slightly better than HCR 18 when weighing tradeoffs for both species. While it did result in Atlantic menhaden SSB lower than its target, striped bass SSB and catch were relatively high (Figures 2.19 and 2.21).

HCR Suggestions and Generalizations

While there was no one HCR that stood out from the rest, there were several that performed well enough to be considered useful for management. The performance of traditional single species constant F HCRs for striped bass (Type 1) was predictable and similar to other studies of single-species HCR performance (e.g., Deroba and Bence 2008). Performance of HCRs for menhaden was sensitive to the biomass of striped bass; however, as long as striped bass biomass does not increase substantially (two or three times its current biomass), then there does not seem to be a great need to manage Atlantic menhaden based on striped bass SSB. Type 1 biomass-based HCRs had variable performance. Reference points for the stocks used in these types of HCRs should be biologically based because the current reference points for striped bass appear to be above F_{MSY} and below SSB_{MSY}. Similar to Kaplan et al. (2020), biomass-based HCRs (referenced as threshold HCRs in their study) resulted in higher variability of catch compared with constant F HCRs.

Type 2 HCRs generally did not perform well and need to be critically evaluated before being applied for practical use in management. Type 2 HCRs have received much less testing than single-species HCRs. Use of these DMSHCRs, in which the predator or prey SSB is used to determine F on the other species, made it difficult to balance the effects of fishing with the effects of predation. In this study, Type 2 HCRs resulted in the widest range of median SSB for striped bass. In HCRs 19 and 20, striped bass SSB was among the highest of all HCRs while Atlantic menhaden SSB was almost depleted entirely (Figures 2.14 and 2.16). Type 2 HCRs were also among those with the highest variation in catch, but this was more likely due to HCR 20 causing Atlantic menhaden SSB to crash and HCR 24 causing striped bass SSB to crash. The most successful Type 2 HCRs typically had low value slopes with either positive slopes for both species or one positive and one negative slope in the HCR pair. HCR 24 did not perform well for either striped bass or Atlantic menhaden, and it included both negative slope parameters with high intercept values.

Other studies investigating performance of HCRs for predator-prey systems reported similar results to my study. Type 2 HCRs implemented in my study were similar to the HCRs in Pérez-Rodríguez et al. (2022). Balancing HCRs among muliple species using a multispecies HCR is challenging, and not all stocks could be maintained at their targets (Perez-Rodriguqz et al. 2022). However, it is important to consider species interactions when managing fish stocks in an ecosystem since there was an impact of striped bass fishing on Atlantic menhaden. In terms of striped bass fishing, DMSHCRs do not perform as well as Type 1 HCRs. DMSHCRs require more study to understand their performance before they should be considered for use in management.

Type 3 HCRs perform very well for both species while taking a multispecies approach, yet single species striped bass HCRs give a more striped bass-focused approach to management. Since these types of HCRs dictate Atlantic menhaden F by striped bass SSB, then reducing striped bass F will always result in a well performing HCR. Type 3 HCRs were modeled after Pikitch et. al (2012) in which Atlantic menhaden are conserved based on the needs of the predator. If striped bass SSB was low, Atlantic menhaden F would be 0 yr^{-1}. However, striped bass biomass was not as responsive to Atlantic menhaden biomass as was seen in Chagaris et al. (2020). HCRs 25 and 26 did not perform well for striped bass because striped bass were fished at its status quo F which currently results in an overfished stock that is also experiencing overfishing. Because striped bass SSB at status quo F is already below the SSB target, it was expected that these two HCRs would result in SSB below the target. However, reducing fishing on Atlantic menhaden was not sufficient to allow striped bass to recover under status quo F. Alternatively, if the striped bass HCRs in a Type 3 HCR were at or below F_{MSY}, then these might have been better performing HCRs. Type 3 HCRs configurations explored in this study performed moderately for Atlantic menhaden in that SSB for HCRs 25-27 was also below the SSB_{TARGET}, but above SSB_{MSY}, had catches above status quo, and had AAVs similar to that of single species HCRs.

Although cessation-based HCRs have been explored, there are no studies that have investigated a multispecies cessation-based HCR like the Type 3 HCRs in my study. Kaplan et al. (2020) investigated the impacts of forage fish productivity on predator fish stocks by implementing threshold HCRs which increased or decreased predator F when prey productivity was high or low. This type of HCR is the opposite of my Type 3 HCRs, which base the prey F on the predator SSB and predator SSB below a threshold, prey F is 0 yr^{-1}.

Implications for Management

The evaluation of HCRs for striped bass and Atlantic menhaden is critical to understanding their potential performance. Management agencies have expanded their interest from a single species standpoint to an ecosystem approach. ASMFC has recently adopted Atlantic menhaden reference points that are set depending on striped bass SSB (SEDAR, 2020a), but striped bass are still managed using a single species, constant F approach (NEFSC, 2019). Multispecies striped bass and Atlantic menhaden reference points deserve additional consideration for effective use within an EAFM framework. Reference points developed from multispecies catch-at-age models may prove the most appropriate approach given the goals for these fisheries and the age-structured, dynamic, predator-prey interactions between these two stocks (e.g. Curti et al., 2013; McNamee, 2018).

One of the main goals of this study was to measure how well the suite of HCRs I developed met the goals set by ASMFC for the striped bass stock. Among all the HCRs evaluated in my study, HCRs 2 and 12-14 were able to achieve all goals set by ASMFC for striped bass. All four HCRs operate under a constant F HCR for striped bass where F is 0.204 yr^{-1} (F_{TARGET}). From a multi-stock perspective, there were no HCRs that met all goals for the striped bass stock and accordingly achieved target SSB for Atlantic menhaden. However, the Atlantic menhaden SSB_{TARGET} was difficult to achieve in all control rules. Therefore, HCRs 2 and 12-14 would be strong candidates for consideration by management. A constant F HCR at F of 0.204 yr^{-1} would attain ASMFC's goals for the stock by achieving an SSB above the SSB_{TARGET}, having low variability in catch, resulting in some of the lowest striped bass M rates among the HCRs tested, and resulting in an abundance of age-15 and older striped bass higher than status quo abundance. It is important to note that striped bass M-at-age 3 and 15 for HCRs 2 and 12-14 were higher than those assumed in the current stock assessment. Defining an adequate nutritional state for striped bass is subjective at present and depends on the threshold I assumed for applying additional natural mortality-at-age as weight-at-age declined.

The reference points for striped bass and Atlantic menhaden management should be reconsidered based on my results. The current F_{TARGET} for striped bass is higher than F_{MSY} from my base operating model (0.186 yr^{-1}), and the current SSB_{TARGET} is lower than SSB_{MSY} (139,254 thousand kg). This indicated that increased yield could be achieved by fishing at a lower rate. HCRs 11, 18, 19, 20, and 27 were the only options that resulted in SSB at or above SSB_{MSY} for striped bass (Figure 2.35). Additionally, the current reference points for the striped bass stock are ad hoc and SSB_0 was not evaluated when these reference points were developed. ASMFC may wish to consider the adoption of biological reference points based on an analysis of the biological potential for the stock. To help rebuild the striped bass stock, achieving the current F_{TARGET} would be beneficial because my study indicated that the most effective way to rebuild the stock appears to be reducing F on striped bass.

In order to continue moving towards EAFM, ASMFC should begin to use multispecies catch-at-age models to develop reference points that include aspects like predator-prey interactions. The development of these reference points should ideally be performed in a one-step process, in which the estimation of stock size and reference points are done within the same model, unlike the process done in this study and Chagaris et al. (2020). One example of the one-step process would be to use the VADER model (McNamee, 2018), which could take into consideration multispecies interactions and directly estimate reference points for the stocks.

I estimated F_{MSY} (0.236 yr^{-1}) to be above both status quo (0.157 yr^{-1}) and the current F_{TARGET} (0.22 yr^{-1}) indicating that Atlantic menhaden could be fished harder than it currently is if the goal was solely to maximize yield. Additionally, the Atlantic menhaden current stock size reference point appears to be difficult to achieve given my results. The SSB_{TARGET} was almost never reached among the suite of HCRs that I evaluated. When HCRs were compared to the SSB_{MSY} reference point, all but three HCRs achieved SSB higher than SSB_{MSY}. Eleven HCRs achieved both an SSB above SSB_{MSY} and below F_{MSY} (Figure 2.36). However, performance of reference points relative to status quo Atlantic menhaden target/threshold may not be useful moving forward with true multispecies management with predator-prey HCRs that are linked because of the strong response of Atlantic menhaden to striped bass predation. While the single species considerations above are relevant for current stock management, ASMFC may not be able to achieve goals of both high striped bass SSB and Atlantic menhaden SSB given striped bass predation on Atlantic menhaden.

The NWACS-MICE model (Chagaris et al. 2020) and my predator-prey simulation model are both linked predator prey models, but they have important differences. Additionally, my predator-prey simulation model was age structured (ages 1-20+ for striped bass and ages 0-6+ for Atlantic menhaden), whereas the NWACS-MICE model used coarser grouped age categories for striped bass (age 0-1, 2-5, and 6+) and Atlantic menhaden (age 0 and 1+). These differences could have contributed to the high reliance of striped bass on Atlantic menhaden shown in Chagaris et al. (2020) compared to my study results. My predator-prey simulation model also assumed constant alternative sources of prey available to striped bass; thus, even when Atlantic menhaden were experiencing fishing mortality, there were still alternate prey available for striped bass, which could have partially contributed to the flatter relationship between striped bass and Atlantic menhaden fishing mortality in my predator-prey simulation model compared with the NWACS-MICE model (Figure 2.8). This may be appropriate given the broad feeding nature of striped bass (Nelson et al., 2006). The stock-recruitment relationship in my predator-prey simulation model also constrained Atlantic menhaden biomass at low F rates as the population neared carrying capacity. This likely resulted in a flatter relationship between striped bass F and Atlantic menhaden F at low F rates. Additionally, my predator-prey simulation model very closely mimicked the current stock assessment. While I used direct estimates of abundance from the stock assessments to calculate biomass, the NWACS-MICE model rescaled the biomass estimates of multiple species in order to mass balance the model, and also grouped adult Atlantic menhaden as age-1 and older and adult striped bass as age-6 and older (Chagaris et al., 2020). Other major differences between these two models are that a) my predator-prey simulation model incorporated a type II functional response which differs from the NWACS-MICE model's type III functional response, and b) my model assumed eight static alternative prey pools whereas Chagaris et al. (2020) had two alternative dynamic prey for striped bass. The predator-prey simulation model has an advantage over the NWACS-MICE model because assumptions, reference points, estimates of SSB, and other outputs from the assessment are more comparable and a better match to real-world conditions (e.g., age-structure).

The NWACS-MICE model is a multi-predator, multi-prey model whereas my predator-prey simulation model is a single predator, multi-prey model with static, non-specific alternative prey categories. The advantage to having a multi-prey, multi-predator model as with the NWACS-MICE model is that it models the broader community and estimates the effect of fishing on multiple stocks, but the predator-prey simulation model directly simulates striped bass and Atlantic menhaden interactions and more realistically models their population dynamics to those in their respective stock assessments. I also modelled varying proportion consumption of Atlantic menhaden by striped bass by changing the alternative prey pool abundance. This approach assumes that striped bass mainly consumes Atlantic menhaden. All my models included the assumptions that an alternative prey of the same size as a menhaden would be equally preferred by striped bass and that the alternative prey had equal nutritional value as Atlantic menhaden. Striped bass are known to consume other prey such as bay anchovy, blue crab, gizzard shad, and other fish and invertebrates which all have varying nutritional value (Hartman & Brandt, 1995; Overton et al., 2009). This could affect striped bass relative weight such that striped bass could supplement their diet with alternative prey that have a higher nutritional value, resulting in lower occurrence of low condition M (Mc); alternatively, if striped bass were to rely on alternative prey with a lower nutritional value than Atlantic menhaden, striped bass relative weight could be lower and M would increase more often.

The alternative available prey pool for striped bass is a source of uncertainty due to the static dynamics of the prey source and the nutritional equivalence to Atlantic menhaden. In the three alternative operating models, I incorporated three prey importance scenarios using various abundances of alternative prey. The alternative prey were static and always available to striped bass as an additional prey source when Atlantic menhaden SSB was low or to account for general prey switching. There is the potential for Atlantic menhaden biomass to have a lower impact on striped bass when SSB is low since the alternative prey pool was static. This meant that if striped bass relied more heavily on the alternative prey and consumed more, the alternative prey pool abundance would not change. However, in my first chapter I noted that there was large variability in size-at-age that the predator-prey model was not able to realize. This may have been a result of changes in alternative prey availability over time which were not mimicked in this study.

Other studies specifically involving HCRs for forage fishes include the Lenfest Forage Fish Working Group report (Pikitch et al., 2012) and Cury et al. (2011). HCRs 12-14 were modelled after Pikitch et al. (2012). These HCRs differed depending on the levels of information available about forage fish and their predators in an ecosystem. They performed reasonably well for Atlantic menhaden, but had relatively small effects on striped bass because striped bass dynamics were only somewhat influenced by Atlantic menhaden SSB. Striped bass SSB was above the target and minimized AAV of catch since the paired HCR in 12-14 were constant F HCR at the striped bass F_{TAGRET} (Figures 2.14, 2.24, and 2.25). A similar response was found in Hilborn et al. (2017) in which forage fish fishing had little effect on the forage fish's predator, particularly in the case of Atlantic menhaden and striped bass for which the portion of the stock subject to predation by striped bass did not overlap with the portion of the stock exploited by the fisheries due to differences in predation vs fishery selectivity. Cury et al (2011) developed a similar HCR based on the idea of conserving at least one third of unfished biomass for avian predators. This principle was applied to conserve one third of unfished Atlantic menhaden SSB for striped bass in HCR 15. This HCR performed similarly to HCRs 12-14 for Atlantic menhaden. Both the Lenfest and Cury et al. (2011) approaches differed from this modeled system in that they developed their HCRs for ecosystems in which predators only had one dominant prey species. Given Atlantic menhaden may not be the most important prey species for striped bass SSB (Hartman & Brandt, 1995; Overton et al., 2009; Walter & Austin, 2003), this approach may not be the most useful for a generalist predator such as striped bass. With the exception of high AAV of catch for Atlantic menhaden in HCR 15, these HCRs performed well for Atlantic menhaden in my study, there were limited benefits of conserving Atlantic menhaden as striped bass prey.

Assumptions and Caveats

I explored the potential impact of uncertainty in the importance of Atlantic menhaden in the striped bass diet by developing operating models that were designed to achieve 30% and 70% Atlantic menhaden in the diets of older striped bass. The 70% assumption was on the high end of observations from diet studies (Hartman & Brandt, 1995). Other studies spanned a wide range of estimated proportion of Atlantic menhaden in the diet of striped bass: 21% (Overton et al., 1999), 44% (Walter & Austin, 2001; Walter & Austin, 2003), and 50% (Overton et al., 2008). Disagreement about the importance of Atlantic menhaden for striped bass creates a broad range of uncertainty. Similarly, the size preference of striped bass for their prey was another source of uncertainty that I addressed because striped bass consume a variety of different-sized prey. I considered normal and lognormal prey preference functions, but found that there was little impact on relative performance of HCRs explored based on differences in striped bass size preference for prey. Although I addressed two key uncertainties in the predator-prey simulation model by comparing HCRs across three operating models, there are still additional assumptions that could be impacting these results that have yet to be explored. These assumptions include accuracy of studies that influence striped bass population dynamics affected by Atlantic menhaden such as weight-at-age and recruitment.

In my model, striped bass M was influenced by consumption of their prey such that low relative weight resulted in higher striped bass M. Equation T.2.2.11 assumes a value of a low relative weight from the Hoenig et al (2017) striped bass tagging study and may not accurately capture the relationship between relative weight and natural mortality. Additionally, uncertainties in relative weight would also impact my estimates of SSB and performance metrics that rely on SSB. Although the relationship between weight-at-age and natural mortality for striped bass is uncertain, this study indicates striped bass F is likely to be the key driver of HCR performance.

Recruitment for striped bass and Atlantic menhaden were calculated using Beverton-Holt stock recruitment functions that included an autocorrelation term between the two stocks. Additionally, stock recruitment functions used estimates of spawning stock biomass and recruitment from the stock assessment rather than raw data. By using estimates from stock assessments as true data, it introduces a source of error into the analysis and model (Brooks & Deroba, 2015). Striped bass spawning stock biomass in the stock recruitment function was calculated using an estimated weight-at-age, abundance, and proportion of females over time establishing a source of potential error associated with stock assessment 'data'. Another area for exploration would be the development of an alternative operating model that explores alternative stock-recruitment dynamics for Atlantic menhaden that are environmentally-driven as has been suggested previously (Buchheister et al., 2017).

There were multiple sources of uncertainty that were beyond the scope of this project such as incorporating a spatial component and accounting for assessment error in my model. The predator-prey simulation model has the ability to include spatial specificity, however spatially-explicit data for striped bass and Atlantic menhaden is limited at this time. Additionally, by not including a term to account for error in the predator-prey model, I assumed that the information being used to inform HCRs in was perfect.

Future Directions

To advance multispecies EAFM for the striped bass and Atlantic menhaden predator-prey system, I recommend incorporating: a) assessment error, b) the addition of alternative recruitment scenarios to explore different assumptions about stock-recruitment relationships vs environmental drivers of recruitment, c) a spatial component to stock and fishery structure, d) additional HCR configurations of potential interest to managers, and e) the further development and testing of a multispecies statistical catch-at-age model for consideration in striped bass-Atlantic menhaden management. The current predator-prey simulation model has the capacity to incorporate these recommendations, as previously mentioned. By incorporating assessment error, the impact of uncertainty on the relative performance of HCRs could be quantified. By exploring alternative recruitment scenarios for both striped bass and Atlantic menhaden, the impact of different temporal patterns in recruitment and their potential drivers on the long-term performance of harvest policies could be examined (Hilborn et al., 2017). Although the current striped bass and Atlantic menhaden stock assessments are not spatially explicit enough to fully parameterize my predator-prey model, the development of new data collection methods and stock assessments for these species may inform future use of this modeling tool for striped bass and Atlantic menhaden.

Also, there are additional HCRs that could be tested that might be useful for consideration in management. These include: constant F HCRs with updated Fs from the most recent stock assessment updates conducted in 2022, type 3 HCRs where the threshold for striped bass that restricts Atlantic menhaden F is reduced to equal or lower than the striped bass SSB threshold, and a biomass-based HCR using the '40-10' rule for both species where the F thresholds are at the respective stocks' F threshold and F_{TARGET}. While these suggested HCRs should be made available for management consideration, they will most likely not change the overarching conclusions of my research that striped bass are less affected by fishing on Atlantic menhaden than Atlantic menhaden are impacted by fishing on striped bass.

Finally, I recommend further development and testing of a multispecies, statistical catch-at-age model such as the VADER model (McNamee, 2018) explored during the 2020 Atlantic menhaden benchmark assessment (SEDAR, 2020b). Such a framework should facilitate more explicit modeling of the age-structured single-species and predator-prey dynamics identified as being important for understanding HCR performance in this project. It may also allow for the potential development of true multispecies biological reference points.

Conclusions

Although weighing the tradeoffs among HCRs and balancing many different stock performance metrics is difficult, it is important to evaluate this type of management in order to be more effective at developing an EAFM that will result in sustainable harvest plans for both these stocks. Studies such as this can help inform managers of the potential consequences of their single or multispecies management decisions on a linked predator-prey system. This type of study also helps managers proactively examine the pros and cons of HCRs and the potential unexpected consequences of implementing them. I conducted a thorough evaluation of striped bass and Atlantic menhaden dynamics across a suite of alternative HCRs. Although accounting for the impacts of the predator-prey relationships is important, it appears to be much more important for managing Atlantic menhaden than striped bass. The striped bass stock's main driver was determined to be striped bass F and future management should concentrate primarily on reducing harvest and discard mortality. To effectively rebuild striped bass, a reduction in F appears to be required. Furthermore, reference points for striped bass and Atlantic menhaden should be reconsidered. The SSB_{TARGET} for Atlantic menhaden was significantly higher than the SSB_{MSY} I calculated in this study, and the striped bass SSB_{TARGET} was lower than my calculated SSB_{MSY}. In addition to re-examining reference points, alternative harvest control rules (e.g., HCRs 11-14, 18, and 27) should be considered to more effectively achieve ASMFC's goals for these two important stocks.

Tables

Table 2.1: Parameters and variable names used in equations for the predator-prey simulation model and consumption dynamics model.

Symbol	Description (units)
Index variables	
y	Year
t	Season
a	Age
a_1	Minimum age
a_2	Maximum age
j	Predator index
i	Prey index
Parameters	
R	Recruitment
α	Productivity at low stock size
SSB	Spawning stock biomass
δ	Recruitment error with logscale deviation
β	Density dependent term
N	Abundance
Z	Instantaneous total mortality
F	Instantaneous fishing mortality
M	Instantaneous natural mortality
Mc	Striped bass natural mortality due to low relative weight
RelW	Relative weight; standard deviation of 2.8
W	Weight
Ws	Standard relative weight
L	Input length-at-age from smoothed chapter 1 estimates
Φ	Cumulative density function for a standard normal distribution
ICR	Instantaneous consumption rate
M_2	Instantaneous natural mortality due to predation
PW	Predicted predator weight
Gmax	Maximal potential growth
Cons	Consumption at age of striped bass
Cmax	Proportion of maximum consumption achieved by the predator
SP	Size preference of the predator or each prey; length-based
Length	Length of either predator or prey as inputs
$Length_{opt}$	Optimum length ratio of predator to prey as reported by Ruderhausen et al (2005)
ω	Variance of the predator-prey length ratio as found in Ruderhausen et al (2005) or recalculated for a lognormal function
TC	Total consumption

ρ	Attack rate calculated as a function of the ratio of prey to predator size
W	Weight
γ	Variable used to control the consumption dynamics of the predator with the prey and other prey pool in the predator prey simulation model
B	Biomass
m	Proportion mature-at-age
PF	Proportion of females in a given age class
C	Catch
AAV	Average annual variation of catch
F_l	Lower fishing mortality rate as describes in a HCR
F_u	Upper fishing mortality rate as described in a HCR
SSB_l	Lower spawning stock biomass threshold
SSB_u	Upper spawning stock biomass threshold
int	Intercept parameter for a Type 2 HCR
slope	Slope parameter for a Type 2 HCR
relSSB	Relative spawning stock biomass using the species SSB as a reference point
SSB_{thresh}	Spawning stock biomass threshold for striped bass as applied in a Type 3 Atlantic menhaden HCR
NC30	An alternative predator-prey dynamics operating model that assumes prey consumption at length is normally distributed and up to 30% of striped bass diet is Atlantic menhaden
NC70	An alternative predator-prey dynamics operating model that assumes prey consumption at length is normally distributed and up to 71% of striped bass diet is Atlantic menhaden
LNC30	An alternative predator-prey dynamics operating model that assumes prey consumption at length is normally distributed and up to 30% of striped bass diet is Atlantic menhaden

Table 2.2: List of equations used in the predator-prey simulation model and consumption dynamics model.

Equation number	Equation	Description
T.2.2.1	$R_y = \frac{\alpha SSB_{y-1}}{1+\beta SSB_{y-1}} e^{\delta(y-1)}$	Beverton-Holt stock-recruitment function for striped bass
T.2.2.2	$R_y = \frac{\alpha SSB_y}{1+\beta SSB_y} e^{\delta y}$	Beverton-Holt stock-recruitment function for Atlantic menhaden
T.2.2.3	$N_{y,t=1,a=a_1} = R_y$	Abundance in the first age and first season
T.2.2.4	$N_{y,t+1,a} = N_{y,t,a} e^{-Z_{y,t,a}}$	Abundance-at-age within the year
T.2.2.5	$N_{y+1,t=1,1,a+1} = N_{y,t=4,a} e^{-Z_{y,t=4,a}}$	Abundance-at-age in the first season
T.2.2.6	$N_{y+1,t=1,a=a_2} = N_{y,t=4,a=a_2} e^{-Z_{y,t=4,a=a_2}} + N_{y,t=4,a=a_2-1} e^{-Z_{y,t=4,a=a_2-1}}$	Abundance at-age in the plus group in the first season
T.2.2.7	$Z_{y,t,a} = F_{y,t,a} + M_a + Mc_{a,t}$	Total instantaneous mortality for striped bass
T.2.2.8	$Z_{a,t} = F_{a,t} + M_{a,t}$	Total instantaneous mortality for Atlantic menhaden
T.2.2.9	$RelW_{a,t} = \frac{W_{y-1,t,a}}{sd(Ws_{t,a})}$	Relative weight for striped bass after the first season
T.2.2.10	$Ws = 10^{-4.924} \bullet L_{j,a}^{3.007}$	Standard relative weight for striped bass

T.2.2.11	$Mc_{y,s,a} = 3.28 * M^{*}_{y,t,a}\Phi\left(\frac{70.52 - RelW_{y,t,a}}{16}\right) + M^{*}_{y,t,a}\left(1 - \Phi\left(\frac{70.52 - RelW_{y,t,a}}{16}\right)\right)$	Natural mortality for striped bass with low relative weight
T.2.2.12	$RelW_{t,a} = \frac{W_{y,t-1,a}}{sd(Ws_{t-1,a})}$	Relative weight of striped bass
T.2.2.13	$M_{2,a,t} = ICR_a N_{a,t,j} e^{\frac{-Z_{a,t,j}}{2}}$	Instantaneous natural mortality rate of Atlantic menhaden due to predation
T.2.2.14	$M_{a,t} = M_a + M_{2,a,t}$	Instantaneous natural mortality rate for Atlantic menhaden
T.2.2.15	$PW_{a,t+1,y} = PW_{a,t,y} + \frac{Gmax_{a,t}Cons_{a,t,y}}{Cmax_{a,t}}$	Predator weight-at-age as a function of their consumption
T.2.2.16	$SP = exp\left[\frac{-\left(\frac{length_i}{length_j} - length_{opt}\right)}{\omega}\right]$	Normal size preference function used in the consumption dynamics for NC30 and NC70
T.2.2.17	$TC_a = \sum_{a=1}^{20} ICR_i * \rho$	Total consumption for each age striped bass
T.2.2.18	$ICR_{a,s,i} = \frac{\rho_a N_{i,s}}{1 + \sum_i \frac{\rho N_{i,s} W_i}{Cmax_i}}$	Instantaneous consumption rate of each prey type for each age striped bass
T.2.2.19	$\rho_a = SP * length_j * \gamma_a$	Instantaneous attack rate of each age predator on each age prey
T.2.2.20	$B_y = \sum_a N_{y,t=1,a} W_{y,t=1,a}$	Biomass
T.2.2.21	$SSB_y = \sum_a N_{y,t=4,a} m_a W_{y,t=4,a}$	Annual spawning stock biomass for

		Atlantic menhaden
T.2.2.22	$$SSB_y = \sum_a N_{y,t=4,a} m_a W_{y,t=4,a} PF_a$$	Annual spawning stock biomass for striped bass
T.2.2.23	$$C_y = \sum_{t \epsilon y} \sum_a \frac{F_{a,t}}{Z_{a,t}} (1 - e^{-Z,a,t}) N_{a,t} W_{a,t}$$	Annual catch in biomass
T.2.2.24	$$C_y = \sum_{t \epsilon y} \sum_a \frac{F_{a,t}}{Z_{a,t}} (1 - e^{-Z,a,t}) N_{a,t}$$	Annual catch in numbers
T.2.2.25	$$AAV_y = \left\| \frac{C_y - C_{y-1}}{C_y} \right\|$$	Average annual variation of catch (in numbers for striped bass and weight for Atlantic menhaden)
T.2.2.26	$$SP = exp \left[\frac{-\left(\frac{ln(length_i}{length_j} \right) - ln\left(length_{opt} \right)}{\omega} \right]$$	Lognormal size preference function used in the consumption dynamics for LNC30

Table 2.3: Equations used to calculate Type 1, Type 2, and Type 3 HCRs.

Equation Number	*Equation*	*Description*
T.2.3.1	$F_y = F_l + \frac{\left(SSB_{y-1} - SSB_l\right) * (F_u - F_l)}{SSB_u - SSB_l}$	Type 1 HCR when F is between the upper and lower SSB thresholds
T.2.3.2	$F = int + slope * relSSB$	Type 2 HCR where F of one species is relative to SSB of the other species
T.2.3.3	$F_y = \begin{cases} 0\ if\ SSB \leq SSB_{thresh} \\ F_u\ if\ SSB > SSB_{thresh} \end{cases}$	Type 3 HCRs for Atlantic menhaden only; F is only F_u when striped bass SSB is above the designated threshold

Table 2.4: Suite of 27 HCRs tested. HCRs included were either single species (SS) or multispecies (MS). There were 3 types of HCRs tested where the number in the column 'Type' represents either Type 1, Type 2, or Type 3 HCRs with a more specific description following. The last 2 columns show the bounding fishing mortality (F) for either striped bass (SB) or Atlantic menhaden (AM). The top number in each row is the lower F bound for the HCR and the second number indicated the upper bound for the HCR. DMSHCRs do not have a designated F since the F and limits for the HCR was not identified by one species. HCRs 4-10 are highlighted in grey indicating they were used for testing model performance and developing reference points but not as desired potential management options for consideration in the HCR performance evaluation.

CR	SS or MS	Type	Description	SB F	AM F
1	SS	1-Constant F	F is operating at status quo for both Atlantic menhaden (0.157) and striped bass (F=0.307).	0 0.307	0 0.157
2	SS	1-Constant F	Atlantic menhaden operates at status quo and striped bass is fished at the target F (0.204).	0 0.204	0 0.157
3	SS	1-Constant F	F for both is the average F from 1998-2017 for the fully selected age along the selectivity curve. (Age-3 for Atlantic menhaden and age-13 for striped bass.	0 0.258	0 0.18
4	SS	1-Constant F	No fishing on either species (F=0).	0 0	0 0
5	SS	1-Constant F	Atlantic menhaden is operating at status quo while there is no fishing on striped bass.	0 0	0 0.157
6	SS	1-Constant F	No fishing on Atlantic menhaden and striped bass is fished at its target F.	0 0.204	0 0
7	SS	1-Constant F	There is no fishing on Atlantic menhaden while striped bass operates under status quo.	0 0.307	0 0
8	SS	1-Constant F	Atlantic menhaden is operating at a high F of 1.0 and striped bass is fished under the target F.	0 0.204	0 1
9	SS	1-Constant F	Intense fishing pressure on striped bass	0 0.8	0 0.157
10	SS	1-Constant F	Intense fishing pressure on both stocks	0 0.8	0 0.8
11	SS	1-AM: constant F, SB: Biomass-based	Atlantic menhaden is operating under a constant F HCR at status quo, but striped bass is operating under a biomass-based HCR where striped bass is fished at F=0.05 under the lower threshold (202 million lbs) and F=striped	0.05 0.204	0 0.157

			bass target above the upper threshold (striped bass target of 250 million lbs). Between those two boundaries, F operates on a calculated slope.		
12	SS	1-AM: Biomass-based, SB: Constant F	Mimics the Lenfest forage fish report low information tier where the Atl. menhaden stock is not depleted lower than 20% of unfished SSB (Pikitch et al 2012)	0 0.204	0 0.157
13	SS	1-AM: Biomass-based, SB: Constant F	Mimics the Lenfest forage fish report intermediate information tier where Atl. menhaden F is 50% of F_{MSY} above or equal to 40% unfished SSB (Pikitch et al 2012)	0 0.204	0 $0.5F_{MSY}$
14	SS	1-AM: Biomass-based, SB: Constant F	Mimics the Lenfest forage fish report high information tier where Atl. menhaden F is 75% of F_{MSY} above 80% of unfished SSB and F is 0 under 30% unfished SSB (Pikitch et al 2012)	0 0.204	0 $0.75F_{MSY}$
15	SS	1-AM: Biomass-based, SB: Constant F	Third for the birds - 1/3 of Atlantic menhaden unfished SSB is the lower SSB threshold for the HCR	0 0.307	0 0.157
16	SS	1-AM: Biomass-based, SB: Constant F	An example of Atl. menhaden operating under a biomass-based HCR while striped bass is under a constant F HCR	0 0.204	0.157 0.55
17	SS	1-Biomass-based	General example of both species operating under a biomass-based HCR; Atl. menhaden lower and upper thresholds are 25% and 85% of SSB0 and striped bass thresholds are the threshold and target, respectively.	0.204 0.307	0.1 0.7
18	SS	1-Biomass-based	Both species are fished at their target above 40% of their unfished SSB and are not fished under 10% SSB	0 0.204	0 0.157
19	MS	2-Dynamic Multispecies	Striped bass F is determined by Atlantic menhaden biomass levels, both slopes are positive	-	-
20	MS	2-Dynamic Multispecies	Example of Type 2 dynamics multispecies control rules where both slopes are positive.	-	-
21	MS	2-Dynamic Multispecies	Testing dynamics of Type 2 HCR with both slopes positive	-	-

22	MS	2-Dynamic Multispecies	Testing dynamics of Type 2 HCR where Atl. menhaden have a positive slope and striped bass have a negative slope	-	-
23	MS	2-Dynamic Multispecies	Testing dynamics of Type 2 HCR where Atl. menhaden have a negative slope and striped bass have a positive slope	-	-
24	MS	2-Dynamic Multispecies	Testing dynamics of Type 2 HCR where both species have negative slopes	-	-
25	MS	3-Dynamic Multispecies	Atlantic menhaden F is at 0.2 when striped bass SSB is above the SSB threshold; striped bass operate under status quo CR	0 0.307	-
26	MS	3-Dynamic Multispecies	Atlantic menhaden F is at 0.5 when striped bass SSB is above the 75,000 thousand kgs; striped bass operate under status quo CR	0 0.307	-
27	MS	3-Dynamic Multispecies	Atl. menhaden F is changed by striped bass SSB; striped bass operate under a biomass-based HCR where the lower threshold is 10% of SSB0 and the upper is at 40% SSB0; reference points for striped bass HCR are generated based on unfished SSB rather than the 1995 reference point used in the stock assessment	0.1 0.307	-

Table 2.5: ASMFC goals and objectives for the striped bass stock were used to compare performance and make HCR recommendations for both the striped bass and Atlantic menhaden stocks. Performance metrics were designed to aligned with the objectives and quantitatively measure relative performance of each HCR.

ASMFC Objectives	ASMFC Performance Measures	Performance Metrics
Manage striped bass using a control rule that manages stock size equal to or greater than target female SSB	Frequency of substantive management action	Average spawning stock biomass is at or above the target SSB set by ASMFC
Provide stability for striped bass fisheries	Variability in yield	% change of catch interannually
Ensure adequate supply of Atlantic menhaden for predators like striped bass	Predators in adequate nutritional state	Average striped bass weight-at-age and natural mortality-at-age
Minimize risk for striped bass stock and fishery collapse		Average and variance of striped bass SSB
Maintain age structure of striped bass stocks in order to conserve spawning stock biomass		Average and variance of striped bass abundance-at-age
		Average % of years striped bass SSB is above target
Establish an F_{TARGET} that will increase the abundance of age-15+ striped bass in the population		Average abundance of age-15 and older striped bass is above status quo abundance

Figures

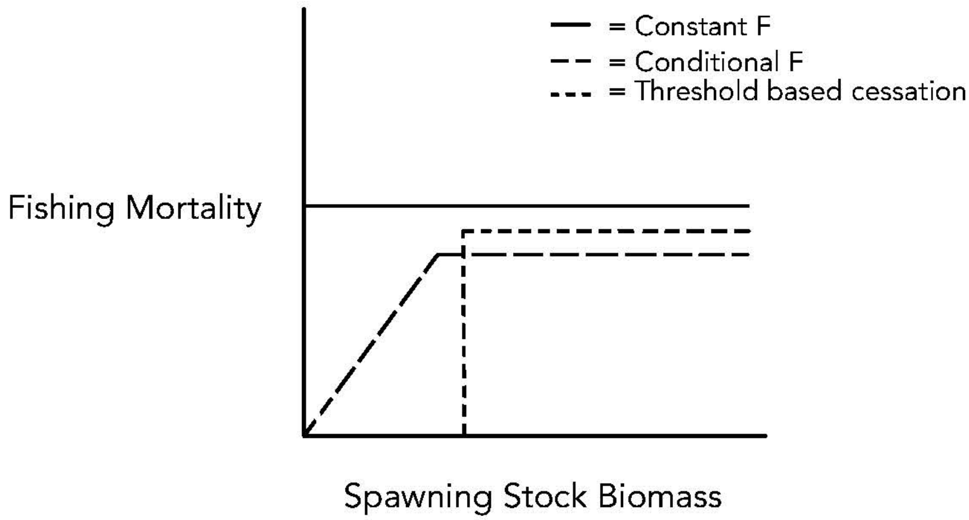

Figure 2.1: Examples of single-species harvest control rules (HCRs), including constant fishing mortality (solid line) and biomass-based HCRs, conditional F (long dashed line; also known as 'hockey-stick'), and threshold based cessation (short dashed line). The shape of the threshold based cessation follows a form of HCR used in this study.

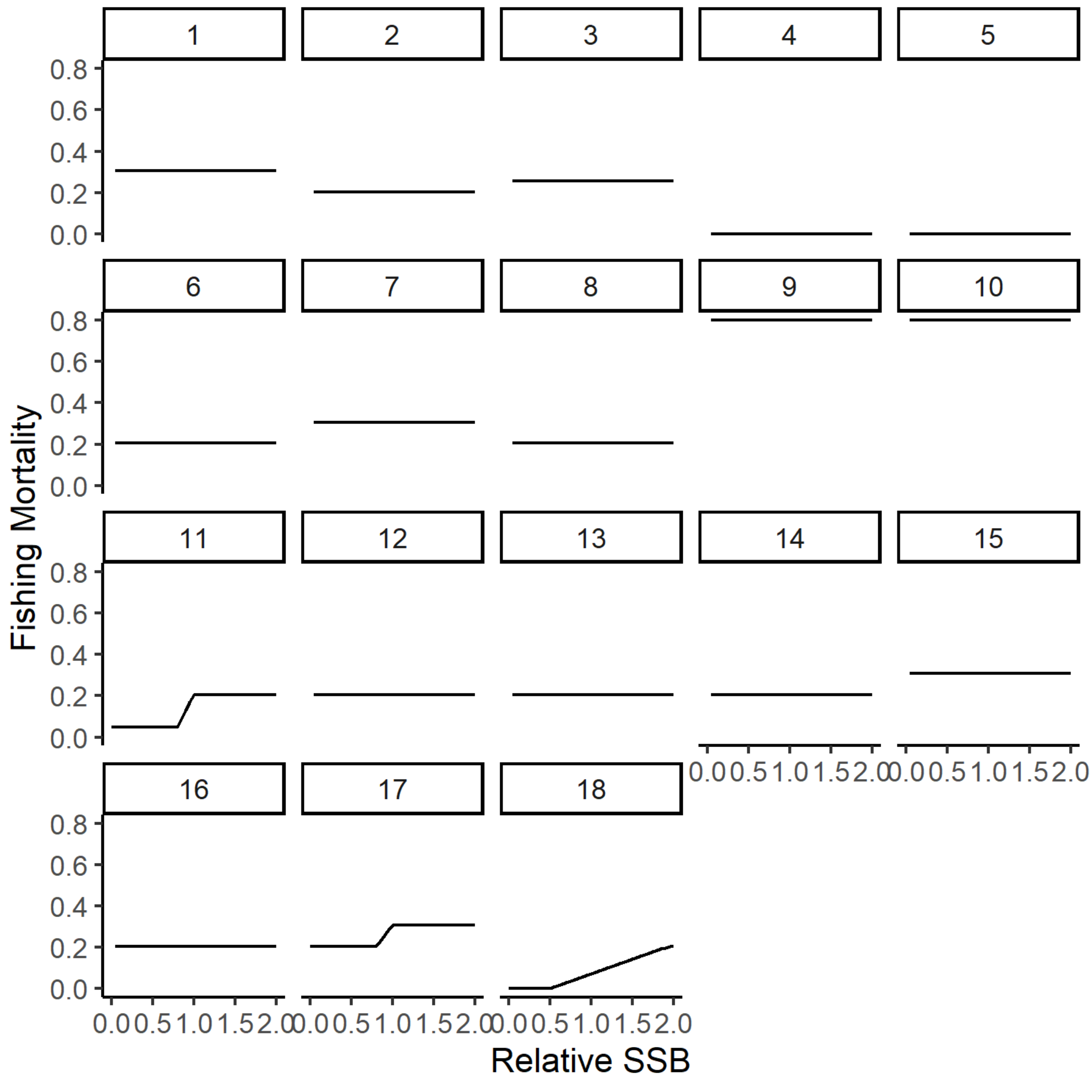

Figure 2.2: Type 1 single species control rules evaluated for striped bass. Headers indicate the control rule number described in Table 1. Relative SSB on the x-axis is the SSB at a given F divided by the striped bass target SSB in metric tons (11,4305.27). When SSB of the previous year is at or below the lower SSB threshold (SSB_l), F is at the designated lower F (F_l). When SSB of the previous year is at or above the upper SSB threshold (SSB_u), F is a designated upper F (F_u). In between the SSB references, Type 1 HCR follow an increasing linear slope using the equation.

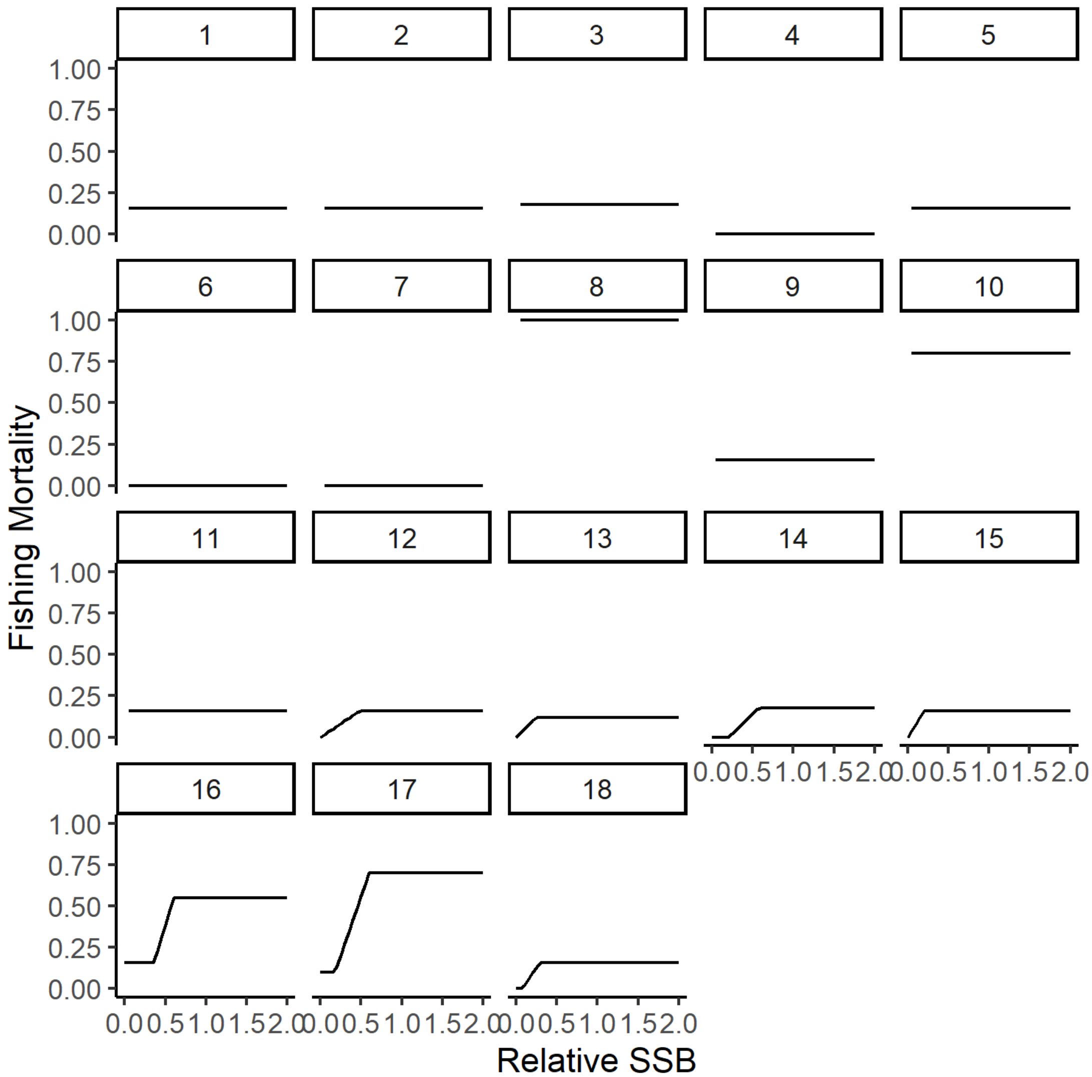

Figure 2.3: Type 1 single species HCR shapes evaluated for Atlantic menhaden. Headers indicate the control rule number described in Table 1. The x-axis of relative SSB is the SSB at a given F divided by the Atlantic menhaden target developed in billions of kgs (0.843018). When SSB of the previous year is at or below the lower SSB threshold (SSB_l), F is at the designated lower F (F_l). When SSB of the previous year is at or above the upper SSB threshold (SSB_u), F is a designated upper F (F_u). In between the SSB references, Type 1 HCR follow an increasing linear slope using the equation.

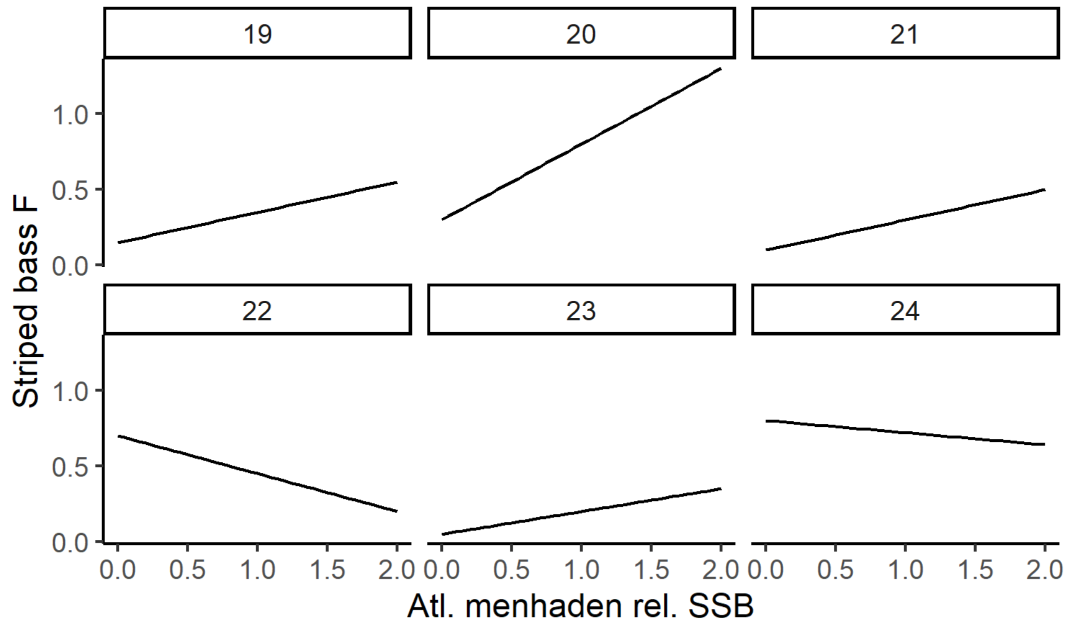

Figure 2.4: Type 2 control rule shapes for striped bass. Striped bass fishing mortality (F) is determined by Atlantic menhaden SSB. Headers indicate the control rule number described in Table 1. The relative SSB on the x-axis follows the same format as the Figures 2.2-2.3.

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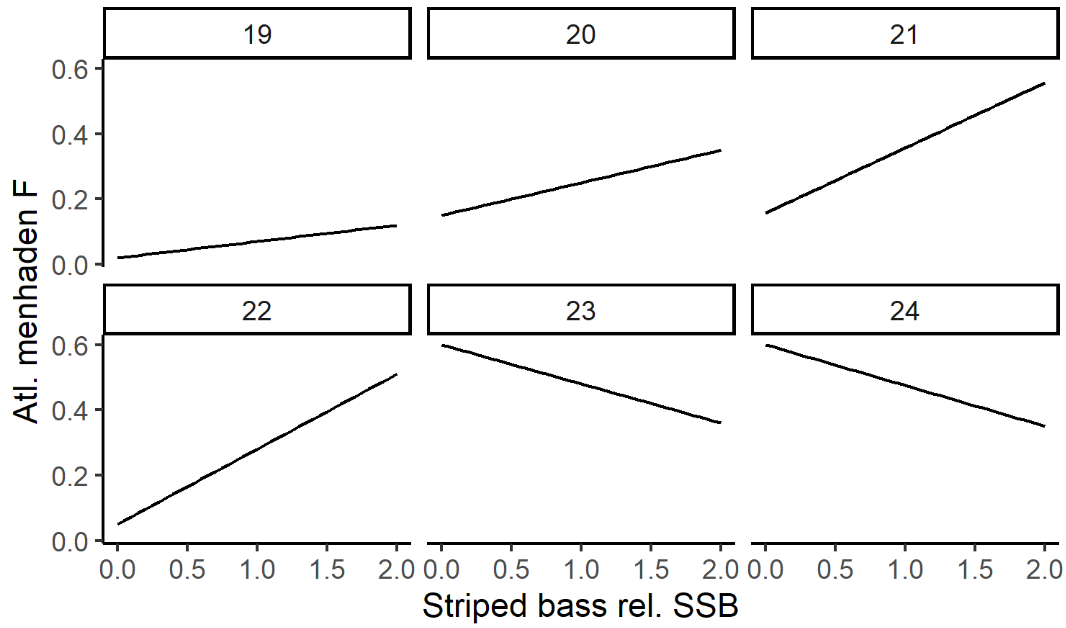

Figure 2.5: Type 2 control rules evaluated for Atlantic menhaden. Atlantic menhaden fishing mortality (F) is determined by striped bass SSB. Headers indicate the control rule number described in Table 1. Relative SSB on the x-axis is SSB relative to Atlantic menhaden's target.

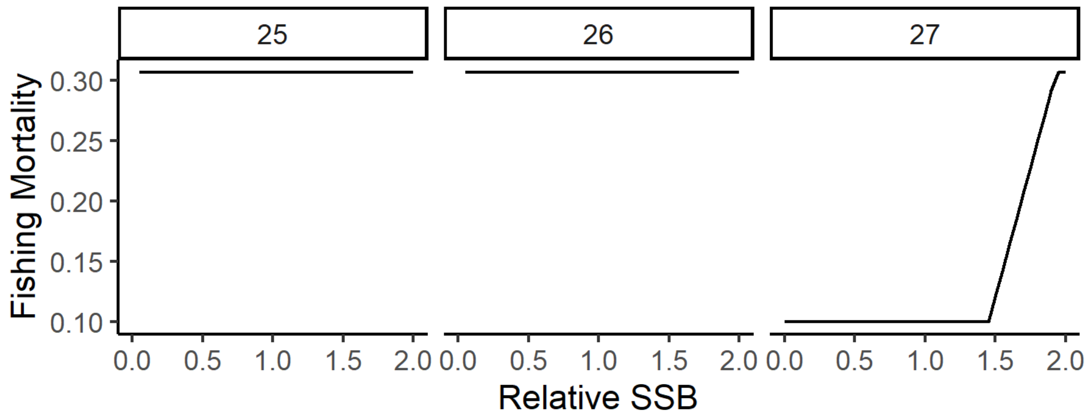

Figure 2.6: Multispecies Type 3 HCRs evaluated. Headers indicate the control rule number described in Table 1. Striped bass in a Type 3 HCR operate under a Type 1 single species while Atlantic menhaden does not. These control rules, unlike Figure 1, are applied under a multispecies standpoint rather than fully single species.

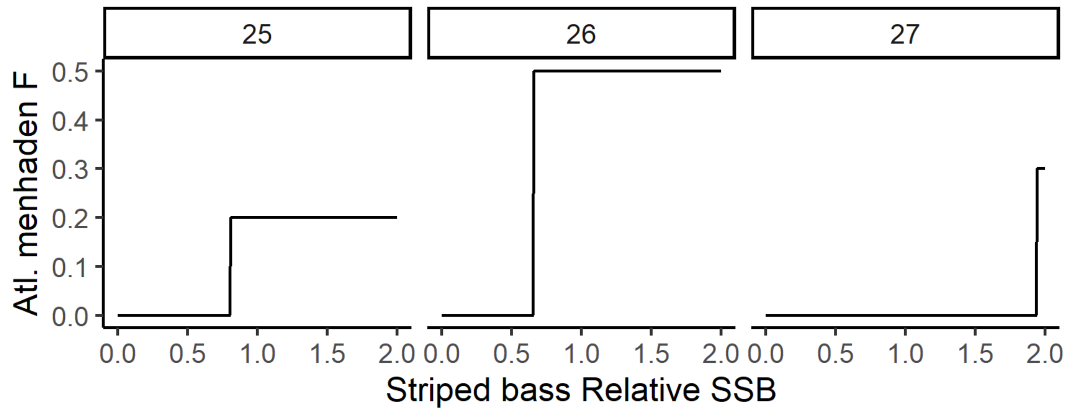

Figure 2.7: Type 3 control rule types for Atlantic menhaden following a cessation based HCR when striped bass relative SSB declines below a specified threshold. Headers indicate the control rule number described in Table 1. Relative SSB on the x-axis is calculated by SSB divided by the striped bass SSB target in the stock assessment. Atlantic menhaden fishing mortality (F) is on the y-axis.

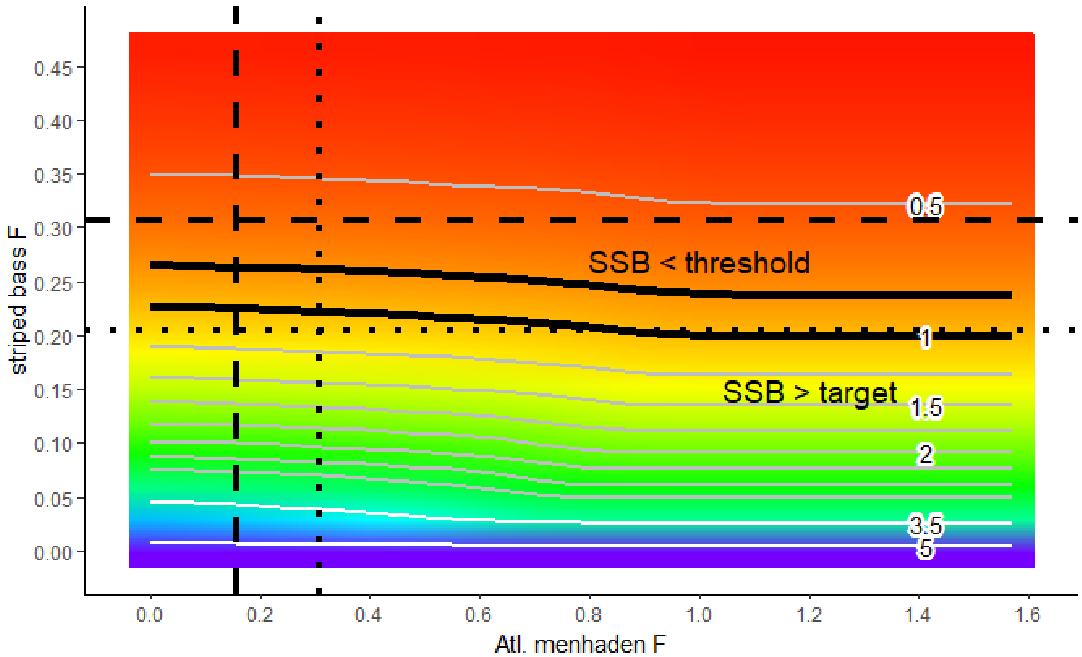

Figure 2.8: Impact of Atlantic menhaden and striped bass F on relative striped bass SSB. A total of 21 Atlantic menhaden Fs were tested, ranging from 0 to 1.49 yr^{-1}, and 16 striped bass Fs were tested, ranging from 0 to 0.47 yr^{-1} following the Chagaris et al. (2020). Rainbow colors within the plot indicate striped bass SSB relative to the striped bass target SSB in the stock assessment. Light grey lines and associated numbers indicate levels of striped bass relative SSB. Long dashed lines indicate the current status quo F for Atlantic menhaden (vertical) and striped bass (horizontal). Dotted lines indicate the target F for Atlantic menhaden (vertical) and striped bass (horizontal). Striped bass SSB is greater than the target (114,295 thousand kg) below the solid black horizontal line labelled 1 and in the space labelled 'SSB>target'. The area above the upper solid black line labelled 'SSB<threshold' indicated striped bass SSB was lower than the threshold SSB (91,436 thousand kg).

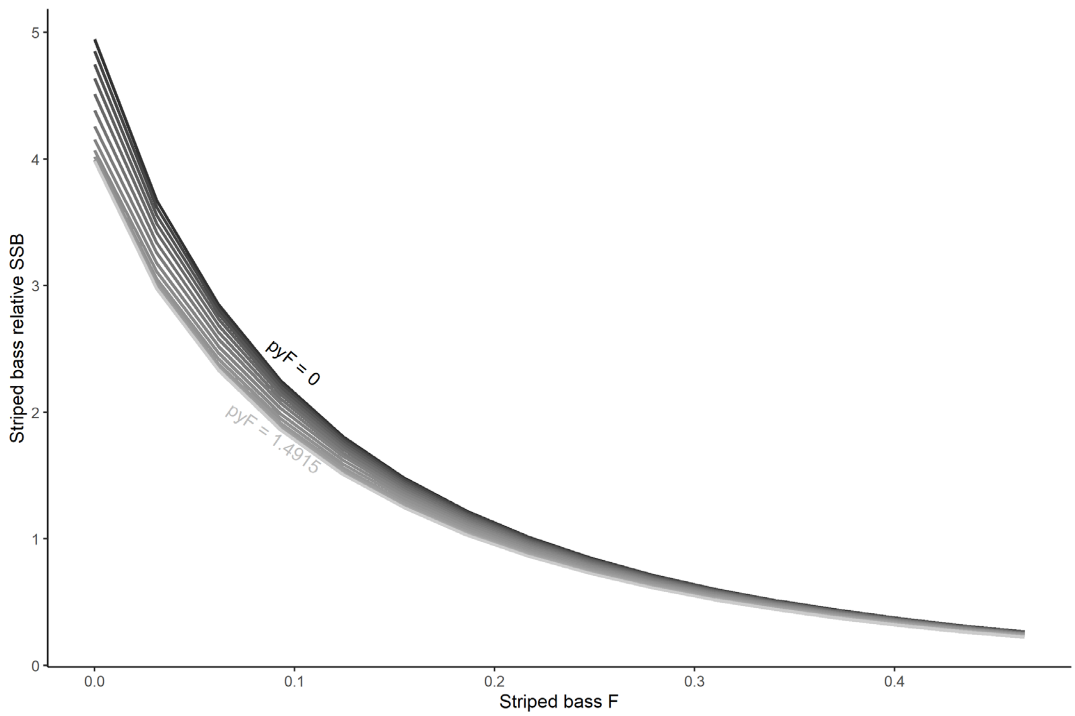

Figure 2.9: Relationship between striped bass F and relative SSB. Relative SSB is SSB under a given HCR divided by their SSB target in the stock assessment (114,295 thousand kg). Each line indicates an Atlantic menhaden F (pyF) input as a constant F HCR into the model. A total of 21 HCRs with pyF ranging from 0 to 1.4915 yr^{-1} were explored. Striped bass operated under a constant F HCR.

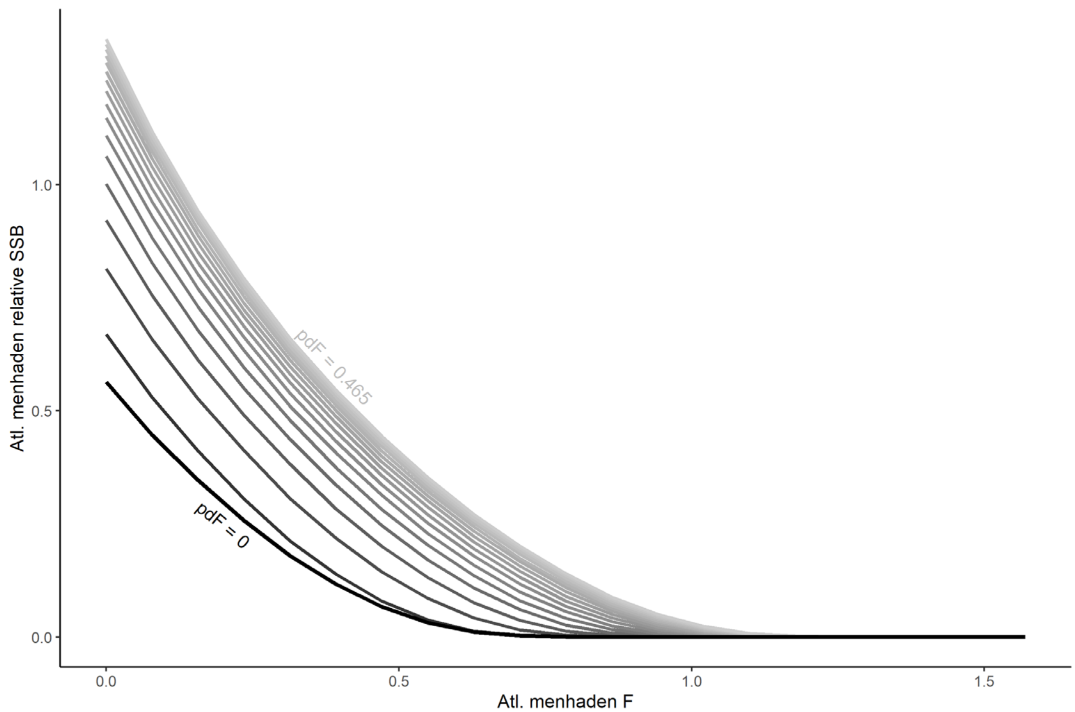

Figure 2.10: Relationship between Atlantic menhaden F and relative SSB. Atlantic menhaden relative SSB is SSB under a given HCR relative to their target SSB recalculated from egg production to billions of kilograms. Each line indicates a striped bass F (pdF) input as a constant F HCR into the model. Atlantic menhaden operated under a constant F HCR. A total of 16 HCRs with pdF ranging from 0 to 0.47 yr^{-1} were explored.

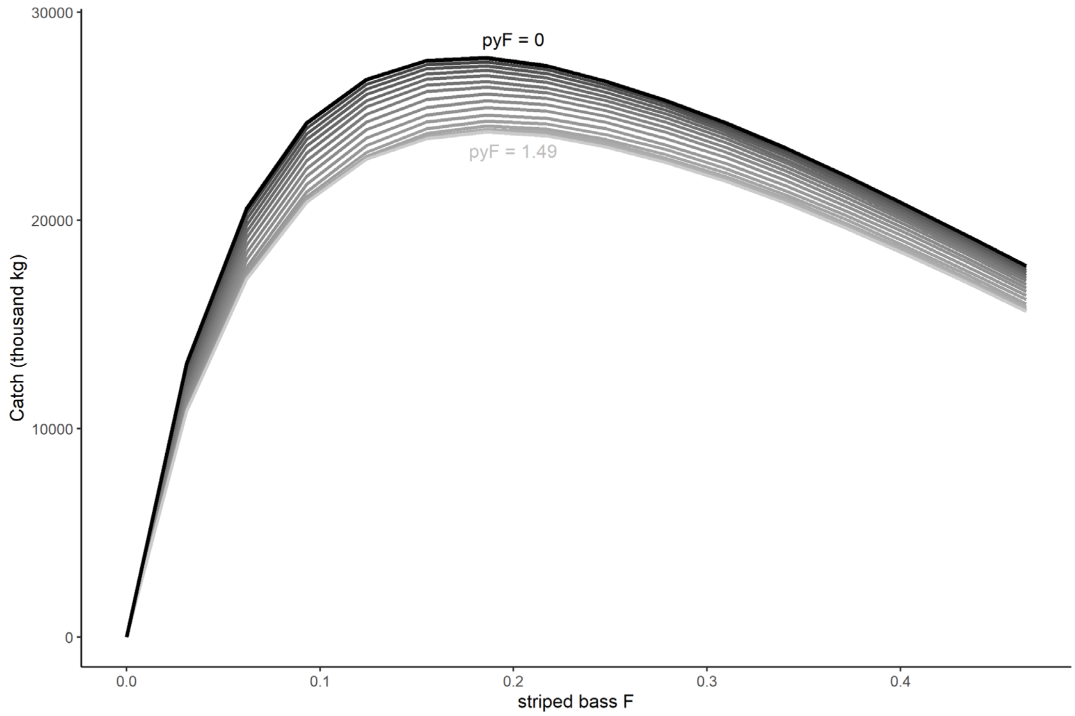

Figure 2.11: Striped bass catch under 21 HCRs where striped bass F was constant and Atlantic menhaden F (pyF) ranged from 0 to 1.49 yr^{-1}. The uppermost solid black line indicates unfished prey conditions (F=0 yr^{-1}), and the lowest curve indicates F for Atlantic menhaden is 1.49 yr^{-1}.

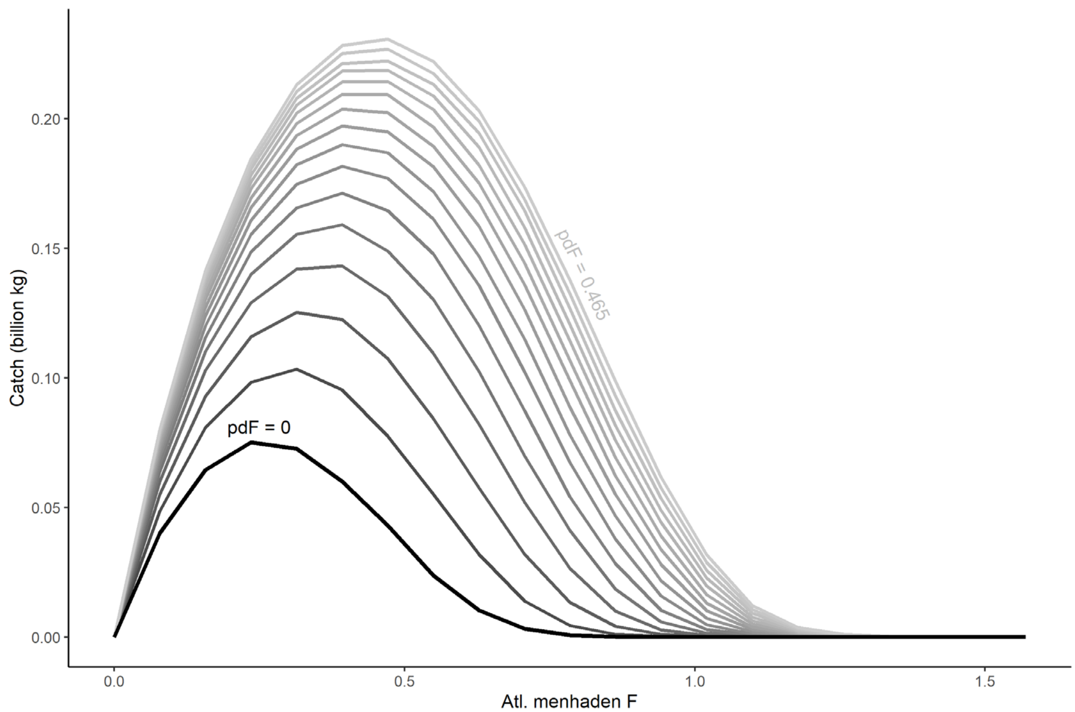

Figure 2.12: Atlantic menhaden catch under 16 HCRs where Atlantic menhaden F is constant and striped bass F (pdF) ranged from 0 to 0.47 yr^{-1}. The lowermost solid black line indicates unfished conditions (F=0 yr^{-1}). The highest curve indicates constant F HCR where F for striped bass is 0.465 yr^{-1}.

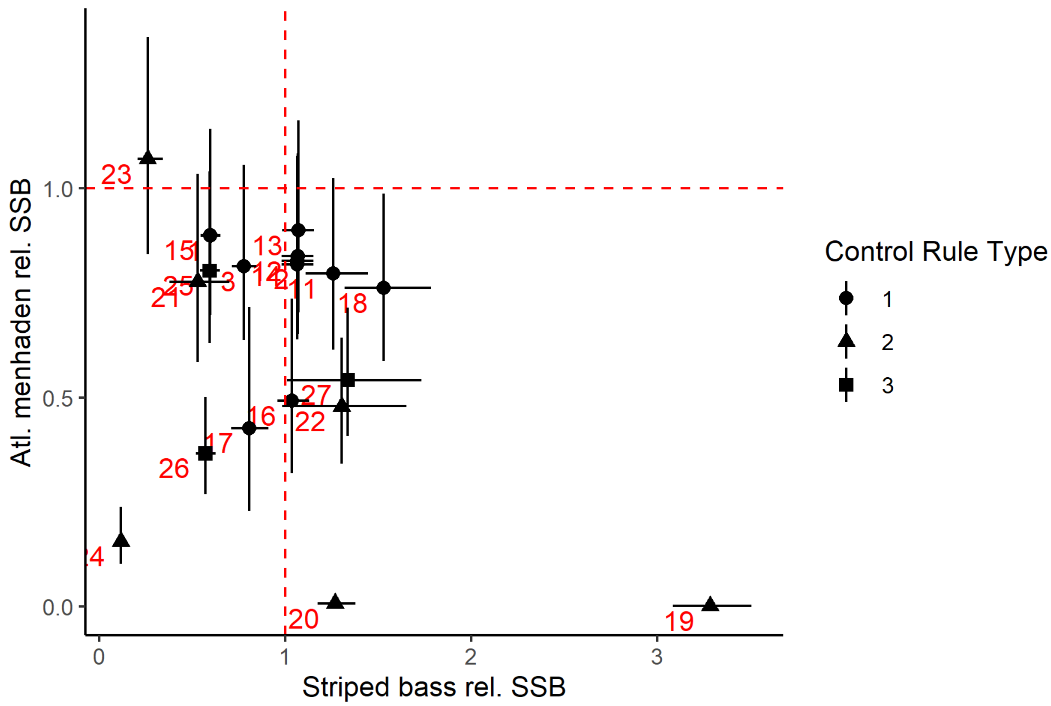

Figure 2.13: Tradeoffs between striped bass relative spawning stock biomass (striped bass rel. SSB) and Atlantic menhaden relative spawning stock biomass (Atl. Menhaden rel. SSB) for 27 harvest control rules (HCR; numbers defined in Table 3). Red dashed lines indicate the relative SSB targets for each species. Points indicate the median SSB and lines show the interquartile range for striped bass (horizontal) and Atlantic menhaden (vertical). HCR types are designated by shapes of the point for Type 1 (circle), Type 2, (triangle), and Type 3 (square).

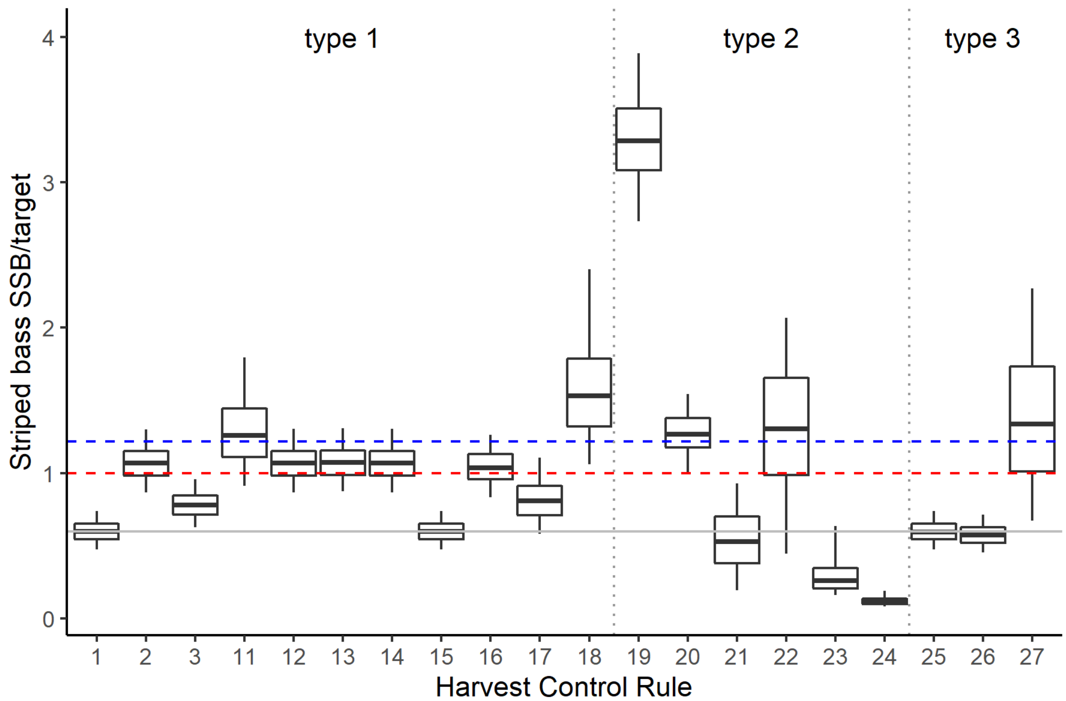

Figure 2.14: Striped bass spawning stock biomass (SSB) relative to the target SSB (target) from the stock assessment for 27 harvest control rules (HCRs; defined in Table 3). The red dashed line indicates the target SSB, the solid grey line indicates SSB at status quo, and the blue dashed line indicates SSB_{MSY}. The vertical dashed lines separate the control rules into categories by type, where HCRs 1-18 are Type 1, 19-24 are Type 2, and 25-27 are Type 3. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

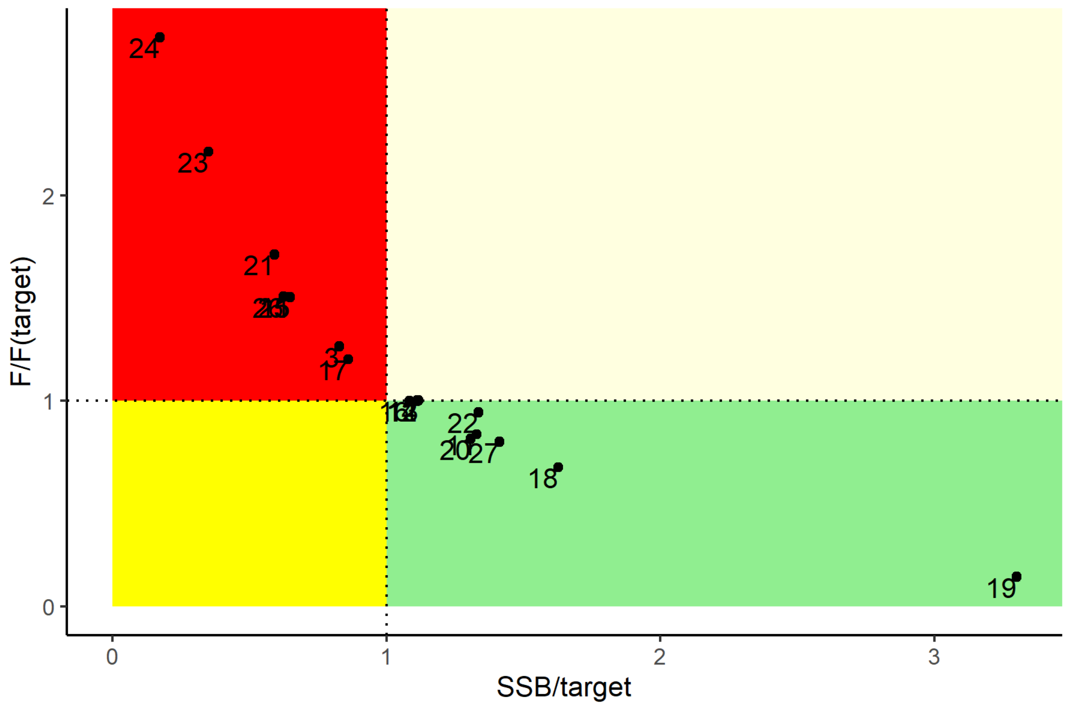

Figure 2.15: Kobe plot showing the relationship between median striped bass spawning stock biomass (SSB) and fishing morality (F) for each HCR. The target refers to the striped bass SSB_{target} found in the stock assessment. Status quo F is 0.204 yr^{-1}. The numbers next to each point indicate the HCR number from Table 3.

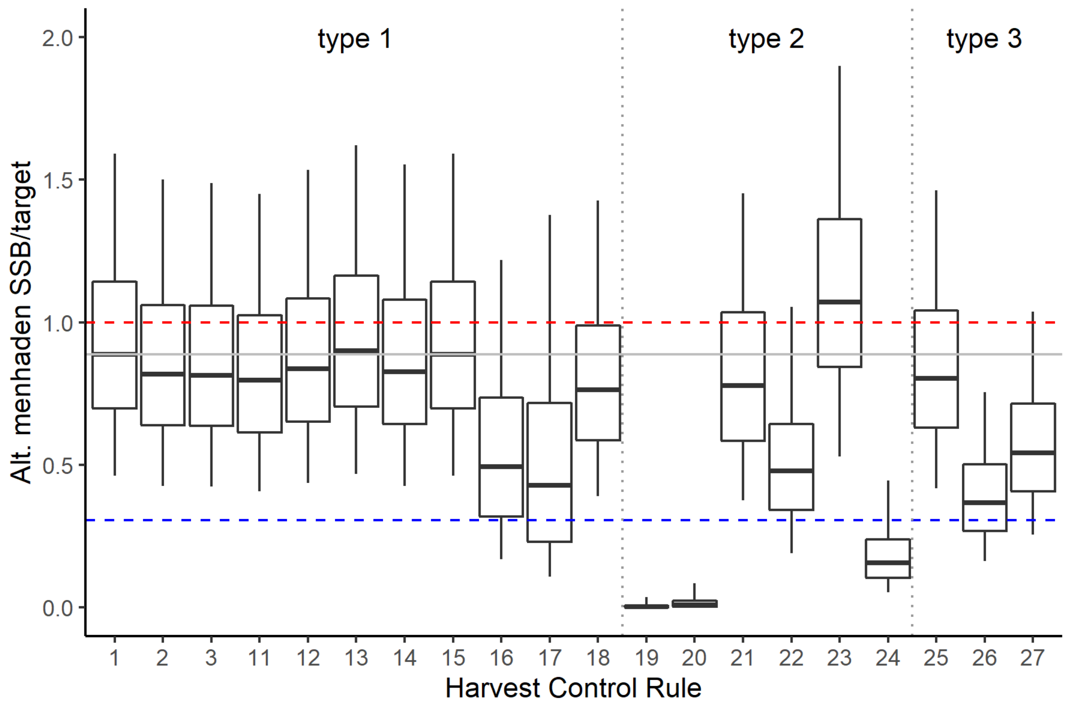

Figure 2.16: Atlantic menhaden spawning stock biomass (SSB) relative to the target SSB (target) from the stock assessment for 27 harvest control rules (HCRs; defined in Table 3). The red dashed line indicates the target SSB, the solid grey line indicates SSB at status quo, and the blue dashed line indicates SSB_{MSY}. The vertical dashed lines separate the control rules into categories by type, where HCRs 1-18 are Type 1, 19-24 are Type 2, and 25-27 are Type 3. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

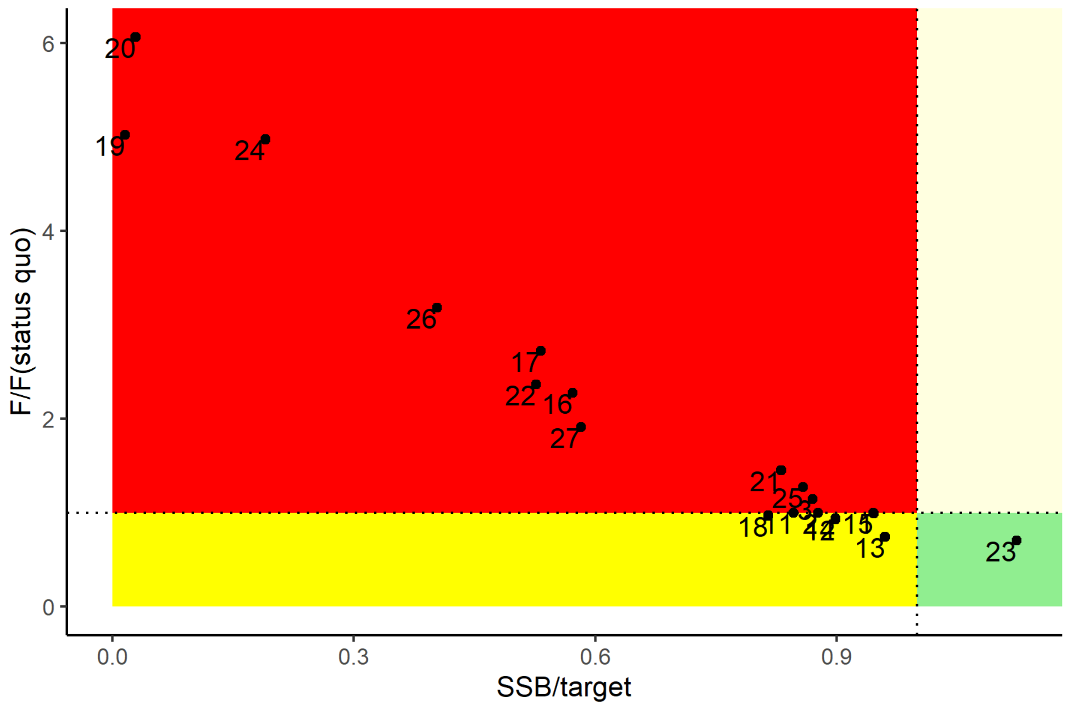

Figure 2.17: Kobe plot showing the relationship between the median Atlantic menhaden spawning stock biomass (SSB) and fishing morality (F) for each HCR. The target refers to the Atlantic menhaden SSB_{target} found in the stock assessment. Status quo F is 0.157 yr^{-1}. The numbers next to each point indicate the HCR number from Table 3.

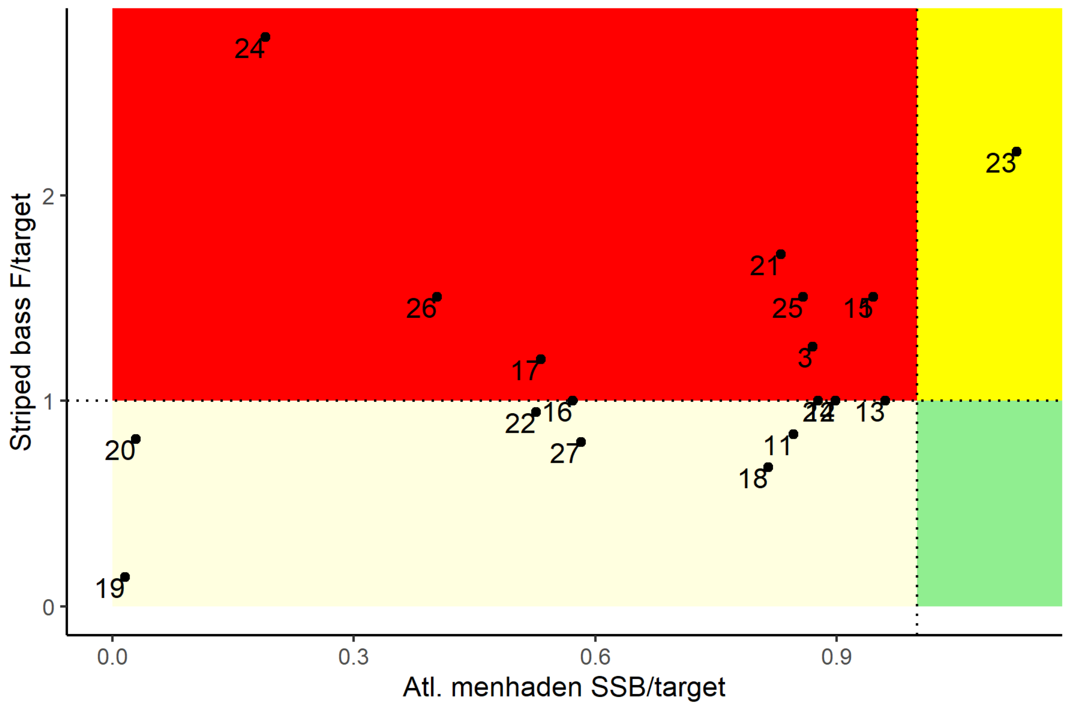

Figure 2.18: A multispecies Kobe plot showing the status of Atlantic menhaden relative SSB (x-axis) and the corresponding striped bass relative F (y-axis). The numbers next to each point correspond to the HCR numbers found in Table 3. The panels in the plot represent varying status of ideal (green), okay (light yellow and yellow), and detrimental (red). F_{target} for striped bass is 0.204 and Atlantic menhaden SSB target is 0.843.

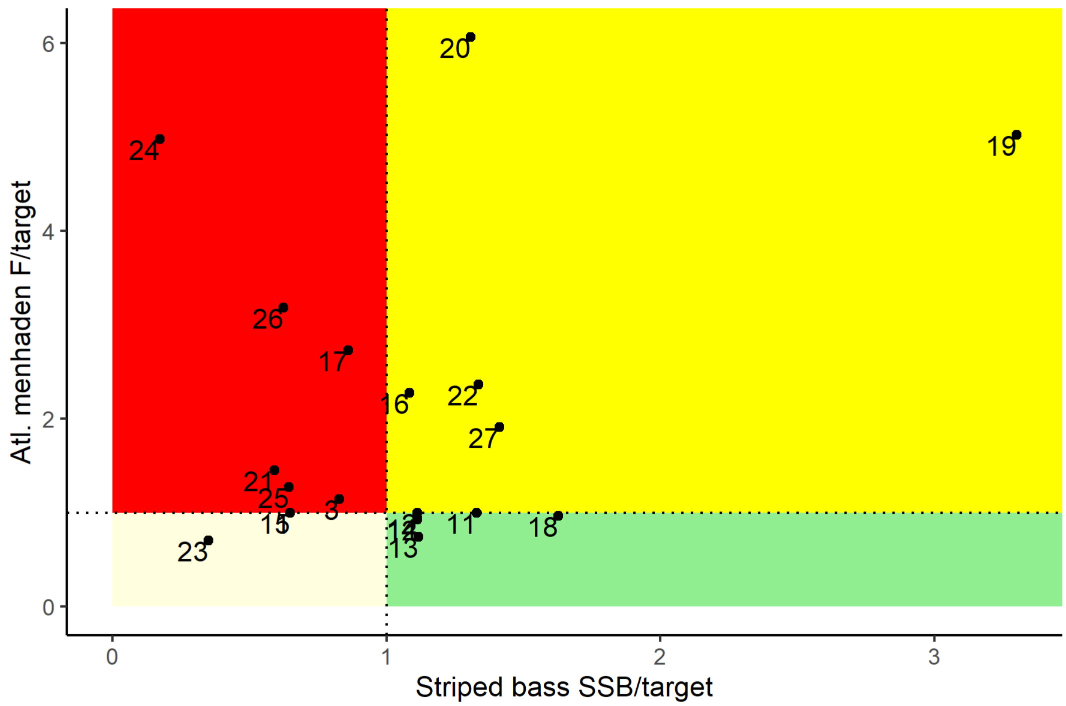

Figure 2.19: A multispecies Kobe plot showing the status of striped bass relative SSB (x-axis) and the corresponding Atlantic menhaden relative F (y-axis). The numbers next to each point correspond to the HCR numbers found in Table 3. The panels in the plot represent varying status of ideal (green), okay (light yellow and yellow), and detrimental (red). F_{TARGET} for Atlantic menhaden is 0.157 and striped bass SSB target is 114,295 thousand kg.

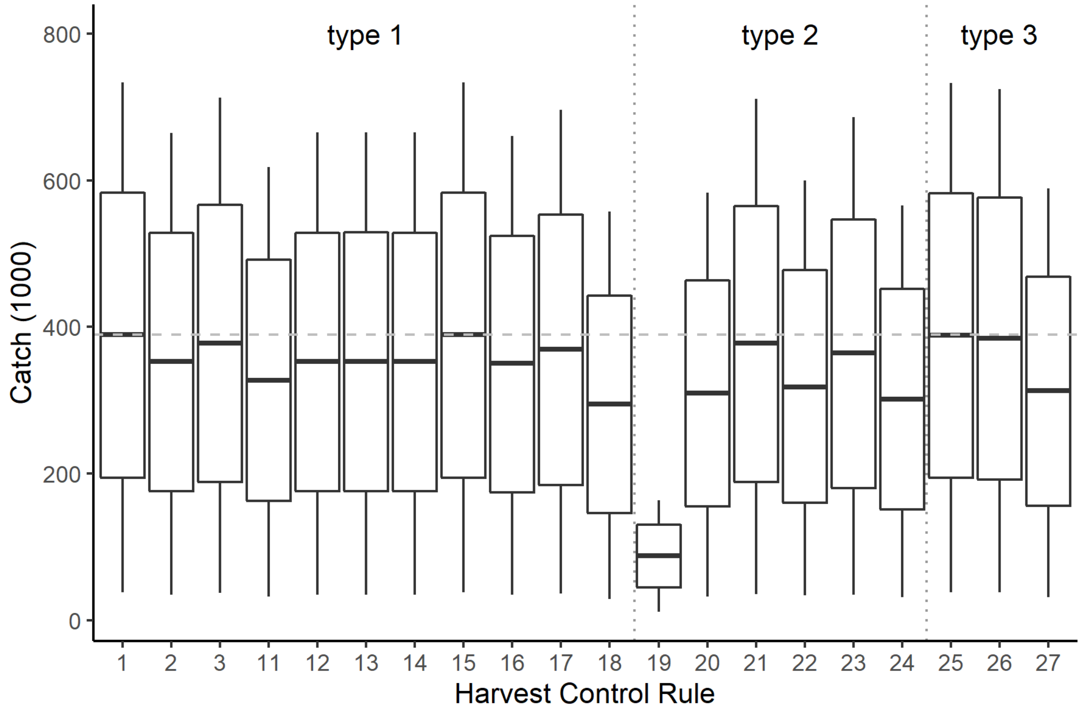

Figure 2.20: Striped bass catch in numbers for 27 harvest control rules (HCRs; defined in Table 3). The horizontal dashed grey line indicates catch at status quo. The vertical dashed lines separate the control rules into categories by type, where HCRs 1-18 are Type 1, 19-24 are Type 2, and 25-27 are Type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

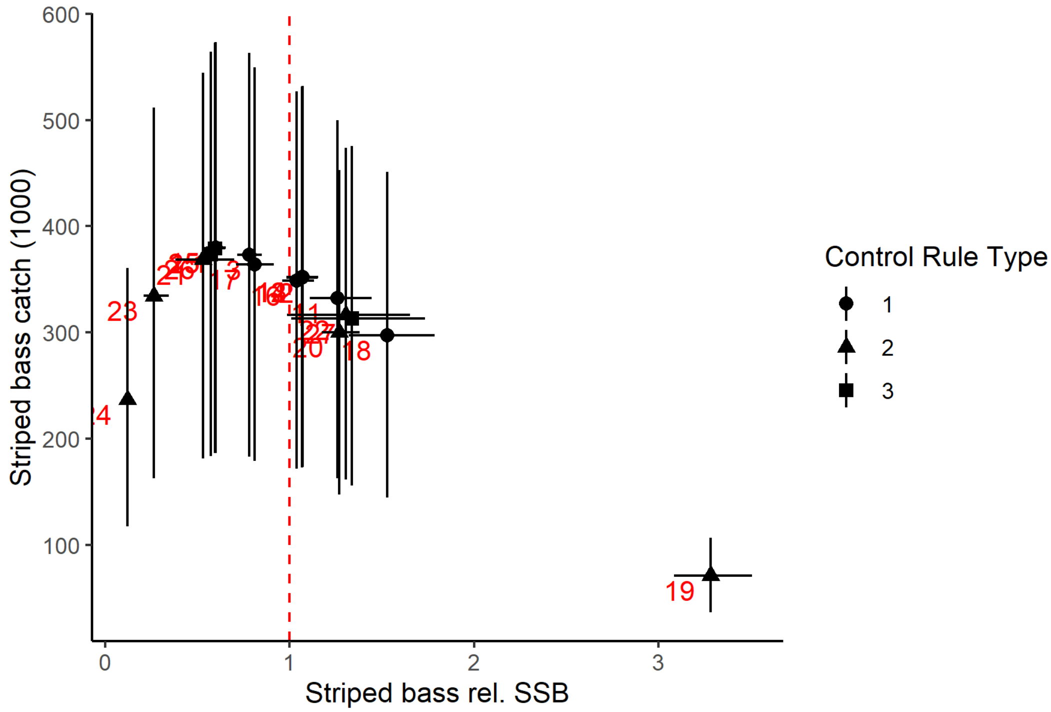

Figure 2.21: Tradeoffs between striped bass relative spawning stock biomass (Striped bass rel. SSB) and catch in numbers for 27 harvest control rules (HCR; numbers defined in Table 3). The red dashed lines indicate the relative SSB targets for striped bass in the stock assessment. The points indicate the median SSB while the lines show the interquartile range for striped bass SSB (horizontal) and catch (vertical). HCR types are designated by shapes of the point for Type 1 (circle), Type 2, (triangle), and Type 3 (square).

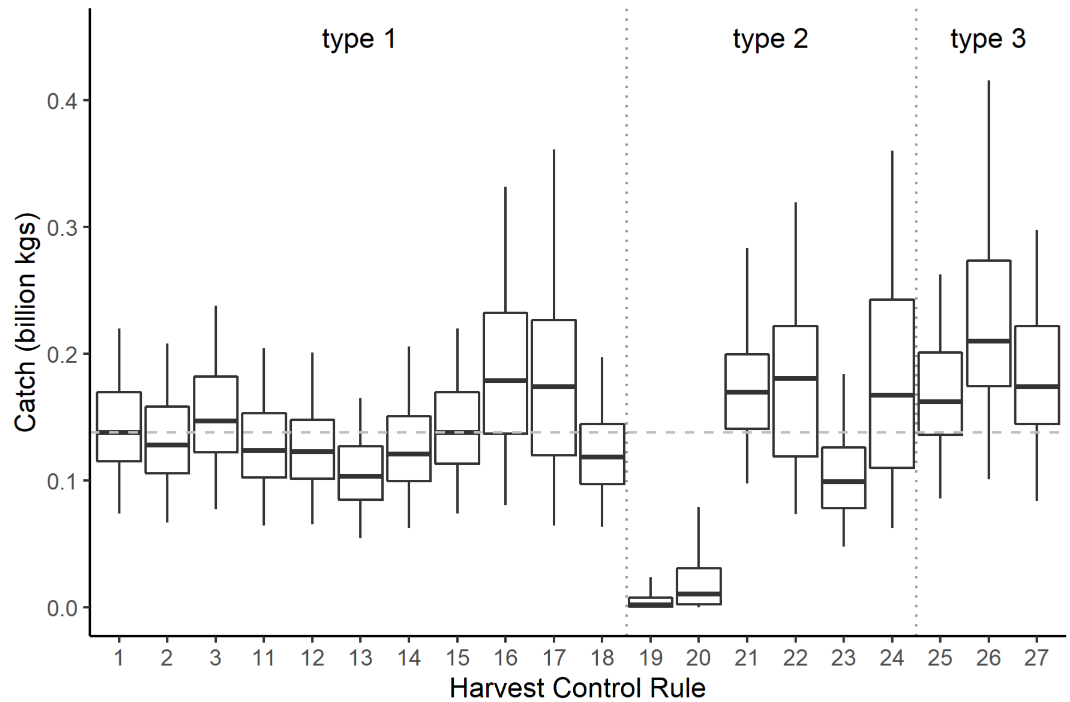

Figure 2.22: Atlantic menhaden catch in weight (billions of kilograms) for 27 harvest control rules (HCRs; defined in Table 3). The horizontal dashed grey line indicates catch at status quo. The vertical dashed lines separate the control rules into categories by type, where HCRs 1-18 are Type 1, 19-24 are Type 2, and 25-27 are Type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

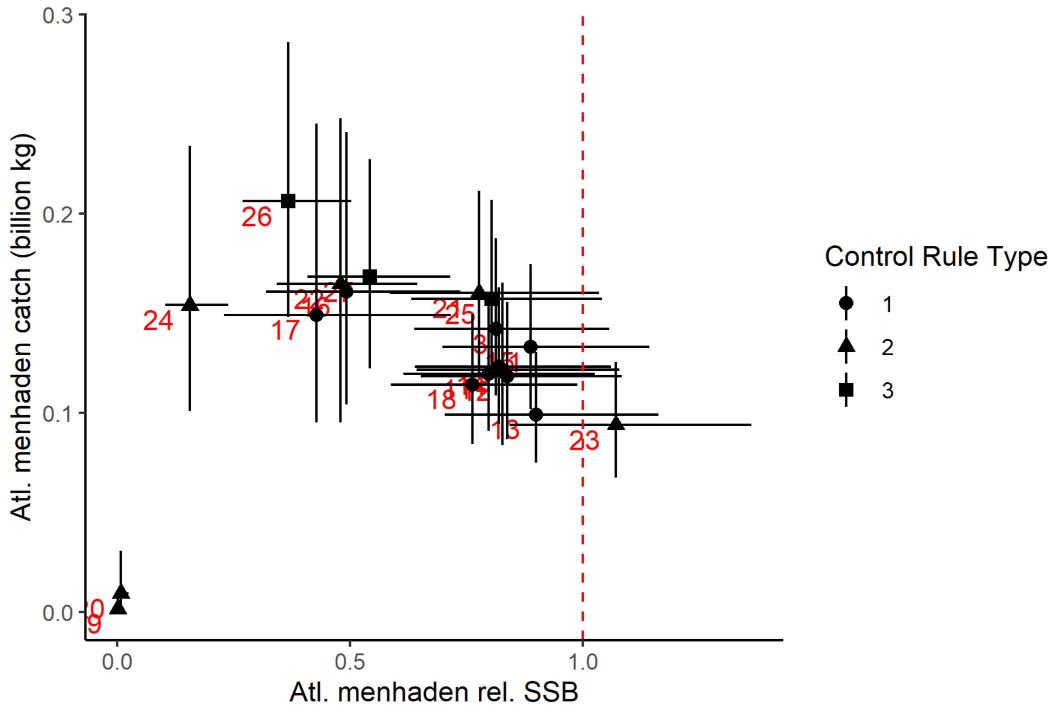

Figure 2.23: Tradeoffs between Atlantic menhaden relative spawning stock biomass and catch for 27 harvest control rules (HCR; numbers defined in Table 3). The red dashed lines indicate the relative SSB targets for Atlantic menhaden in the stock assessment. The points indicate the median SSB while the lines show the interquartile range for SSB (horizontal) and catch (vertical). HCR types are designated by shapes of the point for Type 1 (circle), Type 2, (triangle), and Type 3 (square).

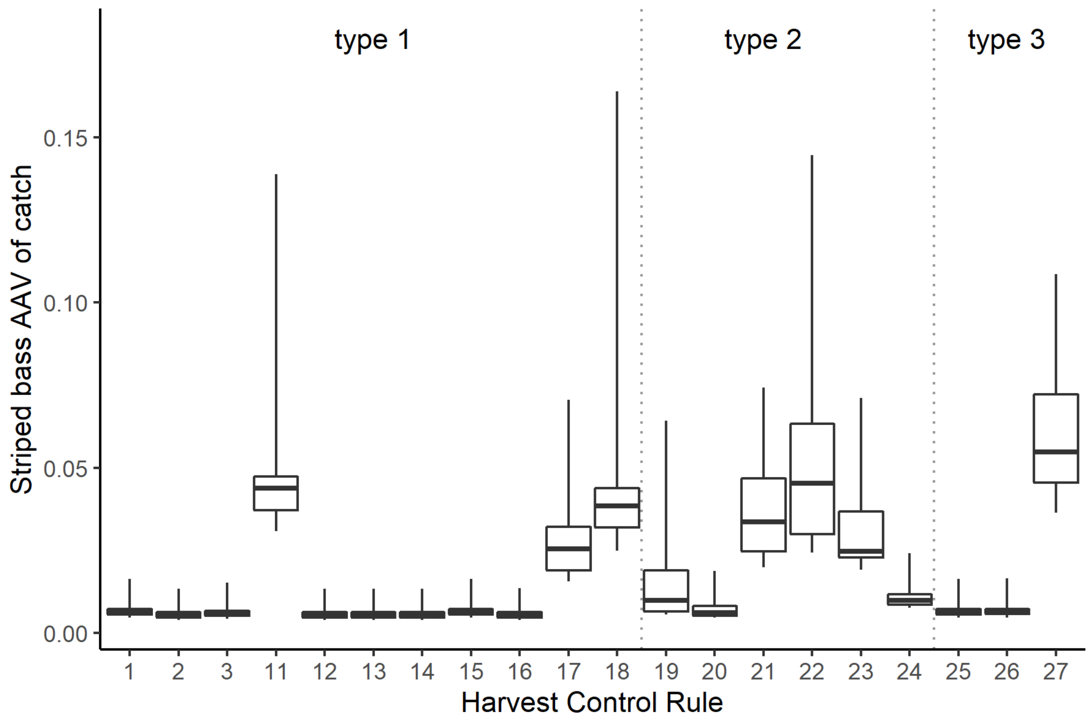

Figure 2.24: Average annual variation (AAV) in striped bass catch calculated in numbers of striped bass. The vertical dashed lines separate the control rules into categories by type, where HCRs 1-18 are Type 1, 19-24 are Type 2, and 25-27 are Type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

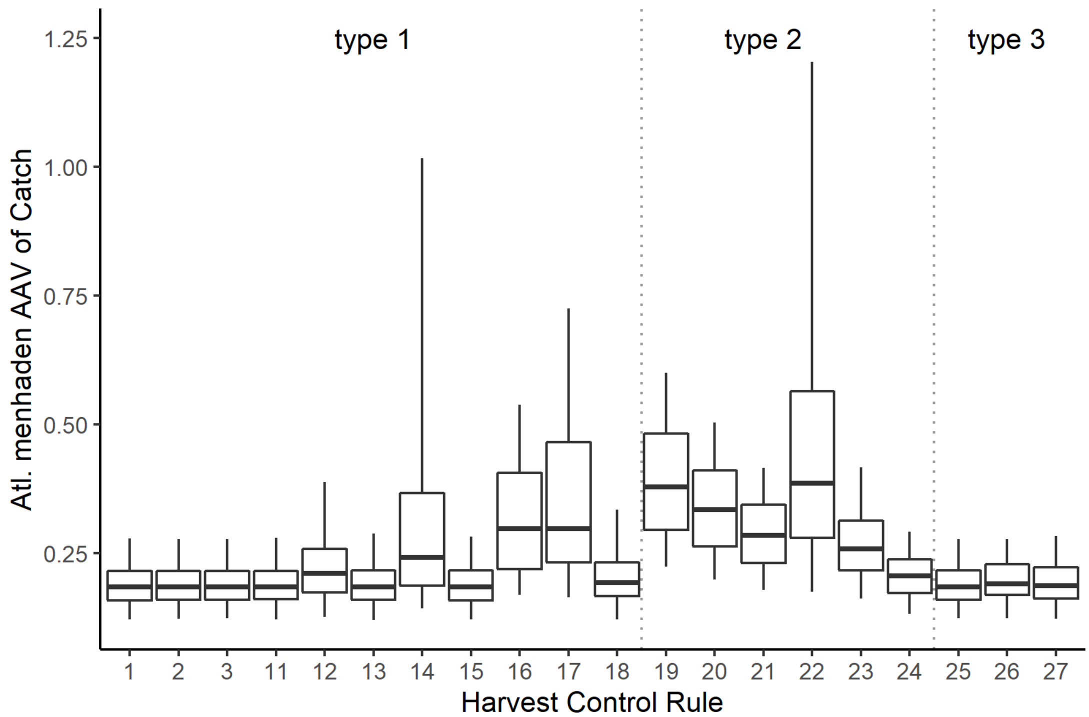

Figure 2.25: Average annual variation (AAV) in Atlantic menhaden catch calculated in billions of kilograms There is no catch for HCR 4, 6, and 7 because F for Atlantic menhaden is 0. The vertical dashed lines separate the control rules into categories by type, where HCRs 1-18 are Type 1, 19-24 are Type 2, and 25-27 are Type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

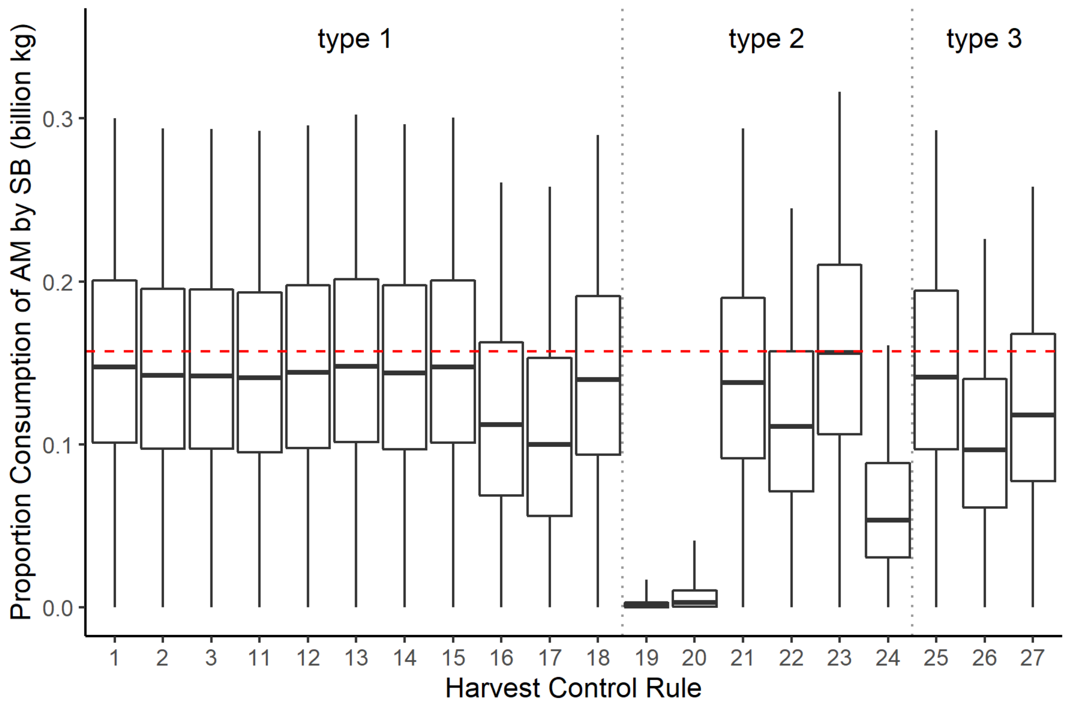

Figure 2.26: Proportion consumption of Atlantic menhaden (AM) by age-3 striped bass (SB) for 27 harvest control rules (HCRs; defined in Table 3). At age-3, Atlantic menhaden comprise 15.7% of striped bass diet according to Chagaris et al (2020) (red dashed line). The vertical dashed lines separate the control rules into categories by type, where HCRs 1-18 are Type 1, 19-24 are Type 2, and 25-27 are Type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

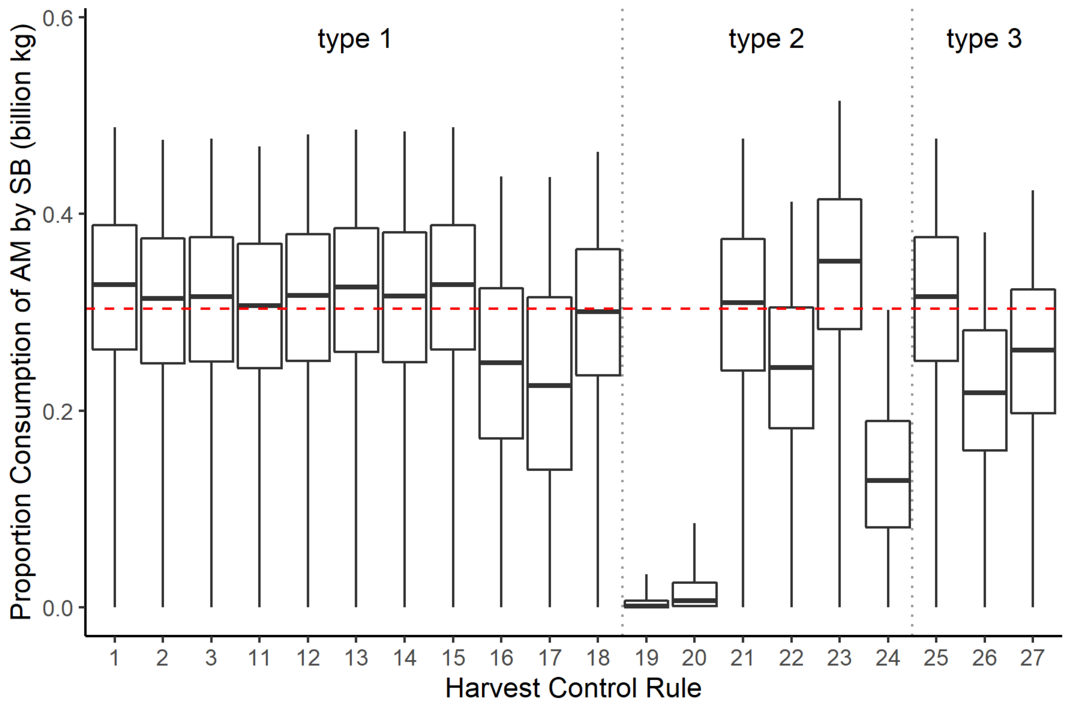

Figure 2.27: Proportion consumption of Atlantic menhaden (AM) by age-15 striped bass (SB) for 27 harvest control rules (HCRs; defined in Table 3). At age-15, Atlantic menhaden comprise 30.4% of striped bass diet according to Chagaris et al (2020) (red dashed line). The vertical dashed lines separate the control rules into categories by type, where HCRs 1-18 are Type 1, 19-24 are Type 2, and 25-27 are Type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

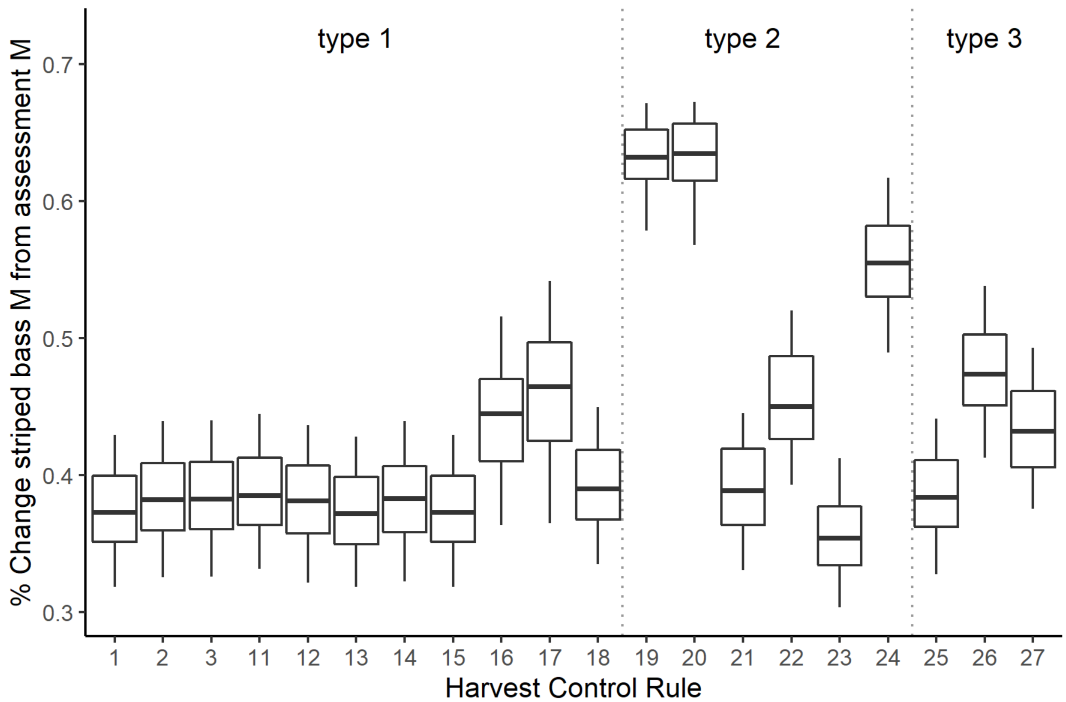

Figure 2.28: Percent change of age-3 striped bass natural mortality (M) from the stock assessment age-3 M for 27 harvest control rules (HCRs; defined in Table 3). The vertical dashed lines separate the control rules into categories by type, where HCRs 1-18 are Type 1, 19-24 are Type 2, and 25-27 are Type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

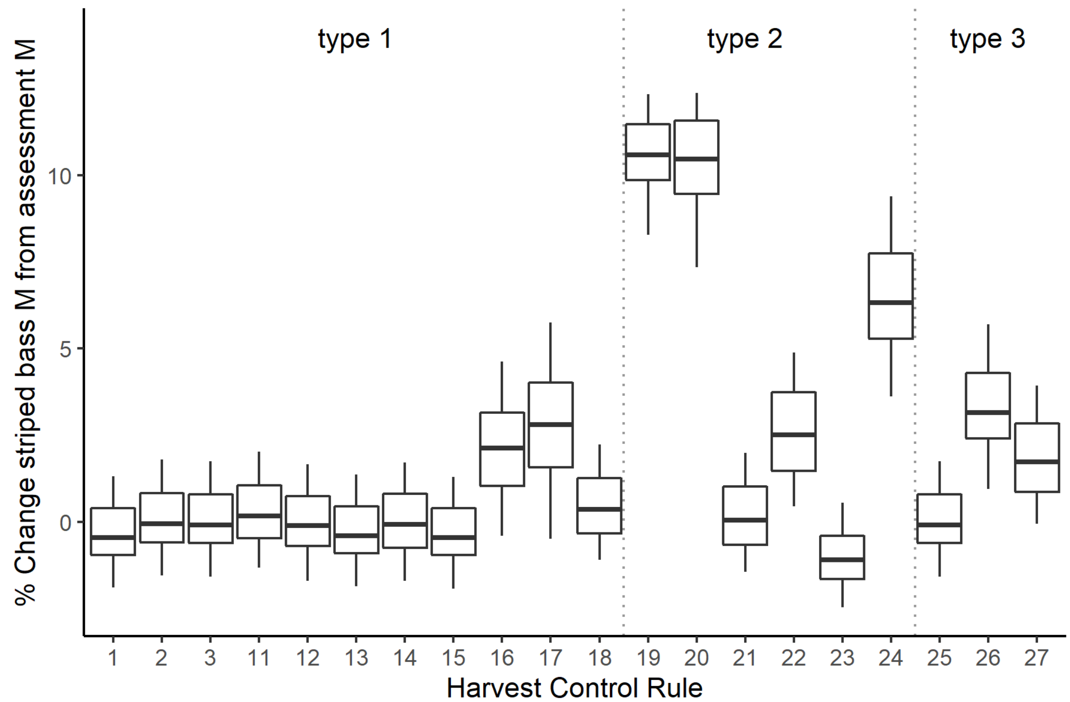

Figure 2.29: Percent change of age-15 striped bass natural mortality (M) from the stock assessment age-15 M for 27 harvest control rules (HCRs; defined in Table 3). The vertical dashed lines separate the control rules into categories by type, where HCRs 1-18 are Type 1, 19-24 are Type 2, and 25-27 are Type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

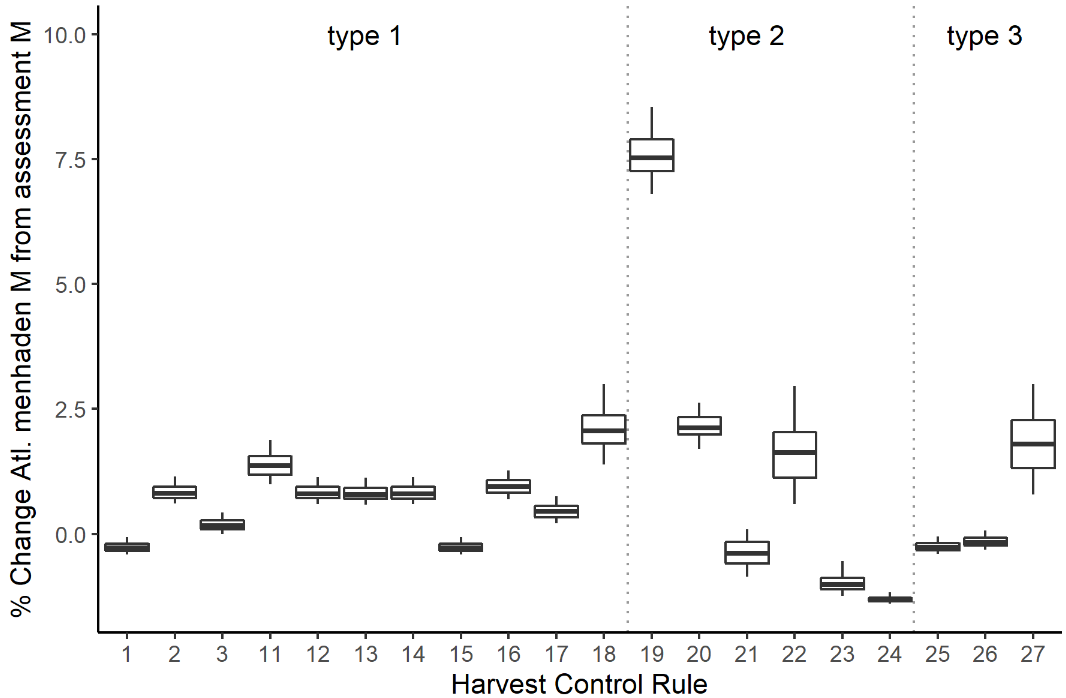

Figure 2.30: Percent change of age-1 Atlantic menhaden M from the stock assessment M. The vertical dashed lines separate the harvest control rules into categories by type, where HCRs 1-18 are Type 1, 19-24 are Type 2, and 25-27 are Type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

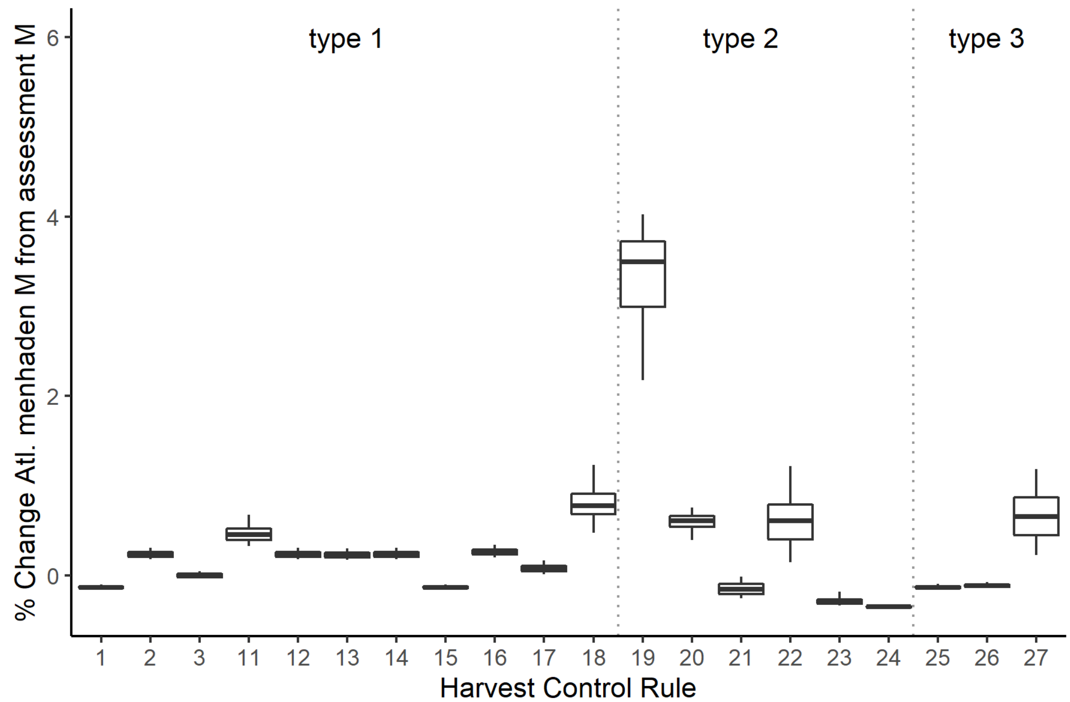

Figure 2.31: Percent change of age-4 Atlantic menhaden natural mortality (M) from the stock assessment age-4 M for 27 harvest control rules (HCRs; defined in Table 3. The vertical dashed lines separate the control rules into categories by type, where HCRs 1-18 are Type 1, 19-24 are Type 2, and 25-27 are Type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

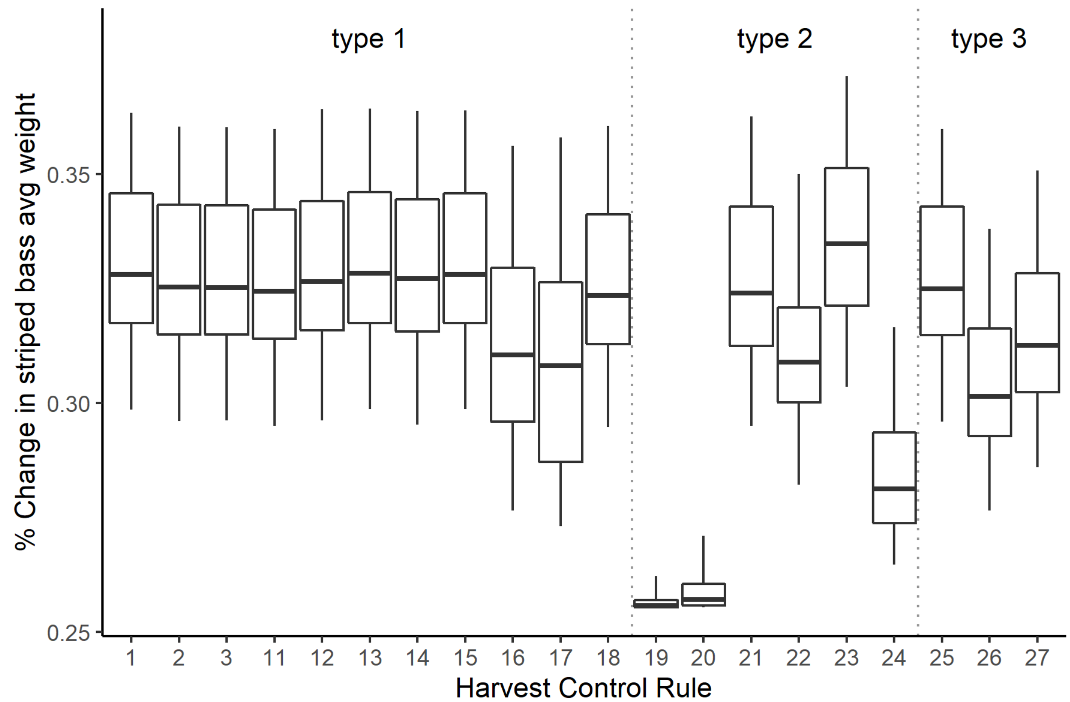

Figure 2.32: Percent change in age-3 striped bass weight from the average age-3 striped bass weight calculated in chapter 1 for 27 harvest control rules (HCRs; defined in Table 3). The vertical dashed lines separate the control rules into categories by type, where HCRs 1-18 are Type 1, 19-24 are Type 2, and 25-27 are Type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

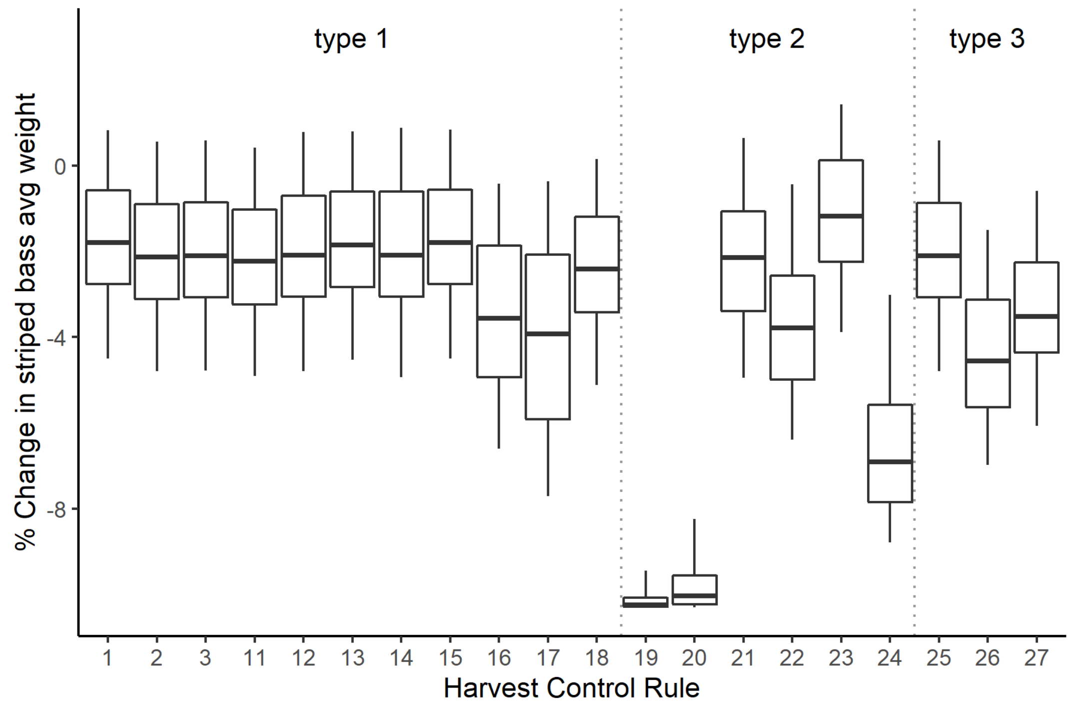

Figure 2.33: Percent change in age-15 striped bass weight from the average age-15 striped bass weight calculated in chapter 1 for 27 harvest control rules (HCRs; defined in Table 3). The vertical dashed lines separate the control rules into categories by type, where HCRs 1-18 are Type 1, 19-24 are Type 2, and 25-27 are Type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

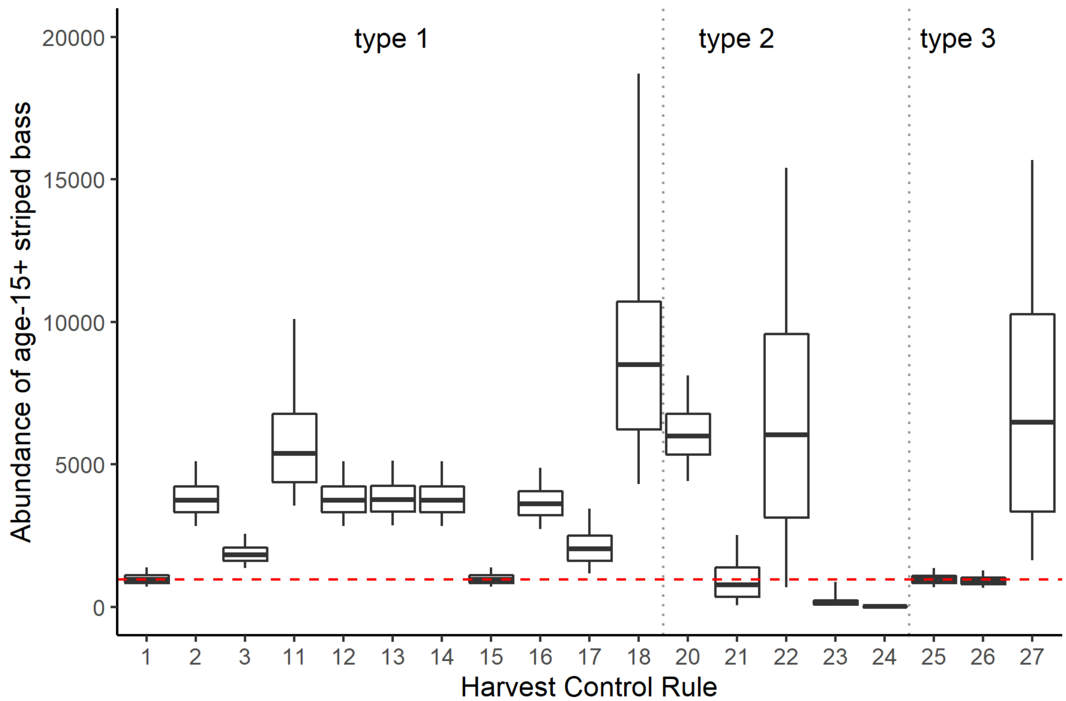

Figure 2.34: Abundance of age-15 and older striped bass (millions) for 24 harvest control rules (HCRs; defined in Table 3). All HCRs are compared except for HCR 4, 5, and 19 which differed by X order(s) of magnitude. The red dashed line indicates the abundance of age-15 and older striped bass when fished at status quo. The vertical dashed lines separate the control rules into categories by type, where HCRs 1-18 are Type 1, 19-24 are Type 2, and 25-27 are Type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

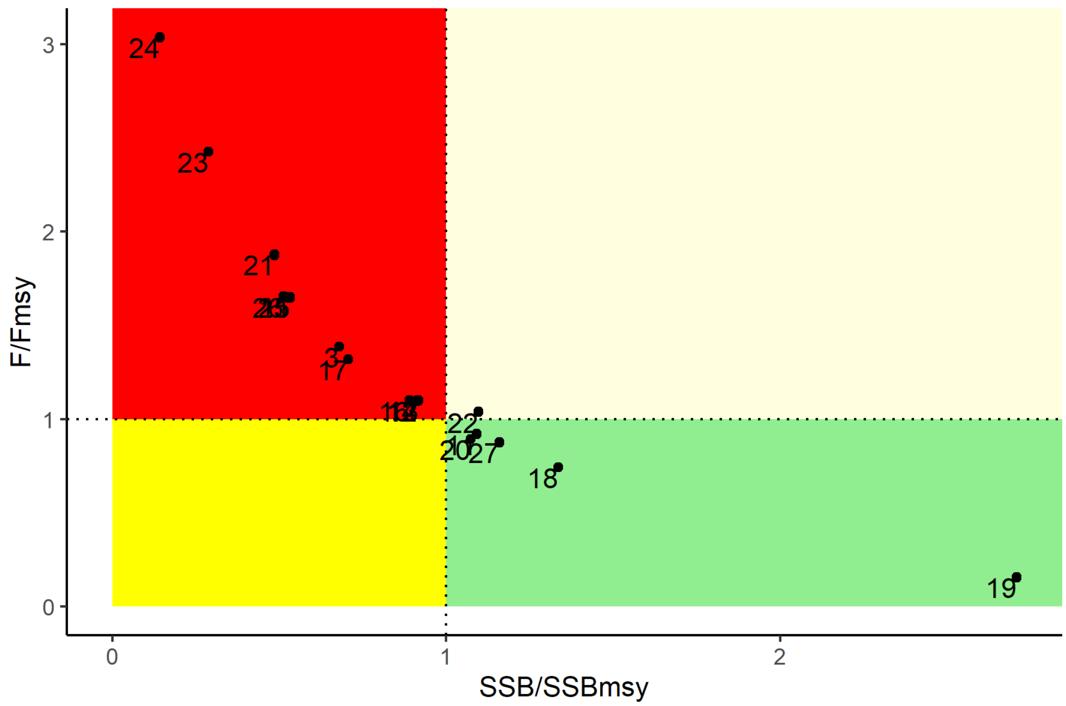

Figure 2.35: Kobe plot showing the relationship between the median striped bass spawning stock biomass (SSB) and fishing morality (F) for each HCR. SSB_{MSY} refers to striped bass SSB_{MSY} found from model performance analysis where SSB_{MSY} is 139,254 thousand kg. F_{MSY} is 0.186 yr^{-1}. The numbers next to each point indicate the HCR number from Table 3.

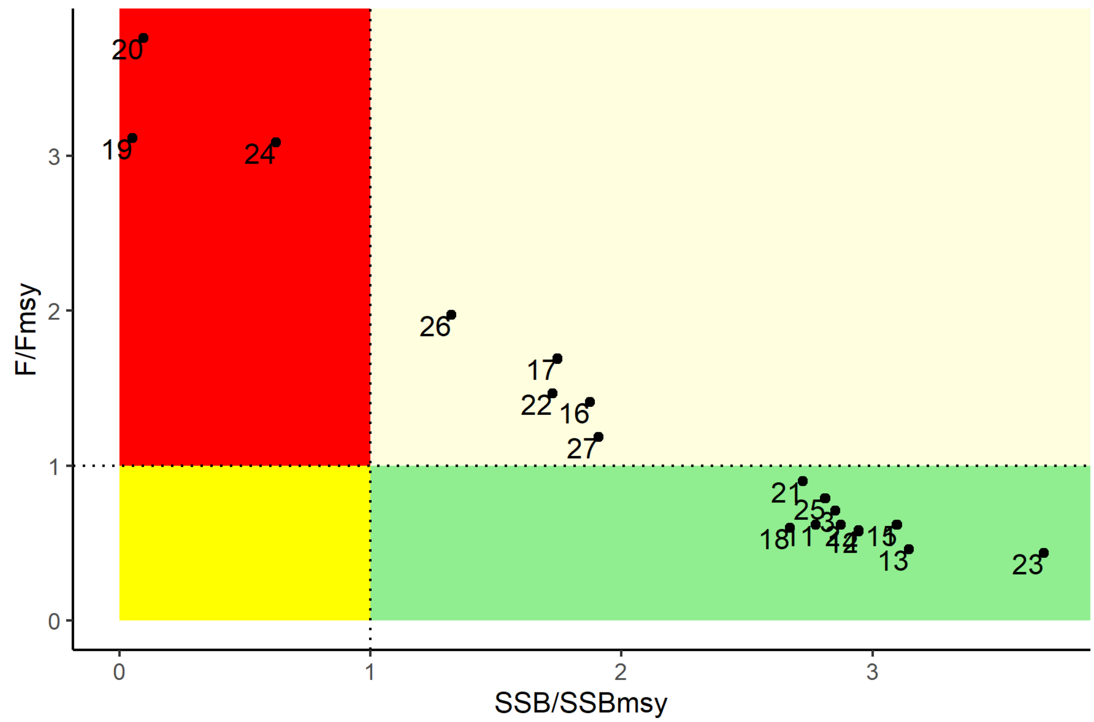

Figure 2.36: Kobe plot showing the relationship between the median Atlantic menhaden spawning stock biomass (SSB) and fishing morality (F) for each HCR. SSB_{MSY} refers to Atlantic menhaden SSB_{MSY} found from model performance analysis where SSB_{MSY} is 0.02572 billion kg. F_{MSY} is 0.2355 yr^{-1}. The numbers next to each point indicate the HCR number from Table 3.

Appendices

Appendix A: Chapter 1 Supplementary Figures

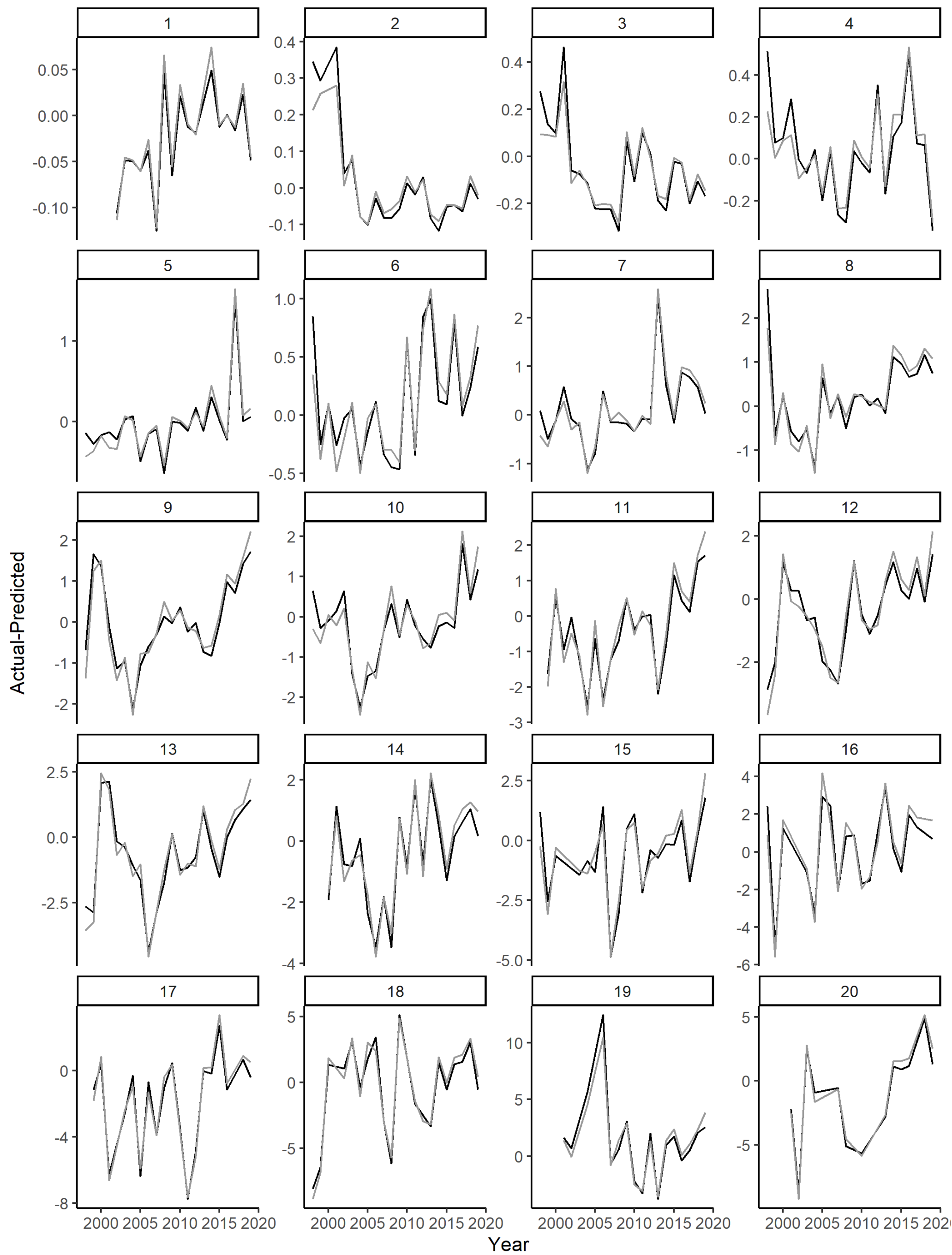

Figure A.1: Comparison of the difference between predicted weights output from mixed effects models and weight-at-age data of striped bass during 1998-2019. The difference between the predicted mean weight from a mixed effects model that does not incorporate a random effect of year and the observed mean weight-at-age from this study is displayed in black. The difference between predicted mean weight from a mixed effects model *incorporating year as a random effect and the observed mean weight-at-age is displayed in grey. The headers of each plot box display the age. Note the y-axis range changes for each plot.*

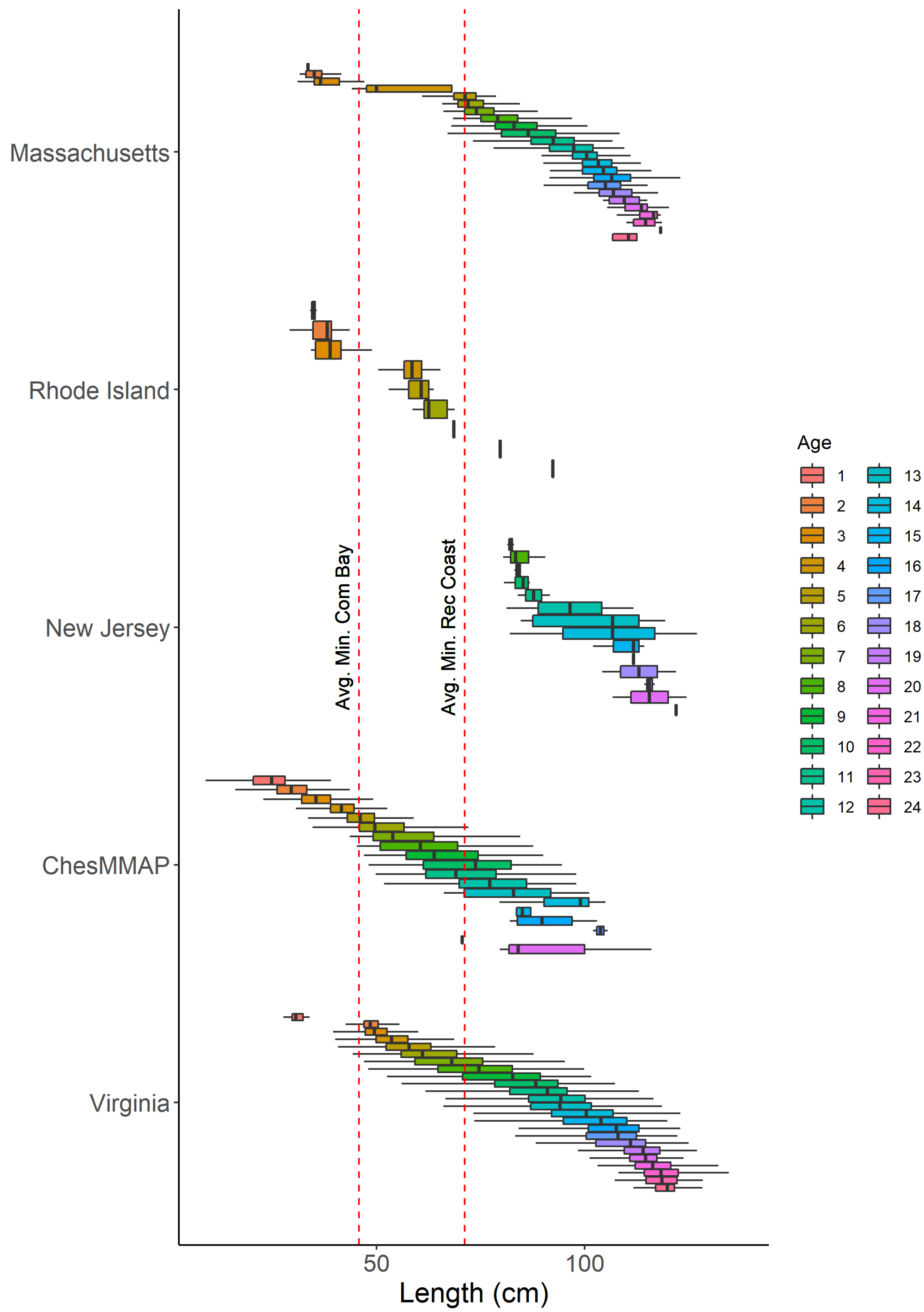

Figure A. 2: Distribution of length-at-age for striped bass by data source. Box plots represent the 25th to 75th percentile with the middle black line of the box representing the median length-at-age. The whiskers in the plot represent 1.5 times the interquartile range above and below the box. The average regulation size limits for striped bass along the Atlantic coast of the U.S. are indicated by the red dashed lines, namely the commercial minimum in the Chesapeake Bay (left), and the recreational minimum for the Atlantic coast (right).

Appendix B: Operating Model Input Preparation and Tuning

Stock-Recruitment

Stock-recruitment function parameter estimates for striped bass and Atlantic menhaden were calculated using information from the most recent stock assessments. For striped bass, annual total spawning stock biomass (SSB) from 1982-2019 was calculated using total abundance-at-age, weight-at-age, and maturity-at-age using the following equation:

$$SSB_y = \sum_a N_{y,a} W_{y,a} M_{y,a}$$

where the total SSB in a given year is the product of abundance, *N*, weight, *W*, and maturity, *M*, in that given year over ages 1 through 15. I used the annual SSB estimated from the stock assessment model to calculate estimated recruitment (Est. R) from 1983-2019 following the Beverton-Holt stock recruitment function where

$$Est.R_y = \frac{\alpha SSB_{y-1}}{1+\beta SSB_{y-1}}.$$

The recruitment in year, y, is estimated using the SSB in the previous year, the productivity of the stock, α, and the density dependent term, β. I calculated the squared residuals between the estimated recruitment in a given year and the actual recruitment in the same year as found in the striped bass stock assessment (NEFSC, 2019). The sum of the negative log-likelihood was summarized and solved for to find the optimal α, β, and σ where the log-likelihood was calculated as

$$LL = \sum_{i=1982}^{2017} l\,n(\sigma) + \frac{\left(ln(R_y) - ln(EstR_y)\right)^2}{2\sigma^2},$$

where σ is the average annual deviation among recruits. The solver plug-in in Microsoft Excel was used to minimize the log-likelihood function. Estimated parameters were used as specified values for the predator-prey simulation model stock recruitment function. Atlantic menhaden stock-recruitment followed the same process as striped bass, but there was no lag between SSB and recruitment.

Striped Bass Consumption

Striped bass seasonal estimates of length were used from a smoothed geometric mean calculated in chapter 1. Change in weight was assumed to be constant over each season such that the average change in weight in a given season between ages was

$$\Delta W = \frac{W_a - W_{a-1}}{4}.$$

A parabolic function was estimated to calculate predicted change in weight of striped bass at a given age:

$$Pred.\Delta W_a = -0.0033a^2 + 0.0674a - 0.0231.$$

I assumed that the maximum proportion of consumption (*Cmax*) was 0.9 and calculated *Gmax* by dividing Pred.ΔG by the proportion maximum consumption. I was then able to estimate *Cmax* as a proportion of *Gmax* and the conversion efficiency of striped bass from reported estimates in the literature from Hartman and Brandt (1995) for age-1 and age-2 and Nelson et al. (2006) for age-3 to age-12. I assumed that growth conversion efficiency began to decline after age-13 and reached 0 at age 20 and older. These estimates of *Gmax* and *Cmax* were used as inputs into both the predator-prey simulation model and additional analysis to estimate γ, effective search area (a variable used to control the consumption dynamics of the predator with the prey and other prey pool).

The age structure of the striped bass stock was expanded beyond age 15+ as in the stock assessment to include age-20 and older. Abundance of age-15 through age-19 striped bass was calculated as

$$N_{a+1} = N_{y,\mathrm{a}}\mathrm{e}^{-\mathrm{Z}},$$

where Z was the total mortality. Z was estimated as

$$Z_a = M_a + F_a,$$

where a was age, M was natural mortality input from the striped bass stock assessment, and F was fishing mortality. I calculated the F imposed upon striped bass at any given age as,

$$F_a = \frac{0.307Sel_a}{3},$$

where 0.307 was the status quo F on the stock and *Sel* is the selectivity at age for striped bass. The abundance of the age-20 and older plus class was calculated as

$$N_y = N_{y-1} * \frac{exp(-Z)}{1-exp(-Z)}.$$

After initial inputs for the consumption dynamics were set, I designed a set of 3 operating models with different consumption dynamics assumptions. The first difference was in the prey preference function such that NC30 and NC70 followed a symmetric prey preference function of

$$SP = exp\left[\frac{-\left(\frac{length_i}{length_j} - length_{opt}\right)}{\omega}\right],$$

where the ratio of predator length, $length_j$, and prey length, $length_i$, was taken from the optimal predator-prey length, $length_{opt}$, of 0.214 found in Ruderhausen et al (2005). The width of the prey size preference function, ω, was 0.006 for NC30 and NC70. Size preference was calculated for each age striped bass over all Atlantic menhaden ages and all alternate prey categories. Alternatively, for operating model LNC30, the size preference function was calculated following a lognormal distribution to match empirical data detailed in Overton et al. (2009) as follows,

$$SP = exp\left[\frac{-\left(\frac{ln(length_i}{length_j}\right) - ln\left(length_{opt}\right)}{\omega}\right].$$

ω was set at 0.16 for the lognormal prey preference function and was calculated based on an optimum ratio of 0.2.

Next, the instantaneous attack rate, ρ, of each age predator on each age prey was calculated as:

$$\rho_a = SP_{a,i} * length_{j,a} * \gamma_a,$$

where the $length_{j,a}$ is the average length of striped bass either in 2017 or 1998 and γ_a is the parameter representing the predator-prey consumption dynamics. Using ρ, I calculated the total instantaneous consumption rate, ICR, of each age prey category by striped bass as the summation of consumption by predator for all age prey (all age menhaden and all age other prey):

$$ICR_{a,s,i} = \sum_{1}^{20} \frac{\rho_a N_{i,s}}{1+\sum_i \frac{\rho N_{i,s} W_i}{Cmax_i}},$$

where W_i was the estimated weight-at-age of a prey category as input from the Atlantic menhaden stock assessment. The alternate prey category weights were input as Atlantic menhaden weight-at-age with an additional ad hoc specified weight lower than age-0 Atlantic menhaden. The total consumption of a given age striped bass was calculated as

$$A_{j,a} = \frac{\rho_a N_{i,a}}{ICR_{a,s,i}},$$

where N is the abundance of a prey category. The proportion of total consumption of prey at a given age in weight was calculated as

$$C/Pred_a = W_i A_{j,a}.$$

The total consumption of all prey by each aged predator was the sum of $C/Pred_a$ over all prey categories. C/*Cmax* represented the total actual consumption of striped bass at age

$$C/Cmax = TotalConsumption_a/Cmax.$$

The predator prey model parameters (both base and alternative operating models) required tuning of consumption dynamics to ensure single species stock dynamics mimicked their stock assessment as closely as possible. Total consumption was tuned to meet the realized proportion of Atlantic menhaden in striped bass diet.

This varied by operating model where consumption was scaled to a maximum of either 30% as in the case of NC30 or LNC30 or 70% as in the case of NC70.

In order to adjust for the change in size of striped bass between 1998 and 2017 as demonstrated in Chapter 1, the maximum consumption of striped bass in 2017 (0.9) and the maximum consumption of striped bass (1998) was scaled down for age-1 to 0.7 at age-20 and older (Table B.1). I then calculated the squared deviations of C/*Cmax* from the maximum consumption for each age in each year and summed them as follows:

$$LL = \sum_{a=1}^{20}(C/Cmax_{2019} - Target_{2019})2 + \sum_{a=1}^{20}(C/Cmax_{1998} - Target_{1998})^2.$$

The resulting γ estimates were used as inputs into the predator prey simulation model. This process was repeated three times to meet alternate assumptions for NC30, NC70, and LNC30.

Once gamma was determined for each operating model, I adjusted the M-at-age for both striped bass and Atlantic menhaden to match the estimated M in the stock assessments and the N-at-age of the alternative prey pool in order to match the estimated weight-at-age of striped bass estimated in my first chapter. Both of these inputs were adjusted against the status quo run of the simulation model (HCR 1). All of these processes were performed ad hoc, but the tuning process as designed so that the predator prey model inputs mimicked the status quo and most recent estimates of both predator and prey stock assessments as closely as possible.

Tables

Table B.1: The alternative proportion target consumption realized in 1998 of striped bass.

Age	Target Consumption
1	0.9
2	0.9
3	0.9
4	0.9
5	0.85
6	0.8
7	0.75
8	0.7
9	0.7
10	0.7
11	0.7
12	0.7
13	0.7
14	0.7
15	0.7
16	0.7
17	0.7
18	0.7
19	0.7
20+	0.7

Appendix C: Alternative Operating Model Dynamics

NC30

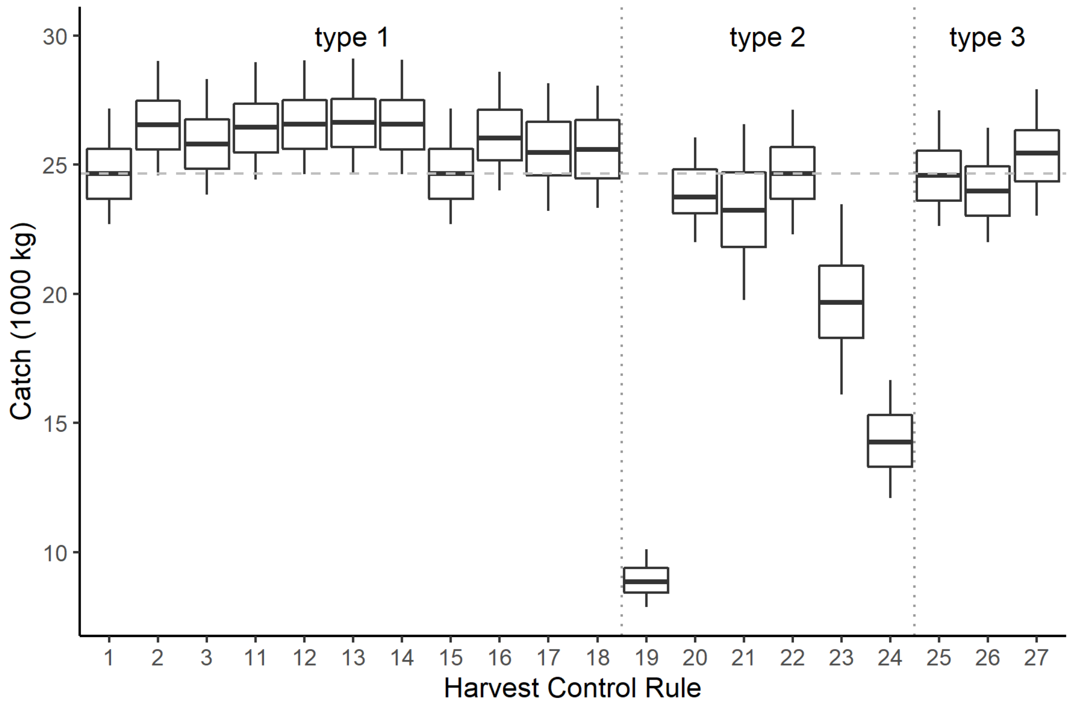

Figure C. 1: Striped bass catch in weight for 27 harvest control rules (HCRs; defined in Table 3). The horizontal dashed grey line indicates catch at status quo. The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

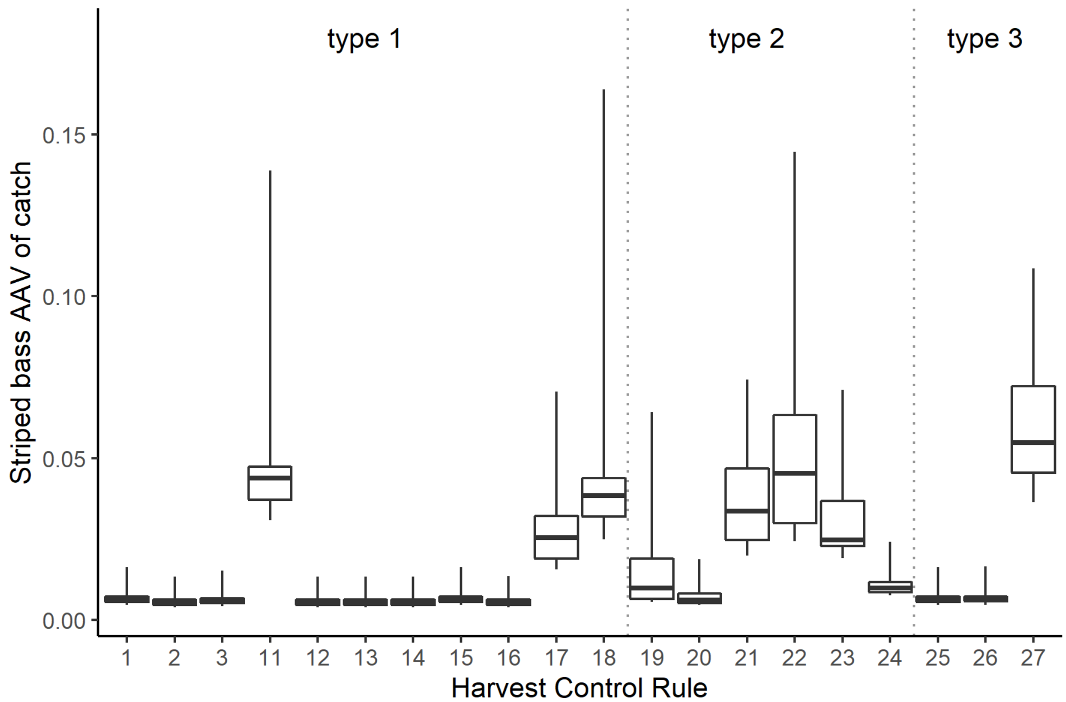

Figure C. 2: Average annual variation (AAV) of striped bass catch calculated in weight of striped bass in NC30. The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

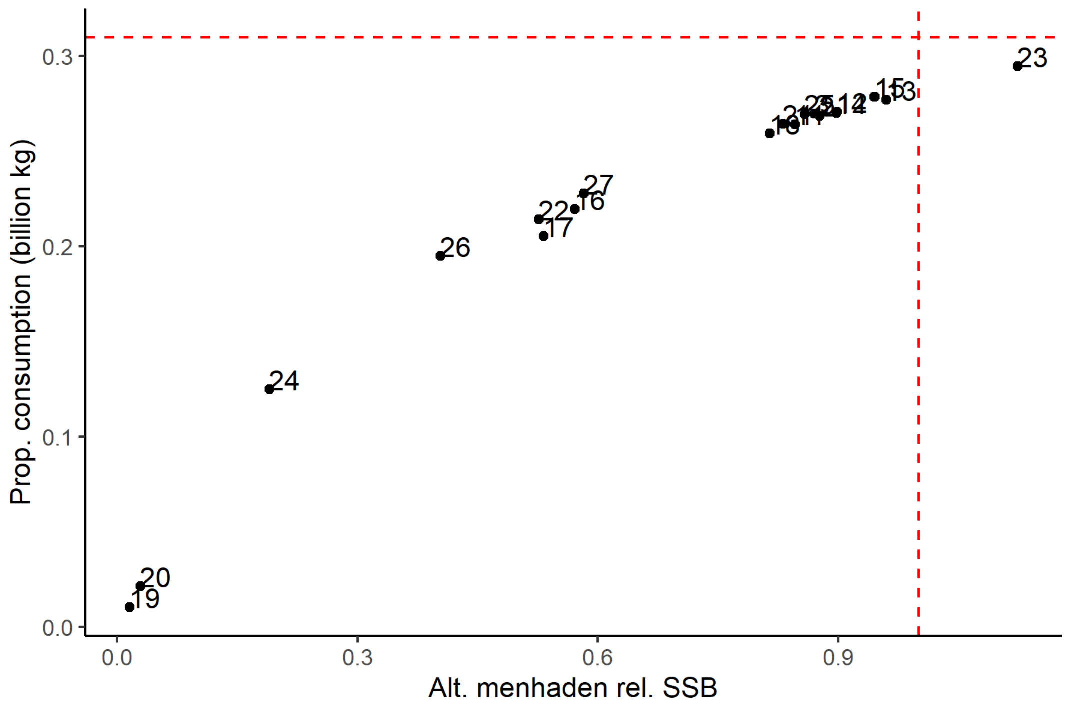

Figure C. 3: Proportion consumption of Atlantic menhaden in relation to Atlantic menhaden relative SSB under NC30. Numbers indicate HCRs as listed in table 1.1. The red vertical line indicates where Atlantic menhaden SSB is equal to its SSB target found in the stock assessment. The red dashed horizontal line indicates the proportion consumption of Atlantic menhaden realized by striped bass age-15 (31%).

NC70

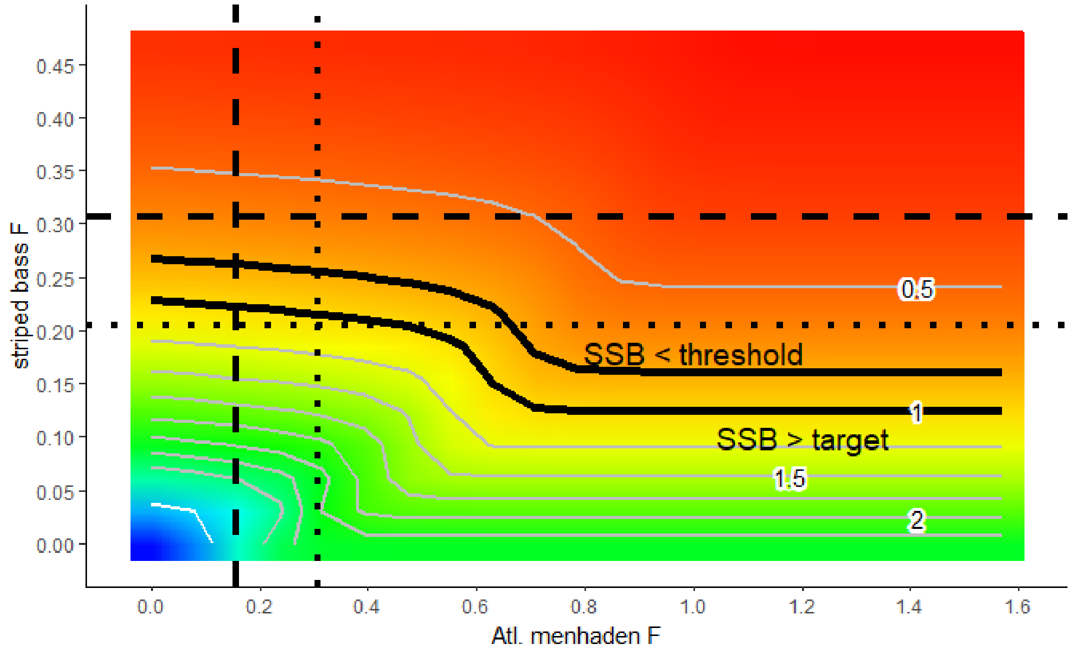

Figure C. 4: Impact of Atlantic menhaden and striped bass F on relative striped bass SSB assuming Atlantic menhaden comprise 70% of striped bass diet (NC70). A total of 21 Atlantic menhaden Fs were tested, ranging from 0 to 1.49 yr^{-1}, and 16 striped bass Fs were tested, ranging from 0 to 0.47 yr^{-1} following the Chagaris et al. (2020). Rainbow colors within the plot indicate striped bass SSB relative to the striped bass target SSB in the stock assessment. Light grey lines and associated numbers indicate levels of striped bass relative SSB. Long dashed lines indicate the current status quo F for Atlantic menhaden (vertical) and striped bass (horizontal). Dotted lines indicate the target F for Atlantic menhaden (vertical) and striped bass (horizontal). Striped bass SSB is greater than the target (114,295 thousand kg) below the solid black horizontal line labelled 1 and in the space labelled 'SSB>target'. The area above the upper solid black line labelled 'SSB<threshold' indicated striped bass SSB was lower than the threshold SSB (91,436 thousand kg).

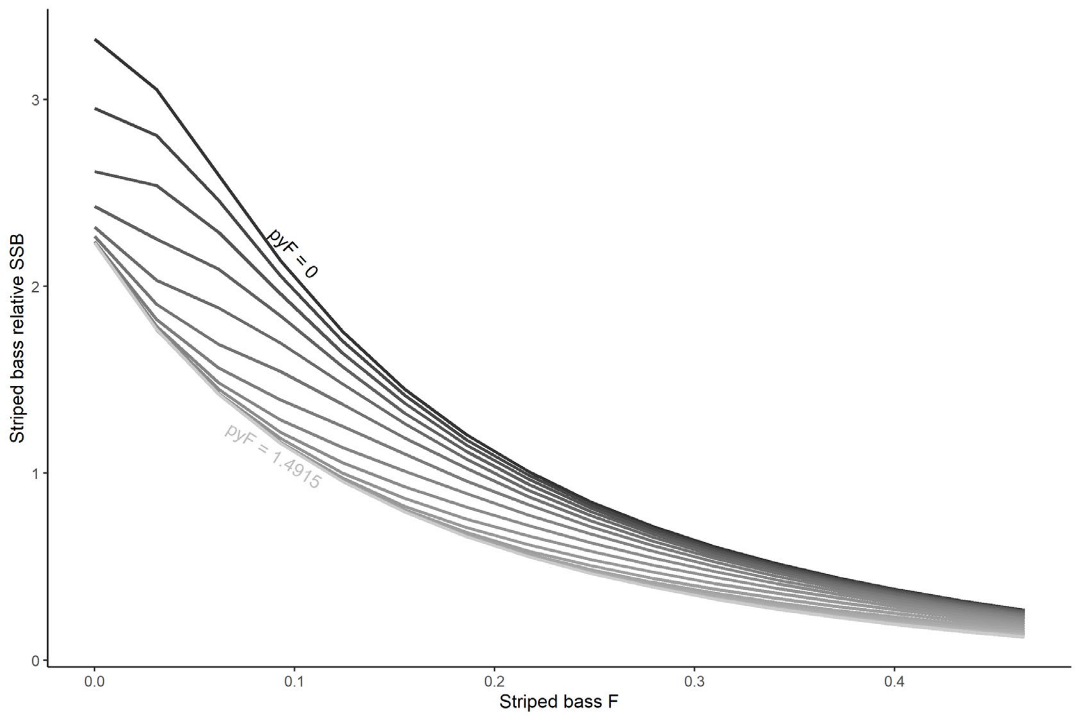

Figure C. 5: Relationship between striped bass F and relative SSB from NC70 operating model. Relative SSB is SSB under a given HCR divided by their SSB target in the stock assessment (114,295 thousand kg). Each line indicates an Atlantic menhaden F (pyF) input as a constant F HCR into the model. A total of 21 HCRs with pyF ranging from 0 to 1.4915 yr^{-1} were explored. Striped bass operated under a constant F HCR.

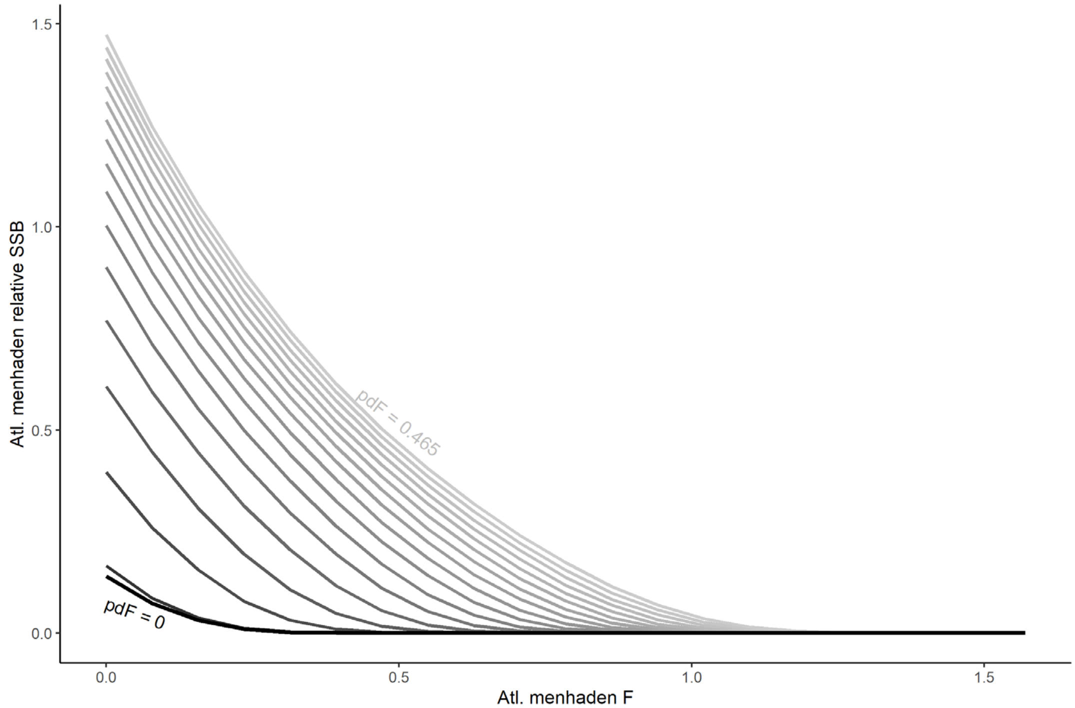

Figure C. 6: Relationship between Atlantic menhaden F and relative SSB from the NC70 operating model. Atlantic menhaden relative SSB is SSB under a given HCR relative to their target SSB recalculated from egg production to billions of kilograms. Each line indicates a striped bass F (pdF) input as a constant F HCR into the model. Atlantic menhaden operated under a constant F HCR. A total of 16 HCRs with pdF ranging from 0 to 0.47 yr^{-1} were explored.

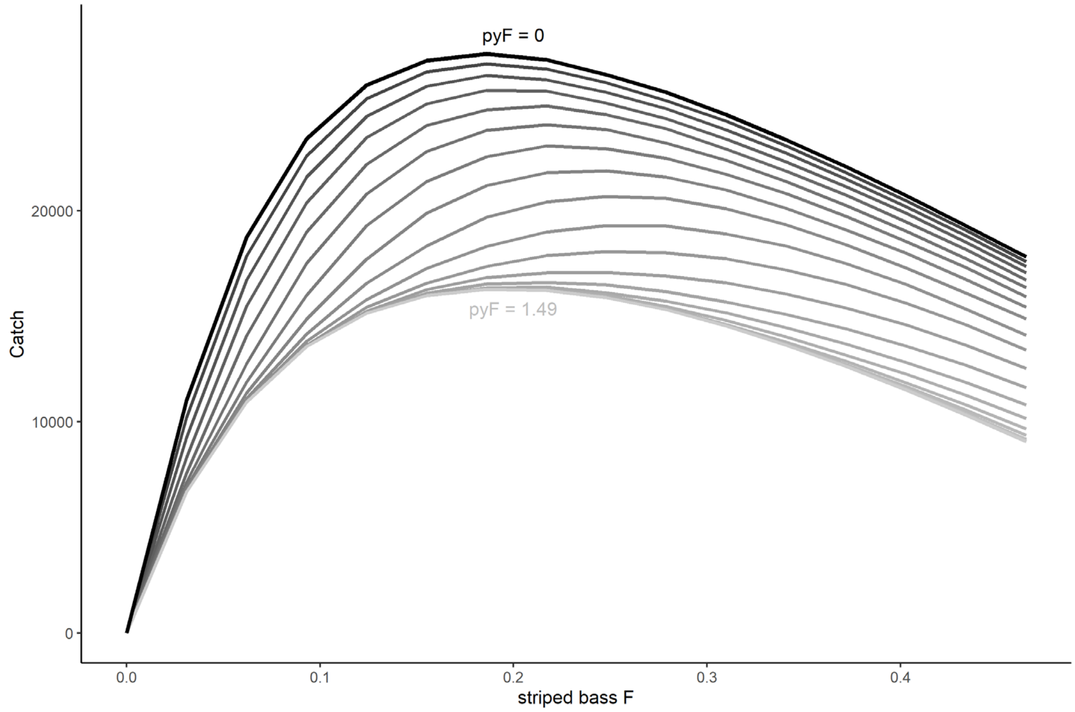

Figure C. 7: Striped bass catch under 21 HCRs where striped bass F was constant and Atlantic menhaden F (pyF) ranged from 0 to 1.49 yr^{-1} from the NC70 operating model. The uppermost solid black line indicates unfished prey conditions (F=0 yr^{-1}), and the lowest curve indicates F for Atlantic menhaden is 1.49 yr^{-1}. Catch is in thousand kgs.

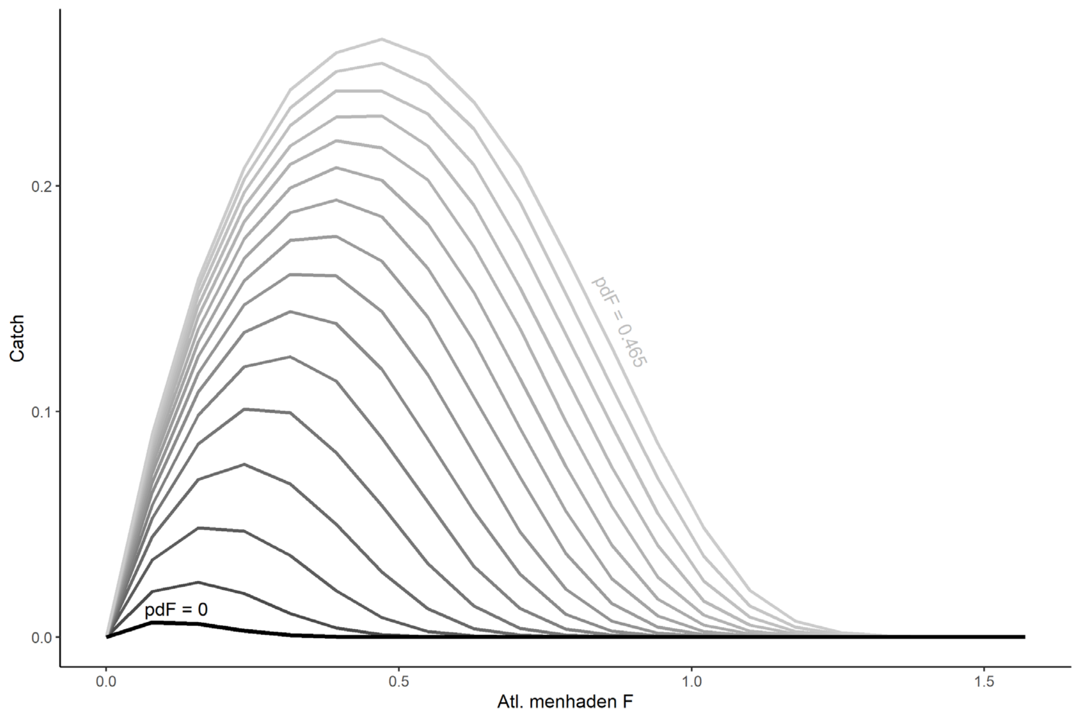

Figure C. 8: Atlantic menhaden catch under 16 HCRs where Atlantic menhaden F is constant and striped bass F (pdF) ranged from 0 to 0.47 yr^{-1}. The lowermost solid black line indicates unfished conditions (F=0 yr^{-1}). The highest curve indicates constant F HCR where F for striped bass is 0.465 yr^{-1}. Results are from the NC70 operating model. Catch is measured in billion kg.

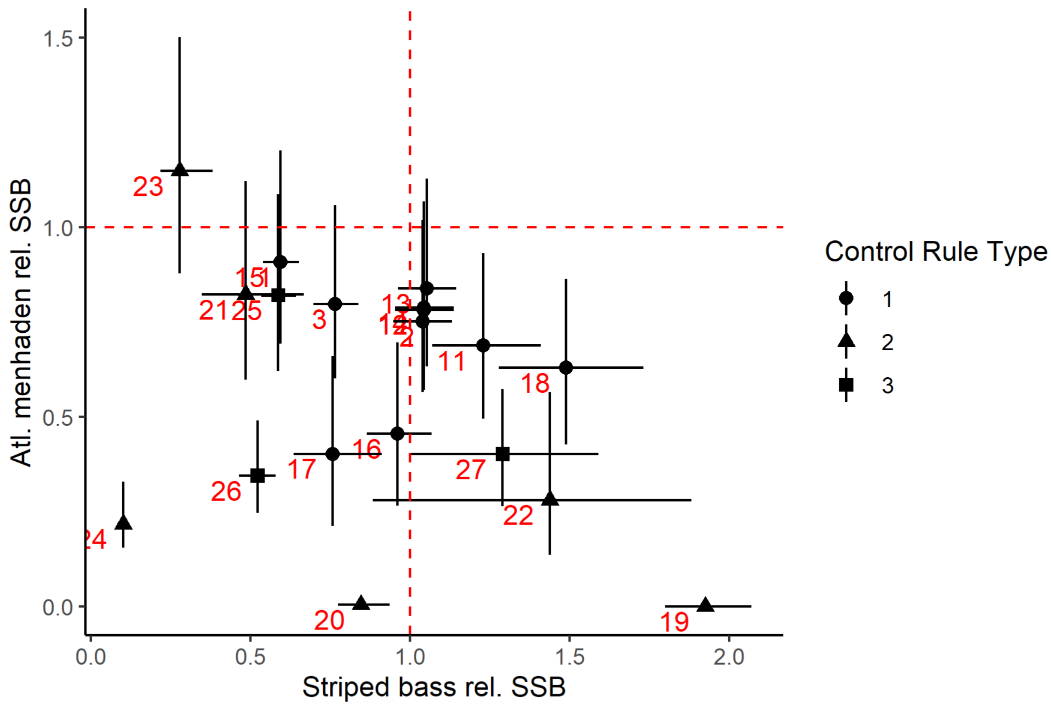

Figure C. 9: Tradeoffs between striped bass relative spawning stock biomass (striped bass rel. SSB) and Atlantic menhaden relative spawning stock biomass (Atl. Menhaden rel. SSB) for 27 harvest control rules under the NC70 alternative operating model (HCR; numbers defined in Table 3). The red dashed lines indicate the relative SSB targets for each species. The points indicate the median SSB while the lines show the interquartile range for striped bass (horizontal) and Atlantic menhaden (vertical). HCR types are designated by shapes of the point for type 1 (circle), type 2, (triangle), and type 3 (square).

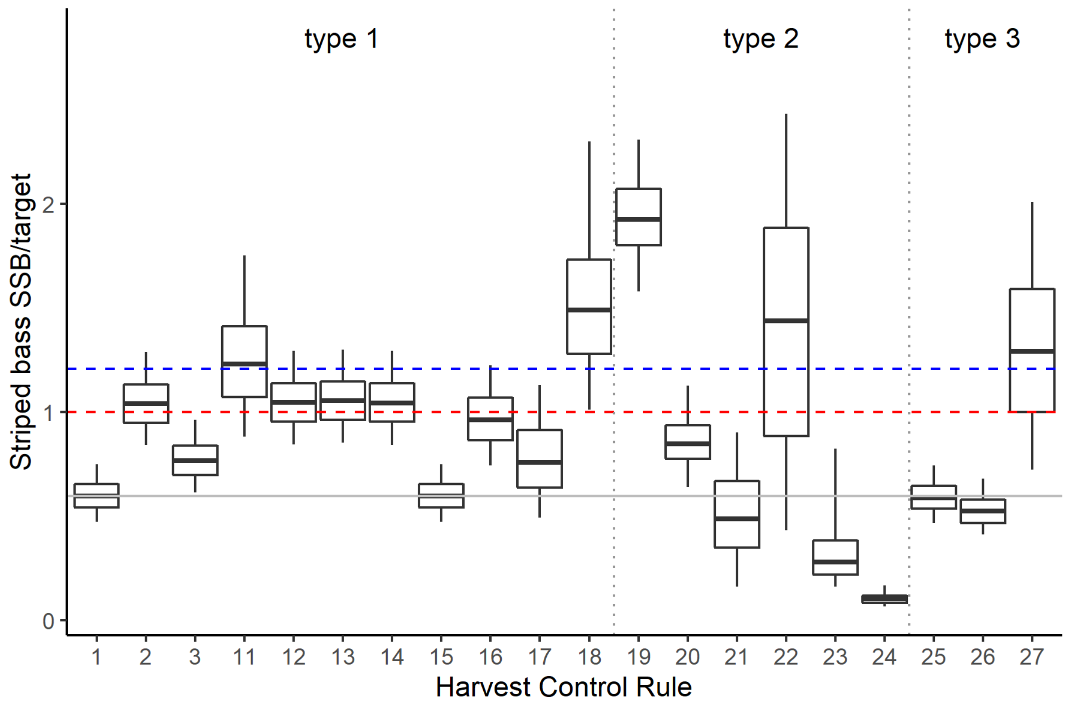

Figure C. 10: Striped bass spawning stock biomass (SSB) relative to the target SSB (target) from the stock assessment for 27 harvest control rules under NC70 (HCRs; defined in Table 3). The red dashed line indicates the target SSB, the solid grey line indicates SSB at status quo, and the blue dashed line indicates SSB_{MSY}. The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25^{th} and 75^{th} percentiles, and the whiskers indicate the 5^{th} and 95^{th} percentiles.

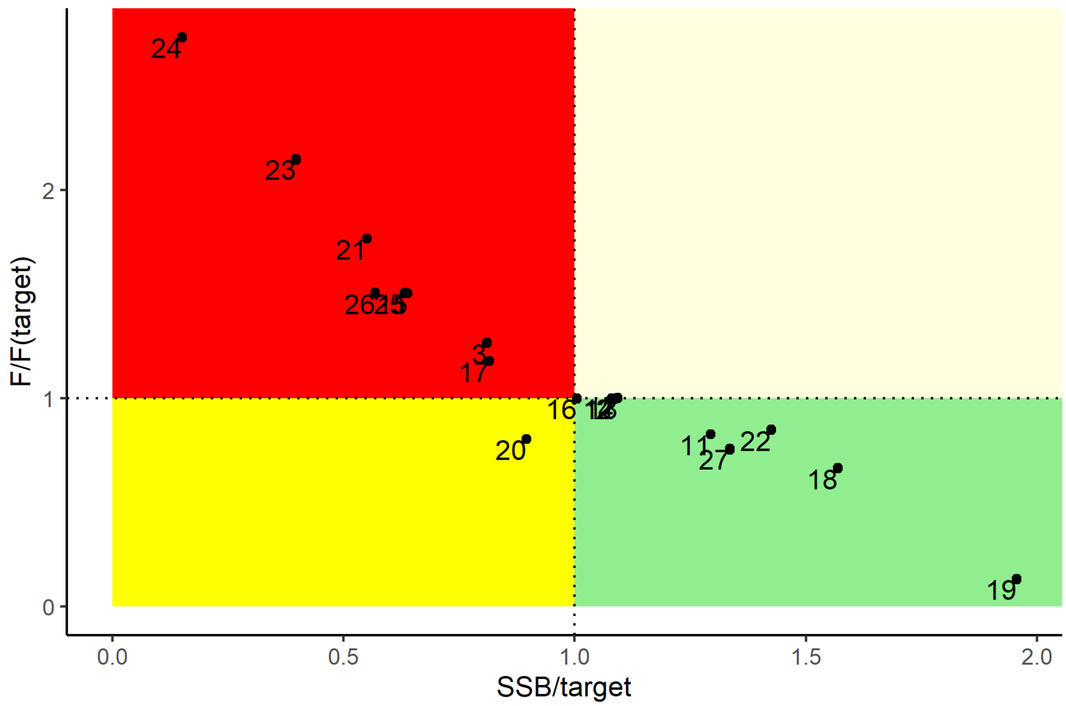

Figure C. 11: Kobe plot showing the relationship between the median striped bass spawning stock biomass (SSB) and fishing morality (F) for each HCR under NC70. The target refers to the striped bass SSB_{target} found in the stock assessment. Target F is 0.204 yr^{-1}. The numbers next to each point indicate the HCR number from Table 3.

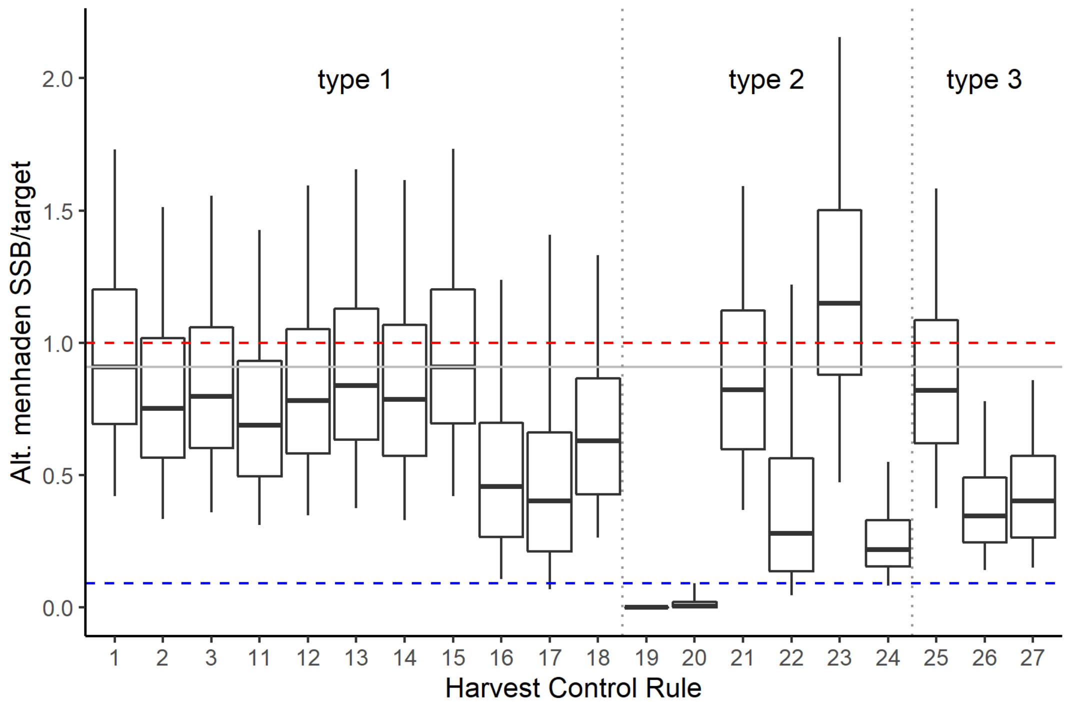

Figure C. 12: Atlantic menhaden spawning stock biomass (SSB) relative to the target SSB (target) from the stock assessment for 27 harvest control rules under NC70 (HCRs; defined in Table 3). The red dashed line indicates the target SSB, the solid grey line indicates SSB at status quo, and the blue dashed line indicates SSB_{MSY}. The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

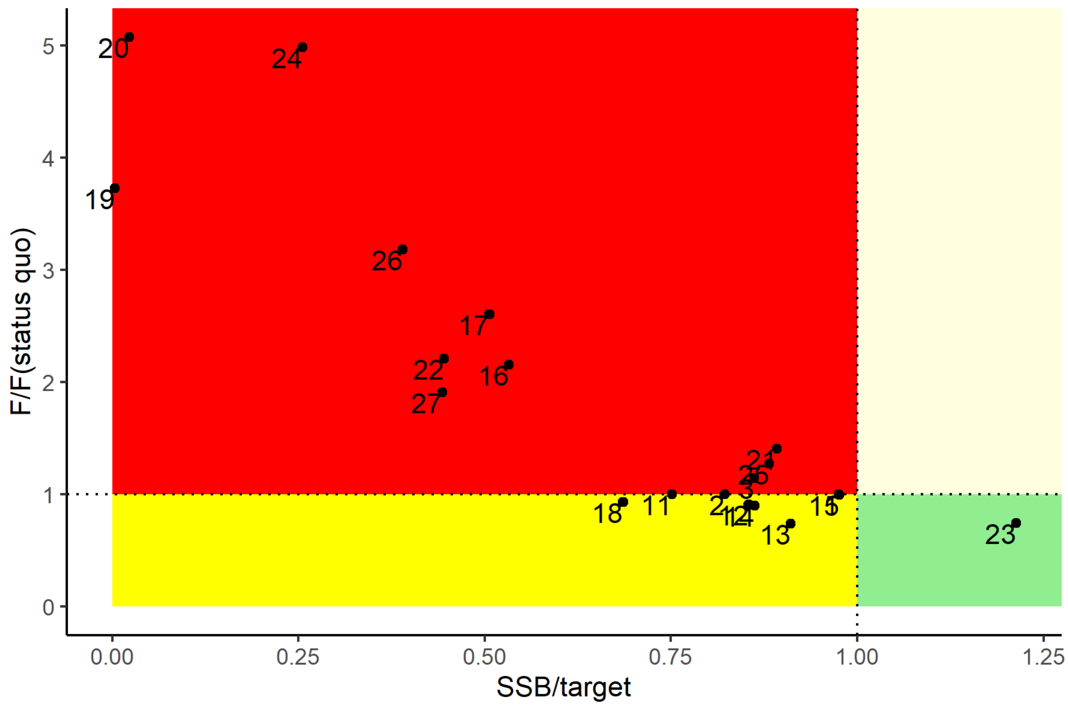

Figure C. 13: Kobe plot showing the relationship between the median Atlantic menhaden spawning stock biomass (SSB) and fishing morality (F) for each HCR under NC70. The target refers to the Atlantic menhaden SSB_{target} found in the stock assessment. Status quo F is 0.157 yr^{-1}. The numbers next to each point indicate the HCR number from Table 3.

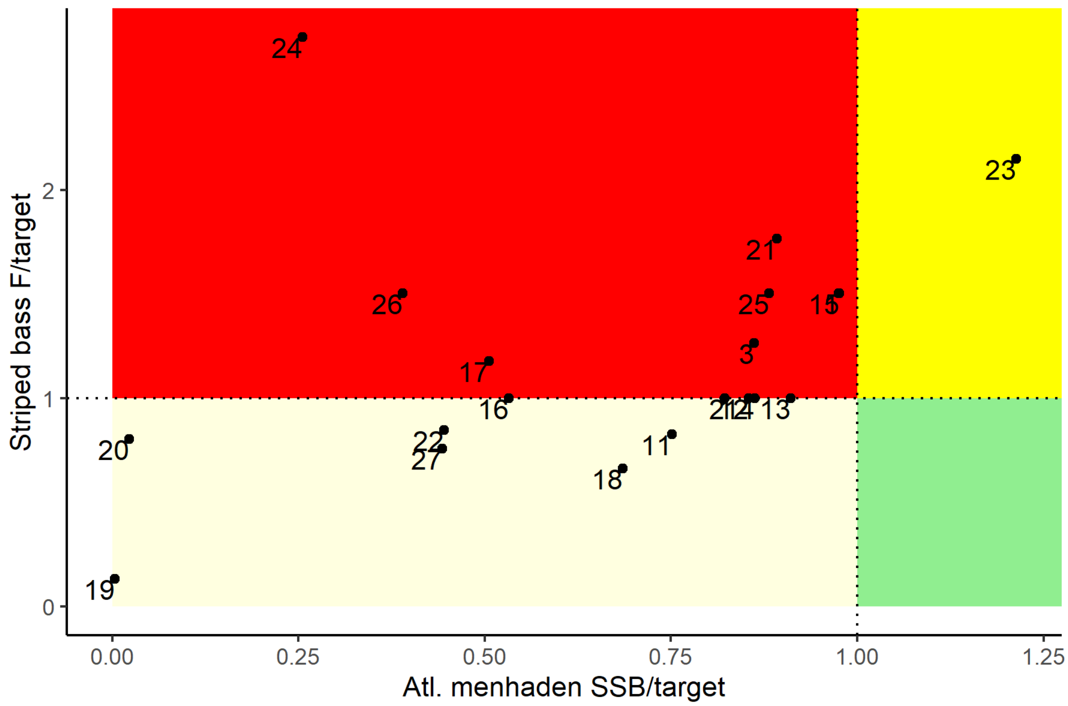

Figure C. 14: A multispecies Kobe plot showing the status of Atlantic menhaden relative SSB (x-axis) and the corresponding striped bass relative F (y-axis) resulting from the NC70 alternative operating model. The numbers next to each point correspond to the HCR numbers found in table 3. The panels in the plot represent varying status of ideal (green), okay (light yellow and yellow), and detrimental (red). F_{target} for striped bass is 0.204 and Atlantic menhaden SSB target is 0.843.

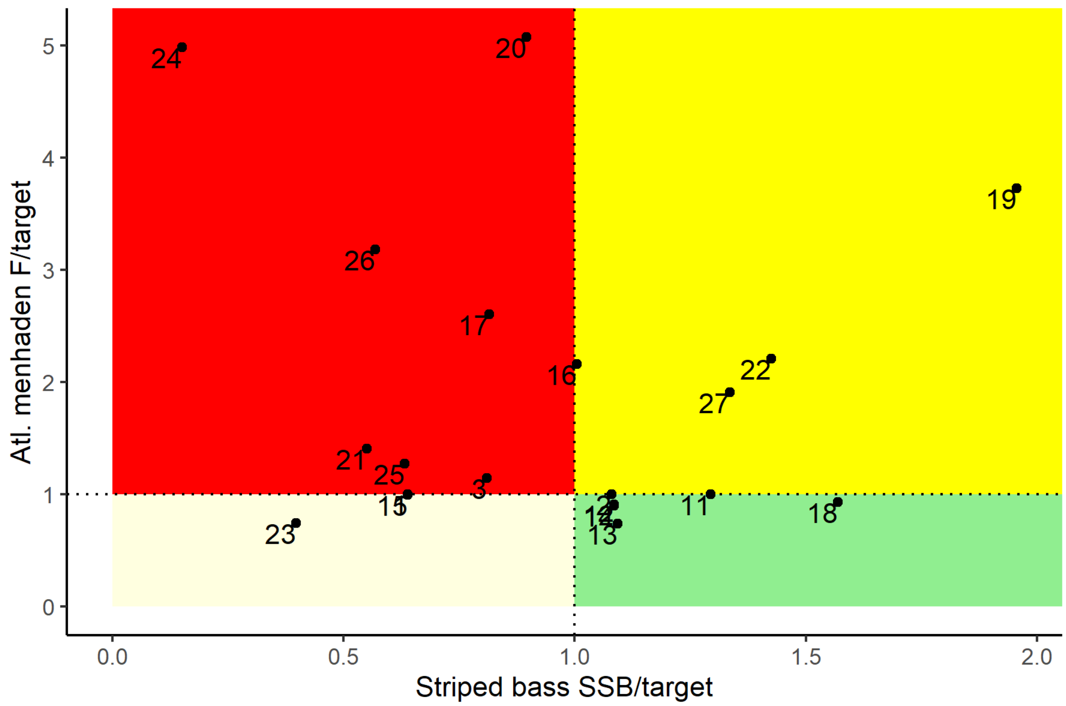

Figure C. 15: A multispecies Kobe plot showing the status of striped bass relative SSB (x-axis) and the corresponding Atlantic menhaden relative F (y-axis) resulting from the NC70 operating model. The numbers next to each point correspond to the HCR numbers found in table 3. The panels in the plot represent varying status of ideal (green), okay (light yellow and yellow), and detrimental (red). F_{target} for Atlantic menhaden is 0.157 and striped bass SSB target is 114,295 thousand kg.

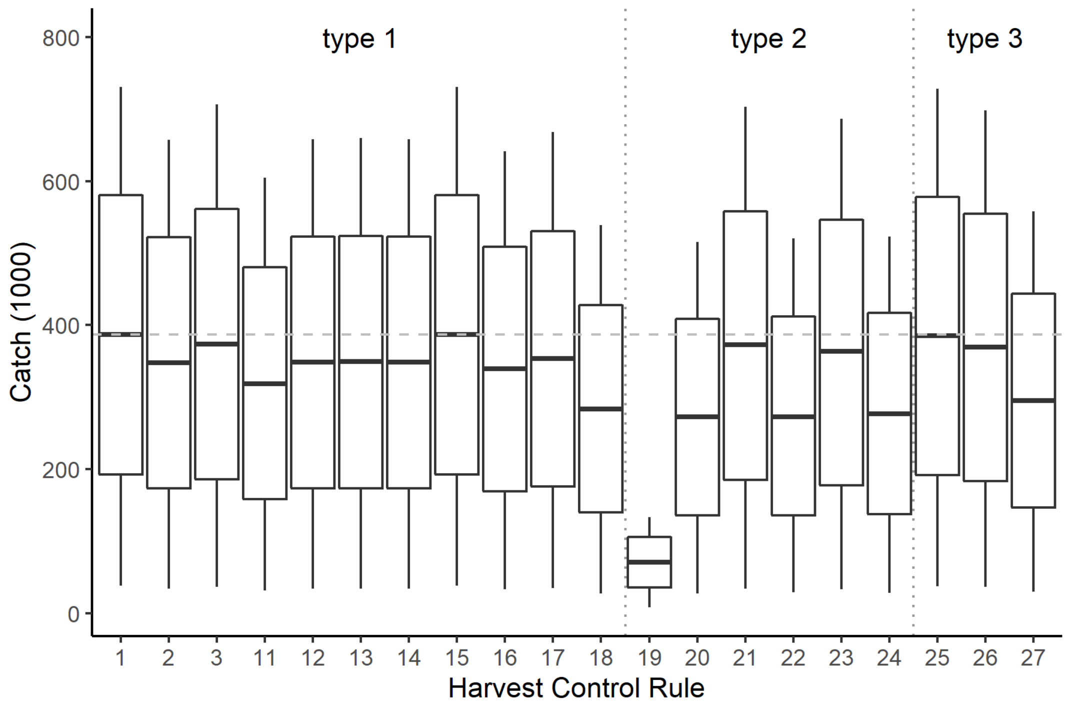

Figure C. 16: Striped bass catch in numbers for 27 harvest control rules in the NC70 operating model (HCRs; defined in Table 3). The horizontal dashed grey line indicates catch at status quo. The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

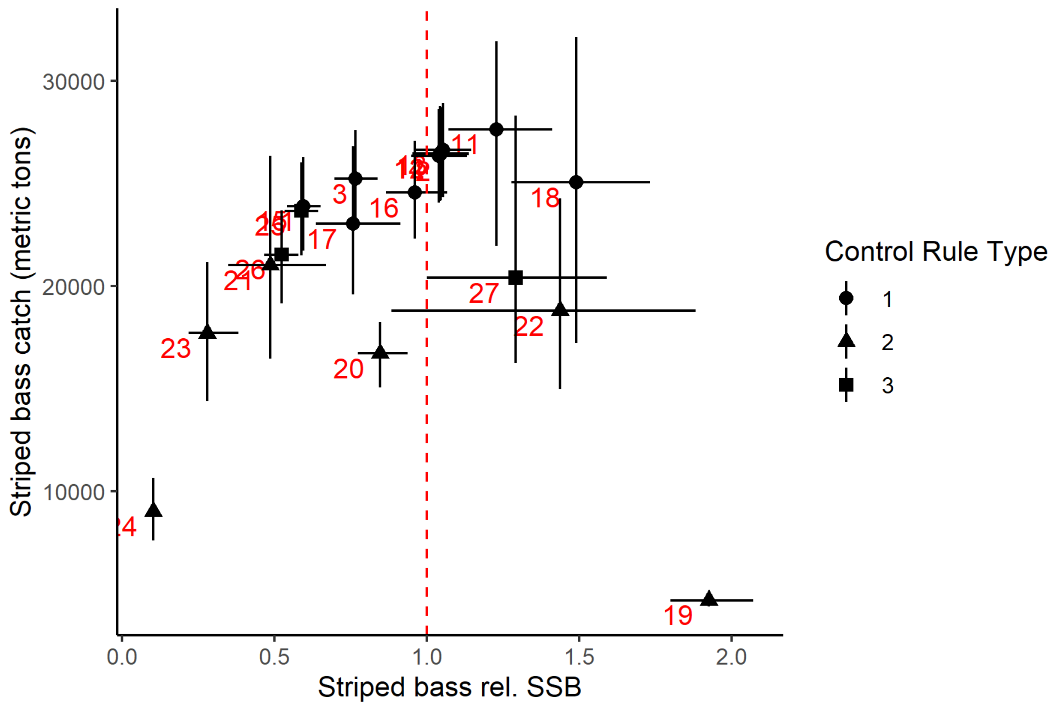

Figure C. 17: Tradeoffs between striped bass relative spawning stock biomass in the NC70 operating model (Striped bass rel. SSB) and catch for 27 harvest control rules (HCR; numbers defined in Table 3). The red dashed lines indicate the relative SSB targets for striped bass in the stock assessment. The points indicate the median SSB while the lines show the interquartile range for striped bass SSB (horizontal) and catch (vertical). HCR types are designated by shapes of the point for type 1 (circle), type 2, (triangle), and type 3 (square).

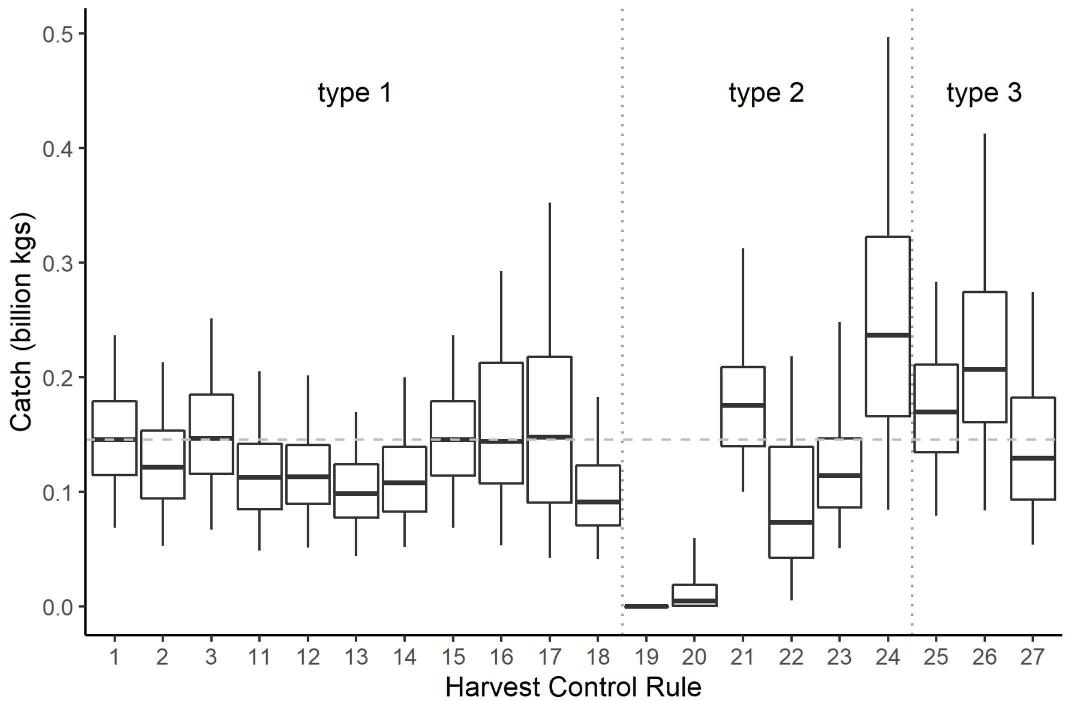

Figure C. 18: Atlantic menhaden catch in weight (billion kg) for 27 harvest control rules in the NC70 operating model (HCRs; defined in Table 3). The horizontal dashed grey line indicates catch at status quo. The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

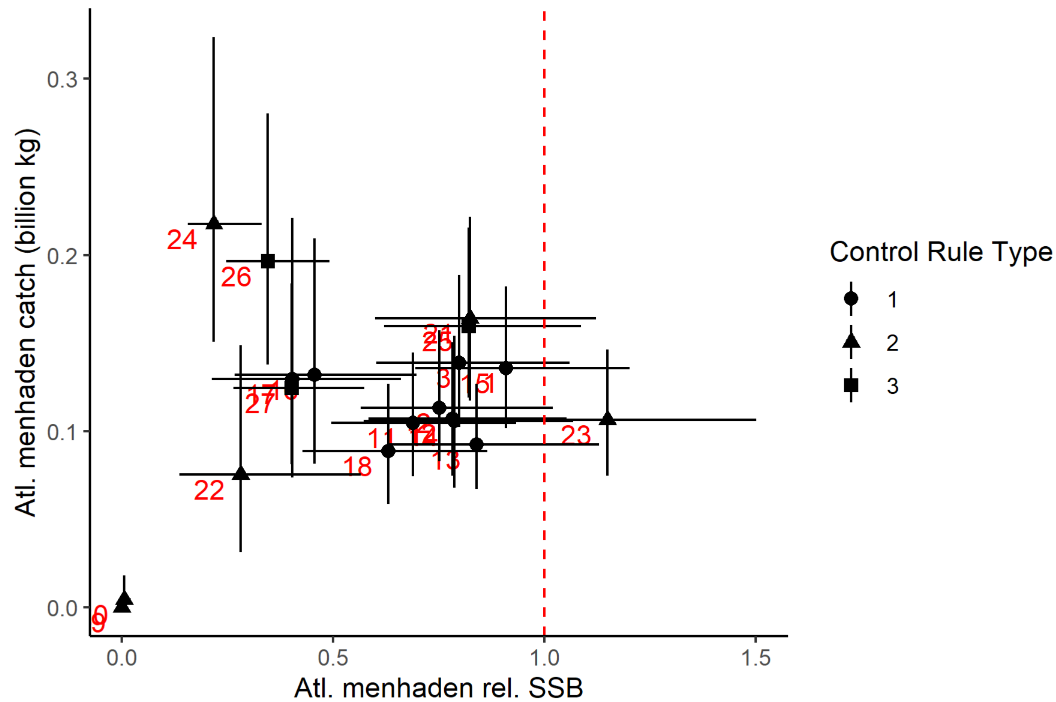

Figure C. 19: Tradeoffs between Atlantic menhaden relative spawning stock biomass and catch for 27 harvest control rules from the NC70 operating model (HCR; numbers defined in Table 3). The red dashed lines indicate the relative SSB targets for Atlantic menhaden in the stock assessment. The points indicate the median SSB while the lines show the interquartile range for SSB (horizontal) and catch (vertical). HCR types are designated by shapes of the point for type 1 (circle), type 2, (triangle), and type 3 (square).

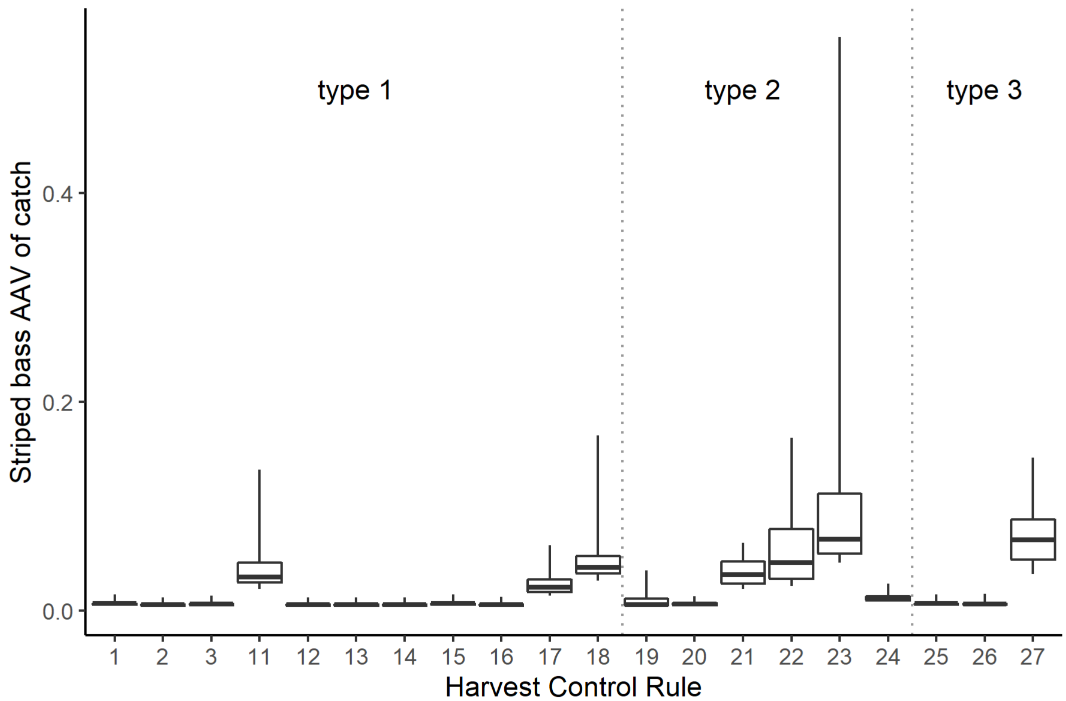

Figure C. 20: Average annual variation (AAV) of striped bass catch calculated in numbers of striped bass rather than weight resulting from the NC70 operating model. The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

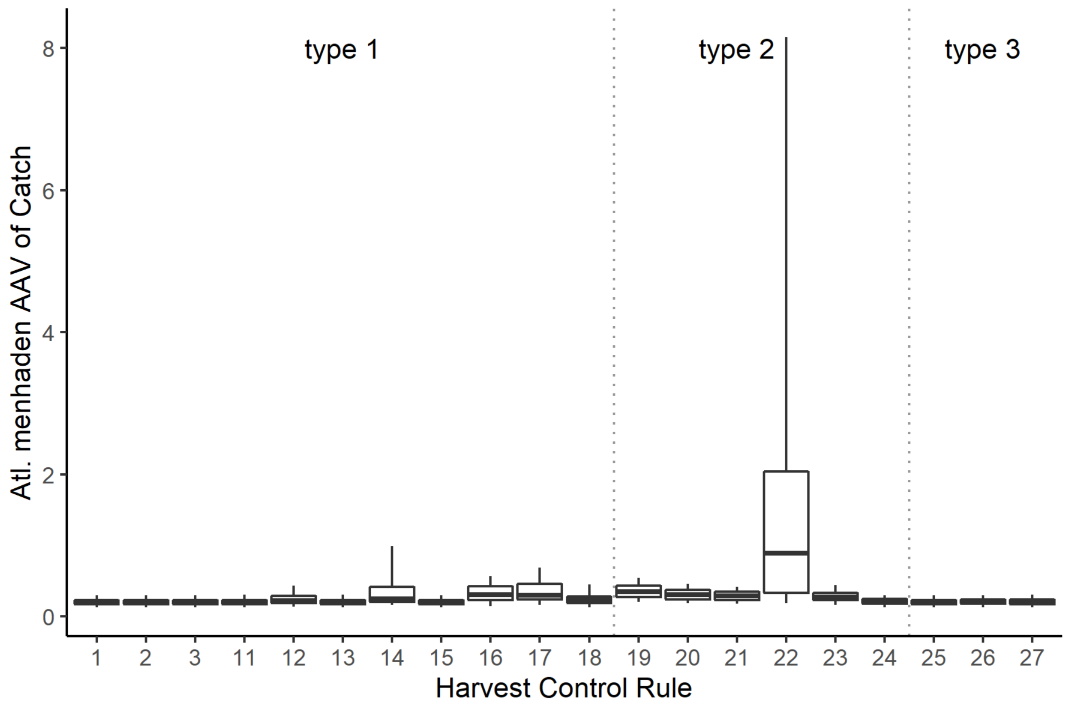

Figure C. 21: Average annual variation (AAV) of Atlantic menhaden catch calculated in billions of kgs resulting from NC70 operating model. There is no catch for HCR 4, 6, and 7 because F for Atlantic menhaden is 0. The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

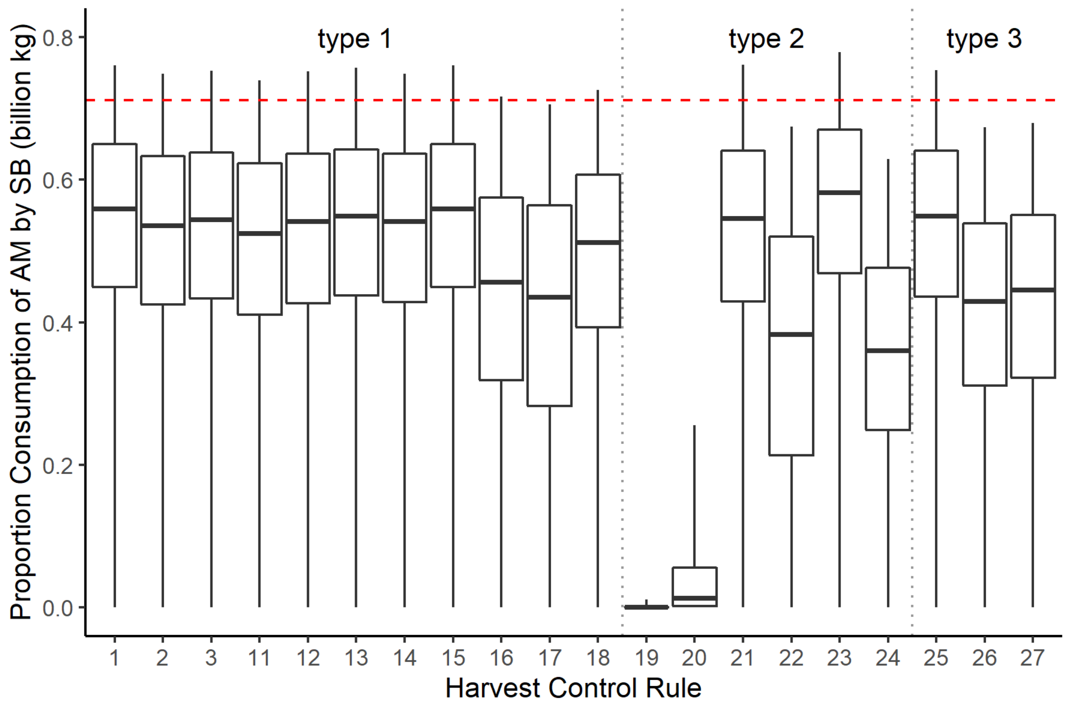

Figure C. 22: Proportion consumption of Atlantic menhaden (AM) by age-3 striped bass (SB) for 27 harvest control rules resulting from NC70 operating model (HCRs; defined in Table 3). At age-3, Atlantic menhaden comprise 15.7% of striped bass diet according to Chagaris et al (2020) (red dashed line). The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

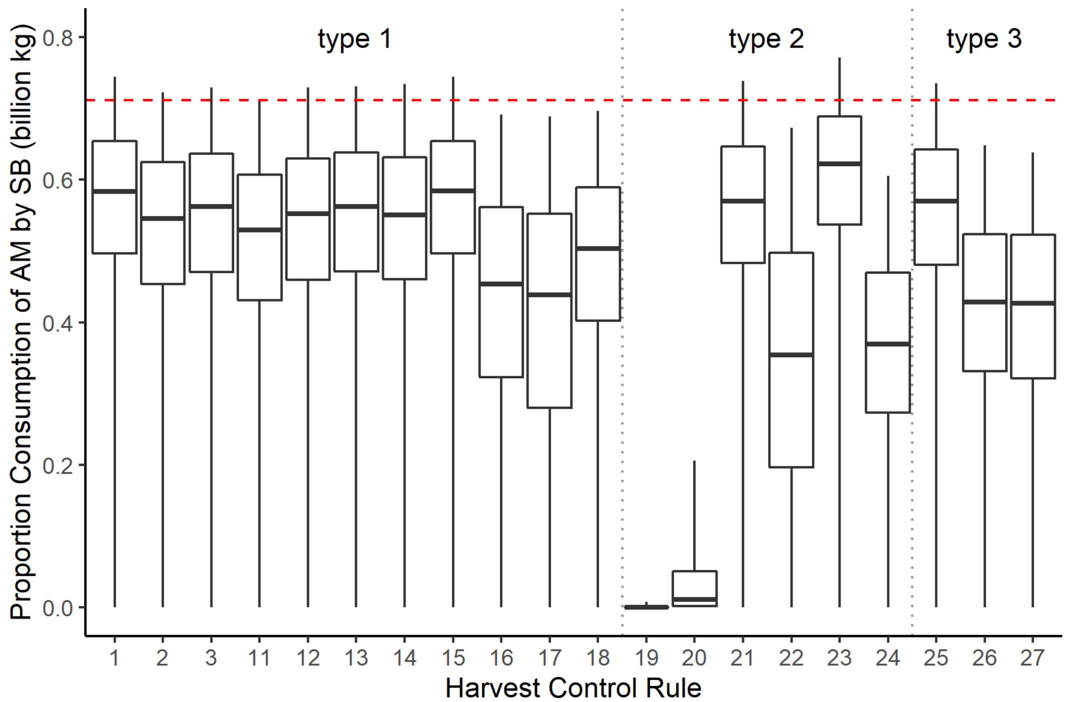

Figure C. 23: Proportion consumption of Atlantic menhaden (AM) by age-15 striped bass (SB) for 27 harvest control rules resulting from NC70 operating model (HCRs; defined in Table 3). At age-15, Atlantic menhaden comprise 30.4% of striped bass diet according to Chagaris et al (2020) (red dashed line). The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

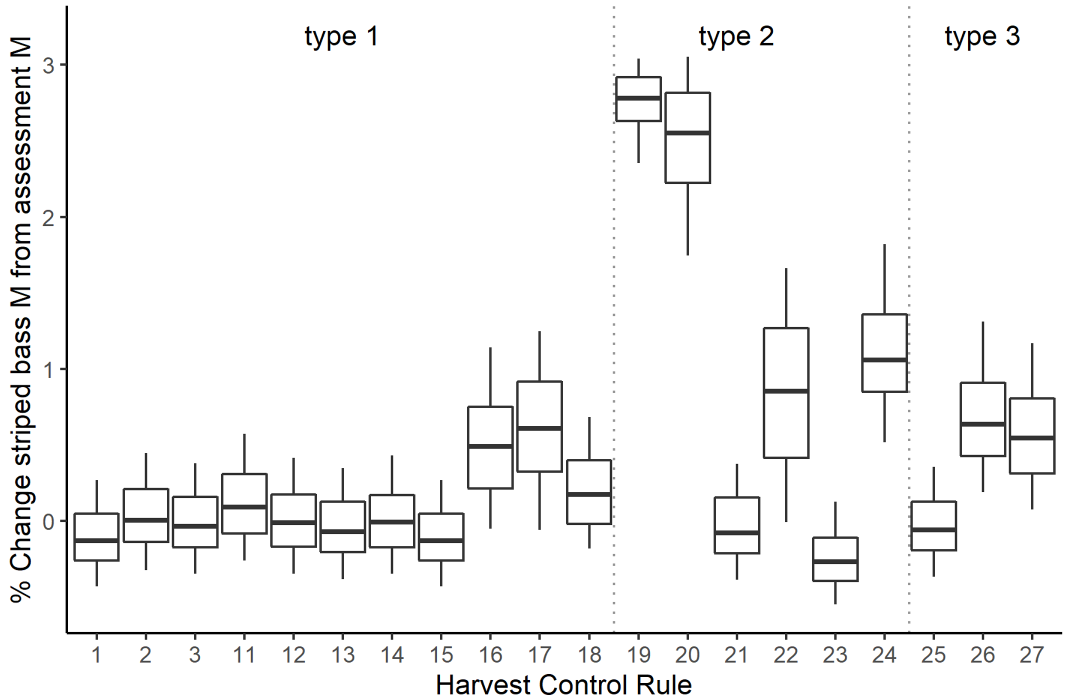

Figure C. 24: Percent change of age-3 striped bass natural mortality (M) from the stock assessment age-3 M for 27 harvest control rules resulting from NC70 operating model (HCRs; defined in Table 3). The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

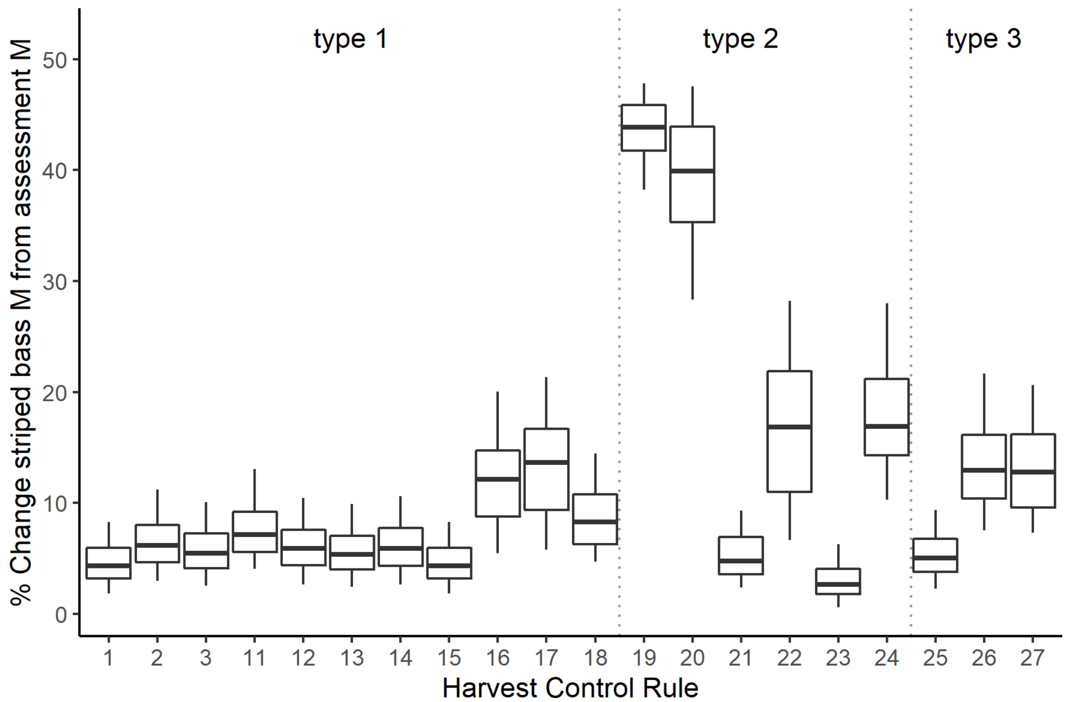

Figure C. 25: Percent change of age-15 striped bass natural mortality (M) from the stock assessment age-15 M for 27 harvest control rules resulting from the NC70 operating model (HCRs; defined in Table 3). The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

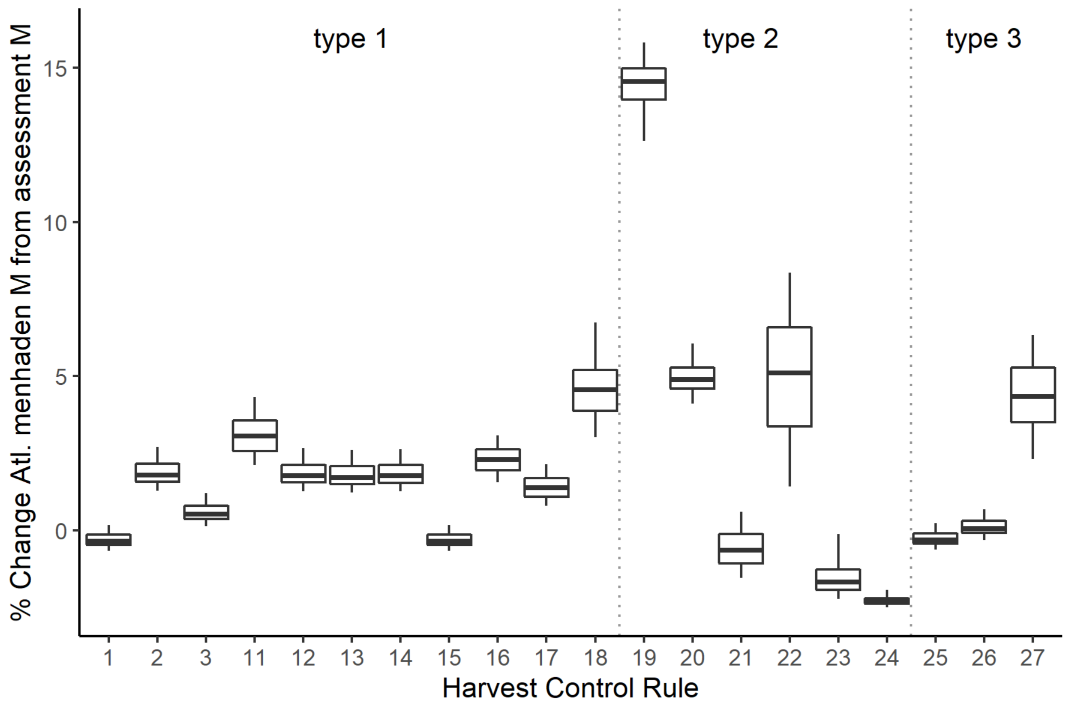

Figure C. 26: Percent change of age-1 Atlantic menhaden M from the stock assessment M resulting from the NC70 operating model. The vertical dashed lines separate the harvest control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

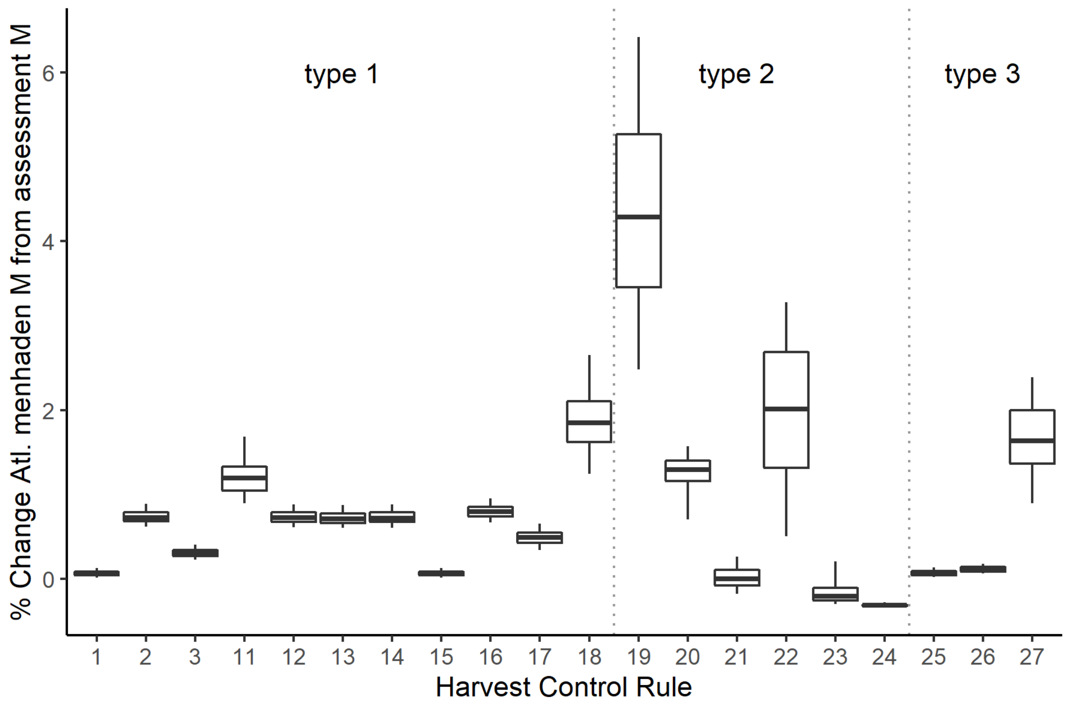

Figure C. 27: Percent change of age-4 Atlantic menhaden natural mortality (M) from the stock assessment age-4 M for 27 harvest control rules resulting from NC70 operating model (HCRs; defined in Table 3. The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

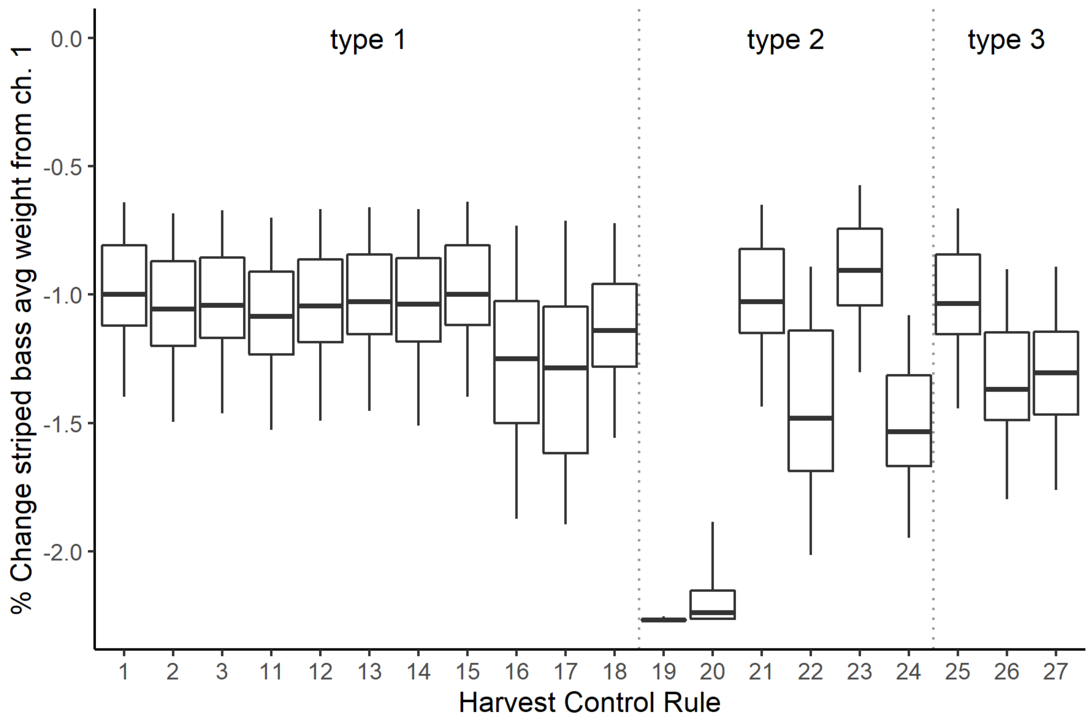

Figure C. 28: Percent change in age-3 striped bass weight from the average age-3 striped bass weight calculated in chapter 1 for 27 harvest control rules resulting from NC70 operating model (HCRs; defined in Table 3). The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

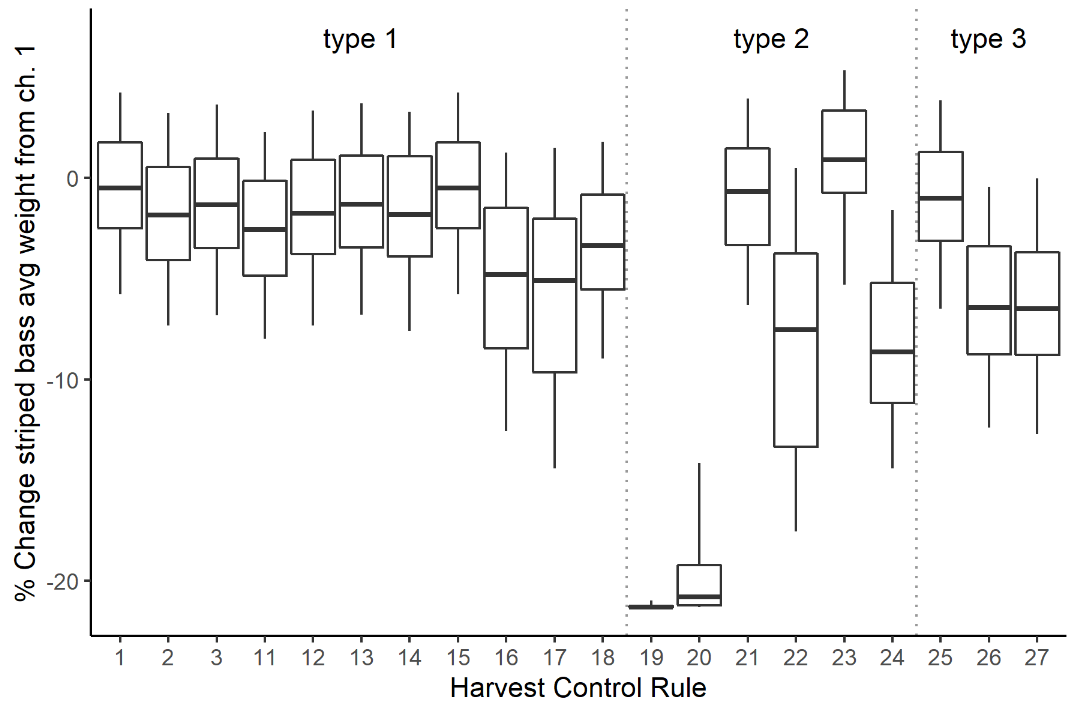

Figure C. 29: Percent change in age-15 striped bass weight from the average age-15 striped bass weight calculated in chapter 1 for 27 harvest control rules resulting from the NC70 operating model (HCRs; defined in Table 3). The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

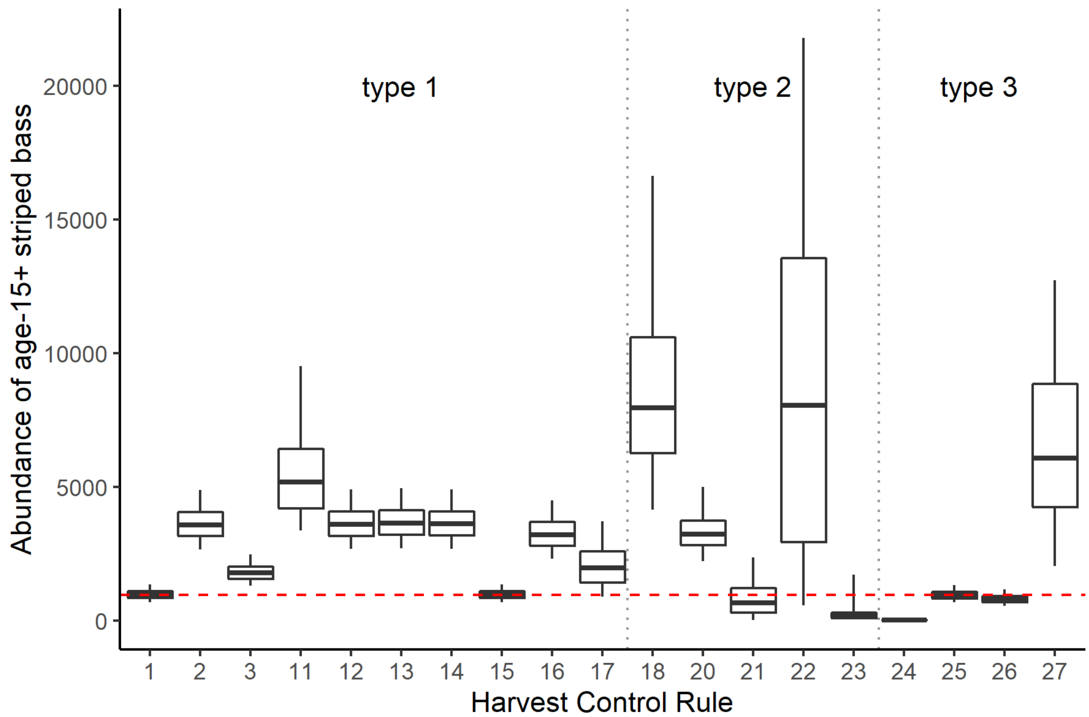

Figure C. 30: The abundance of age-15 and older striped bass (million) for 24 harvest control rules resulting from the NC70 operating model (HCRs; defined in Table 3). All HCRs are compared except for HCR 4, 5, and 19 which had exponentially more abundance of age-15 and older striped bass. The red dashed line indicates the abundance of age-15 and older striped bass when fished at status quo. The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

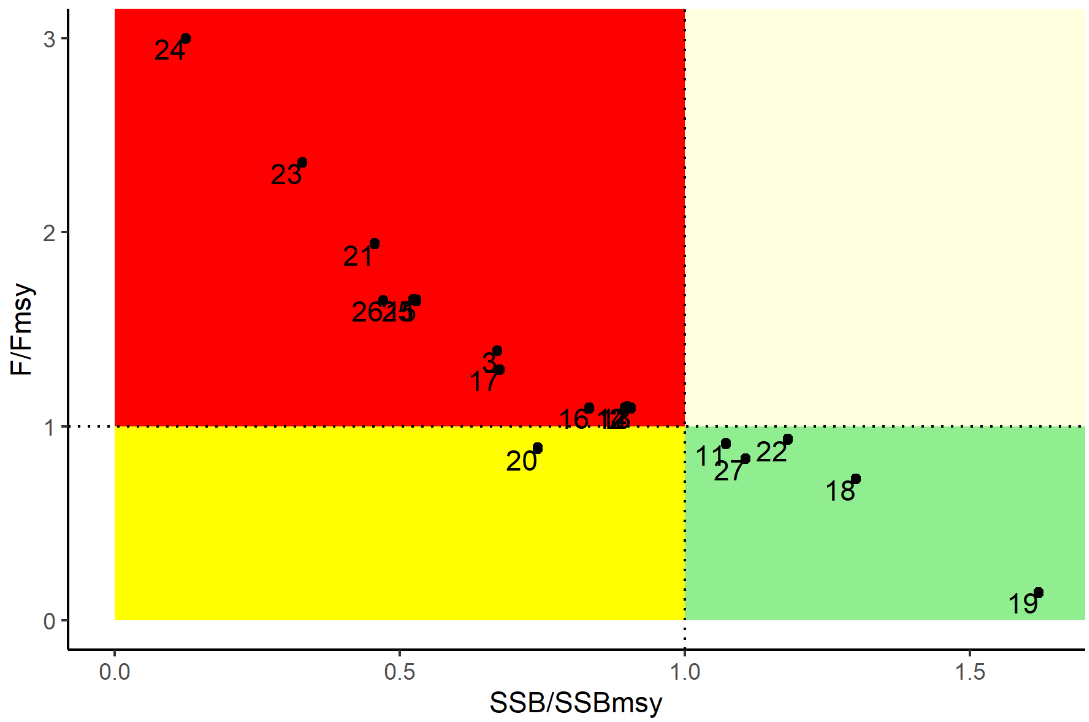

Figure C. 31: Kobe plot showing the relationship between the median striped bass spawning stock biomass (SSB) and fishing morality (F) for each HCR resulting from the NC70 operating model. SSB_{MSY} refers to striped bass SSB_{MSY} found from model performance analysis where SSB_{MSY} is 139,254 thousand kg. F_{MSY} is 0.186 yr^{-1}. The numbers next to each point indicate the HCR number from Table 3.

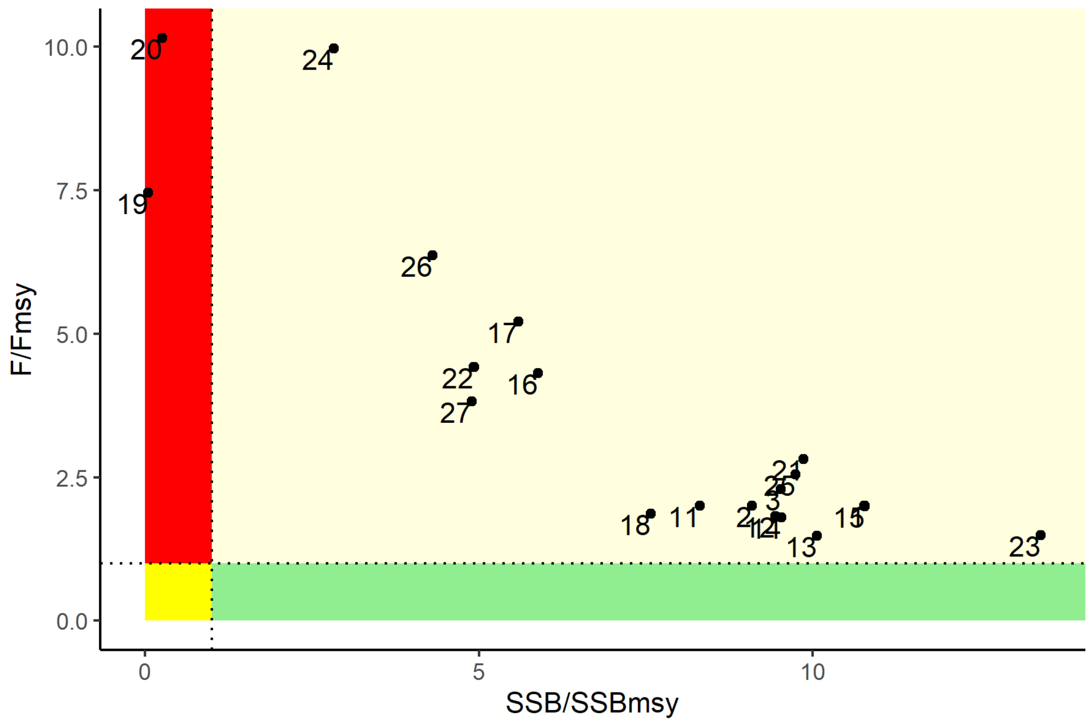

Figure C. 32: Kobe plot showing the relationship between the median Atlantic menhaden spawning stock biomass (SSB) and fishing morality (F) for each HCR resulting from the NC70 operating model. SSB_{MSY} refers to Atlantic menhaden SSB_{MSY} found from model performance analysis where SSB_{MSY} is 0.02572 billion kg. F_{MSY} is 0.2355 yr^{-1}. The numbers next to each point indicate the HCR number from Table 3.

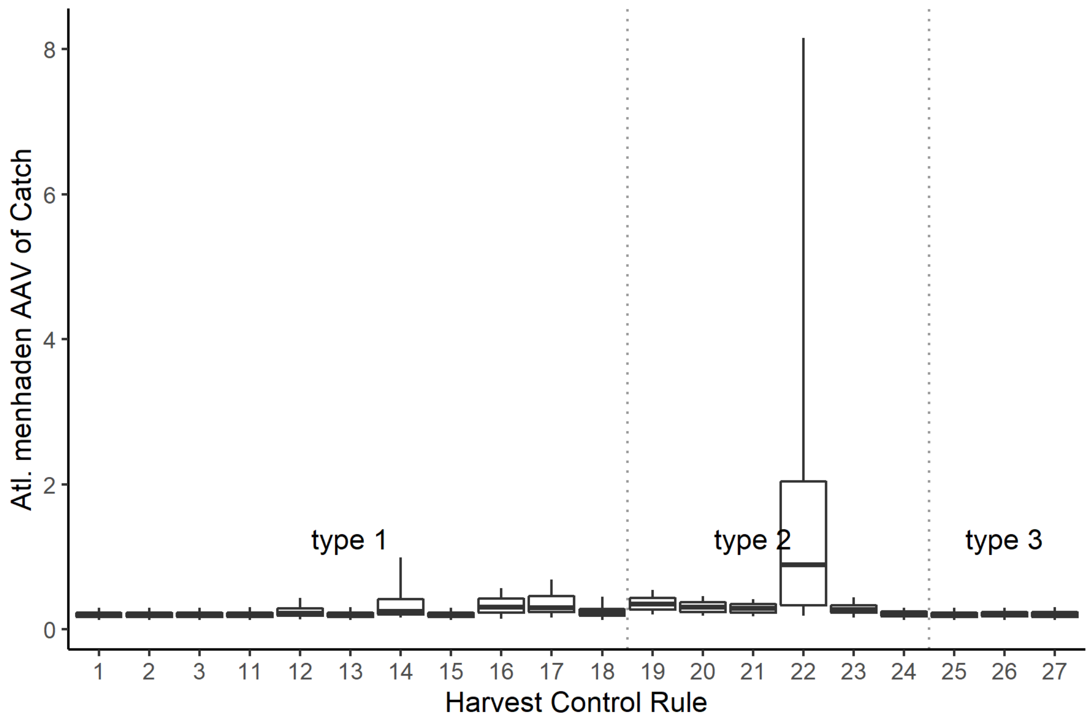

Figure C. 33: Average annual variation (AAV) of striped bass catch calculated in weight of striped bass in NC70. The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

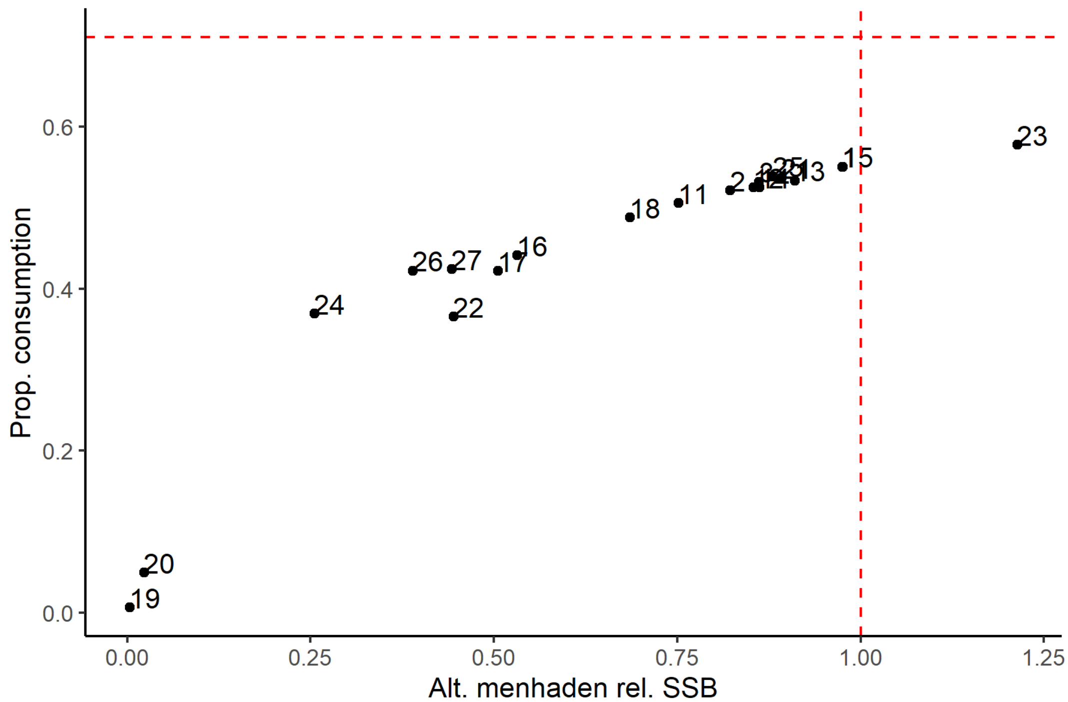

Figure C. 34: Proportion consumption of Atlantic menhaden in relation to Atlantic menhaden relative SSB under NC70. Numbers indicate HCRs as listed in table 1.1. The red vertical line indicates where Atlantic menhaden SSB is equal to its SSB target found in the stock assessment. The red dashed horizontal line indicates the proportion consumption of Atlantic menhaden realized by striped bass age-15 (70%).

LNC30

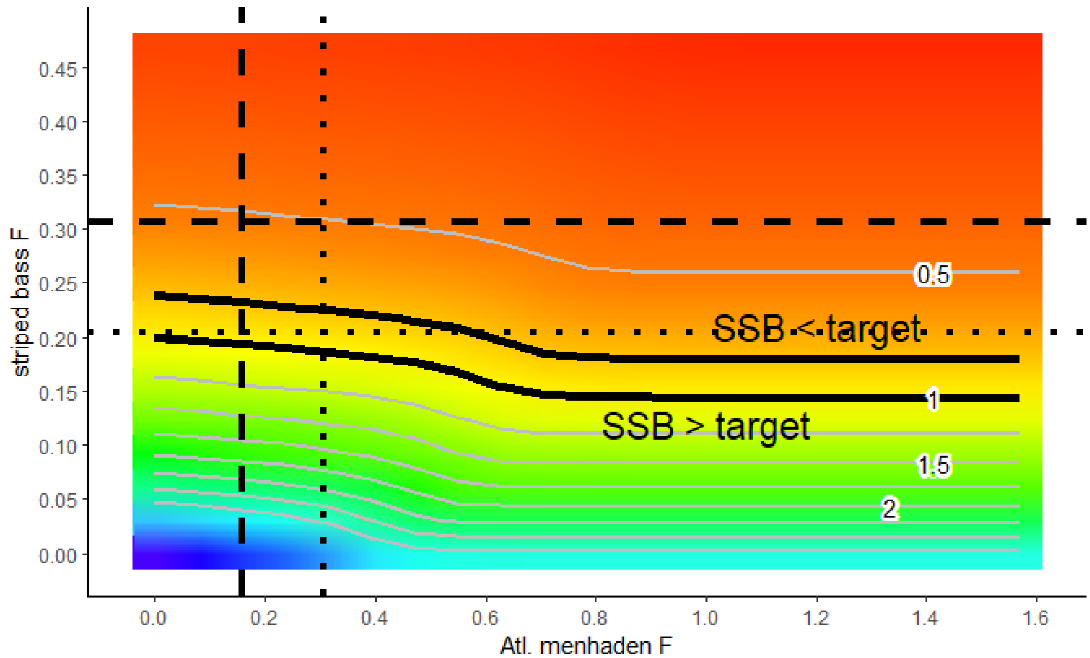

Figure C. 35: Impact of Atlantic menhaden and striped bass F on relative striped bass SSB assuming a log normal prey preference function (LNC30). A total of 21 Atlantic menhaden Fs were tested, ranging from 0 to 1.49 yr^{-1}, and 16 striped bass Fs were tested, ranging from 0 to 0.47 yr^{-1} following the Chagaris et al. (2020). Rainbow colors within the plot indicate striped bass SSB relative to the striped bass target SSB in the stock assessment. Light grey lines and associated numbers indicate levels of striped bass relative SSB. Long dashed lines indicate the current status quo F for Atlantic menhaden (vertical) and striped bass (horizontal). Dotted lines indicate the target F for Atlantic menhaden (vertical) and striped bass (horizontal). Striped bass SSB is greater than the target (114,295 thousand kg) below the solid black horizontal line labelled 1 and in the space labelled 'SSB>target'. The area above the upper solid black line labelled 'SSB<threshold' indicated striped bass SSB was lower than the threshold SSB (91,436 thousand kg).

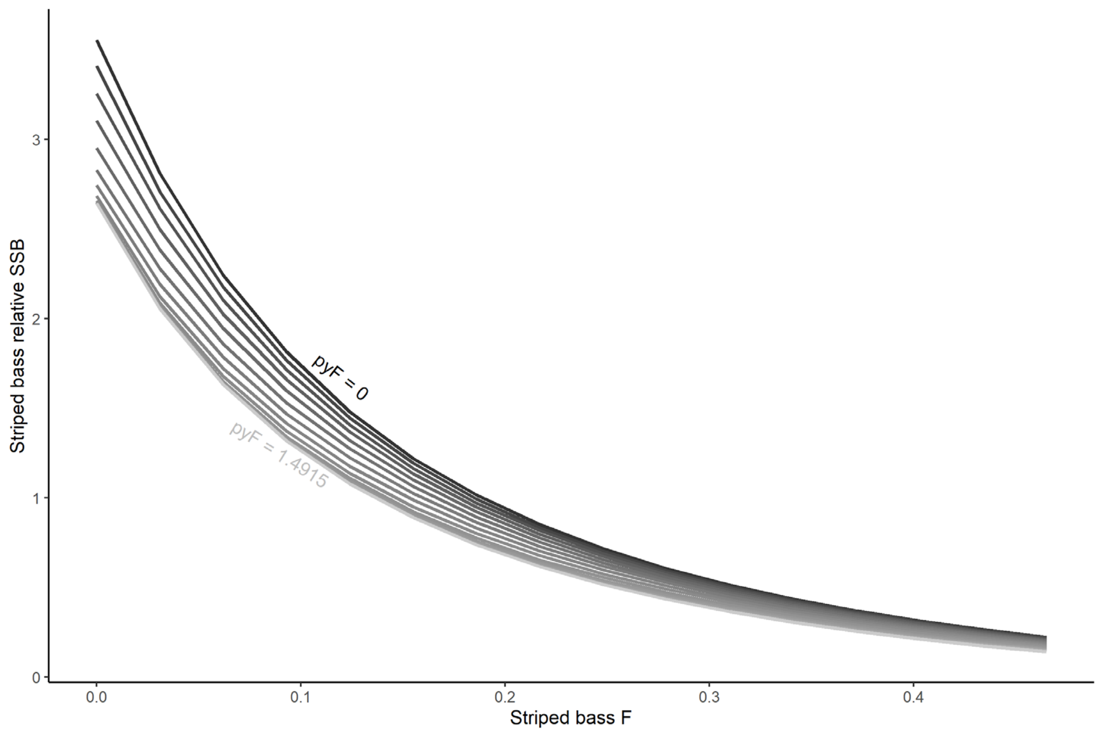

Figure C. 36: Relationship between striped bass F and relative SSB from LNC30 operating model. Relative SSB is SSB under a given HCR divided by their SSB target in the stock assessment (114,295 thousand kg). Each line indicates an Atlantic menhaden F (pyF) input as a constant F HCR into the model. A total of 21 HCRs with pyF ranging from 0 to 1.4915 yr^{-1} were explored. Striped bass operated under a constant F HCR.

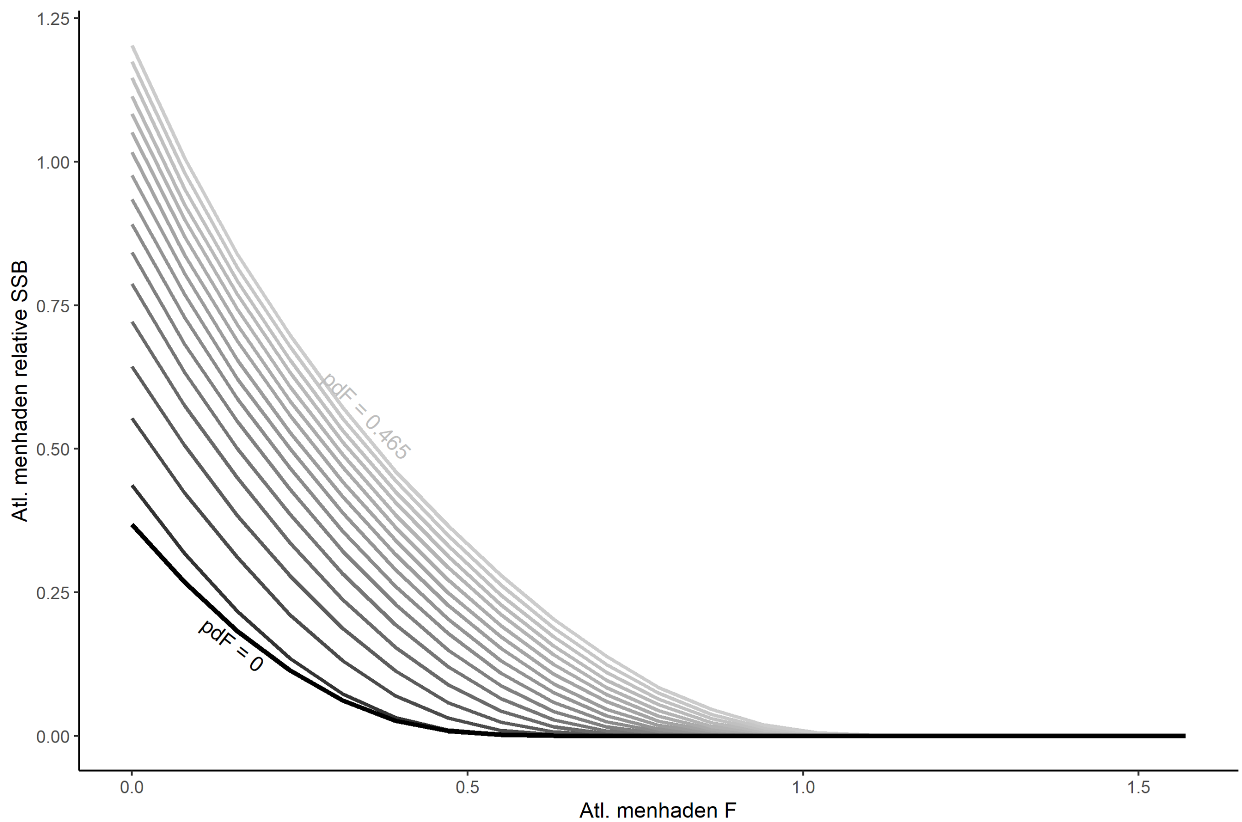

Figure C. 37: Relationship between Atlantic menhaden F and relative SSB from the LNC30 operating model. Atlantic menhaden relative SSB is SSB under a given HCR relative to their target SSB recalculated from egg production to billions of kilograms. Each line indicates a striped bass F (pdF) input as a constant F HCR into the model. Atlantic menhaden operated under a constant F HCR. A total of 16 HCRs with pdF ranging from 0 to 0.47 yr^{-1} were explored.

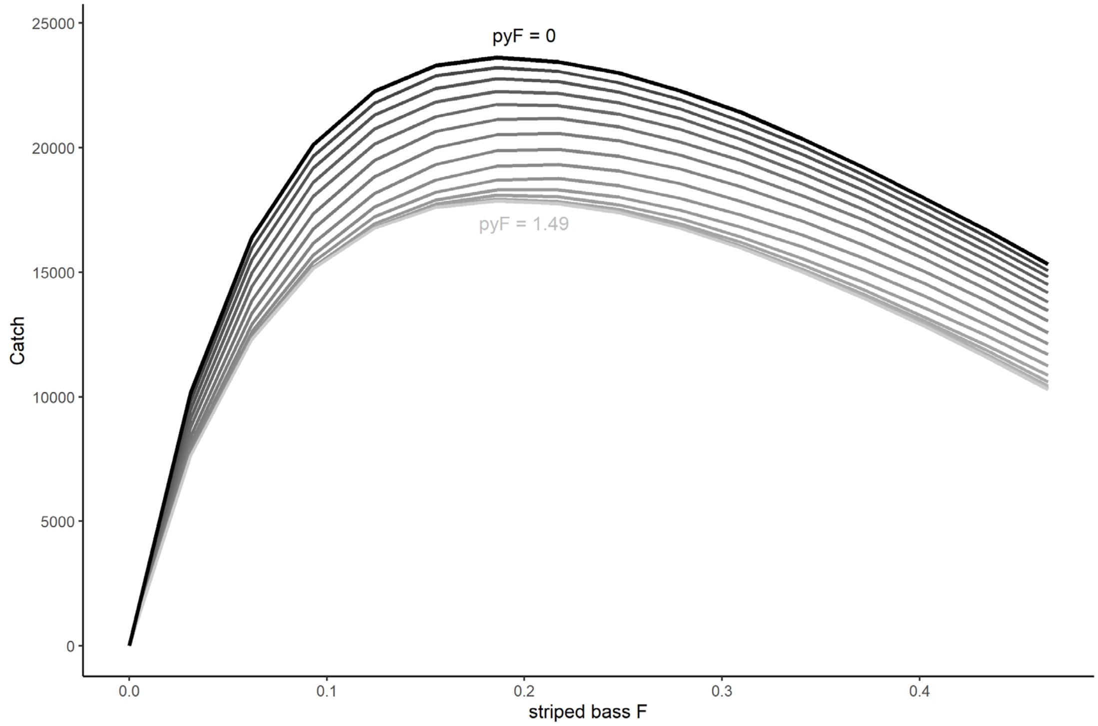

Figure C. 38: Striped bass catch under 21 HCRs where striped bass F was constant and Atlantic menhaden F (pyF) ranged from 0 to 1.49 yr^{-1} under the LNC30 operating model. The uppermost solid black line indicates unfished prey conditions (F=0 yr^{-1}), and the lowest curve indicates F for Atlantic menhaden is 1.49 yr^{-1}. Catch is in thousand kgs.

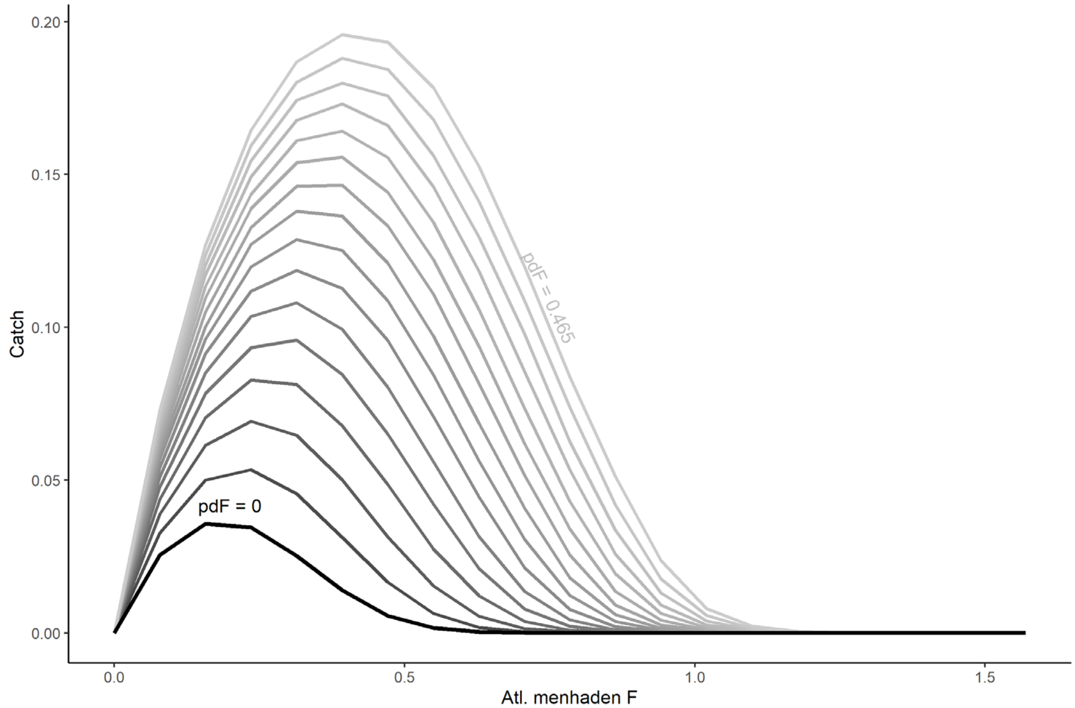

Figure C. 39: Atlantic menhaden catch under 16 HCRs where Atlantic menhaden F is constant and striped bass F (pdF) ranged from 0 to 0.47 yr^{-1}. The lowermost solid black line indicates unfished conditions (F=0 yr^{-1}). The highest curve indicates constant F HCR where F for striped bass is 0.465 yr^{-1}. Results are from the LNC30 operating model. Catch is measured in billion kg.

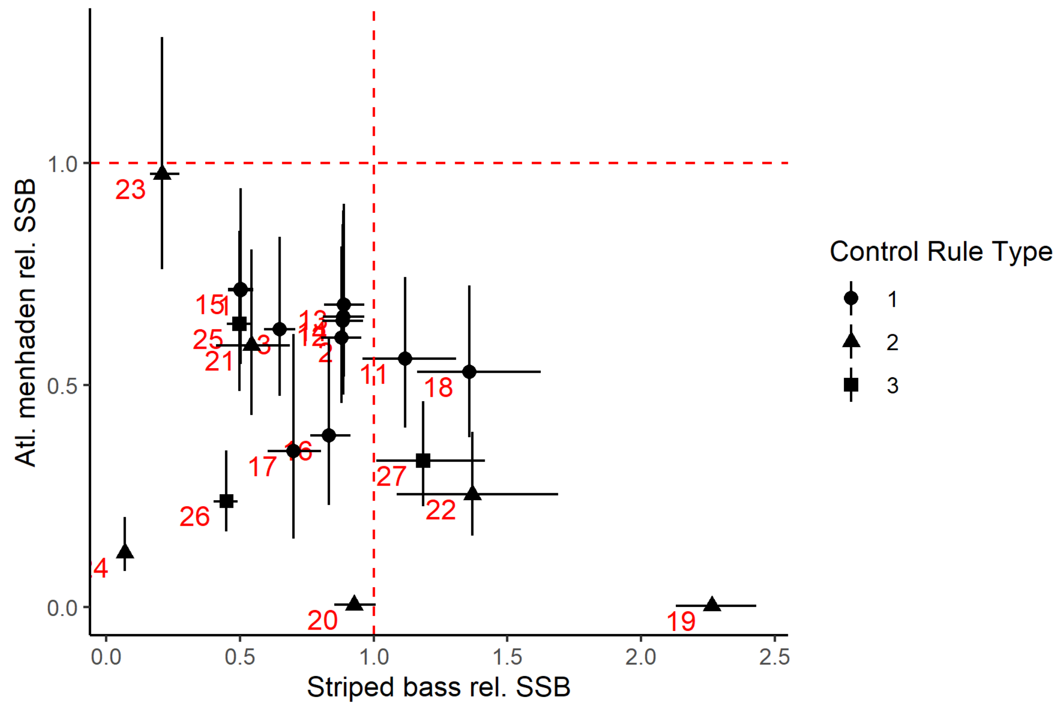

Figure C. 40: Tradeoffs between striped bass relative spawning stock biomass (striped bass rel. SSB) and Atlantic menhaden relative spawning stock biomass (Atl. Menhaden rel. SSB) for 27 harvest control rules under the LNC30 alternative operating model (HCR; numbers defined in Table 3). The red dashed lines indicate the relative SSB targets for each species. The points indicate the median SSB while the lines show the interquartile range for striped bass (horizontal) and Atlantic menhaden (vertical). HCR types are designated by shapes of the point for type 1 (circle), type 2, (triangle), and type 3 (square).

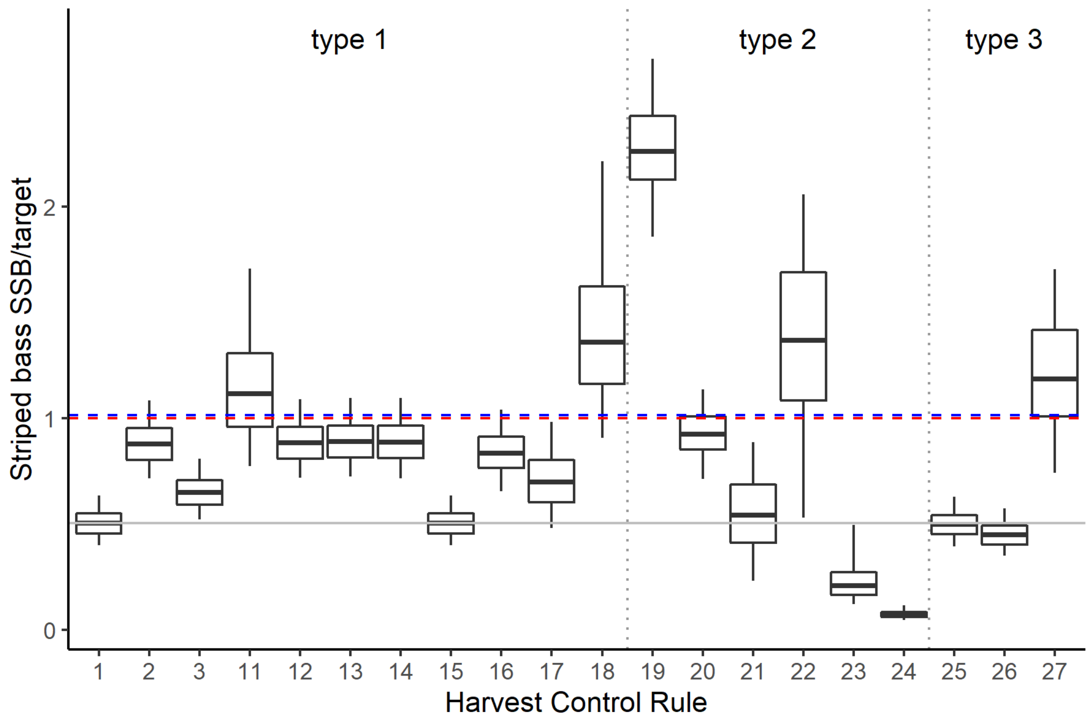

Figure C. 41: Striped bass spawning stock biomass (SSB) relative to the target SSB (target) from the stock assessment for 27 harvest control rules under LNC30 (HCRs; defined in Table 3). The red dashed line indicates the target SSB, the solid grey line indicates SSB at status quo, and the blue dashed line indicates SSB_{MSY}. The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

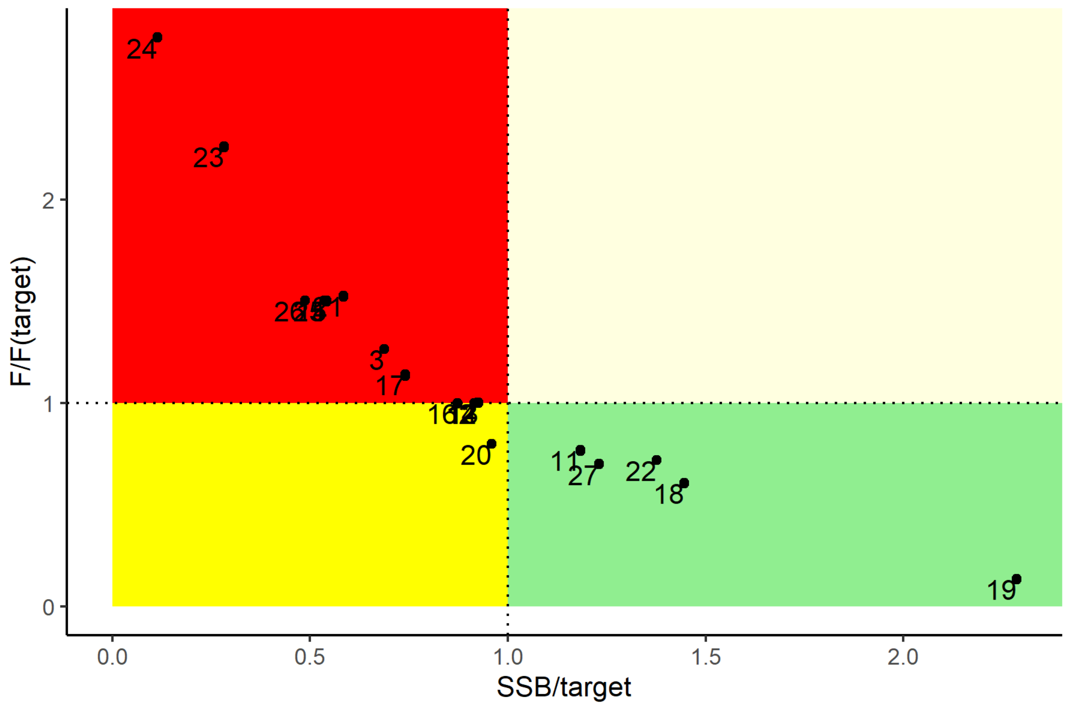

Figure C. 42: Kobe plot showing the relationship between the median striped bass spawning stock biomass (SSB) and fishing morality (F) for each HCR under LNC30. The target refers to the striped bass SSB_{target} found in the stock assessment. Target F is 0.204 yr^{-1}. The numbers next to each point indicate the HCR number from Table 3.

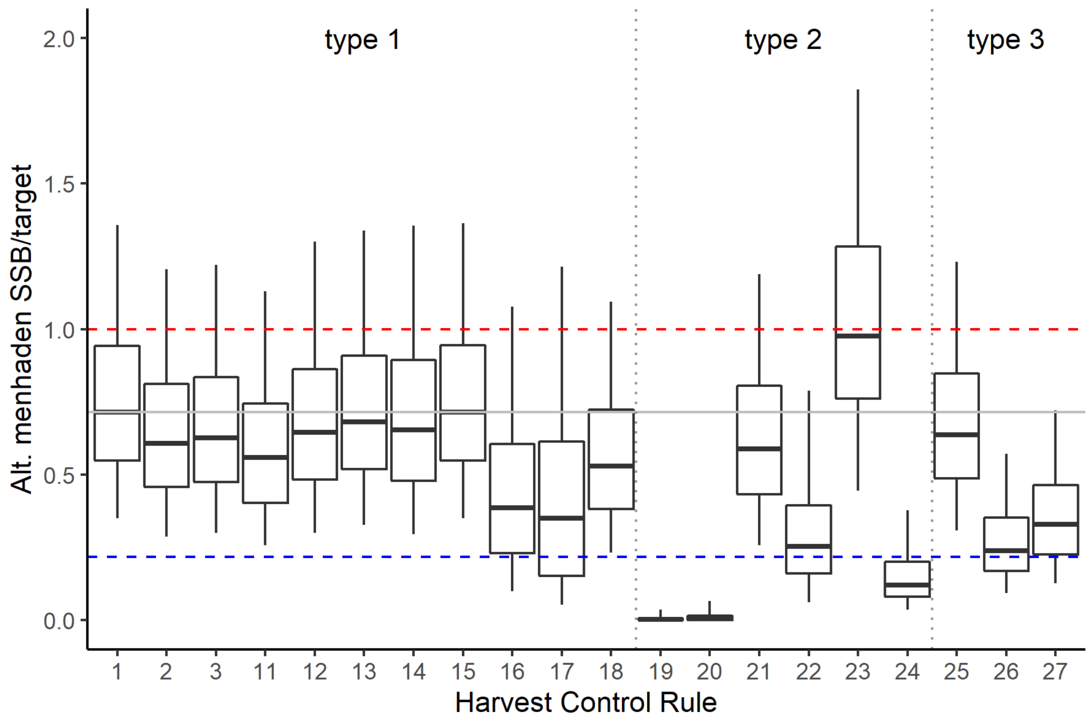

Figure C. 43: Atlantic menhaden spawning stock biomass (SSB) relative to the target SSB (target) from the stock assessment for 27 harvest control rules under LNC30 (HCRs; defined in Table 3). The red dashed line indicates the target SSB, the solid grey line indicates SSB at status quo, and the blue dashed line indicates SSB_{MSY}. The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

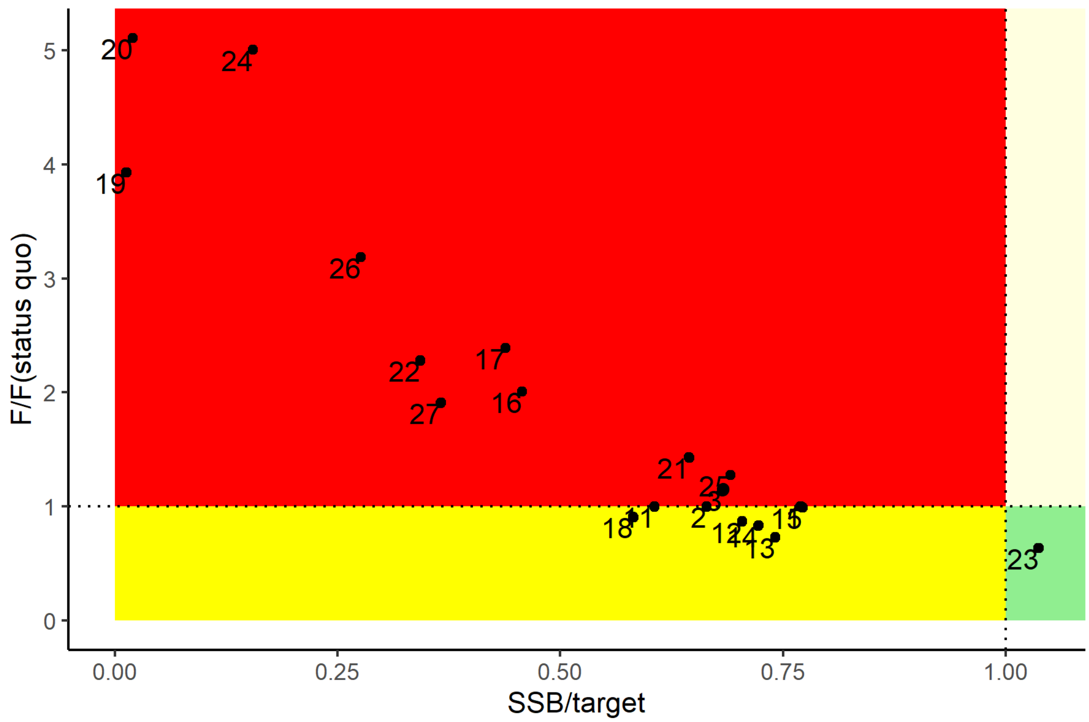

Figure C. 44: Kobe plot showing the relationship between the Atlantic menhaden spawning stock biomass (SSB) and fishing morality (F) for each HCR under LNC30. The target refers to the Atlantic menhaden SSB_{target} found in the stock assessment. Status quo F is 0.157 yr^{-1}. The numbers next to each point indicate the HCR number from Table 3.

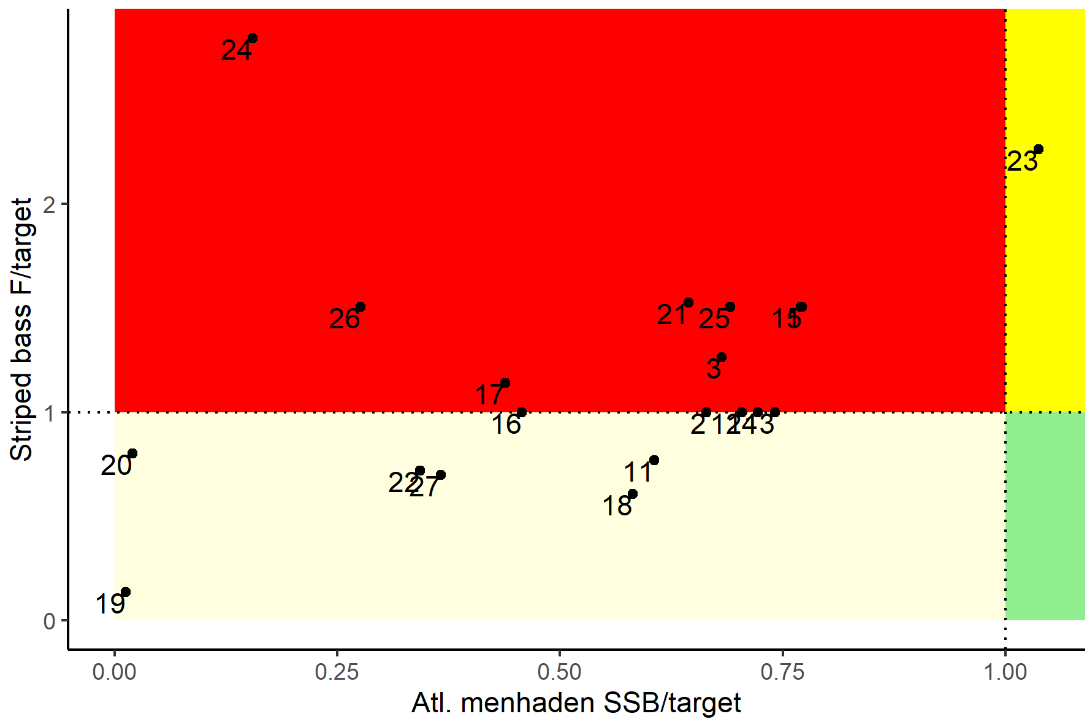

Figure C. 45: A multispecies Kobe plot showing the status of Atlantic menhaden relative SSB (x-axis) and the corresponding striped bass relative F (y-axis) resulting from the LNC30 alternative operating model. The numbers next to each point correspond to the HCR numbers found in table 3. The panels in the plot represent varying status of ideal (green), okay (light yellow and yellow), and detrimental (red). F_{target} for striped bass is 0.204 and Atlantic menhaden SSB target is 0.843.

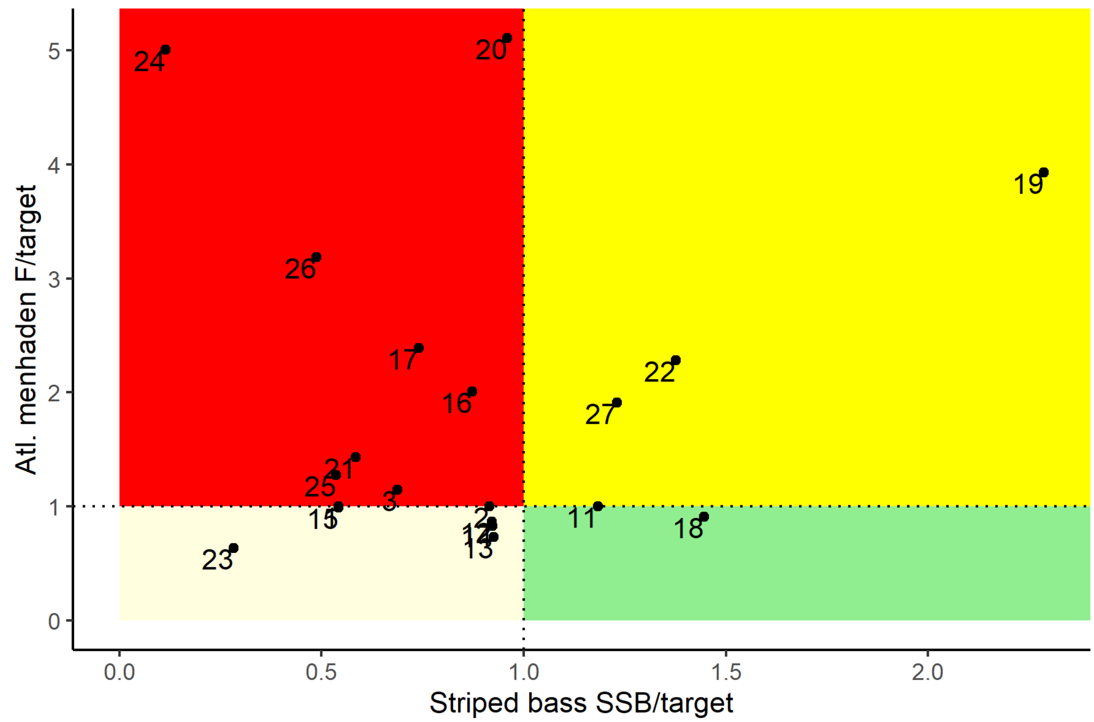

Figure C. 46: A multispecies Kobe plot showing the status of striped bass relative SSB (x-axis) and the corresponding Atlantic menhaden relative F (y-axis) resulting from the LNC30 operating model. The numbers next to each point correspond to the HCR numbers found in table 3. The panels in the plot represent varying status of ideal (green), okay (light yellow and yellow), and detrimental (red). F_{target} for Atlantic menhaden is 0.157 and striped bass SSB target is 114,295 thousand kg.

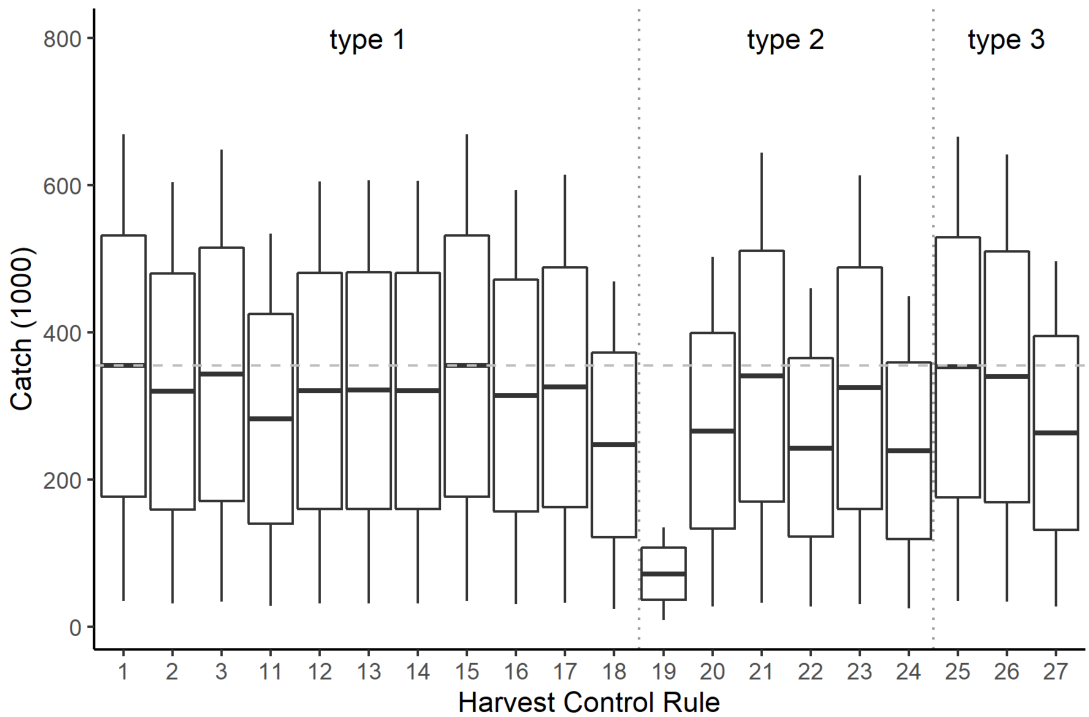

Figure C. 47: Striped bass catch in numbers for 27 harvest control rules in the LNC30 operating model (HCRs; defined in Table 3). The horizontal dashed grey line indicates catch at status quo. The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

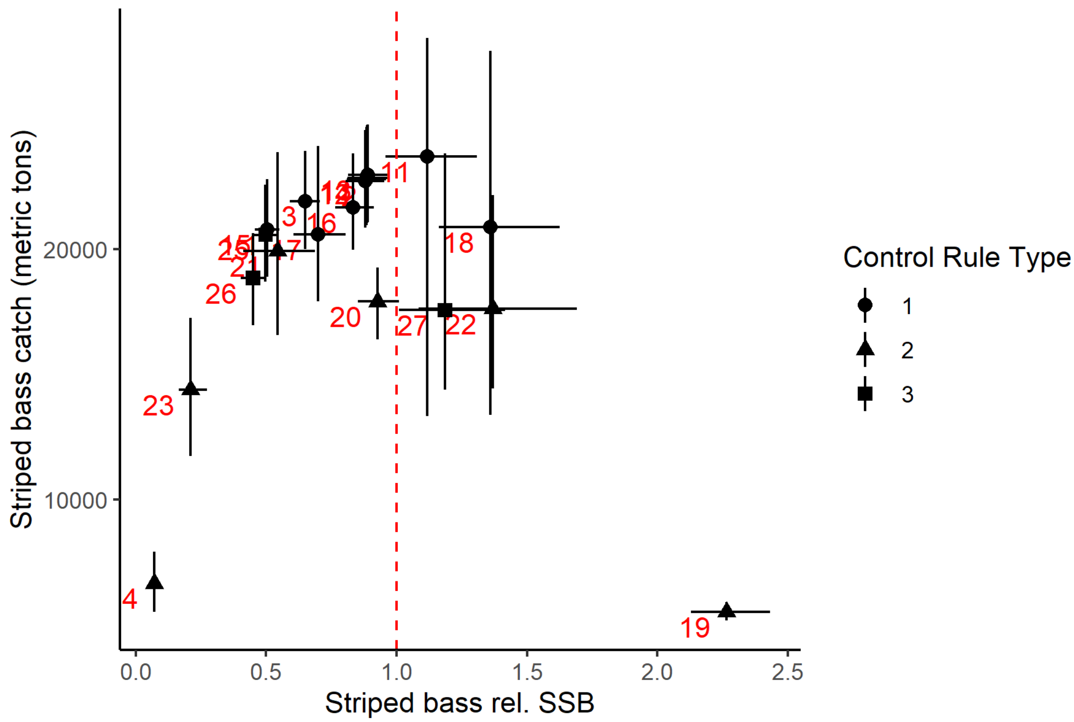

Figure C. 48: Tradeoffs between striped bass relative spawning stock biomass in the LNC30 operating model (Striped bass rel. SSB) and catch for 27 harvest control rules (HCR; numbers defined in Table 3). The red dashed lines indicate the relative SSB targets for striped bass in the stock assessment. The points indicate the median SSB while the lines show the interquartile range for striped bass SSB (horizontal) and catch (vertical). HCR types are designated by shapes of the point for type 1 (circle), type 2, (triangle), and type 3 (square).

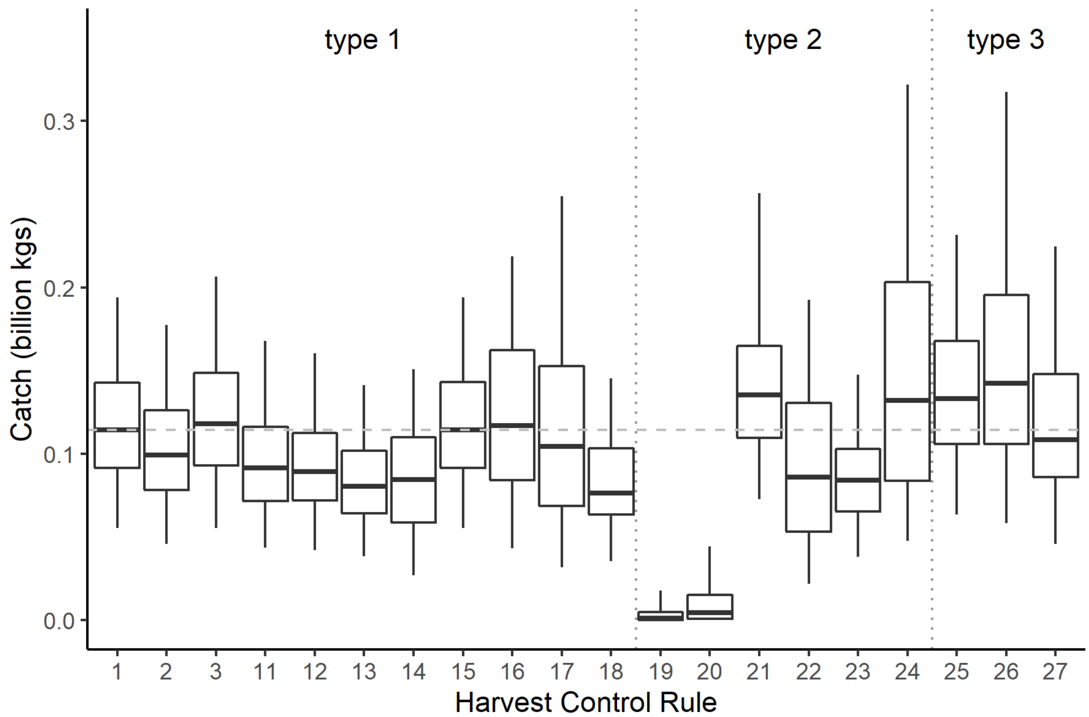

Figure C. 49: Atlantic menhaden catch in weight (billion kg) for 27 harvest control rules in the LNC30 operating model (HCRs; defined in Table 3). The horizontal dashed grey line indicates catch at status quo. The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

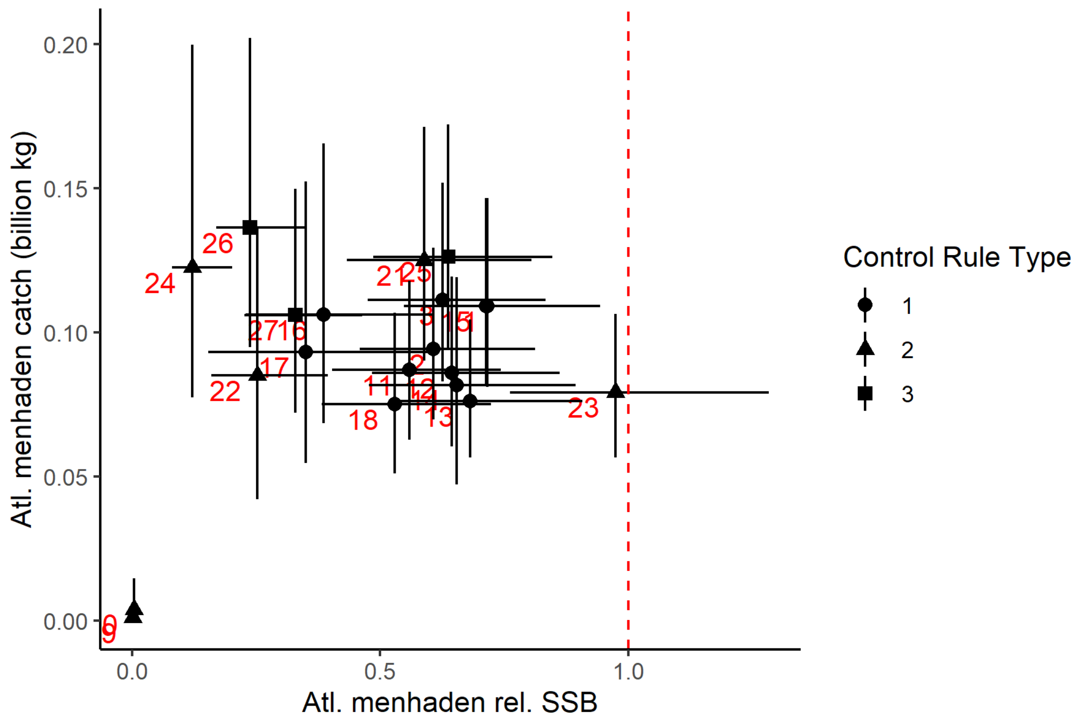

Figure C. 50: Tradeoffs between Atlantic menhaden relative spawning stock biomass and catch for 27 harvest control rules from the LNC30 operating model (HCR; numbers defined in Table 3). The red dashed lines indicate the relative SSB targets for Atlantic menhaden in the stock assessment. The points indicate the median SSB while the lines show the interquartile range for SSB (horizontal) and catch (vertical). HCR types are designated by shapes of the point for type 1 (circle), type 2, (triangle), and type 3 (square).

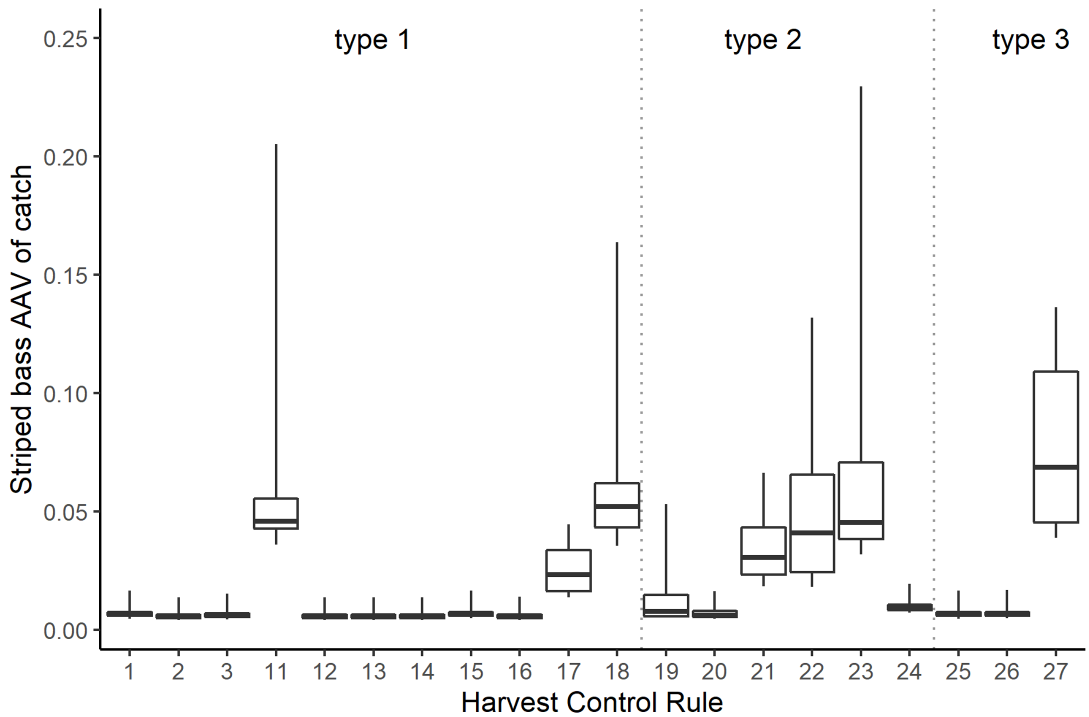

Figure C. 51: Average annual variation (AAV) of striped bass catch calculated in numbers of striped bass rather than weight resulting from the LNC30 operating model. The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

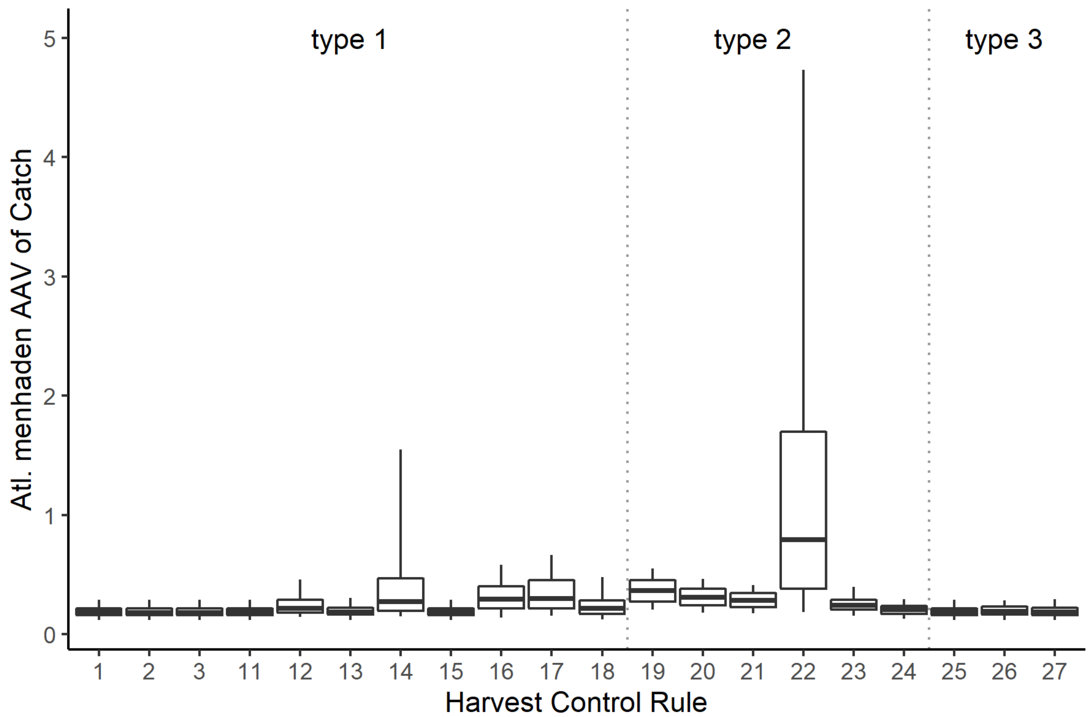

Figure C. 52: Average annual variation (AAV) of Atlantic menhaden catch calculated in billions of kg resulting from LNC30 operating model. There is no catch for HCR 4, 6, and 7 because F for Atlantic menhaden is 0. The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

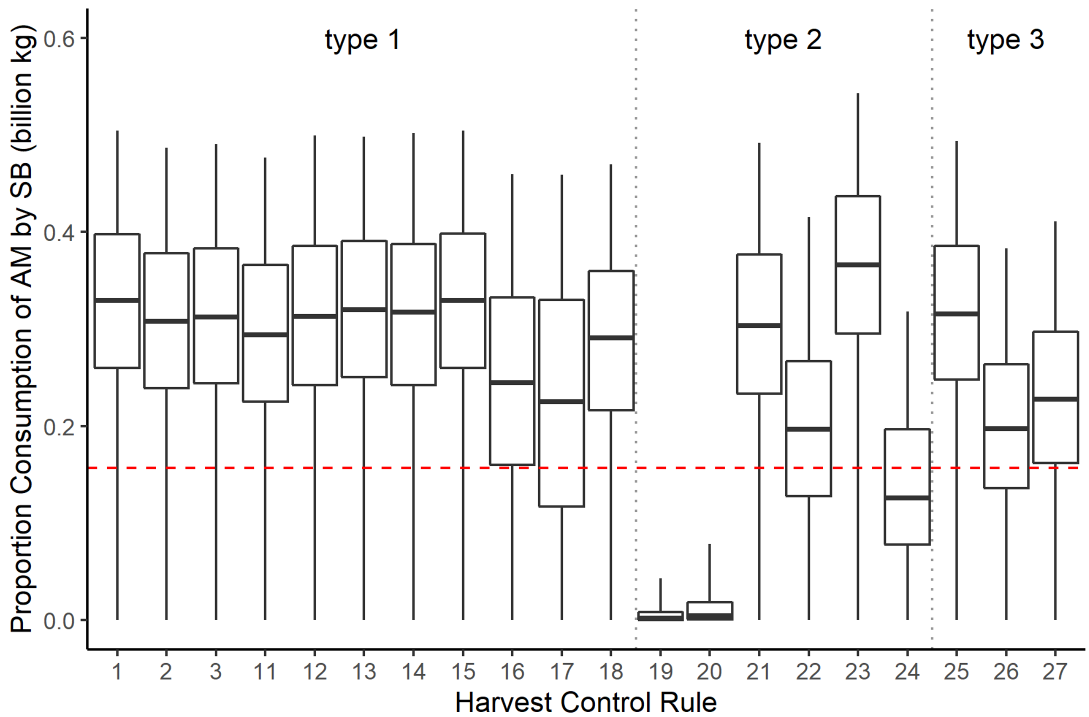

Figure C. 53: Proportion consumption of Atlantic menhaden (AM) by age-3 striped bass (SB) for 27 harvest control rules resulting from LNC30 operating model (HCRs; defined in Table 3). At age-3, Atlantic menhaden comprise 15.7% of striped bass diet according to Chagaris et al (2020) (red dashed line). The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

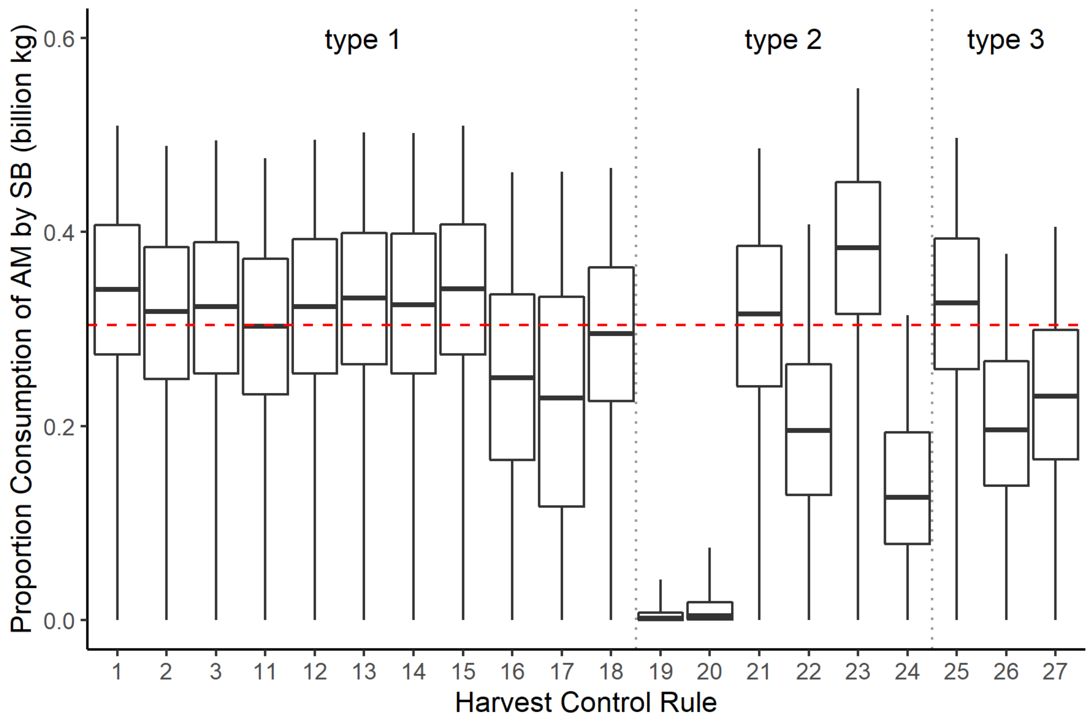

Figure C. 54: Proportion consumption of Atlantic menhaden (AM) by age-15 striped bass (SB) for 27 harvest control rules resulting from LNC30 operating model (HCRs; defined in Table 3). At age-15, Atlantic menhaden comprise 30.4% of striped bass diet according to Chagaris et al (2020) (red dashed line). The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

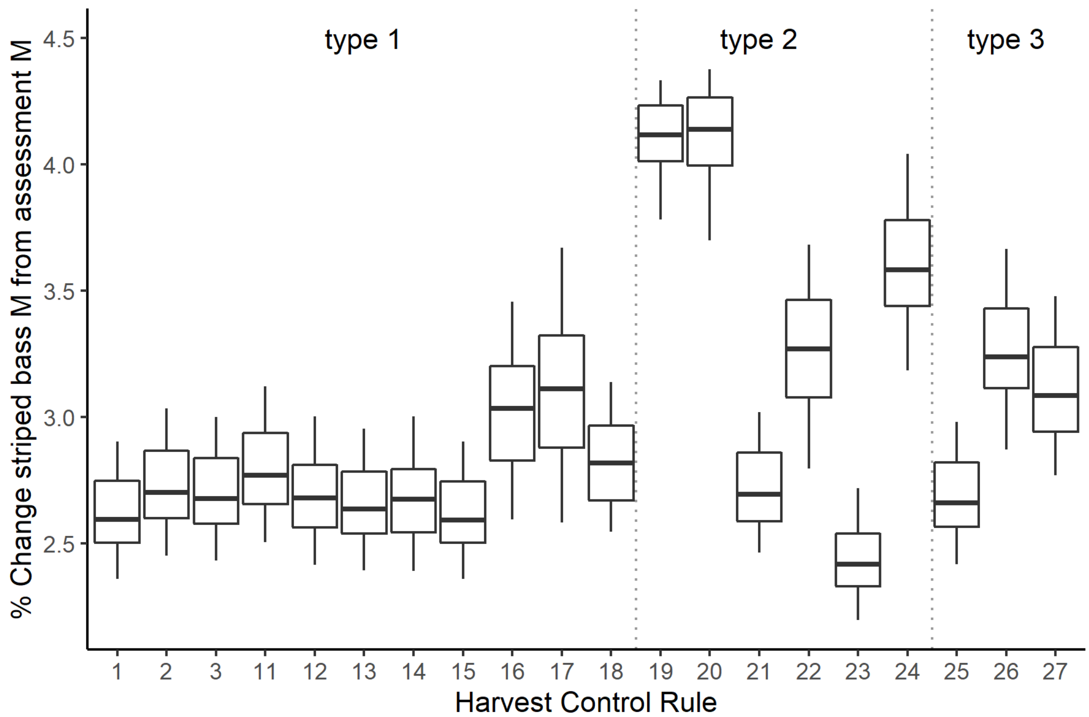

Figure C. 55: Percent change of age-3 striped bass natural mortality (M) from the stock assessment age-3 M for 27 harvest control rules resulting from LNC30 operating model (HCRs; defined in Table 3). The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

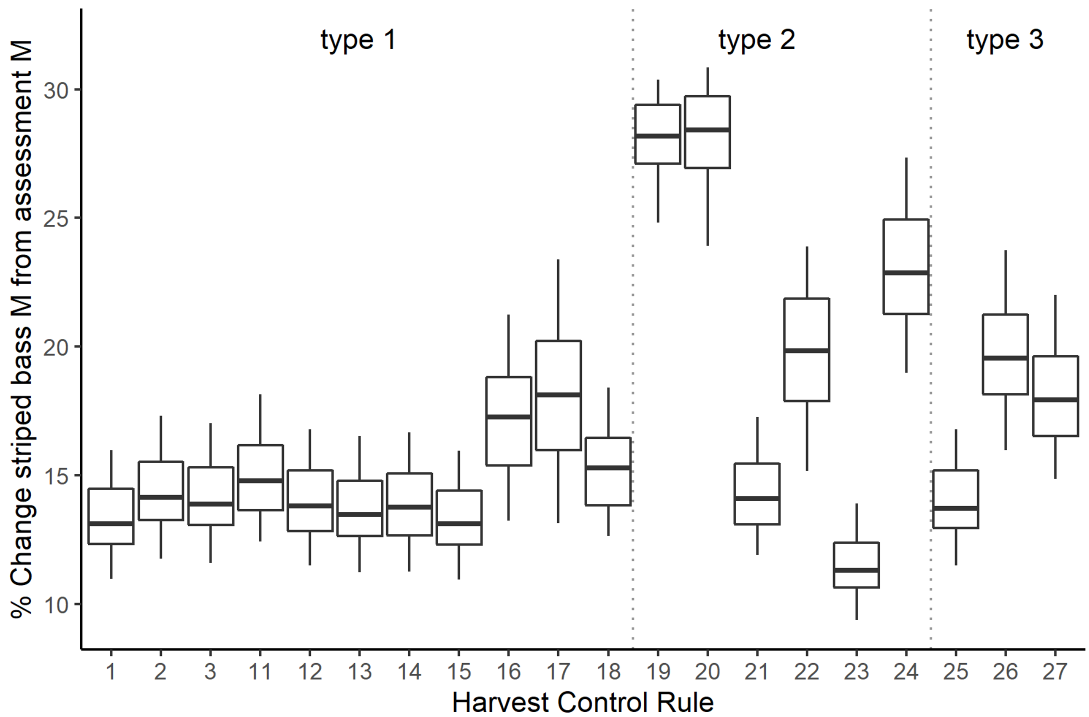

Figure C. 56: Percent change of age-15 striped bass natural mortality (M) from the stock assessment age-15 M for 27 harvest control rules resulting from the LNC30 operating model (HCRs; defined in Table 3). The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

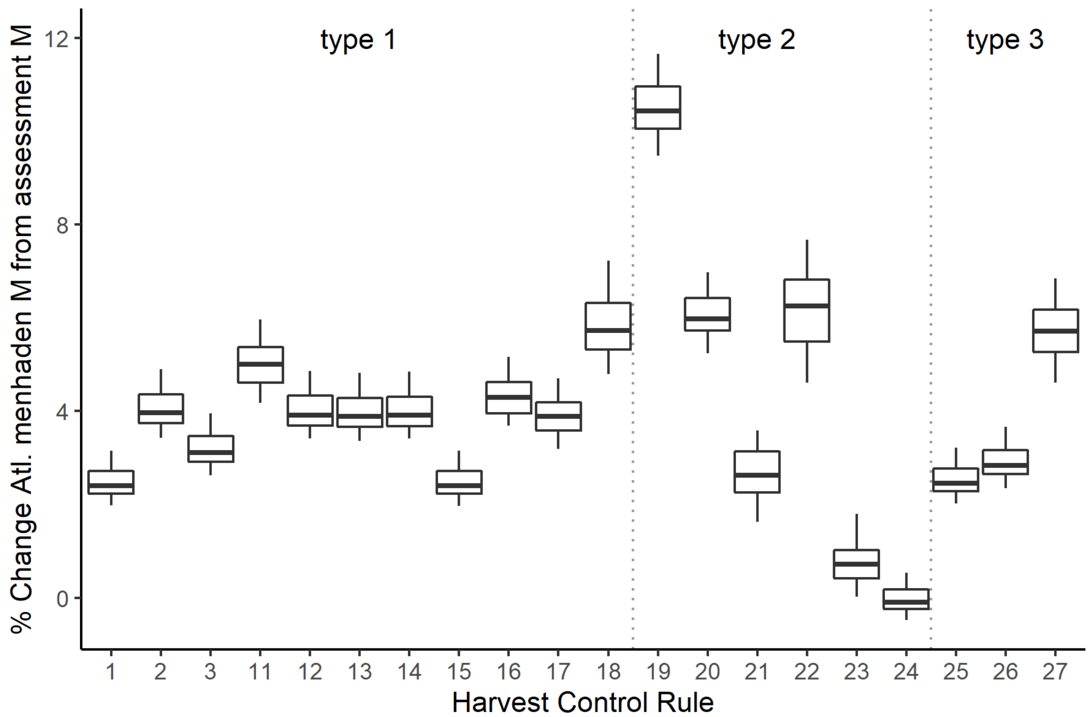

Figure C. 57: Percent change of age-1 Atlantic menhaden M from the stock assessment M resulting from the LNC30 operating model. The vertical dashed lines separate the harvest control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

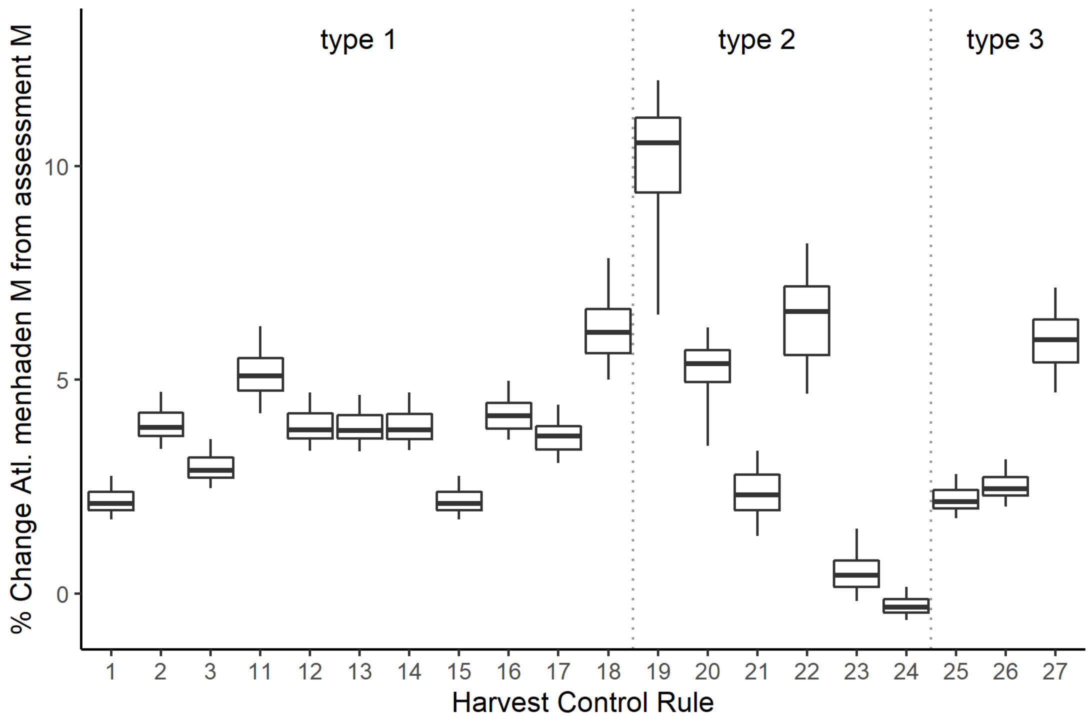

Figure C. 58: Percent change of age-4 Atlantic menhaden natural mortality (M) from the stock assessment age-4 M for 27 harvest control rules resulting from LNC30 operating model (HCRs; defined in Table 3. The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

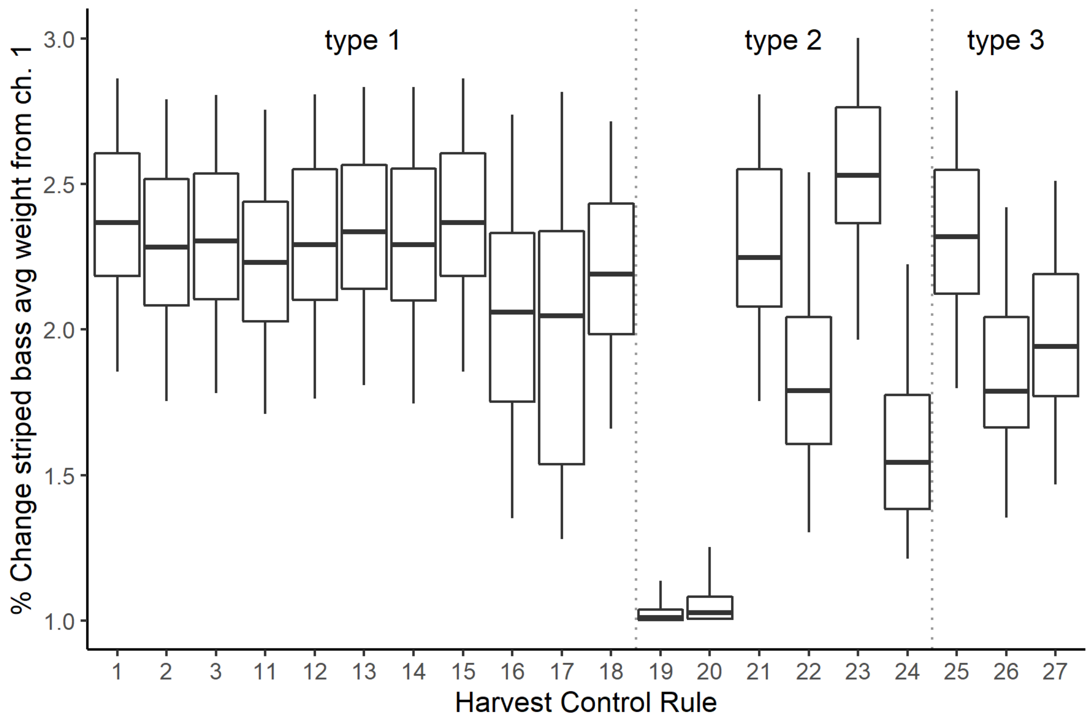

Figure C. 59: Percent change in age-3 striped bass weight from the average age-3 striped bass weight calculated in chapter 1 for 27 harvest control rules resulting from LNC30 operating model (HCRs; defined in Table 3). The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

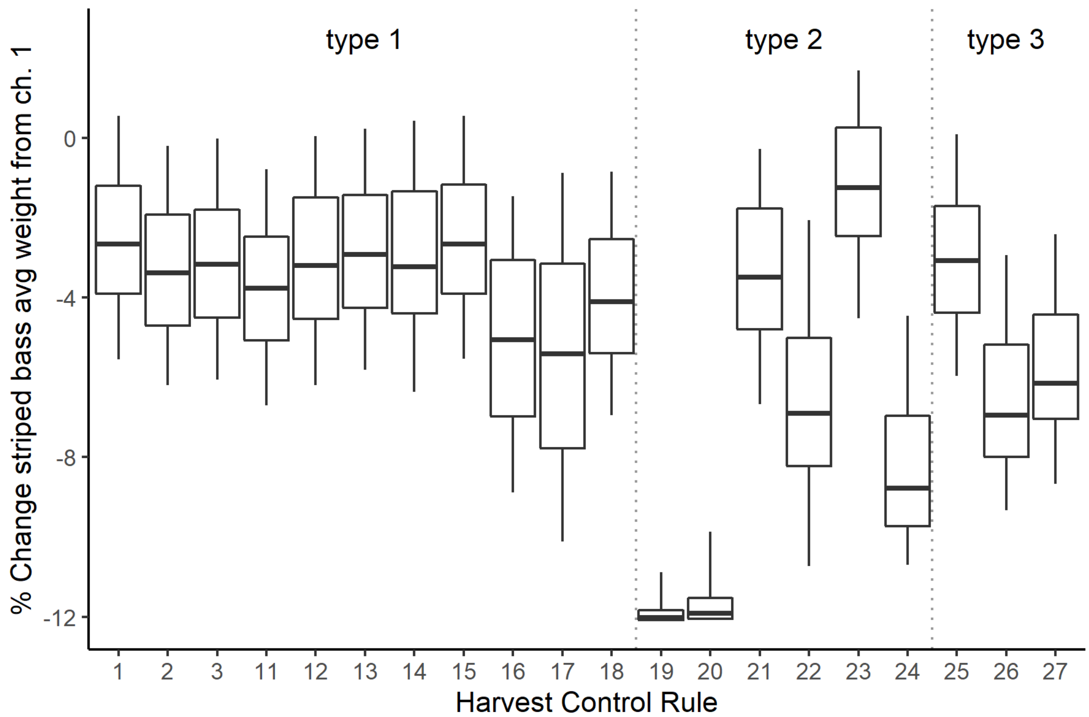

Figure C. 60: Percent change in age-15 striped bass weight from the average age-15 striped bass weight calculated in chapter 1 for 27 harvest control rules resulting from the LNC30 operating model (HCRs; defined in Table 3). The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

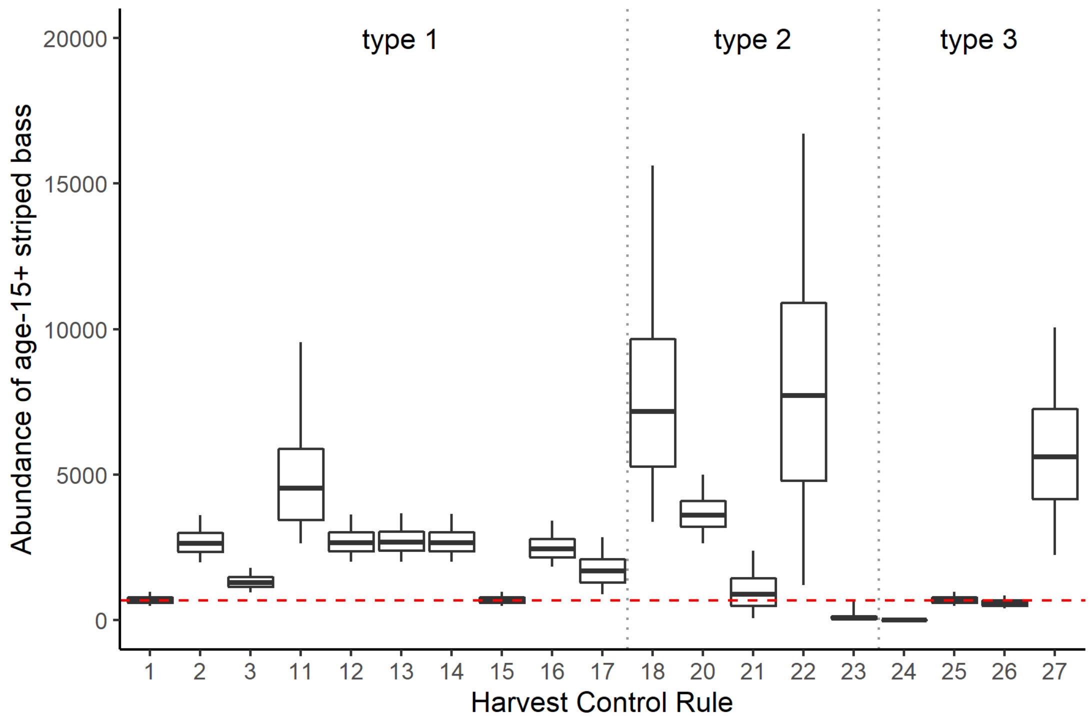

Figure C. 61: The abundance of age-15 and older striped bass (million) for 24 harvest control rules resulting from the LNC30 operating model (HCRs; defined in Table 3). All HCRs are compared except for HCR 4, 5, and 19 which had exponentially more abundance of age-15 and older striped bass. The red dashed line indicates the abundance of age-15 and older striped bass when fished at status quo. The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

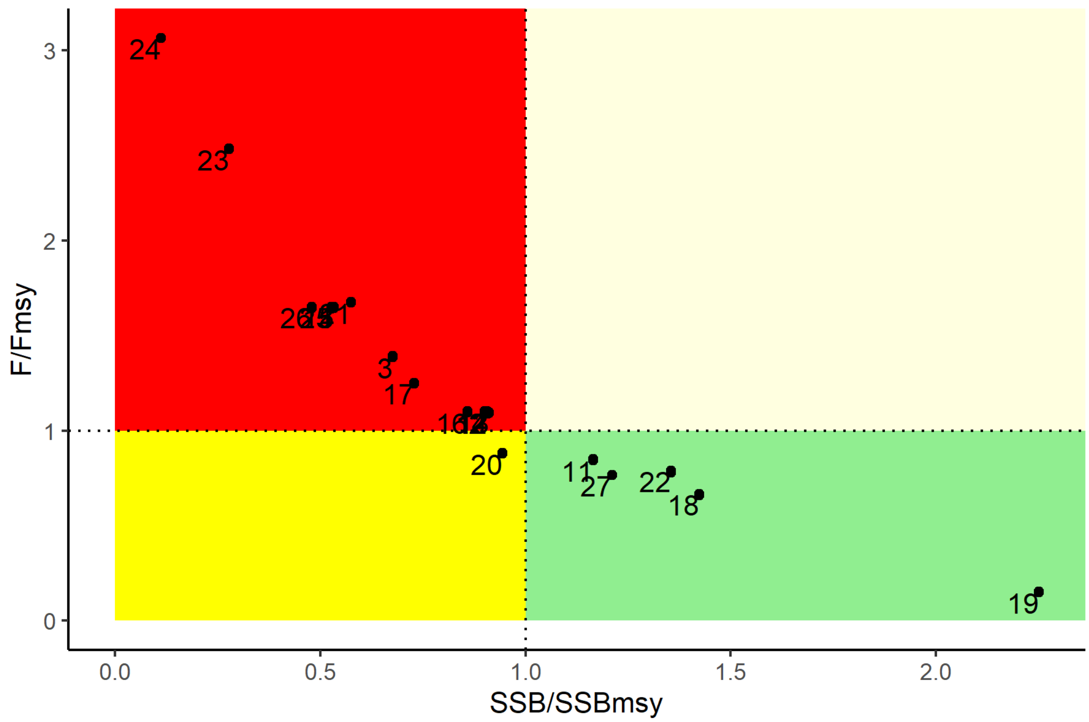

Figure C. 62: Kobe plot showing the relationship between the median striped bass spawning stock biomass (SSB) and fishing morality (F) for each HCR resulting from the LNC30 operating model. SSB_{MSY} refers to striped bass SSB_{MSY} found from model performance analysis where SSB_{MSY} is 139,254 thousand kg. F_{MSY} is 0.186 yr^{-1}. The numbers next to each point indicate the HCR number from Table 3.

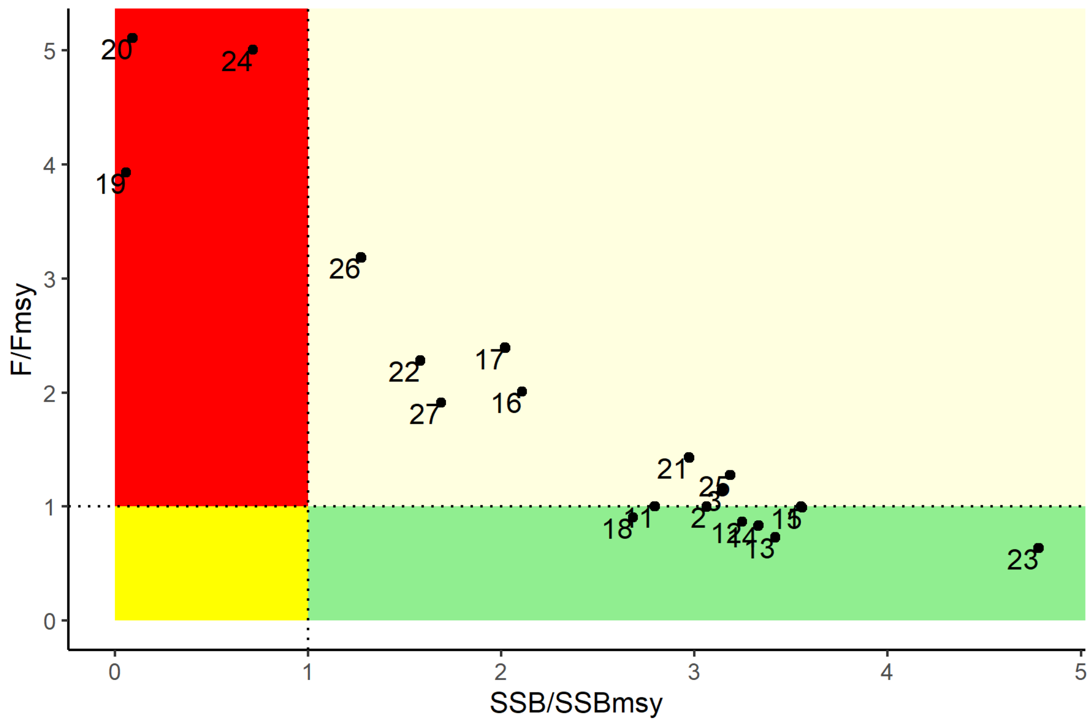

Figure C. 63: Kobe plot showing the relationship between the median Atlantic menhaden spawning stock biomass (SSB) and fishing morality (F) for each HCR resulting from the LNC30 operating model. SSB_{MSY} refers to Atlantic menhaden SSB_{MSY} found from model performance analysis where SSB_{MSY} is 0.02572 billion kg. F_{MSY} is 0.2355 yr^{-1}. The numbers next to each point indicate the HCR number from Table 3.

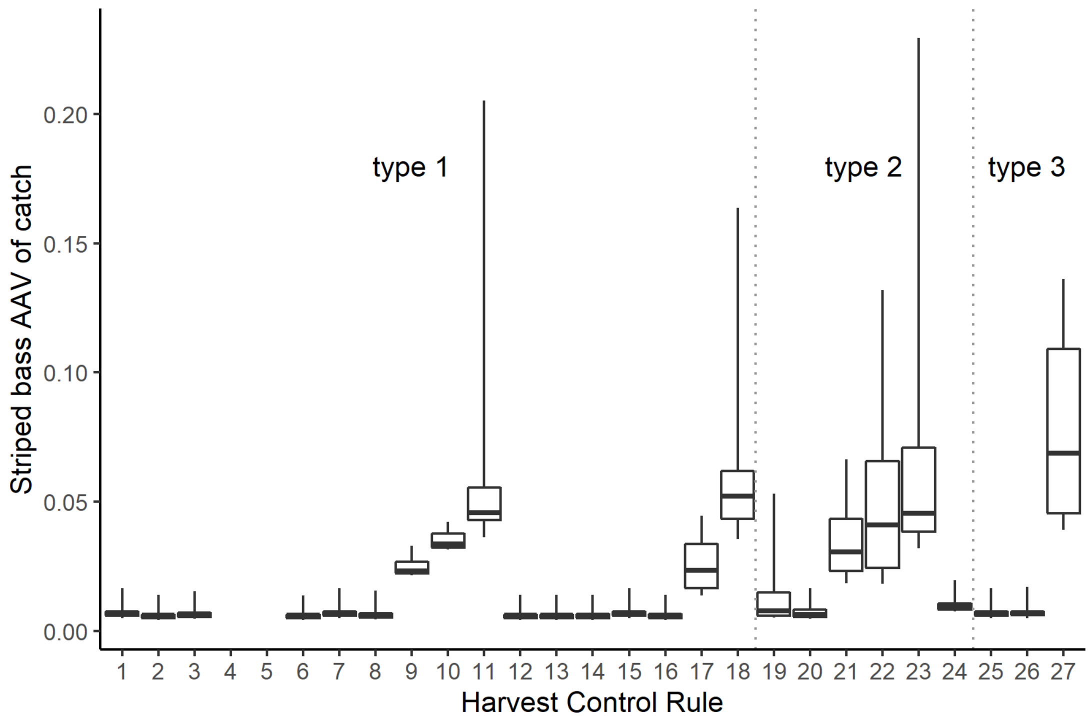

Figure C. 64: Average annual variation (AAV) of striped bass catch calculated in weight of striped bass in LNC30. The vertical dashed lines separate the control rules into categories by typing where HCRs 1-18 are type 1, 19-24 are type 2, and 25-27 are type 3 HCRs. The solid lines indicate the medians, the boxes represent the 25th and 75th percentiles, and the whiskers indicate the 5th and 95th percentiles.

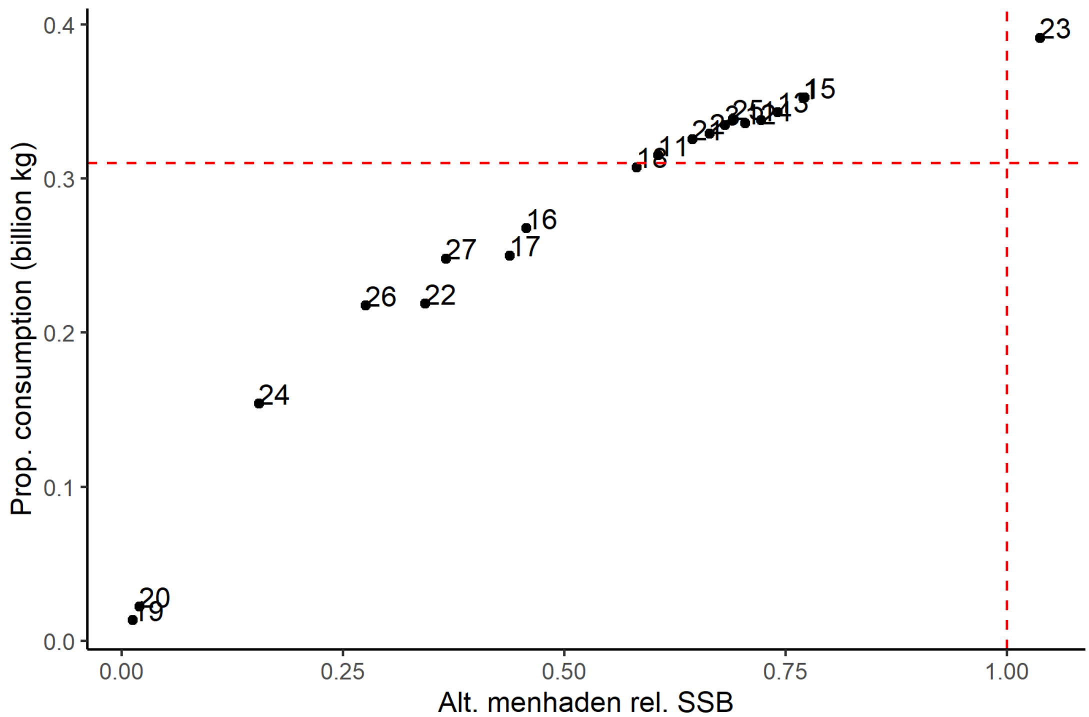

Figure C. 65: Proportion consumption of Atlantic menhaden in relation to Atlantic menhaden relative SSB under LNC30. Numbers indicate HCRs as listed in table 1.1. The red vertical line indicates where Atlantic menhaden SSB is equal to its SSB target found in the stock assessment. The red dashed horizontal line indicates the proportion consumption of Atlantic menhaden realized by striped bass age-15 (31%).

References

Abecasis, D., Bentes, L., Coelho, R., Correia, C., Lino, P. G., Monteiro, P., Gonçalves, J. M. S., Ribeiro, J., & Erzini, K. (2008). Ageing seabreams: A comparative study between scales and otoliths. *Fisheries Research*, *89*(1), 37–48. https://doi.org/10.1016/j.fishres.2007.08.013

Able, K. W., Grothues, T. M., Turnure, J. T., Byrne, D. M., & Clerkin, P. (2012). Distribution, movements, and habitat use of small striped bass (Morone saxatilis) across multiple spatial scales. *Fishery Bulletin*, *110*(2), 176–192.

Abrams, P. A., & Ginzburg, L. R. (2000). The nature of predation: Prey dependent, ratio dependent or neither? *Trends in Ecology and Evolution*, *15*(8), 337–341. https://doi.org/10.1016/S0169-5347(00)01908-X

Ahti, P., Kuparinen, A., & Uusi-Heikkila, S. (2020). Size does matter - the eco-evolutionary effects of changing body size in fish. *Environmental Reviews*. https://doi-org.proxy-um.researchport.umd.edu/10.1139/er-2019-0076

Anstead, K. A., Drew, K., Chagaris, D., Schueller, A. M., McNamee, J. E., Buchheister, A., Nesslage, G., Uphoff, J. H., Wilberg, M. J., Sharov, A., Dean, M. J., Brust, J., Celestino, M., Madsen, S., Murray, S., Appelman, M., Ballenger, J. C., Brito, J., Cosby, E., … Townsend, H. (2021). The Path to an Ecosystem Approach for Forage Fish Management: A Case Study of Atlantic Menhaden. *Frontiers in Marine Science*, *8*(May). https://doi.org/10.3389/fmars.2021.607657

ASFMC. (2016). *ASMFC Stock Assessment Overview: Weakfish*. *May*, 5. http://www.asmfc.org/uploads/file//572b74a22016WeakfishAssessmentOverview_Final.pdf

ASMFC. (2013). *57 th SAW Assessment Report B. STRIPED BASS STOCK ASSESSMENT FOR 2013*. 492–967.

ASMFC. (2015). *Atlantic States Marine Fisheries Commission Atlantic Menhaden Management Board Meeting*.

ASMFC. (2021). Addendum VI to Amendment 6 to the Atlantic striped bass Interstate Fishery Management Plan: 18% reduction in removals & circle hook measures. Retrieved from http://www.asmfc.org/uploads/file/60b7bf2bStripedBassAddendumVI_Am6_RevisedMay2021.pdf.

ASMFC. (2022). *Draft Amendment 7 to the Interstate Fishery Management Plan for Atlantic Striped Bass For Public Comment Draft Document for Public Comment*. *February*.

Austin, H. M., & Walter, J. F. (2001). *Food Habits of Large Striped Bass in the Lower Chesapeake Bay and its Tributaries March 1997-May 1998*.

Bailey, K. M., Ciannelli, L., Hunsicker, M., Rindorf, A., Neuenfeldt, S., Mollmann, C., Guichard, F., & Huse, G. (2010). Comparative analysis of marine ecosystems: workshop on predator-prey interactions. *Biology Letters*, *6*, 579–581. https://doi.org/https://doi.org/10.1098/rsbl.2010.0326

Bates, D., Machler, M., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software*, *67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01

Bonzek, C. F., Gartland, J., Gauthier, D. J., & Latour, R. J. (2022). Data collection and analysis in support of single and multispecies stock assessments in Chesapeake Bay: The Chesapeake Bay Multispecies Monitoring and Assessment Program. *Report to VA Marine Resources Commission and U.S. Fish & Wildlife Service*, 1–155. https://doi.org/10.25773/k7xj-e205

Brooks, E. N., & Deroba, J. J. (2015). When "data" are not data: The pitfalls of post hoc analyses that use stock assessment model output. *Canadian Journal of Fisheries and Aquatic Sciences*, *72*(4), 634–641. https://doi.org/10.1139/cjfas-2014-0231

Buchheister, A., Miller, T. J., & Houde, E. D. (2017). Evaluating ecosystem-based reference points for Atlantic Menhaden. *Marine and Coastal Fisheries*, *9*(1), 457–478. https://doi.org/10.1080/19425120.2017.1360420

Chagaris, D., Drew, K., Schueller, A., Cieri, M., Brito, J., & Buchheister, A. (2020). Ecological Reference Points for Atlantic Menhaden Established Using an Ecosystem Model of Intermediate Complexity. *Frontiers in Marine Science*, *7*(November), 1–17. https://doi.org/10.3389/fmars.2020.606417

Curti, K. L., Collie, J. S., Legault, C. M., & Link, J. S. (2013). Evaluating the performance of a multispecies statistical catch-at-age model. *Canadian Journal of Fisheries and Aquatic Sciences*, *70*(3), 470–484. https://doi.org/10.1139/cjfas-2012-0229

Cury, P. M., Boyd, I. L., Bonhommeau, S., Anker-Nilssen, T., Crawford, R. J. M., Furness, R. W., Mills, J. A., Murphy, E. J., Österblom, H., Paleczny, M., Piatt, J. F., Roux, J.-P., Shannon, L., & Sydeman, W. J. (2011). Global Seabird Response to Forage Fish Depletion-One-Third for the Birds. *Science*, *334*(December), 1703–1706. https://medium.com/@arifwicaksanaa/pengertian-use-case-a7e576e1b6bf

Deroba, J. J., & Bence, J. R. (2008). A review of harvest policies: Understanding relative performance of control rules. *Fisheries Research*, *94*(3), 210–223. https://doi.org/10.1016/j.fishres.2008.01.003

Dickey-collas, M., Link, J. S., Snelgrove, P., Anderson, M. R., Kenchington, E., Roberts, J. M., Brady, M. M. P., Shuford, R. L., Rudd, M. A., Johnson, D., Townsend, H., Rindorf, A., & Johannesen, E. (2022). *Exploring ecosystem-based management in the North Atlantic*. *July 2021*, 342–350. https://doi.org/10.1111/jfb.15168

Dorazio, R. M., Hattala, K. A., McCollough, C. B., & Skjeveland, J. E. (1994). Tag recovery estimates of migration of striped bass from spawning areas of the Chesapeake Bay. *Transactions of the American Fisheries Society*, *123*(6), 950–963. https://doi.org/10.1577/1548-8659(1994)123<0950:TREOMO>2.3.CO;2

Drew, K., Cieri, M., Schueller, A. M., Buchheister, A., Chagaris, D., Nesslage, G., Mcnamee, J. E., & Jr, J. H. U. (2021). *Balancing Model Complexity , Data Requirements , and Management Objectives in Developing Ecological Reference Points for Atlantic Menhaden*. *8*(February), 1–17. https://doi.org/10.3389/fmars.2021.608059

Eikeset, A. M., Dunlop, E. S., Heino, M., Storvik, G., Stenseth, N. C., & Dieckmann, U. (2016). Roles of density-dependent growth and life history evolution in accounting for fisheries-induced trait changes. *Proceedings of the National Academy of Sciences of the United States of America*, *113*(52), 15030–15035.

https://doi.org/10.1073/pnas.1525749113
Flinn, S. A., & Midway, S. R. (2021). Trends in growth modeling in fisheries science. *Fishes*, *6*(1), 1–18. https://doi.org/10.3390/fishes6010001
Gaichas, S. K., DePiper, G. S., Seagraves, R. J., Muffley, B. W., Sabo, M. G., Colburn, L. L., & Loftus, A. J. (2018). Implementing ecosystem approaches to fishery management: Risk assessment in the US Mid-Atlantic. *Frontiers in Marine Science*, *5*(NOV), 1–25. https://doi.org/10.3389/fmars.2018.00442
Garrison, L. P., Link, J. S., Kilduff, D. P., Cieri, M. D., Muffley, B., Vaughan, D. S., Sharov, A., Mahmoudi, B., & Latour, R. J. (2010). An expansion of the MSVPA approach for quantifying predator-prey interactions in exploited fish communities. *ICES Journal of Marine Science*, *67*(5), 856–870. https://doi.org/10.1093/icesjms/fsq005
Gislason, H., Daan, N., Rice, J. C., & Pope, J. G. (2010). Size, growth, temperature and the natural mortality of marine fish. *Fish and Fisheries*, *11*(2), 149–158. https://doi.org/10.1111/j.1467-2979.2009.00350.x
Gislason, H., & Helgason, T. (1985). Species interaction in assessment of fish stocks with special application to the North Sea. *Dana*, *5*, 1–44.
Goodyear, C. P. (1998). *Negative Implications of Striped Bass Minimum Size Regulations*. 1–23.
Goodyear, C. P. (2002). Negative implications of large minimum size regulations on future mean size at age: An evaluation using simulated striped bass data. *American Fisheries Society Symposium*, *2002*(30), 217–229.
Griffin, J. C., & Margraf, F. J. (2003). *The diet of Chesapeake Bay striped bass in the late 1950s*. *10*.
Hartman, K. J., & Brandt, S. B. (1995). Predatory demand and impact of striped bass, bluefish, and weakfish in the Chesapeake Bay: applications of bioenergetics models. *Canadian Journal of Fisheries and Aquatic Sciences*, *52*(8), 1667–1687. https://doi.org/10.1139/f95-760
Hartman, Kyle J., & Brandt, S. B. (1995). Trophic resource partitioning, diets, and growth of sympatric estuarine predators. *Transactions of the American Fisheries Society*, *124*(4), 520–537. https://doi.org/10.1080/1548-8659(1995)124[lt]0520[co]TRPDAG[gt]2.3.CO;2
Hartman, Kyle J., & Margraf, F. J. (2003). US Atlantic coast striped bass: Issues with a recovered population. *Fisheries Management and Ecology*, *10*(5), 309–312. https://doi.org/10.1046/j.1365-2400.2003.00361.x
Helgason, T., & Gislason, H. (1979). VPA-analysis with special interaction due to predation. *ICES CM*, *10*.
Henriquez, V., Licandeo, R. R., Cubillos, L. A., & Cox, S. P. (2016). *Interactions between ageing error and selectivity in statistical catch-at-age models: simulations and implications for assessment of the Chilean Patagonian toothfish fishery*. *73*(February), 1074–1090. https://doi.org/10.1093/icesjms/fsv270
Hilborn, R., Amoroso, R. O., Bogazzi, E., Jensen, O. P., Parma, A. M., Szuwalski, C., & Walters, C. J. (2017). When does fishing forage species affect their predators? *Fisheries Research*, *191*, 211–221. https://doi.org/10.1016/j.fishres.2017.01.008
Hilborn, R., & Ovando, D. (2014). Reflections on the success of traditional fisheries management. *ICES Journal of Marine Science*, *71*(5), 1040–1046.

https://doi.org/10.1093/icesjms/fsu034
Hoenig, J. M., Groner, M. L., Smith, M. W., Vogelbein, W. K., Taylor, D. M., Landers, D. F., Swenarton, J. T., Gauthier, D. T., Sadler, P., Matsche, M. A., Haines, A. N., Small, H. J., Pradel, R., Choquet, R., & Shields, J. D. (2017). Impact of disease on the survival of three commercially fished species: *Ecological Applications*, *27*(7), 2116–2127. https://doi.org/10.1002/eap.1595
Houde, E. D. (1997). Patterns and trends in larval-stage growth and mortality of teleost fish. *Journal of Fish Biology*, *51*(SUPPL. A), 52–83. https://doi.org/10.1111/j.1095-8649.1997.tb06093.x
Howell, D., Schueller, A. M., Bentley, J. W., Buchheister, A., Chagaris, D., Cieri, M., Drew, K., Lundy, M. G., Pedreschi, D., Reid, D. G., & Townsend, H. (2021). Combining Ecosystem and Single-Species Modeling to Provide Ecosystem-Based Fisheries Management Advice Within Current Management Systems. *Frontiers in Marine Science*, *7*(January). https://doi.org/10.3389/fmars.2020.607831
Kaplan, I. C., Hansen, C., Morzaria-Luna, H. N., Girardin, R., & Marshall, K. N. (2020). Ecosystem-Based Harvest Control Rules for Norwegian and US Ecosystems. *Frontiers in Marine Science*, *7*(August), 1–15. https://doi.org/10.3389/fmars.2020.00652
King, J. R., & McFarlane, G. A. (2003). Marine fish life history strategies: Applications to fishery management. *Fisheries Management and Ecology*, *10*(4), 249–264. https://doi.org/10.1046/j.1365-2400.2003.00359.x
Koen-Alonso, M., Pepin, P., Fogarty, M. J., Kenny, A., & Kenchington, E. (2019). The Northwest Atlantic Fisheries Organization Roadmap for the development and implementation of an Ecosystem Approach to Fisheries: structure, state of development, and challenges. *Marine Policy*, *100*(November 2018), 342–352. https://doi.org/10.1016/j.marpol.2018.11.025
Kvamsdal, S. F., Eide, A., Ekerhovd, N. A., Enberg, K., Gudmundsdottir, A., Hoel, A. H., Mills, K. E., Mueter, F. J., Ravn-Jonsen, L., Sandal, L. K., Stiansen, J. E., & Vestergaard, N. (2016). Harvest control rules in modern fisheries managementharvest control rules in modern fisheries management. *Elementa*, *2016*, 1–22. https://doi.org/10.12952/journal.elementa.000114
Liang, Z., Sun, P., Yan, W., Huang, L., & Tang, Y. (2014). Significant effects of fishing gear selectivity on fish life history. *Journal of Ocean University of China*, *13*(3), 467–471. https://doi.org/10.1007/s11802-014-2167-7
Liao, H., Sharov, A. F., & Nelson, G. A. (2013). Quantifying the effects of aging bias in atlantic striped bass stock assessment. *Transactions of the American Fisheries Society*, *142*(1), 193–207. https://doi.org/10.1080/00028487.2012.705255
Link, J. S., & Browman, H. I. (2014). Integrating what? Levels of marine ecosystem-based assessment and management. *ICES Journal of Marine Science*, *71*(5), 1170–1173. https://doi.org/10.1093/icesjms/fsu026 Contribution
Mace, P. M. (2001). A new role for MSY in single-species and ecosystem approaches to fisheries stock assessment and management. *Fish and Fisheries*, *2*(1), 2–32. https://doi.org/10.1046/j.1467-2979.2001.00033.x
Mansueti, R. J. (1961). Age, growth, and movements of the striped bass, Roccus saxatilis, taken in size selective fishing gear in Maryland. *Chesapeake Science*,

2(1), 9–36. https://doi.org/10.2307/1350717
Mardle, S., & Pascoe, S. (2002). Modelling the effects of trade-offs between long and short-term objectives in fisheries management. *Journal of Environmental Management*, *65*(1), 49–62. https://doi.org/10.1006/jema.2001.0518
McGowan, C. P., Smith, D. R., Sweka, J. A., Martin, J., Nichols, J. D., Wong, R., Lyons, J. E., Niles, L. J., Kalasz, K., Brust, J., Klopfer, M., & Spear, B. (2011). Multispecies modeling for adaptive management of horseshoe crabs and red knots in the delaware bay. *Natural Resource Modeling*, *24*(1), 117–156. https://doi.org/10.1111/j.1939-7445.2010.00085.x
McNamee, J. E. (2018). A multispecies statistical catch-at-age (MSSCAA) model for a mid-Atlantic species complex. *Open Access Dissertations*, *Paper 758*(https://digitalcommons.uri.edu/oa_diss/758), 288. https://digitalcommons.uri.edu/oa_diss/758
Merriman, D. (1941). STUDIES ON THE STRIPED BASS (Roccus saxatilis) OF THE ATLANTIC COAST. *Fishery Bulletin of the Fish and Wildlife Service*, *35*, 1–81. https://doi.org/10.1520/stp15747s
Morgan, M. J. (1999). The effect of a change in perception of length distribution of a population on maturity-at-age, weight-at-age and spawning stock biomass. *Journal of Northwest Atlantic Fishery Science*, *25*, 141–150. https://doi.org/10.2960/j.v25.a13
Muffley, B., Gaichas, S., DePiper, G., Seagraves, R., & Lucey, S. (2021). There Is no I in EAFM Adapting Integrated Ecosystem Assessment for Mid-Atlantic Fisheries Management. *Coastal Management*, *49*(1), 90–106. https://doi.org/10.1080/08920753.2021.1846156
NEFSC. (2019). 66th Northeast Regional Stock Assessment Workshop (66th SAW) Assessment Report. *Northeast Fisheries Science Center Reference Document*, *19–08*, 457–1170.
Nelson, G. A. (2018). Historical Review of Commercial Fishery Regulations for Striped Bass (Morone saxatilis Walbaum) in Massachusetts. *Northeastern Naturalist*, *25*(1), 143–160. https://doi.org/10.1656/045.025.0111
Nelson, G. A., Chase, B. C., & Stockwell, J. D. (2006). Population consumption of fish and invertebrate prey by striped bass (Morone saxatilis) from coastal waters of Northern Massachusetts, USA. *Journal of Northwest Atlantic Fishery Science*, *36*, 111–126. https://doi.org/10.2960/J.v36.m576
Nesslage, G. M., & Wilberg, M. J. (2019). A performance evaluation of surplus production models with time-varying intrinsic growth in dynamic ecosystems. *Canadian Journal of Fisheries and Aquatic Sciences*, *76*(12), 2245–2255. https://doi.org/10.1139/cjfas-2018-0292
NMFS. (2020). *U.S. Department of Commerce, NOAA Current Fishery Statistics No. 2018*. https://www.fisheries.noaa.gov/national/commercial-fishing/fisheries-united-states-2018
NEFSC. (2019). 66th Northeast Regional Stock Assessment Workshop (66th SAW) Assessment Report. US Dept Commer, Northeast Fish Sci Cent Ref Doc. 19-08; 1170 p. Available from: http://www.nefsc.noaa.gov/ publications/
Overton, A. S., Griffin, J., & Margraf, F. J. (1999). *A bioenergetics approach for determining the effect of increased striped bass population on its prey in the*

Chesapeake Bay.

Overton, A. S., Manooch, C. S., Smith, J. W., & Brennan, K. (2008). Interactions between adult migratory striped bass (Morone saxatilis) and their prey during winter off the Virginia and North Carolina Atlantic coast from 1994 through 2007. *Fishery Bulletin*, *106*(2), 174–182.

Overton, A. S., Margraf, F. J., & May, E. B. (2009). Spatial and Temporal Patterns in the Diet of Striped Bass in Chesapeake Bay. *Transactions of the American Fisheries Society*, *138*(4), 915–926. https://doi.org/10.1577/t07-261.1

Pacific Fishery Managment Council. (2012). *Terms of Reference for the Groundfish and Coastal Pelagic Species Stock Assessment and Review Process for 2013-2014*.

Patrick, W. S., & Link, J. S. (2015). Myths that Continue to Impede Progress in Ecosystem-Based Fisheries Management. *Fisheries*, *40*(4), 155–160. https://doi.org/10.1080/03632415.2015.1024308

Pearson, J. C. (1938). THE LIFE HISTORY OF THE STRIPED BASS , OR ROCKFISH , Roccus saxatilis. *Fisheries Bulletin*, *28*, 825–851.

Pérez-Rodríguez, A., Umar, I., Goto, D., Howell, D., Mosqueira, I., & González-Troncoso, D. (2022). Evaluation of harvest control rules for a group of interacting commercial stocks using a multispecies MSE framework. *Canadian Journal of Fisheries and Aquatic Sciences*, *1320*(January), 1–19. https://doi.org/10.1139/cjfas-2021-0069

Pikitch, E., Boersma, P. D., Boyd, I. L., Conover, D. O., Cury, P., Essington, T., Heppell, S. S., Houde, E. D., Mangel, M., Pauly, D., Plagányi, É., Sainsbury, K., & Steneck, R. S. (2012). Little fish, big impact: managing a crucial link in ocean food webs. *Lenfest Ocean …*, 108 pp. https://publications.csiro.au/rpr/pub?list=BRO&pid=csiro:EP124359&sb=RECENT&n=10&rpp=10&page=292&tr=4231&dr=all&dc4.browseYear=2012

Pikitch, E. K., Rountos, K. J., Essington, T. E., Santora, C., Pauly, D., Watson, R., Sumaila, U. R., Boersma, P. D., Boyd, I. L., Conover, D. O., Cury, P., Heppell, S. S., Houde, E. D., Mangel, M., Plagányi, É., Sainsbury, K., Steneck, R. S., Geers, T. M., Gownaris, N., & Munch, S. B. (2014). The global contribution of forage fish to marine fisheries and ecosystems. *Fish and Fisheries*, *15*(1), 43–64. https://doi.org/10.1111/faf.12004

Punt, A. E. (2014). Harvest Control Rules and Fisheries Managment. In R. Q. Grafton, R. Hilborn, D. Squires, M. Tait, & M. J. Williams (Eds.), *Handbook of Marine Fisheries Conservation and Managment* (Issue January, pp. 582–594). Oxford University Press. https://www.researchgate.net/publication/288847099

Quinn, T. J., & Deriso, R. B. (1999). *Quantitative Fish Dynamics*. Oxford University Press.

Reeves, S. A. (2003). A simulation study of the implications of age-reading errors for stock assessment and management advice. *ICES Journal of Marine Science*, *60*(2), 314–328. https://doi.org/10.1016/S1054-3139(03)00011-0

Richards, R. A., & Rago, P. J. (1999). A Case History of Effective Fishery Management: Chesapeake Bay Striped Bass. *North American Journal of Fisheries Management*, *19*(2), 356–375. https://doi.org/10.1577/1548-8675(1999)019<0356:achoef>2.0.co;2

Rudershausen, P. J., Tuomikoski, J. E., Buckel, J. A., & Hightower, J. E. (2005). Prey Selectivity and Diet of Striped Bass in Western Albemarle Sound, North Carolina. *Transactions of the American Fisheries Society*, *134*(5), 1059–1074. https://doi.org/10.1577/t04-115.1

Safiq, A., Free, C. M., Caracappa, J., Valenti, J. L., & Jensen, O. (2021). Perceptions of Ecosystem-Based Fisheries Management Among State Natural Resource Agency Scientists in the Northeastern United States. *Fisheries*, *46*(2), 66–75. https://doi.org/10.1002/fsh.10527

Secor, D. H. (2000). Longevity and resilience of Chesapeake Bay striped bass. *ICES Journal of Marine Science*, *57*(4), 808–815. https://doi.org/10.1006/jmsc.2000.0560

Secor, D. H., Trice, T. M., & Hornick, H. T. (1995). Validation of otolith-based ageing and a comparison of otolith and scale-based ageing in mark-recaptured Chesapeake Bay striped bass, Morone saxatilis. *Fishery Bulletin*, *93*(1), 186–190.

Secor, David H., O'Brien, M. H. P., Gahagan, B. I., Carter Watterson, J., & Fox, D. A. (2020). Differential migration in Chesapeake Bay striped bass. *PLoS ONE*, *15*(5), 1–19. https://doi.org/10.1371/journal.pone.0233103

SEDAR. (2020a). *ASMFC Stock Assessment Overview: Atlantic Menhaden*. *February*, 5. http://www.asmfc.org/uploads/file//572b74a22016WeakfishAssessmentOverview_Final.pdf

SEDAR. (2020b). SEDAR 69 – Atlantic Menhaden Benchmark Stock Assessment Report. SEDAR, North Charleston SC. 691 pp. available online at: http://sedarweb.org/sedar-69

Smith, J. (1991). The Atlantic and Gulf Menhaden Purse Seine Fisheries: Origins, Harvesting Technologies, Biostatistical Monitoring, Recent Trends in Fisheries Statistics, and Forecasting. *Marine Fisheries Review*, *53*(4), 28–41.

Thompson, G. G. (1999). Optimizing Harvest Control Rules In the Presence of Natural Variability and Parameter Uncertainty. *Proceedings of the Fifth National NMFS Stock Assessment Workshop Providing Scientific Advice to Implement the Precautionary Approach Under the Magnuson-Stevens Fishery Conservation and Management Act (February 24-26, 1998, Key Largo, Florida) (No. NOAA Te*, *1970*, 124–145.

Trent, L., & Hassler, W. W. (1968). Gill net selection, migration, size and age composition, sex ratio, harvest efficiency, and management of striped bass in the Roanoke river, North Carolina. *Chesapeake Science*, *9*(4), 217–232. https://doi.org/10.2307/1351312

Tsehaye, I., Jones, M. L., Bence, J. R., Brenden, T. O., Madenjian, C. P., & Warner, D. M. (2014). A multispecies statistical age-structured model to assess predator-prey balance: Application to an intensively managed Lake Michigan pelagic fish community. *Canadian Journal of Fisheries and Aquatic Sciences*, *71*(4), 627–644. https://doi.org/10.1139/cjfas-2013-0313

Tuckey, T. D., & Fabrizio, M. C. (2011). *Estimating Relative Juvenile Abundance of Ecologically Important Finfish in the Virginia Portion of Chesapeake Bay Prepared by : Estimating Relative Juvenile Abundance of Ecologically*

Important. *July 2020*, 0–96. https://doi.org/10.25773/bx0d-7n02

Uphoff, J. H., & Sharov, A. (2018). Striped Bass and Atlantic Menhaden Predator–Prey Dynamics: Model Choice Makes the Difference. *Marine and Coastal Fisheries*, *10*(4), 370–385. https://doi.org/10.1002/mcf2.10030

Walter III, J. F., & Austin, H. M. (2001). Diet composition of large striped bass (Morone saxatilis) in Chesapeake Bay. *Fish Bulletin*, *101*(2), 414–423.

Walter, J. F., & Austin, H. M. (2003). Diet composition of large striped bass (Morone saxatilis) in Chesapeake Bay. *Fishery Bulletin*, *101*(2), 414–423.

Walter, J. F., Overton, A. S., Ferry, K. H., & Mather, M. E. (2003). Atlantic coast feeding habits of striped bass: A synthesis supporting a coast-wide understanding of trophic biology. *Fisheries Management and Ecology*, *10*(5), 349–360. https://doi.org/10.1046/j.1365-2400.2003.00373.x