Southeast Data, Assessment, and Review

SEDAR 40
Stock Assessment Report

Atlantic Menhaden

January 2015

SEDAR
4055 Faber Place Drive, Suite 201
North Charleston, SC 29405

Please cite this document as:

SEDAR. 2015. SEDAR 40 – Atlantic Menhaden Stock Assessment Report. SEDAR, North Charleston SC. 643 pp. available online at: http://www.sefsc.noaa.gov/sedar/Sedar_Workshops.jsp?WorkshopNum=40.

Table of Contents

Pages of each Section are numbered separately.

Preface

The development and peer review of the 2014 Atlantic Menhaden Stock Assessment occurred through a joint Atlantic States Marine Fisheries Commission (ASMFC) and Southeast Data, Assessment, and Review (SEDAR) process. The ASMFC coordinated a Data Workshop in St. Petersburg, Florida, and two Assessment Workshops in Beaufort, North Carolina, while SEDAR coordinated the Review Workshop in Atlantic Beach, North Carolina. This report is the culmination of a two-year effort to gather and analyze available data for Atlantic menhaden from the fishery-independent sampling programs of the Atlantic States, commercial purse-seine reduction fishery, and commercial bait fishery. ASMFC developed the stock assessment through its Atlantic Menhaden Technical Committee (TC) and Stock Assessment Subcommittee (SAS). The ASMFC facilitated numerous conference calls and webinars in preparation for the Data, Assessment, and Review workshops. Participants in the stock assessment process included TC and SAS members, as well as representatives from Non-Governmental Organizations and the fishing industry with an interest in menhaden.

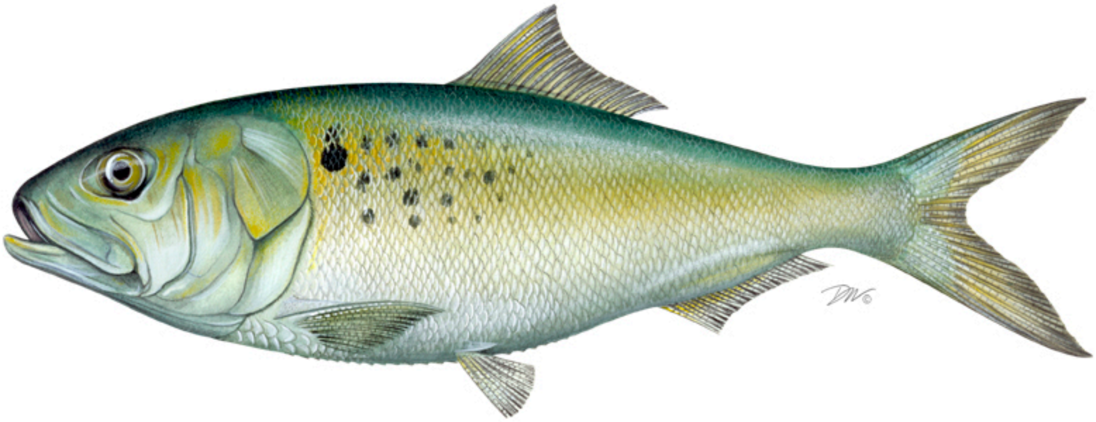
In addition to the single-species menhaden stock assessment report, an Ecosystem Reference Points (ERP) Plan was developed by a subcommittee of the TC and the ASMFC Multispecies Technical Committee, and reviewed by the SEDAR 40 panel. The ASMFC facilitated several webinars and meetings of the subcommittee to develop the ERP Plan. The Plan describes ecosystem monitoring and modeling approaches that may address multispecies issues faced by the ASMFC, including management of menhaden for forage services in a broader ecosystem management context.

The SEDAR40 stock assessment report and ERP Plan were generated and provided to three reviewers appointed by the Center for Independent Experts (CIE) and the review panel chair appointed by ASMFC. The Review Workshop was held in Atlantic Beach, North Carolina, on December 9-11, 2014. At the Workshop, the reviewers had opportunities to raise questions to the SAS and ERP subcommittee, and provide critiques and constructive comments on the data and models used. A Review Workshop Report (Section III) was generated with comments and overall opinions about the data sources, models, and assessment results. The Review Panel suggested one minor revision to the base model run, to down-weight the length composition data from the adult survey indices. The revised base run, detailed in an addendum to the stock assessment report (Section II), resulted in marginal changes to the model results and did not change stock status. The Review Report, full Stock Assessment Report, and Ecosystem Reference Points Plan will be provided to the ASMFC Atlantic Menhaden Management Board in February 2015.

The ASMFC and its committees thank the reviewers for their time and expertise in providing a thorough review of the coast wide Atlantic menhaden stock assessment and the Ecosystem Reference Points Plan. Additionally, ASMFC thanks all of the individuals that contributed to the completion of the stock assessment and ERP Plan.

Atlantic States Marine Fisheries Commission

2014 Atlantic Menhaden Benchmark Stock Assessment



December 2014

Vision: Sustainably Managing Atlantic Coastal Fisheries

Atlantic States Marine Fisheries Commission

2014 Atlantic Menhaden Benchmark Stock Assessment

Draft for Peer Review December 9-11, 2014

Prepared by the
ASMFC Atlantic Menhaden Stock Assessment Subcommittee

Dr. Amy Schueller (Chair), National Marine Fisheries Service
Dr. Matt Cieri, Maine Department of Marine Resources
Mr. Micah Dean, Massachusetts Division of Marine Fisheries
Dr. Robert Latour, Virginia Institute of Marine Science
Dr. Behzad Mahmoudi, Florida Fish and Wildlife Research Institute
Mr. Jason McNamee, Department of Environmental Management Marine Fisheries Section
Dr. Genevieve Nesslage, Atlantic States Marine Fisheries Commission
Dr. Alexei Sharov, Maryland Department of Natural Resources
Mr. Joseph Smith, National Marine Fisheries Service
Mr. Michael Waine, Atlantic States Marine Fisheries Commission

A publication of the Atlantic States Marine Fisheries Commission pursuant to National Oceanic and Atmospheric Administration Award No. NA10NMF4740016

Acknowledgements

The Atlantic States Marine Fisheries Commission (ASMFC or Commission) thanks all of the individuals who contributed to the development of the Atlantic menhaden stock assessment. The Commission specifically thanks the ASMFC Atlantic Menhaden Technical Committee (TC) and Stock Assessment Subcommittee (SAS) members who developed the consensus stock assessment report as well as Commission staff Mike Waine, Genny Nesslage, and Shanna Madsen for helping prepare the report for review.

Executive Summary

Stock Identification and Management Unit

Based on size-frequency information and tagging studies, the Atlantic menhaden resource is believed to consist of a single unit stock or population. Recent genetic studies support the single stock hypothesis. Menhaden are distributed along the U.S. East Coast with the management unit consisting of states from Maine to Florida as defined in Amendment 2.

Landings

The Atlantic menhaden commercial fishery has two major components, a purse-seine reduction sector that harvests fish for fish meal and oil, and a bait sector that supplies bait to other commercial and recreational fisheries. In recent years (2007-2013) total landings have averaged approximately 205,000 mt with reduction landings accounting for ~77% and bait landings accounting for ~23% of the total. Landings in the reduction fishery are currently at their lowest levels in the time series because only one plant remains operational along the coast. In contrast, bait landings have increased in recent years as demand has grown because of recent limitations in other species used as bait (e.g., Atlantic herring). Landing levels were recently restricted through the implementation of Amendment 2 that imposed a 170,800 mt total allowable catch starting in 2013.

Data and Assessment

In late 2012, the Technical Committee initiated the current benchmark stock assessment to focus on several issues which occurred in the 2009 benchmark assessment or the 2012 assessment update including:

1. Overweighting of the age composition data.
2. Lack of spatial modeling to address changes in the fishery over time.
3. Lack of a coastwide adult abundance index.
4. Poor fit to the Potomac River Fisheries Commission index of relative abundance.
5. Strong retrospective pattern.

Through the consideration of new and existing datasets and the exploration of alternative model configurations, significant changes were made in this assessment to address the issues listed above as well as the 2009 peer review recommendations. The table below details the major changes that exist in the 2014 benchmark assessment and the results of those changes.

Topic	2009 Benchmark Assessment	2014 Benchmark Assessment	Result of Change
Maturity	Incorrect maturity at age from a misinterpretation of Higham and Nicholson (1964) study.	Corrected maturity using 240,000 maturity data records found in the reduction fishery database. Corroborated by NEAMAP survey data. Used a logistic regression on length and maturity and time varying maturity based on time varying length at age.	A higher proportion of age-1, age-2, and age-3 fish are mature. Accounted for the changes in length at age over time with time varying maturity.
Natural mortality (*M*)	Time varying *M* at age from MSVPA-X.	Age specific Lorenzen curve scaled to tagging data.	Similar estimates of age-specific M with both approaches. Static ***M***.
Growth	-Time varying weight-length relationship. -Population growth equations based on fishery-dependent data.	-Time invariant weight-length relationship. -Population growth equations based on fishery-dependent data with a bias correction.	Corrected for the lack of larger fish in the fishery-dependent database, given those larger fish were sampled using fishery-independent surveys.
Indices of relative abundance	-Fishery-dependent adult index developed from Potomac River pound net fishery. -Fishery-independent JAI based on state seine surveys.	-Two adult fishery-independent indices based on nine state surveys, one each for the northern and southern regions. Both indices have associated length compositions. -Fishery-independent JAI based on state seine, trawl, and other gear surveys.	Aggregated relative abundance of adults across a broader spatial scale using a composite of standardized fishery-independent indices.
Index catchability	Constant catchability for JAI index.	Catchability blocks with a constant catchability being estimated for the JAI from 1959-1986 and 1987-2013	Allowed the model to better fit recruitment in the 1970s and 1980s and accounted for differences in index composition over time.
Assessment model age classes	Included ages-0 to -8+.	Included ages-0 to 6+.	Reduced model complexity and grouped older ages with few observations.
Assessment model fishery structure	Bait and reduction fleets only, no time or space blocks.	"Fleets-as-areas" base model with reduction and bait divided into northern and southern regions. Created four separate fleets based on migratory patterns of the population and differences in the sampled data by area.	Ability to estimate population dynamics in both space and time relative to changes in both the fishery and Atlantic menhaden stock.
Fishery selectivity	-Flat topped logistic function for both bait and reduction fisheries. -No time blocks.	-Dome-shaped selectivity function for all fishery fleets supported by larger sized individuals observed in multiple fishery-independent surveys than captured by the fisheries (bait and reduction). -Time blocks included for reduction fishery to account for changes in plant locations and fishery practices over time.	Both the bait and reduction fisheries underrepresented the amount of large (older) fish in the population, which is now accounted for with dome-shaped selectivity. Support for this decision comes from multiple sources – see text for details.
Weighting of likelihood components	Likelihood components unweighted.	Likelihood components weighted such that standard deviation of normalized residuals equaled 1. Additional weight placed on indices.	Improved fits to the indices of abundance. Balance between data components and the information that the components provide.
Likelihood for multinomial data	Used multinomial likelihood for composition data.	Used robust multinomial likelihood for composition data.	Accounting for correlations in the composition data.

Indices of Relative Abundance

Young of the Year (YOY) Index

The YOY index developed from 16 fishery-independent surveys shows the largest recruitments occurred during the 1970s and 1980s. Recruitment has since been lower with notable year classes in 2005 and 2010. This index was used to inform annual recruitment deviations in the model along with the catch at age data.

Age-1+ Indices

Two new regional adult indices were generated for the assessment using nine fishery-independent survey data sets spanning the coast from New England to Florida. Both indices indicate an increase in abundance in the most recent years, a trend also observed in other fishery-dependent and -independent data sets. A significant correlation of 0.47 ($p = 0.02$) was observed between the northern and southern adult indices with a one-year lag (given smaller sizes of fish caught in the southern index length compositions). This agreement provides additional weight of evidence that the age-1+ population is increasing over the latter part of the time period and that both indices provide similar information on stock abundance.

Fishing Mortality

Highly variable fishing mortalities were noted throughout the entire time series and were dependent upon fishing effort. The highest fishing mortalities for the commercial reduction fishery in the north were estimated to have occurred in the 1950s, whereas the highest fishing mortality rates for the commercial reduction fishery in the south were estimated to have occurred during the 1970s to 1990s. The highest fishing mortalities for the commercial bait fishery in the north were estimated to have occurred in the 1950s and 1990s, while the highest fishing mortality rates for the commercial bait fishery in the south were estimated to have occurred during the late 1990s and early 2000s.

Biomass

Biomass has fluctuated over time from an estimated high of over 2,284,000 mt in 1958 to a low of 667,000 mt in the mid-1990s. Biomass was estimated to have been largest during the late-1950s and late-2000s, with lows occurring during the mid-1990s to mid-2000s. Biomass was estimated to have been relatively stable through much of the 1970s and 1980s. The oldest age classes comprise the smallest proportion of the population, but that proportion has increased in recent years. Biomass is likely increasing at a faster rate than abundance because of the increase in the number of older fish at age and an increase in weight at age.

Fecundity

Population fecundity (i.e., Total Egg Production) was the measure of reproductive output used as that is what has been used in the past. Population fecundity (*FEC*, number of maturing ova) was highest in the early 1960s, early 1970s, and during the present decade and has generally been higher with older age classes making up a larger proportion of the *FEC*. The largest values of population fecundity were present in 2012 and 2013, which were the last two years of the model, but were similar in magnitude to historical values of population fecundity. Throughout the time series, age-2 and age-3 fish have produced most of the total estimated number of eggs spawned annually; however, in more recent years, ages-4+ have contributed more significantly to the overall number of eggs.

Stock Status

Current benchmarks for Atlantic menhaden are $F_{30\%}$, $F_{15\%}$, $FEC_{30\%}$, and $FEC_{15\%}$. The current benchmarks are calculated through spawner-per-recruit analysis using the mean values of any time-varying components (i.e., growth, maturity) over the time series 1955-2013 and full fishing mortality rate defined as the maximum rate across ages for each year. Based on the current adopted benchmarks, **the Atlantic menhaden stock status is not overfished and overfishing is not occurring**. In addition, the stock is currently below the current fishing mortality target and above the current *FEC* target. The fishing mortality rate is currently at $F_{65\%}$, which is the lowest *F* in the time series.

Biological Reference Points

The TC does not recommend that the current, interim SPR-based overfishing and overfished definitions continue to be used for management. Specifically, the values for the SPR-based reference points seem unreasonable given the choices were based on the last stock assessment during which the population was thought to be at $F_{8\%}$. Given the new assessment, the TC does not feel that the current reference points provide a measure of sustainability.

The TC recommends that the Atlantic Menhaden Management Board adopt SPR reference points based on the maximum *F* value experienced at age-2 during the 1960-2012 time period as the threshold and the median *F* value experienced at age-2 during the 1960-2012 time period as the target along with the associated FEC values. The 1960-2012 time period represents a time with little to no restrictions on total harvest in which the population appears to have been sustainable given that the population did not experience collapse. Age-2 fishing mortality rate was chosen for consistency over time. Because the fisheries have dome-shaped selectivity, which varies by fleet over time, the age at full fishing mortality changes over time. The majority of the removals come from the southern commercial reduction fishery, which is fully selected at age-2; thus, age-2 was chosen as the reference age for comparisons. Using these metrics, the maximum F experienced was $F_{20\%} = 2.01$, and the median was $F_{36\%} = 0.82$. The associated *FEC* reference points would be $FEC_{20\%} = 61{,}401$ and $FEC_{36\%} = 111{,}077$ (billions of eggs). With these suggested reference points, the stock status for the base run is still not overfished and overfishing is not occurring. In addition, the current stock would still be below the suggested fishing mortality target and above the suggested *FEC* target.

Single Species and Ecological Based Reference Points

The menhaden stock is unlikely to experience unsustainable harvest rates or drop to depleted biomass levels in the short term under the current management plan. The TC noted, however, that the stock-recruitment relationship observed to date is weak at best; therefore, the current fecundity-based reference points used to identify overfished conditions may not be useful for management of menhaden in general. In other words, at this time the TC cannot reliably predict the magnitude of a recruitment response to increased biomass under any harvest scenario. Other single species reference point options were discussed by the TC during the benchmark assessment process, but the TC cannot comment on the relative performance of these reference points until a formal Management Strategy Evaluation is conducted. Additionally, the TC recommends that the Atlantic Menhaden Management Board more clearly define the objectives and goals for managing Atlantic menhaden especially if it plans to pursue ecosystem based management.

Table of Contents

List of Tables

(See Tables.doc)

List of Figures

(See Figures.doc)

Stock Assessment Terms of Reference

1. Review and vet all available data sources, including current and historical fishery-dependent and fishery-independent data. Justify inclusion or elimination of each data source. If possible, identify and prepare new data that could be used to inform the assessment of mortality and migration rates, commercial selectivity, and coastwide adult and/or spawning stock trends.

2. Characterize precision and accuracy of all data sources used in the assessment.
    a. Provide descriptions of each included data source (e.g., geographic location, sampling methodology, potential explanation for outlying or anomalous data).
    b. Discuss data strengths and weaknesses (e.g. temporal and spatial scale, gear selectivities, sample size) and their potential effects on the assessment.
    c. Describe calculation and potential standardization of abundance indices.
    d. Discuss trends and magnitude of uncertainty estimates (e.g., standard errors).

3. Develop population assessment models that are compatible with available data and can be used to estimate population parameters (e.g., F, biomass, abundance) and biological reference points. Analyze model performance.
    a. Clearly and thoroughly explain model strengths and limitations.
    b. Justify choice of CVs, effective sample sizes, selectivity parameterization, and/or likelihood weighting schemes.
    c. Describe stability of the model(s). Perform sensitivity analyses for starting parameter values, priors, etc. and conduct other model diagnostics as necessary.
    d. Briefly describe history of model usage, its theory and framework, and document associated peer-reviewed literature. If using a new model, test using simulated data.
    e. State assumptions made for all models and explain the likely effects of assumption violations on model outputs.
    f. If multiple models were considered, justify the choice of preferred model and attempt to explain any differences in results among models.

4. Characterize uncertainty of model estimates and biological or empirical reference points.

5. Perform retrospective analyses, assess magnitude and direction of any pattern detected, and discuss implications of any observed retrospective pattern for uncertainty in population parameters (e.g., F, SSB), reference points, and/or management measures.

6. Recommend stock status as related to current reference points (thresholds and targets). Recommend alternative reference points, if appropriate.

7. Identify potential ecological reference points that account for Atlantic menhaden's role as a forage fish. Provide proposed methodology, a model development plan, and example results using preliminary model configurations, if time allows. *Note: finalized ERPs will not be developed in time for the 2014 Atlantic menhaden peer review or 2015 Management Board meetings. Additional technical work and peer review will be necessary before ERPs will be available for management use.*

8. Develop detailed short and long-term lists of prioritized recommendations for future research, data collection, and assessment methodology. Highlight improvements to be made by next benchmark review.

9. Recommend timing of next benchmark assessment and intermediate updates, if necessary, relative to biology and current management of the species.

1.0 Introduction

The 2014 benchmark stock assessment for Atlantic menhaden (*Brevoortia tyrannus*) was initiated by the Atlantic States Marine Fisheries Commission (ASMFC or Commission) Atlantic Menhaden Management Board, prepared by the ASMFC Atlantic Menhaden Stock Assessment Subcommittee (SAS), and reviewed and approved by the ASMFC Atlantic Menhaden Technical Committee (TC) as part of the interstate fisheries management process. The previous stock assessment was completed and peer reviewed through a joint ASMFC and Southeast Data, Assessment, and Review (SEDAR) process in 2009, and then updated using the same methodology in 2012. However, during the 2012 assessment update the TC identified several areas of concern:

1. Overweighting of the age composition data.
2. Lack of spatial modeling to address changes in the fishery over time.
3. Lack of a coastwide adult abundance index.
4. Poor fit to the PRFC index.
5. Strong retrospective pattern.

Following completion of the 2012 update, the TC called for an expedited benchmark assessment to address these issues.

In late 2012, the TC initiated the current benchmark stock assessment to identify and evaluate all available data sources and explore alternative model configurations as recommended by the 2009 peer review panel. In this benchmark assessment, significant changes were made to growth, maturity, natural mortality, indices of relative abundance, and fishery selectivities. Additionally, this benchmark assessment incorporates a “fleets-as-areas” base model configuration such that the reduction and bait fisheries were divided into northern and southern regions, creating four separate fleets. This assessment models the population dynamics of Atlantic menhaden from 1955 to 2013.

2.0 Regulatory History

The first coastwide fishery management plan (FMP) for Atlantic menhaden was passed in 1981 (ASMFC 1981). The 1981 FMP did not recommend or require specific management actions, but provided a suite of options should they be needed. After the FMP was approved, a combination of additional state restrictions, imposition of local land use rules, and changing economic conditions resulted in the closure of most reduction plants north of Virginia by the late 1980s (ASMFC 1992). In 1988, the ASMFC concluded that the 1981 FMP had become obsolete and initiated a revision to the plan.

The 1992 Plan Revision included a suite of objectives to improve data collection and promote awareness of the fishery and its research needs (ASMFC 1992). Under this revision, the menhaden program was directed by the ASMFC Atlantic Menhaden Management Board, which at the time was composed of up to five state directors, up to five industry representatives, and one representative each from the National Marine Fisheries Service and the National Fish Meal and Oil Association.

Representation on the Management Board was revised in 2001 to include three representatives from each state Maine through Florida, including the state fisheries director, a legislator, and a governor’s appointee. The reformatted board has passed two amendments to the 1992 FMP revision.

Amendment 1, passed in 2001, provided specific biological, social/economic, ecological, and management objectives. Addendum I (2004) addressed biological reference points for menhaden, the frequency of stock assessments (every three years), and updated the habitat section of the FMP.

Addendum II (2005) instituted a harvest cap on Atlantic menhaden by the reduction fishery in Chesapeake Bay. This cap was established for the fishing seasons in 2006 through 2010. The TC determined the following research priorities to examine the possibility of localized depletion of Atlantic menhaden in Chesapeake Bay: determine menhaden abundance in Chesapeake Bay; determine estimates of removal of menhaden by predators; exchange of menhaden between Bay and coastal systems; and larval studies (determining recruitment to the Bay).

Addendum III (2006) was initiated in response to a proposal submitted by the Commonwealth of Virginia that essentially mirrors the intent and provisions of Addendum II. It placed a five-year annual cap on reduction fishery removals from Chesapeake Bay. The cap, based on the mean landings from 2001 – 2005, was in place from 2006 through 2010. Addendum III also allowed a harvest underage in one year to be added to the next year’s quota. The maximum cap in a given year was 122,740 metric tons. Though not required by the plan, other states have implemented additional conservation management measures in their waters. Addendum IV (2009) extended the Chesapeake Bay harvest cap three additional years (2011-2013) at the same cap levels as established in Addendum III.

Addendum V (2011) established a new F threshold and target rate (based on maximum spawning potential; MSP) with the goal of increasing abundance, spawning stock biomass, and menhaden availability as a forage species.

Amendment 2 (2012) established a 170,800 MT total allowable catch (TAC) beginning in 2013 and continuing until completion of, and Board action on, the next benchmark stock assessment, scheduled for 2014. The TAC represented a 20% reduction from the average of landings from 2009-2011 and an approximately 25% reduction from 2011 levels. The Amendment also established new biological reference points for biomass based on MSP, with the goal of increasing abundance, spawning stock biomass, and menhaden availability as a forage species. These new reference points use the same metric (e.g., MSP) used to define overfishing (fishing mortality target of $F_{30\%}$ MSP and threshold of $F_{15\%}$ MSP).

Amendment 2 allocated the TAC on a state-by-state basis based on landings history of the fishery from 2009-2011; allocation will be revisited three years after implementation. Further, it reduced the Chesapeake Bay reduction fishery harvest cap by 20% (this is an adjustment of cap that has been in place since 2006). States are required to close their fisheries when the state-specific portion of the TAC has been reached; any overages must be paid back the following year.

Amendment 2 enabled the Atlantic Menhaden Management Board to set aside 1% of the overall TAC for episodic events (Section 4.2.1.8). Episodic events are defined as times and areas where Atlantic menhaden are available in higher abundance than they normally occur. The set aside was designed to enable increased harvest of Atlantic menhaden during episodic events. Technical Addendum I to Amendment 2 (May 2013) established a mechanism for New England state(s) to use the set aside through Board action that includes a qualifying definition of episodic events, required effort controls to scale a state's fishery to the set aside amount, and a timely reporting system to monitor the set aside. If the episodic event set aside quota is unused as of October 31, it is redistributed to all the states on November 1 based on the Amendment 2 allocation percentages.

3.0 Life History

3.1 Stock Definition

Ahrenholz (1991) pointed out that historically, considerable debate existed relative to stock structure of Atlantic menhaden on the US East coast, with a northern and southern stock hypothesized based on meristics and morphometrics (Sutherland 1963; June 1965). Nicholson (1972) and Dryfoos et al. (1973) argued convincingly, from back-calculated length-frequency information and tag recoveries, for a single biological population of Atlantic menhaden. Ahrenholz (1991) noted that although different temporal spawning cohorts of menhaden exist, they appear to mix rapidly as a result of their extensive migratory movements and are virtually inseparable in the commercial fishery. Thus primarily based on size-frequency information and tagging studies (Nicholson 1972 and 1978; Dryfoos et al. 1973), the Atlantic menhaden resource is believed to consist of a single unit stock or population. Recent genetic studies (Anderson 2007; Lynch et al. 2010) support the single stock hypothesis.

3.2 Age

Background

In 1955, the NOAA Laboratory at Beaufort, NC, began monitoring the Atlantic menhaden purse-seine fishery for size and age composition of the catch (June and Reintjes 1959). From the outset, program managers realized it was impractical to utilize otoliths to age Atlantic menhaden because 1) sagittae were so small and fragile and 2) large amounts of time and effort would be required to extract, process, and read whole or sectioned otoliths. Moreover, large numbers of ageing parts (> ca. 10,000) would be required to adequately characterize the fishery with annual landings of several hundred thousand metric tons. Thus, scales were selected as the ageing tool of choice for Atlantic menhaden.

The seminal study on ageing Atlantic menhaden was conducted by June and Roithmayr (1960) at the NMFS Beaufort Laboratory (henceforth, the Beaufort Laboratory); their specimens were collected mostly from purse-seine landings during 1952-1956. They validated rings on the scales of menhaden as reliable age marks based on timing of scale ring deposition and marginal increment analysis. Additionally, they examined scales from fish that were impounded for up to 14 months to further demonstrate that only one ring forms annually on menhaden scales. Accordingly, Atlantic menhaden are assigned ages based on a March 1 "birthdate". Menhaden field sampling protocols remain relatively unchanged from the 1950s.

Atlantic menhaden scales are generally thin and translucent. Unlike most herrings, the posterior margins of menhaden scales are pectinate. The anterior field is embedded in the integument. The entire scale is sculptured with fine circuli, which are roughly semi-circular and parallel to the anterior and lateral margins. The largest and most symmetrical (nearly rectangular) scales occur in a median lateral band above the lateral line and below the dorsal fin. Scale samples for ageing are removed from this area.

A scale patch (~20-30 scales) is removed from specimens with a blunt-edged scalpel by port agents. Individual scales are mounted between two glass microscope slides. The cover slide is labeled with a unique port and specimen number combination. Mounted Atlantic menhaden scales are viewed on an Eberbach macro-projector at 48x magnification. Age rings on Atlantic menhaden scales are defined as compressions or interruptions of uniformly spaced circuli in the anterior field of the scale, which are continuous through the lateral fields. Under transmitted light age rings form narrow, continuous, dark bands roughly paralleling the lateral and anterior margins of the scale. A focus is arbitrarily chosen near the center of the posterior field at the base of the circuli. Straight-line measurements are made from the focus to successive scale rings and the scale edge.

Precision and accuracy

During the early decades of the Menhaden Program at the Beaufort Laboratory scales from individual menhaden specimens were read multiple times by several readers. Disagreements on age estimates were decided by an additional reading. By the early 1970s - probably because of budget constraints - only a single reader was retained on staff to age menhaden scales. This employee, Ethel A. Hall (EAH), has been reading menhaden scales for the Beaufort Laboratory from 1969 to the present.

In an effort to estimate contemporary precision of age estimates of Atlantic menhaden, EAH was asked to re-read scale samples from the 2008 fishing season. Re-ageing efforts occurred in early 2009. EAH was instructed to re-assign estimated ages to as many fish as possible from the 2008 biostatistical data set, but not to make measurements to successive annuli (as per protocols for general menhaden ageing at the Beaufort Laboratory).

A total of 3,711 Atlantic menhaden were re-aged. Overall, 80.3% (2,978 of 3,711) of the paired readings agreed. Within age classes, the younger age classes (age-0 through age-3) showed better agreement than older age classes (ages-4 and -5). Paired readings for age-0's agreed 95.2% (n = 40) of the time, age-1's agreed 74.5% (n = 152), age-2's agreed 87.0% (n = 1,850), while age-3's agreed 74.4% (n = 821). For the older age classes, ages-4’s agreed 51.9% (n = 111), while age-5’s agreed only 19.1% (n = 4). Most disagreements were +/- one year for ages-1 through -3 (98.1%, 86.3%, and 96.5%, respectively).

Alternate to the percent agreement statistic, an average percent error, APE (Beamish and Fournier 1981), was calculated for all paired readings combined. The APE for paired Atlantic menhaden ageings was relatively low at 4.1%, suggesting good agreement between readings. The APE was calculated as:

$$APE_j = 100 * \frac{1}{R}\sum_{i=1}^{R}\frac{\left|x_{ij} - x_j\right|}{x_j}$$

$$APE = \frac{\sum_{j=1}^{n} APE_j}{n}$$

where x_{ij} is the *i*th age determination of the *j*th fish, x_j is the mean age across the readings of the individual j, R is the number of readings, and n is the sample size.

The scale-to-scale comparison assessed within reader error or within reader precision. Accounting for error in age estimation is important for age composition data used in stock assessments. An ageing uncertainty matrix was created using the program agemat (Table 3.2.1; Punt et al. 2008), which assumed symmetrical error, for use in a sensitivity run of the stock assessment. In addition, agemat assumes that one of the reads from an age structure is the true age; thus estimating true ageing error. However, this study only measured ageing uncertainty within a reader, rather than true ageing error; thus, it was not included in the base run of the stock assessment (which also assumes any ageing uncertainty is error in the estimation of the true age).

Finally, a small study comparing Atlantic menhaden scales to otoliths (n=60) was completed at Old Dominion University. Assuming that the otolith represents the true age of the fish, this comparison assesses the accuracy of scale ages compared to the true otolith age. The results from the study suggest that the accuracy of scales is very good, with only one of the scale to otolith comparisons showing a difference in age of one year. The range in ages covered by this study included ages-0 to -5.

3.3 Growth

The growing season begins in spring and ends in fall as water temperatures rise above and decline below 15° C (Kroger et al. 1974). Atlantic menhaden reach lengths of up to 500 mm total length (TL) and weights of over 1.5 kg (Cooper 1965; Smith and O’Bier 1996). Due to their greater migratory range, larger fish of a given age are captured farther north than smaller fish of the same age (Nicholson 1978; Reish et al. 1985). This fact complicates any attempt to estimate overall growth for the entire stock from size-at-age data compiled from any individual area along the coast. To account for this, catch in numbers by year, season, and fishing area were developed for weighting corresponding sampled weights of Atlantic menhaden. This was then used to calculate the mean weight at age for fish from 1955-2013, which was then used in the stock assessment for matching to landings. These “weighted” mean weights increased during the 1960s, declined dramatically during the 1970s, and remained low during most of the 1980s. Increasing mean weights were estimated during the 1990s followed by recent declines in mean weight. Various publications have suggested that density dependent growth is prevalent with Atlantic menhaden (Reish et al. 1985, Ahrenholz et al. 1987, Ahrenholz 1991, Vaughan and Smith 1988). That is, there is an inverse relation between size of menhaden (size of age-0 menhaden) and number of recruits at age 0.

Weighting by catch in numbers by year, season, and fishing area was also applied to calculate average fork lengths (mm) by age and year. When sample size was less than 10 fish, substitution was accomplished by one of two methods: (1) use average of pre- and post-year values for that age when missing cell(s) are embedded between estimated values, or (2) average across all values when no post-year value was available.

An overall regression of weight (W in g) on fork length (FL in mm) for port samples of Atlantic menhaden was fit based on the natural logarithm transformation:

$$\ln \mathrm{W} = \mathrm{a} + \mathrm{b} \ln \mathrm{FL}$$

and was corrected for transformation bias (root MSE) when retransformed back to the form:

$$\mathrm{W} = \mathrm{a(FL)}^{\mathrm{b}}.$$

As in previous menhaden assessments, regressions of fork length (mm) on age (yr) were based on the von Bertalanffy growth curve:

$$\mathrm{FL} = L_{\infty}(1 - \exp(-K(\mathrm{age} - t_0))).$$

Von Bertalanffy fits were made with the size at age data aligned by cohort (year class). Because of concerns that density-dependent growth is a characteristic of the cohort, cohort-based analyses were thought to be a better approach. Attempts were made to fit the von Bertalanffy growth equation to each year class from 1947 (age-8 in 1955) to 2013 (age-0 in 2013). For most cohorts, a full range of ages were available (1955-2006). For the incomplete cohorts at the beginning of the time period (1947-1955), all fits converged, although specific parameter estimates became progressively unrealistic for the earlier years (especially 1947-1949). Similarly, incomplete cohorts for the recent time period (2006-2013) generally converged with the exception of the last three years (2011-2013). Thus, for age-0 during 2011-2013, age-1 during 2012-2013, and age-2 during 2013, the size and weight at age were the average of the three years preceding.

Annual estimates of length at age for the population were bias corrected using methods in Schueller et al. (2014). Specifically, the methods correct for the absence of samples at the youngest, smallest and largest, oldest sizes and ages. Evidence is available from the fishery-independent data that both smaller and larger fish are available for capture in the population; however, those fish sizes are not represented in the commercial reduction fishery database (the only data available to estimate growth parameters). Therefore, the growth curves for the population would be biased to smaller maximum sizes than occur in the population. The correction was done on the cohort-based annually estimated growth curves with a minimum size of 100 mm FL (unless samples had a larger minimum size) and the maximum size was set at the 99.95% size for encountered fish rounded to the nearest whole number ending in 0 or 5. In a few cases, t_0 was fixed at the uncorrected value. The reference age selected was age-2 as that age reflects the full distribution of sizes at the age. The corrected values of L_{∞} and K were within the observed range of uncorrected values (Figure 3.3.1; Table 3.3.1). The growth curve parameters vary year to year and are influenced by both density dependent processes and the fact that each cohort experiences a different set of conditions leading to differing growth.

Annual estimates of fork length-at-age were interpolated from the annual, cohort-based von Bertalanffy growth fits with a bias correction in order to represent the population or start of the fishing year (March 1) for use in estimating population fecundity (Table 3.3.2). Annual estimates of length-at-age were interpolated based on the non-biased corrected von Bertalanffy estimates to represent the fishery or middle of the fishing year (September 1), and converted to weight-at-age (Eq. 2) for use in the statistical catch-at-age models when comparing model estimated catch to observed catch (Table 3.3.3).

3.4 Maturity

In past assessments, maturity had been fixed based on estimates from Higham and Nicholson (1964). However, during the current assessment process, the data workshop participants realized the classification of maturity from that paper was active versus inactive, rather than mature versus immature. Thus, the ogive used in the past was not representative of maturity in the population. Two data sets came to the table during the assessment process for determining maturity at age: 1) Northeast Area Monitoring and Assessment Program (NEAMAP) data and 2) commercial reduction fishery data.

For the current (2014) stock assessment, data from the NEAMAP Southern New England/Mid-Atlantic Neashore Trawl Survey were analyzed to evaluate maturity at age. NEAMAP is a cooperative state and federal program developed to coordinate fishery-independent data collection efforts in coastal northeastern states (Maine through North Carolina). The Southern New England/Mid-Atlantic Nearshore Trawl Survey began in fall 2007 and is conducted twice per year (spring/fall) between Cape Hatteras, NC, and Martha's Vineyard, MA. Captured fish are sampled or subsampled for biological characteristics, including length and gonad stage. A full description of on-board and laboratory sampling methods can be found in Bonzek et al. (2012).

Raw data on menhaden were obtained from the NEAMAP staff (J. Gartland, pers. comm.) and subset to include only fall caught fish (N = 341, all years combined) to correspond to previous studies. Gonad stage was determined macroscopically and categorized as A (immature), B (mature resting and mature developing), C (running ripe), or D (spent). Gonad stage was re-coded as immature (A) and mature (B-D), and a binomial regression of maturity on length (10mm bins) was conducted in R (version 2.15.1).

To convert maturity at size to maturity at age, age-length data from 1955 to 2011 (fall fish only, all years combined) were first used to determine percent size at age. This was multiplied by predicted maturity at size from the binomial regression, and the product was summed across sizes for a given age. Results of the analysis indicate a higher proportion of age 2 and 3 fish are mature than was used for the 2009 assessment and found in Higham and Nicholson (1964; Table 3.4.1).

When delving into the commercial reduction fishery data set, it was discovered that maturity records exist for 1955-1970 (n > 240,000; Huntsman and Chapoton 1973). Specifically, age-based maturity could be determined for females using the codes for sexual maturity in the database of 1 = immature, 2 = resting, 3 = ripening, 4 = ripe, 5 = spent, and 6 = unknown (Huntsman and Chapoton 1973). Data were filtered by month, keeping September through January because those are the months of peak spawning activity and would give the most accurate representation of maturity by age. Sample sizes were adequate for plants located in VA and NC during those months (plants 7-17 and 28). All other plants were excluded from the analysis, as were all of the code 6 records.

The consensus of the SAS was that maturity is a length-based process and that Atlantic menhaden mature due to reaching a certain size and energy content as opposed to reaching a specific age. Given this discussion, a logistic regression was fit to the maturity and length data from the commercial reduction fishery database. Fish were coded as immature or mature, as in the analysis completed on the NEAMAP data. Because the growth of Atlantic menhaden varies greatly among years, the SAS determined that maturity must also vary among years. Thus, the time-varying lengths at age for the population were used along with the logistic regression to provide time-varying maturity at age for 1955-2013 for the assessment. This decision was internally consistent with the other growth decisions, which also include time and age varying values. The mean resultant percentage mature at age was very similar to the percentage as estimated with the NEAMAP data (Table 3.4.1), but did vary among years (Table 3.4.2). Because the commercial reduction fishery had more years of data and a larger sample size, the maturity based on those data were used in the final base run model.

3.5 Fecundity

Often reproductive capacity of a stock is modeled using female weight-at-age, primarily because of lack of fecundity data. To the extent that egg production is not linearly related to female weight, indices of egg production (fecundity) are considered better measures of reproductive output of a stock of a given size and age structure. Additionally, fecundity better emphasizes the important contribution of older and larger individuals to population egg production. Thus, in this benchmark stock assessment, modeling increases in egg production with size is preferable to female biomass as a measure of reproductive ability of the stock.

Atlantic menhaden are relatively prolific spawners. Predicted fecundities are:

$$\text{number of maturing ova} = 2563 * e^{0.015 * FL}$$

according to the equation derived by Lewis et al. (1987). Annual fecundity at age was calculated using the Lewis et al. (1987) equation as well as the bias corrected, cohort based estimates of length at age for the population at the beginning of the fishing year (March 1; Table 3.5.1).

Most historical fecundity studies of Atlantic menhaden have concentrated on acquiring gravid females off the coast of North Carolina during the fall fishery when most age classes in the stock tend to be available (Higham and Nicholson 1964, Dietrich 1979, Lewis et al. 1987). Repeating these studies in contemporary times will be difficult relative to the acquisition of adequate number of specimens. The last menhaden factory in North Carolina, Beaufort Fisheries Inc., closed in winter 2004-05. Moreover, the North Carolina Marine Fisheries Commission recently moved to prohibit purse seining for reduction purposes 0-3 miles from the state’s coastline (http://portal.ncdenr.org/web/mf/proclamation-m-25-2012). Thus, procuring specimens from traditional fall fishing grounds will be challenging for future updates, and would most likely rely on specific scientific projects rather than collaboratively working with industry to procure samples.

3.6 Natural Mortality

Atlantic menhaden are vulnerable to multiple sources of natural mortality (*M*) throughout their range including, but not limited to, predation, pollution, habitat degradation, toxic algal blooms, and hypoxia. Estimating the relative contribution and magnitude of these mortality sources continues to be a challenge for stock assessments especially for a short lived forage fish like Atlantic menhaden. The SAS examined a number of different methods to calculate M in this assessment before settling on the preferred method of Lorenzen scaled to the tagging estimate of *M* for ages 4-6+ (average $M_{\text{ages 4-6+}} = 0.5$). Constant values of *M* estimated from life history analogies (e.g., maximum age, growth rate parameters) are often used because of the limited availability of natural mortality datasets. However, given the importance of menhaden as a forage species, and the assumed high predation on young of the year and juvenile fish, time and age-varying natural mortality rates were also explored by the SAS.

Age-Constant *M* Approaches

Several methods are available for determining an age-constant *M* based on life history characteristics, notably maximum age (t_{max}), von Bertalanffy growth parameters (K, L_∞), and average water temperature (T^oC). Results from the following approaches are summarized in Table 3.6.1.

Source	Equation
Alverson and Carney (1975)	$M = 3K/(exp(0.38*t_{max}*K)-1)$
Hoenig (1983; *F* ~ 0)	$M = exp(1.46 - 1.01*ln(t_{max}))$
Jensen (1996)	$M = 1.5*K$
Pauly (1980)	$M = exp(-0.0152+0.6543*ln(K)-0.279*ln(L_\infty, \text{cm})$ $+0.4634*ln(T^oC))$
"Rule of thumb" (Hewitt & Hoenig 2005)	$M = 3/t_{max}$

Mean environmental temperature (T^oC), or mean annual temperature where the fish is caught, used here was 19°C [from Williams et al. (1973) for NC]. Quinn and Deriso (1999) have converted Pauly's equation from base 10 to natural logarithms as presented above. The "rule of thumb" method has a long history in fisheries science, but it is difficult to pin down its source. Hewitt and Hoenig (2005) recently compared the rule of thumb approach to that of Hoenig (1983) and noted that the Hoenig (1983) method provides an estimate of *M* only when fishing mortality can be assumed small (*F* ~ 0) otherwise it was suggested to be an upper bound on *M*. We calculated average annual values of *M* for those equations above for which we have annual values of input parameters (e.g., Alverson and Carney 1975, Jensen 1996, Pauly 1980; Figure 3.6.1).

Estimates of *M* in the early literature on Atlantic menhaden vary, though not widely (Ahrenholz 1991). Schaaf and Huntsman (1972) estimated $M = 0.37$ yr^{-1} based on an *ad hoc* approach regressing total mortality rate (*Z*) on fishing effort. Estimates were $M = 0.52$ yr^{-1} from a preliminary tag-recovery analysis (Dryfoos et al. 1973) and $M = 0.50$ yr^{-1} from a more extensive tag-recovery analysis (Reish et al. 1985). The mean of the range ($M = 0.45$ yr^{-1}) has been used previously in Atlantic menhaden assessments beginning with Ahrenholz et al. (1987).

Age-Varying M Approaches

Several approaches have been developed to provide age-varying estimates of M (Peterson and Wroblewski 1984, Boudreau and Dickie 1989, Lorenzen 1996, Charnov, et al. 2013). All use an inverse relationship between size or weight and M.

The method of Peterson and Wroblewski (1984) was used to describe M for young-of-year Atlantic menhaden (Heimbuch et al. 2007), and uses a dry weight as its independent variable. The method of Boudreau and Dickie (1989) has been applied in several assessments, notably for Gulf menhaden (Vaughan et al. 2007). Recently Charnov et al. (2013) used the weight relationship of the von Bertalanffy growth equation to look at how growth in weight and M, prior to and after maturity, can affect estimation of natural mortality.

The method of Lorenzen (1996) and similar approaches have gained favor in recent years, especially in the SEDAR arena. When applying the method of Lorenzen (1996), estimates of age-varying M are often scaled. Unscaled and scaled estimates of M based on the approaches of Lorenzen (1996) were developed from von Bertalanffy growth parameters using the von Bertalanffy growth equation. Additionally, a range in Hoenig-based estimates of M can be used to rescale the Lorenzen estimates of M so as to provide a range of age-varying M.

The Hoenig-based estimate of M is 0.42, which produces a scaling to 1.5% survival from age 1 through age 10. Corresponding percentages can be developed to scale M ranging from $M = 0.37$ to 0.52 (or 2.5% and 0.6% survival, respectively). Unscaled age-varying estimates of M are summarized for ages 0-6 (Table 3.6.2).

Natural Mortality from the Multi-Species VPA

Using a Multi-Species Virtual Population Analysis model (MSVPA-X) to estimate an age- and time-varying M allows for further decomposition of M into predation mortality, M_2, and other sources of natural mortality, M_1. M_2 is more appropriately described as M due to predators (Garrison et al. 2010). Total instantaneous mortality rate, Z, can then be formulated as:

$$Z = F + M_1 + M_2$$

Examinations of age variable predation mortality rates suggest greater mortality on the youngest age classes and subsequently lower predation mortality on older age classes, in keeping with the life history of short lived forage species. Incorporation of age-variable mortality rates into age-structured population models usually results in increased abundance in younger age classes to offset this increase in M; particularly when the bulk of the increased M comes before full recruitment to the fishery. It should be noted that whether using age-variable or multi-species derived M, some component of the M is assumed, rather than empirically derived.

To address the concerns of menhaden as an important forage species and explore the role of M_2 in the population dynamics of this stock, the Commission began developing a MSVPA-X in 2001 (Garrison et al. 2010). The MSVPA-X model initially focused on the effects of predation by bluefish, striped bass, and weakfish on the Atlantic menhaden population, and has since been extended to adjust for the population estimates of the predators and alternative prey species. The Commission hosted several workshops to verify the data used in the model and obtain feedback from various technical committees on features to include in the model. Early versions of the MSVPA-X model were used by the TC to explore some basic questions about the abundance of age 0 and 1 menhaden, as well as effects on reference points. Additionally, an age-varying ***M*** was derived in some part by that version of the MSVPA-X.

A subsequent revision of the MSVPA-X was reviewed by the 42nd SAW (Stock Assessment Working-group; http://www.nefsc.noaa.gov/nefsc/publications/crd/crd0609) in December 2005 (NEFSC 2006). At that meeting the SAW suggested improvements to the model; however, overall the SAW approved model formation, inputs, and its use in providing ancillary management advice on the predator prey interactions of these stocks. More recently, this model and data input have undergone an additional update as part of the ASMFC Multi-Species Technical Committee during 2008-2009.

While the model only explicitly models menhaden, bluefish (as a biomass predator), weakfish, and striped bass interactions and population dynamics, other prey items have been included to produce a more realistic ecosystem picture across the predators' size and spatial ranges. These include:

Sciaenids (spot, croaker)
Bay anchovy
Medium Forage species (butterfish)
Squids
Clupeids (Atlantic herring,)
Benthic invertebrates (worms)
Benthic crustaceans (lobsters, blue crabs, rock and Jonah crabs)
Macrozooplankton (shrimps, mysids, and amphipods)

For the MSVPA-X, estimates of *M* decline with increasing age, similar in pattern to that obtained from the inverse growth pattern described in the previous section (Figure 3.6.2). In the last peer reviewed assessment (ASMFC 2010) the full MSVPA-X *M* output was used within the single species assessment. However, in past assessments the MSVPA-X results have been scaled to tagging results. Alternatively, various methods to scale the MSVPA-X results are compared in Figure 3.6.3. The age-varying estimates of *M* from MSVPA-X were provided for 1982-2012 (Table 3.6.3).

Annual age-averaged estimates of *M* from MSVPA-X are compared with both the annually varying estimates of *M* from the fixed life history approaches (Figure 3.6.1; e.g., Alverson and Carney, Jensen, and Pauly) and the annually varying estimates of *M* (Figure 3.6.4) from the age-varying inverse weight approaches (e.g., Peterson and Wroblewski, Boudreau and Dickie, and Lorenzen, Charnov). All of these estimation methods for *M* produce relatively similar values.

During the most recent deliberations and examinations by the SAS, the group did not choose to use the output of the MSVPA-X for the base run of the assessment; however, the MSVPA-X output was used in a sensitivity run. Partly this was due to concerns over how to approach the natural mortality of menhaden between base model start year (1955) and the start year of the MSVPA-X (1982). A further concern was how sensitive the MSVPA-X approach was to small changes in either prey preferences or predator/prey overlap. However, it was recognized that the MSVPA-X showed a different population trajectory than the preferred base model for the following reasons:

1. The current programming framework of the MSVPA-X does not allow for a fleet/area approach currently in use in the preferred base model.
2. The current configuration of the MSVPA-X does not allow for the use of age disaggregated indices as found in the preferred base model.
3. The menhaden VPA may not estimate the same time/fleet selectivity blocks as that specified in BAM.

Therefore, as a result of 1-3, the MSVPA-X showed a starkly different trajectory in stock abundance and biomass compared to the preferred base model (see Appendix A, Figure 20).

As such the SAS had concerns that the MSVPA-x was not accurately reflecting the proper natural mortality vector. The SAS did decide to utilize the variability in the MSVPA-X *M* matrix to inform the Monte Carlo bootstrap analysis.

Conclusions on Natural Mortality

After careful consideration, the SAS excluded the MSVPA-X-derived *M* matrix in favor of an age-varying, but time invariant approach using the methods of Lorenzen (1996) scaled to tagging estimates of natural mortality for ages 4-6 (see below); a departure from previous assessments (see above). When averaged by age over the available time series, the time invariant but age varying approaches showed remarkable similarity (Figure 3.6.2) with the exception of Charnov.

The SAS was apprehensive to apply a time and age invariant *M* via Alverson and Carney (1975), Hoenig (1983; F ~ 0), Jensen (1996), or Pauly (1980), as these methods were not meant to create time varying *M* with but rather constant invariant *M*. The SAS decision to use time invariant *M* is in contrast to Deroba and Schueller (2013), which found that it was usually more important to specify a time-varying rather than an age-varying natural mortality. However, no good estimates of time-varying *M* are available for menhaden even though they are an important forage fish.

Expansion of methods by Peterson and Wroblewski 1984, Boudreau and Dickie 1989, Lorenzen 1996, and Charnov, et al. 2013, to age and time invariant was also not favored because of the variability in growth and weight at age of menhaden. The SAS was concerned that such an application was beyond the intent of these methods.

The time invariant but age varying method of Charnov was also not used. This method is premised on the observation that much of the individual's growth and natural mortality occurs prior to first spawning; which is thought to be not true for Atlantic menhaden. Because of this the Charnov method resulted in unrealistic natural mortality prior to maturity, especial at age-0 (Figure 3.6.2). The methods of Peterson and Wroblewski were also not used as this required dry weight, which is not readily available for Atlantic menhaden across the time series.

3.7 Migration and Tagging

Adult Atlantic menhaden undergo extensive seasonal migrations north and south along the US East coast (ASMFC 2004b). Roithmayr (1963) found evidence of this migratory behavior based on the decrease in the number of purse-seine sets north of Cape Cod in September. Also, Reintjes (1969) reported the disappearance of fish in October north of Chesapeake Bay and their appearance off the coast of NC in November. Nicholson (1971b) examined latitudinal differences in length-frequency distributions of individual age groups at different times of year and described a cyclic north-south movement with the largest and oldest fish proceeding farthest north such that the population stratifies itself by age and size along the coast during summer. A study of length frequencies at the time of first annulus formation on scales (Nicholson 1972) supported the concept of a north-south migratory movement and also indicated that a great deal of mixing of fish from all areas occurs off the North Carolina coast before fish move northward in spring.

Returns of tagged Atlantic menhaden (Dryfoos et al. 1973; Nicholson 1978) generally confirmed what was already concluded from earlier work and added some important details (ASMFC 2004b). Adults begin migrating inshore and north in early spring following the end of the major spawning season off the Carolinas during December-February. The oldest and largest fish migrate farthest, reaching southern New England by May and the Gulf of Maine by June. Fish begin migrating south from northern areas to the Carolinas in late fall. Adults that remain in the south Atlantic region for spring and summer migrate south later in the year, reaching northern Florida by fall. During November and December, most of the adult population that summered north of Chesapeake Bay moves south of the Virginia and North Carolina capes. After winter dispersal along the south Atlantic coast, adults again begin migrating north in early spring.

As with the adults, Kroger and Guthrie (1973) found that juvenile Atlantic menhaden also exhibit a seasonal north-south movement along the Eastern Seaboard. From tag recoveries during the late 1960s and early 1970s, they reported that juveniles (age-0s) migrate as far south as Florida in fall and winter, then redistribute northward along the coast by size as age-1 fish during the following spring and summer. Larger age-1 menhaden migrate north earlier than smaller age-1 fish, which tend to remain along the south Atlantic coast; however, some age-1s move from the south Atlantic into Chesapeake Bay through midsummer.

Historic Atlantic menhaden tag-return data collected during 1966–1970 were recently redigitized from raw data sheets. While the dataset had been examined previously, it had not been analyzed using a modern tag-return modeling approach. Appendix B presents a preliminary analysis of the Atlantic menhaden tag-return data using a multistate or spatial tag-return model that accounts for important model assumptions, including tag-return efficiencies (or reporting rates) and tag retention. The model is used to quantify instantaneous rates of fishing mortality and age-specific movement probabilities among three spatial strata, New York, New Jersey, and a final stratum including all areas from Chesapeake Bay to Florida. These strata were used to best get at the question of movement given the data available, which included these specific strata. Fishing mortality was highest in the southern region, and fish movement appeared to vary by season and age, with older fish having a high probability of moving from southern to northern regions in spring and summer and lower probabilities of northward movement in fall and winter. Additional details on these analyses are presented in Appendix B.

4.0 Fishery-Dependent Data Sources

4.1 Commercial Reduction Fishery

Some fishing for Atlantic menhaden has occurred since colonial times, but the use of purse-seine gear began in New England about 1850 (Ahrenholz et al. 1987). No longer bound to shore-based seining sites, the purse-seine fishery spread south to the Mid-Atlantic states and the Carolinas by the late 1800s. Purse-seine landings reached their zenith in the 1950s, and peak landings of 712,100 metric tons occurred in 1956 (Figure 4.1.1); extant menhaden factories at the time numbered over 20 (ASMFC 2004b) and ranged from northern Florida to southern Maine (Table 4.1.1 and Figure 4.1.2). In the 1960s, the Atlantic menhaden stock contracted geographically, and many of the fish factories north of Chesapeake Bay closed because of a scarcity of fish (Nicholson 1975).

During the 1970s and 1980s, the menhaden population began to expand. Adult menhaden were again abundant in the northern half of their range, that is, Long Island Sound north to the southern Gulf of Maine. By the mid-1970s, reduction factories in Rhode Island, Massachusetts, and Maine began processing menhaden again (Table 4.1.1 and Figure 4.1.2). In 1987, a reduction plant in New Brunswick, Canada, processed menhaden harvested in southern Maine, but transported by carrier vessel to Canada. Beginning in 1988, Maine entered into an Internal Waters Processing venture (IWP) with the Soviet Union, which brought up to three foreign factory ships into Maine territorial waters (<3 miles from the coast). American vessels harvested the menhaden and unloaded the catch for processing on the factory ships. By 1989, all shore-side reduction plants in New England had closed mainly because of odor abatement issues with local municipalities. A second Canadian plant in Nova Scotia also processed Atlantic menhaden caught in southern Maine in 1992-93. The Russian-Maine IWP and the Canadian plants last processed menhaden during summer 1993.

During the 1990s, the Atlantic menhaden stock contracted again (as in the 1960s). Fish became scarce again north of Long Island Sound. After 1993, only three factories remained in the fishery, two factories in Reedville, VA, and one factory in Beaufort, NC. Virginia vessels (about 18-20) fished primarily in Virginian waters, but occasionally ranged north to New Jersey and south to about Cape Hatteras, NC. The North Carolina vessels (usually two) fished mostly in North Carolina waters.

Major changes in the industry occurred following the 1997 fishing season, when the two reduction plants operating in Reedville, VA, consolidated into a single company and a single factory; this significantly reduced effort and overall production capacity. Seven of the 20 vessels operating out of Reedville, VA, were removed from the fleet prior to the 1998 fishing year and three more vessels were removed prior to the 2000 fishing year, reducing the Virginia fleet to about 10 or 11 vessels during 2000 to 2012. In 2013, the factory at Reedville further reduced its fleet to seven vessels because of the coastwide TAC imposed by Amendment 2 of the FMP for Atlantic menhaden (see below).

In recent years, up to four purse-seine vessels that fish primarily for bait near Northern Neck, VA, unloaded their catch sporadically for reduction at the Reedville fish factory when bait markets were weak or individual fish were too small for bait sales.

Another major event within the industry occurred in winter 2004-2005 when the fish factory at Beaufort, NC, closed permanently, and the property was sold to developers. Thus, beginning in 2005 the lone, surviving Atlantic menhaden plant was in Reedville, VA, with about ten vessels.

In spring 2012, NC moved to prohibit purse seining for Atlantic menhaden within its territorial sea (0-3 miles from shore). Thus, menhaden reduction vessels from Virginia were prohibited from fishing on traditional fishing grounds along the northern and central North Carolina coast; peak catches from this area usually occurred in fall and targeted migratory menhaden schools.

Also in 2012, the TC concluded that although the recent Stock Assessment Update (ASMFC 2012b) had major flaws, the Atlantic menhaden stock was probably experiencing overfishing, but the magnitude could not be determined. The TC suggested *ad hoc* alternatives to harvest limits (reducing mean landings of recent years by a certain percentage) until a new benchmark assessment could be completed. In December 2012, the Atlantic Menhaden Management Board approved Amendment 2 to the Atlantic Menhaden FMP which established a coastwide quota for menhaden (reduction and bait fisheries combined) based on mean total landings of the previous three years decremented by 20%. This TAC of 170,800 mt is in place for the 2013-14 fishing seasons and until the Atlantic Menhaden Management Board takes action pending this benchmark stock assessment. The reduction fishery's portion of the TAC is about 129,900 mt. This increased slightly in late 2013 to include an unused set-aside of the TAC; total landings for the reduction fishery in 2013 were 131,031 mt.

4.1.1 Modus Operandi and Processed Products of the Commercial Fishery

The reduction fishery for Atlantic menhaden employs purse-seine gear to encircle schools of menhaden. Two purse boats (ca. 40 ft long), each holding one-half of the seine, are deployed from a large carrier vessel (ca. 160-200 ft long; also called a 'steamer'). A pilot in a spotter aircraft directs the purse boats via radio to the fish schools and assists in setting the net. Spotter pilots assist with about 80% of purse-seine sets (Smith 1999). The fish are 'hardened' into the center of the net, and then pumped onboard the steamer. The purse-seine fleet averages about 5 sets per fishing day (Smith 1999). At the end of the fishing trip, the catch is pumped at dockside into the fish factory, where it is reduced into the three main processed products of the menhaden industry - fish meal, fish oil, and fish solubles.

Prior to World War II, most menhaden was dried and sold as 'fish scrap' for fertilizer. By the early 1950s, the demand for fish meal as an ingredient in poultry feeds increased as the 'fryer' chicken industry expanded. During the latter half of the twentieth century, menhaden meal also became an integral component in swine and ruminant feeds. Since the 1990s, menhaden meal has been milled in greater quantities into aquaculture feeds. Historically, most menhaden oil was exported to Europe where it was processed into cooking oil or margarine. Beginning in the late 1990s, greater quantities of menhaden oil, a high-grade source of omega-3 fatty acids, have been utilized by the pharmaceutical and processed-food industries of the U.S. Currently, large amounts of menhaden oil are formulated by the aquaculture industry into fish feeds, especially for the culture of salmonids.

4.1.2 Selectivity Time Blocks or Breaks in the BAM Model as Related to Changes in the Reduction Fishery

When addressing selectivity in the reduction fishery and potential time blocks or breaks, the SAS considered residual patterns in the age composition data and major changes within the fishery. With regard to the latter, the SAS adopted three time blocks for the reduction fishery in the northern region (defined as waters north of Machipongo Inlet, VA). The first time block is 1955-1969. Comprehensive and coastwide data collection for the reduction fishery began at the Beaufort Laboratory in 1955. The 1950s were also the years of peak landings for the fishery. After the 1958 year class phased through the fishery (by about 1963), what followed in the 1960s were a series of poor to mediocre recruitment years. The stock contracted and many fish plants north of New Jersey closed (Figure 4.1.2). Year 1969 was chosen as the end of this first time block for the northern region due to the consistent poor recruitment and the contraction of the fishery. The second time block for the northern region is 1970-1993. During the 1970s the stock once more expanded into the northern half of its range. Fish plants in New England reopened (Figure 4.1.2) and fish were abundant there through about 1993, the end of this time block when the Russian factory ships ceased operating in Maine waters because of lack of fish. The third time block is 1994-2013 when there were no factories and no reduction landings in the northern region, although there were removals off the Mid-Atlantic coast by Virginia vessels that landed their catch in Reedville, VA.

The SAS also adopted three time blocks for the reduction fishery in the southern region (defined as waters south of Machipongo Inlet, VA, including Chesapeake Bay). The first was 1955-1971 as 1971 was when several factories closed in the southern region (Figure 4.1.2). The second time block for the southern region began in 1972 and ended in 2004 when the last menhaden factory in North Carolina closed, leaving only one active fish plant on the US East coast at Reedville, VA (Figure 4.1.2). The third time block for the southern region is 2005-2013.

In both regions, the introduction of selectivity time blocks noticeably improved the residual pattern apparent in the age composition data.

4.1.3 Fishery-Dependent Data Collection and Survey Methods

Fishery-dependent data for the Atlantic menhaden purse-seine reduction fishery have been maintained by the Beaufort Laboratory of the National Marine Fisheries Service since 1955 and they consist of three major data sets: 1) fishery landings or catch records, 2) port samples for age and size composition of the catch, and 3) daily logbooks, or Captains Daily Fishing Reports (CDFRs).

Detailed landings data for the reduction purse-seine fishery are available 1940-2013. The biostatistical data, or port samples, for length and weight at age are available from 1955 through 2013, and represent one of the longest and most complete time series of fishery data sets in the nation. The CDFRs itemize purse-seine set locations and estimated at-sea catches; vessel compliance is 100%. CDFR data for the Atlantic menhaden fleet are available for 1985-2013.

As the directed bait fishery for menhaden has grown in recent decades, greater emphasis has been placed on acquiring more representative port samples and more accurate landings records from this fishery, which is discussed in detail in Section 4.2.

4.1.3.1 Reduction Fishery Landings, or Catch Records

When the Menhaden Program began at the Beaufort Laboratory in the early 1950s, staff visited menhaden plants along the Atlantic coast, obtaining detailed fishery landings for reduction back to 1940. Subsequently, landings data from the reduction fishery by fishing year (March 1 through February 28 of the following year) have been maintained from 1955 through the present. Historically, daily vessel unloads were reported weekly or monthly during the fishing year. In recent years (since about 2005) individual vessel unloads are available daily via email from the clerical staff at the fish factory. Landings are provided in thousands of standard fish (1,000 standard fish = 670 lbs), which are converted to kilograms (see below). A chronology of menhaden plant activity since 1955 is shown in Table 4.1.1 and Figure 4.1.2.

Landings and nominal fishing effort (vessel-weeks, measured as number of weeks a vessel unloaded at least one time during the fishing year; see Section 4.1.5 below) are available since 1940 (Table 4.1.3.1.1). Landings rose during the 1940s (from 167,000 to 379,000 mt), peaked during the late 1950s (>600,000 mt for five of six years; record landings of 712,100 mt in 1956), and then declined to low levels during the 1960s (from 576,000 mt in 1961 to 162,000 mt in 1969). During the 1970s the stock rebuilt (landings rose from 250,000 mt in 1971 to 376,000 mt in 1979) and then maintained intermediate levels during the 1980s (varying between 238,000 mt in 1986 [when fish meal prices were extremely low] to 418,600 mt in 1983). Landings during the 1990s declined from 401,200 mt in 1990 to 171,200 mt in 1999.

By 1998, the fishery had contracted to only two factories, one in Virginia and one in North Carolina. Landings dipped to 167,200 mt in 2000, rose to 233,700 mt in 2001, and then varied annually from 174,000 mt to 166,100 to 183,400 mt through 2004. Landings during 2000-04 when the fishery was relatively stable with two plants and about twelve vessels averaged 184,900 mt. Since 2005 only the factory in Virginia operated and landings ranged from 131,000 mt (2013, which was the first year of the TAC) to 174,500 mt (2007), and averaged 156,900 mt. Reduction landings in 2012 (one year prior to the TAC) accounted for approximately 72% of total coastwide landings of Atlantic menhaden (bait and reduction combined); in 2013 reduction landings accounted for approximately 78% of total coastwide harvest.

Measuring Devices Used to Unload Menhaden

Regarding landings by the menhaden fishery, in the SEDAR 27 Review Workshop Report for Gulf Menhaden (SEDAR 2011), review panelists expressed concern over the fact that the industry self-reports landings in 1,000s of standard fish. This convention dates to the early days of the fishery on the Atlantic coast when 1,000 standard fish were taken to weigh 670 pounds and the volume of a standardized hopper used at reduction plants to offload landings held 1,000 standard fish (Greer 1915). Review panelists expressed some concern about the consistency of fish hopper dimensions, and therefore landings estimates across the menhaden time series.

The question of consistency among measuring devices for landings at menhaden factories on the Atlantic coast no doubt concerned staff during the early years of the Menhaden Program at the Beaufort Laboratory. Kutkuhn[1] noted that the traditional unit of measurement for landings in the

---

[1] "Verification of menhaden conversion factor", prepared by Joseph Kutkuhn (JHK), 1-26-66. Available on PDF format.

menhaden fishery is the “quarter-box” dump [or hopper], which volumetrically, by the menhaden industry’s definition, measures 22,000 cubic inches, and traditionally was recognized to hold 667 lbs. Kutkuhn[1] empirically showed that “the factor 0.667 - or 0.67, whichever is more convenient - should now be affirmed as the official standard for converting to weight all landings of menhaden measured volumetrically in ‘quarter-box’ dumps and reported by the industry in terms of thousands-fish units (i.e., 1,000 ‘standard’ fish weigh on the average, 667 pounds or one-third short ton).” Furthermore, a coefficient of variation about his results of 3.7% suggested a high degree of accuracy for the landings. June and Reintjes (1976), in describing the evolution and methods of the menhaden fishery, reaffirmed that each segment of the rotating hopper device used to measure landings holds volumetrically 22,000 cubic inches, “representing a unit measure of 1,000 ‘standard’ fish.” They also noted that regardless of the weighing equipment employed, this “unit of measure [1,000 standard fish] is used throughout the industry to express the quantity of catch.” Based on the information above, the conversion factor of 0.670 (1,000 standard fish = 670 lbs) was adopted by Beaufort’s Menhaden Program.

The fish dumps at the factory in Reedville, VA, were rebuilt in 2008; the paired fish dumps were redesigned to each hold 2,000 standard fish (M. Deihl, plant manager, personal communication). A local metal fabricator built the dumps from a set of mechanical drawings. A second engineering company was hired to certify the dumps as holding 44,000 cubic inches. They found the dumps slightly oversized and installed a small spacer in the bottom to bring the dumps to the desired 44,000 cubic inches. Thus, the new fish dumps at Reedville each hold approximately 1,340 lb (2,000 standard fish) of menhaden.

In summary, the fish measuring convention for landings in the menhaden industry has been exceptionally consistent since the late 1800s. The basic unit-of-measure remains the fish hopper, or dump, which holds 1,000 “standard” fish, or one-third of a short ton. Vessel crews, and to some extent spotter pilots, are paid based on each measure of 22,000 in^3 of fish unloaded. For convenience, the NMFS has used the conversion factor of 670 lbs for each one thousand “standard” fish measure reported by the industry. Reduction landings of menhaden since the 1940s are believed to be both accurate and precise compared to most other high-volume US fisheries.

4.1.3.2 Port Samples - Biological Sampling Routines

Biological sampling for the menhaden purse-seine fishery is based on a two-stage cluster design and is conducted over the range of the fishery, both temporally and geographically (Chester 1984; Chester and Waters 1985). The number of fish sampled in the first cluster was reduced after 1971 from 20 fish to 10 fish to increase sampling of the second cluster (number of purse-seine sets). Port agents randomly select vessels and at dockside retrieve a bucket of fish (first cluster) from the top of the vessel’s fish hold. The sample is assumed to represent fish from the last purse-seine set of the day, not the entire boat load or trip. The agent ascertains from the crew the location and date of the last set. From the bucket the agent randomly selects ten fish (second cluster), which are measured (fork length in mm), weighed (grams), and the scales are removed for ageing. Information on sample sizes can be found in the Life History section on growth.

4.1.3.3 Commercial Reduction Catch at Age - Methods and Intensity

Detailed sampling of the reduction fishery allows landings in biomass to be converted to landings in numbers at age. For each port/week/area caught, biostatistical sampling provides an estimate of mean weight and the age distribution of fish caught. Hence, dividing landings for that port/week/area caught by the mean weight of fish allows the numbers of fish landed to be estimated. The age proportion then allows numbers at age to be estimated. Developing the catch matrix at the port/week/area caught level of stratification provides for considerably greater precision than is typical for most assessments.

For statistical reporting purposes the Atlantic menhaden purse-seine fishery was divided into four geographic fishing areas and one temporal area (Figure 4.1.2; June and Reintjes 1959), namely, North Atlantic, Middle Atlantic, Chesapeake Bay, and South Atlantic, and the temporal area, the North Carolina Fall Fishery (fall migratory fish caught after about November 1 off the North Carolina capes and landed in North Carolina). Through the 1970s menhaden vessels tended to fish within the reporting area of their home port. For example, vessels from Reedville, VA, tended to fish in the Chesapeake Bay area, while vessels from North Carolina tended to fish in the South Atlantic area. Exceptions occurred most often in the Middle Atlantic area where vessels from Port Monmouth, NJ, fished in the North Atlantic area in Long Island Sound and off Rhode Island and Massachusetts (Nicholson 1975).

During summer Atlantic menhaden stratify along the US East Coast by size and age with older and larger fish occurring farther north (Nicholson 1972). This distributional pattern had the potential to compromise numbers-at-age estimates because vessels fishing beyond the area of their home port might return to the fish factory with fish of different sizes and ages from the area of their home port (Chester 1984). To adjust for vessels fishing in two statistical areas, weekly landings for a port were apportioned based on areas from which that week's port samples were acquired, for it was assumed that the random acquisition of samples reflected geographic fishing activity of the fleet.

By the early 1980s, numerous changes within the menhaden fishery lead program biologists and fishing industry representatives to suspect that the extant routines to estimate numbers of fish at age no longer accurately reflected geographic activity of the fleet, especially for vessels from Reedville. In 1981, the last menhaden plant in the Middle Atlantic area at Port Monmouth, NJ, closed. Thereafter, vessels from Reedville periodically harvested fish off Delaware and New Jersey during summer in waters vacated by vessels from Port Monmouth. As vessels returned to Reedville from fishing in the Middle Atlantic area, the catch tends to settle in the fish hold during the 18 to 24-hr transit. Some, but not all captains often chose to make a final set in Chesapeake Bay – on presumably younger and smaller fish - to "top off" the fish hold before unloading. Apportioning weekly landings based on port samples became problematic, for although a particular port sample from the top of the fish hold could be verified as a catch from Chesapeake Bay, an unknown portion of the underlying catch may have been larger and older fish from the Middle Atlantic area. Thus, port samples at Reedville were not accurately reflecting the true proportion of catch by fishing area.

In the mid-1990s Menhaden Program staff at the Beaufort Laboratory began key-entry of the daily logbooks, CDFRs, maintained by menhaden vessels (see Sect 4.1.3.4 below), which enumerate for each purse-seine set: set time, set location, at-sea estimate of catch, distance from shore, and several weather variables (Smith 1999). CDFRs, with 100% fleet compliance, were seen as a means to better apportion weekly catch by area when the Virginia fleet fished in the Middle Atlantic area.

The traditional computer program used to generate catch by numbers at age (BBL01 in Hunstman and Chapoton 1973) was re-written in the late 1990s to incorporate CDFR estimates of weekly areal catch by port-week (Smith et al[2]). Weekly estimates of removals by area from CDFRs replaced the weekly apportionment of number of port samples by area for port-weeks (Reedville only) when Virginia vessels fished in Middle Atlantic waters. For example under the old numbers-at-age program, if ten port samples were acquired for a given week and nine were from Chesapeake Bay and one was from the Middle Atlantic, then total weekly landings were apportioned 90% from the Bay and 10% from the Middle Atlantic. However, CDFRs provide a more accurate accounting of removals by area if “topping off” occurred, and actual harvest for the given week may have been 75%:25%. The CDFR apportionment replaced the port sampling ratio in the new number-at-age statistical routine. Using the CDFR ratio, generally for a port-week at Reedville (when vessels fished in the two adjoining areas) the estimated numbers of age-1 and age-2 fish from Chesapeake Bay declined (fewer smaller and younger fish), while the estimated number of age-2 and age-3 fish from the Middle Atlantic increased (more larger and older fish). In summary, CDFRs allowed staff to better estimate actual proportion of catch by area, and in turn properly weight biostatistical samples.

Annual CDFR data sets for 1985-2013 were used to better apportion weekly-plant catches by fishing area and to correct for the “topping off” bias. Coastwide, only minor differences were found in catch-at-age estimates. Thus, based on temporal and areal distribution of current and historical port samples for the reduction fishery, and the complete accounting of landings by the menhaden companies, biases in the reduction fishery sampling data set are believed to be minimal.

Sampling Intensity

About 2,335 Atlantic menhaden from the reduction fishery have been processed annually for size and age composition over the past three fishing seasons, 2011-13 (Table 4.1.3.3.1). While the sampling intensity in the menhaden fishery is below the rule-of-thumb criteria used by the Northeast Fisheries Science Center (e.g. <200 mt/100n), the results of Chester (1984) suggest this sampling level is more than adequate; as mentioned above (Section 4.1.3.2), in menhaden catches there is more variability in size and age composition across purse seine sets than within sets.

Catch At Age in Recent Years

Over the past three years, age-2 Atlantic menhaden have comprised on average 58% of the total numbers of fish landed (Table 4.1.3.3.2). In 2011, the age composition of the coastwide landings for reduction was 42% age-1’s, 50% age-2’s, and 8% age-3+’s; in 2012, it was 1% age-0’s, 16%

---

[2] Smith, J.W., D.S. Vaughan and D.R Colby. 2002. Improving catch-at-age matrices for Atlantic menhaden, *Brevoortia tyrannus*, purse-seine reduction fishery using logbooks. Unpublished manuscript, 16 p.

age-1’s, 79% age-2’s, and 4% age-3+’s; and in 2013, it was 3% age-0’s, 38% age-1’s, 45% age-2’s, and 14% age-3+’s. Overall mean weights of Atlantic menhaden for reduction in port samples for 2011 through 2013 were 187 g, 204 g, and 213 g, respectively.

4.1.3.4 Captains Daily Fishing Reports (CDFRs), or Logbooks

Beginning in the late 1970s, the menhaden industry, state fisheries agencies, and the NMFS entered into a joint CDFR program to better document menhaden catch and fishing effort. For each fishing day, captains are asked to specify, among other things, time and location of each purse-seine set, estimated at-sea catch, and distance from shore. Since the mid-1980s, compliance by menhaden fleets in Virginia and NC has been almost 100%. CDFR data sets for fishing years 1985 through 2013 have been computerized at the Beaufort Laboratory.

Smith (1999) summarized the distribution of Atlantic menhaden purse-seine catches and sets during 1985-1996 using the CDFR data sets for the Virginia and North Carolina vessels. He found that on average the fleet (up to 22 vessels) made 10,488 sets annually. Virginia vessels made at least one set on 67-83% of the available fishing days between May and December. In most years, five was the median number of sets attempted each fishing day. Median catch per set ranged from 15-30 mt annually. Spotter aircraft assisted in 83% of the sets. Regionally, median catch per set was 24 mt off Rhode Island, New York, New Jersey and Delaware; 23 mt off the ocean beaches of Virginia; 18 mt in the Virginia portion of Chesapeake Bay; 26 mt off North Carolina in summer; and 38 mt off North Carolina in fall.

In recent years, median catches (and maximum from CDFR data sets) in Chesapeake Bay have been 21 mt (231 mt) in 2011, 22 mt (274 mt) in 2012, and 21 mt (202 mt) in 2013. Similarly, recent median catches (and maximum) in Atlantic Ocean waters have been 42 mt (348 mt) in 2011, 44 mt (281 mt) in 2012, and 39 mt (323 mt) in 2013.

Between 2000 to 2005 when the reduction fishery contracted to only one fish plant and about ten vessels in Virginia, removals from Chesapeake Bay by the reduction fleet averaged 104,400 mt annually, a 28% decline versus 1990-99 when removals from the Bay averaged 145,700 mt per year. Beginning in 2006, a “Cap” on removals by the reduction fleet (109,020 mt) was imposed through Amendment 1 to the FMP (see Section 2.0). During 2006-2013 the harvest for reduction in Chesapeake Bay averaged 71,300 mt. In 2012, the “Cap” was further reduced by 20% (as per the coastwide decrement to landings in Amendment 2) to about 87,200 mt. The fishery has never exceeded the “Cap”.

Since 2005, menhaden reduction vessels have reported the GPS coordinates of their purse-seine set locations on CDFRs. Figures 4.1.3.4.1 to 4.1.3.4.3 show set locations of the reduction fleet for 2011-13. Clearly from these data: 1) Virginia is the center of the extant reduction fishery, 2) the Virginia fleet occasionally ranges north to the central New Jersey coast (beyond three miles from shore), and 3) a majority of sets in Virginia waters in recent years have been near the mouth of Chesapeake Bay and along the barrier islands of Eastern Shore. The figures showing set locations (Figures 4.1.3.4.1 to 4.1.3.4.3) are also annotated with fishing locations from which port samples (last set of a given fishing trip) were acquired; the reason for its inclusion is to demonstrate that port samples adequately represent the current distribution and range of the reduction fishery for Atlantic menhaden.

Landings, Removals by Areas, and the Beaufort Assessment Model (BAM)

As per recommendations by peer reviewers of the 2010 Atlantic menhaden stock assessment (ASMFC 2010), in the current benchmark assessment the menhaden fishery is addressed in terms of a northern and a southern fishery versus solely as a reduction and a bait fishery as in the last peer review. To this end, this benchmark assessment incorporates “fleets-as-areas” components where both the bait and reduction fisheries are divided into northern and southern regions (Tables 4.1.3.4.1 – 4.1.3.4.3). By consensus, the SAS divided the northern and southern fisheries using a line that runs due east from Great Machipongo Inlet on the Eastern Shore of Virginia. Historically and for statistical reporting purposes, this has been the dividing line for the Mid-Atlantic and Chesapeake Bay areas for the Menhaden Program at the Beaufort Laboratory (June and Reintjes 1959). Nicholson (1971) noted that “Similarities in age and size composition of the catches, time and duration of fishing, and range of vessels from home port tended to set each area apart”. Through about the 1970s, reduction vessels from menhaden plants in New Jersey and Delaware rarely fished below this line; conversely, reduction vessels from Chesapeake Bay rarely fished north of this line. Thus, it is a convenient line of demarcation to sort port samples and landings data for the fleet-as-areas model. Moreover, empirical data for mean lengths of port sampled fish indicated appreciable size differences between areas north and south of this line (Figure 4.1.3.4.4).

For the “fleets-as-areas” model, assignment of reduction landings and port samples by region (north vs. south) was relatively straightforward through 1993 when the Russian factory ships last operated in the southern Gulf of Maine (see Section 4.1). However, after 1981 the last menhaden factory in the Mid-Atlantic area closed (Port Monmouth, NJ) and by the mid-1980s reduction vessels from Chesapeake Bay in mid-summer tended to fish farther north in the Atlantic Ocean up to the coast of New Jersey. Technically, there were no reduction landings in the northern “fleets-as areas” region after 1993, although there were removals of fish for reduction purposes by Virginia-based vessels. These removals in the northern region were estimated beginning in 1985 using the CDFRs (see Section 4.1.3.4) and for the purposes of this assessment were treated as reduction landings in the northern region. Similarly and beginning in the mid-1980s, port samples from the northern region (by Virginia vessels returning from more northern waters) were used to develop age compositions of removals from the northern region.

Landings for the bait fleets were uncomplicated as these vessels typically operate over a much smaller geographic range than the reduction fleet; therefore, it was assumed that bait removals came from the state in which the fish were landed.

4.1.4 Commercial Reduction Catch Rates (CPUEs)

For many fisheries, catch-per-unit-effort (CPUE) from fishery-dependent sources is used as an index of abundance, where a proportional change in CPUE is expected to represent the same proportional change in stock size. However, for purse-seine fisheries it has been demonstrated that CPUE and nominal or observed fishing effort are poor measures of population abundance due to hyperstability (Clark and Mangel 1979), which is especially true for those fisheries that utilize spotter aircraft. Therefore, fishery-dependent CPUEs have not been considered a relevant measure of population abundance for menhaden assessments. For reference purposes, CPUEs in total landings divided by vessel-weeks for the Atlantic menhaden fishery for 1948-2013, are tabulated in Table 4.1.3.1.1.

Effort Based on Vessel-Week, 1940-2013

Historic catch summations and estimates of fishing effort in the menhaden purse-seine fishery for reduction are based on company records of unloads by individual vessels. At dockside, menhaden are hydraulically pumped from the carrier vessel, or “steamer”, into a rotating hopper device (see above). Companies report daily vessel unloads in terms of 1,000s of “standard” fish, which are converted to kilograms.

Normally, menhaden vessels unload their catches daily; however, trips of 2-3 days are common. The menhaden plant records, while showing the date and amount of fish unloaded per vessel, do not list number of days fished, nor days when the catch is zero. Logbooks were placed on menhaden vessels during the late 1950s and early 1960s to try and capture better information on “fishing” and “non-fishing” days at sea (Roithmayr 1963), but compliance was incomplete (Nicholson 1971). Thus, through about the 1970s there was no satisfactory way to acquire a complete at-sea history of each vessel.

Considering that menhaden vessels generally operate continuously over the course of a fishing season and fish every day that weather permits, Nicholson (1971) argued that the vessel-week (one vessel fishing at least one day of a given week) was a satisfactory unit of nominal fishing effort for the Atlantic menhaden purse-seine fishery. Thus, a vessel unloading a catch at least one time during a given week was assigned one vessel-week of effort. Vessel-weeks for all vessels in the fleet are calculated across all months of operation, and then summed for an estimate of annual nominal fishing effort for the fishery. These data are available for 1940-2013 (Table 4.1.3.1.1). The linear regression for landings on nominal fishing effort (1940-2013) is:

$$L = 0.16\,E + 140.3,$$

where L is landings in thousands of metric tons and E is nominal fishing effort in vessel-weeks (Figure 4.1.4.1).

4.1.5 Potential Biases, Uncertainty, and Measures of Precision

When the Menhaden Program began in the early 1950s at the Beaufort Laboratory, staff visited menhaden plants along the Atlantic coast to obtain detailed catch/effort information back to 1940. These landings and those subsequently collected are thought to be quite accurate. Kutkuhn’s[1] study was conducted to determine the quantity of fish passing through the plant based on the number of dumps (hopper). The results suggest that these are accurate to about 3.7% coefficient of variation. It was noted that greater uncertainty was associated with fish spoilage (more likely in the earlier years with unrefrigerated fish holds). Reduction landings since 1940 are believed to be both accurate and precise compared to most other high-volume U.S. fisheries.

Development of catch matrices depends on three data sources, including the landings, sampling for weight, and age determination. Sampling for size and age has been conducted weekly by port since 1955[3]. The catch matrix is built from samples by port, week, and area fished. Concerns about bias related to “topping off” by vessels from Reedville fishing outside its fishing area has been addressed through post-stratification using the CDFRs (see Section 4.1.3.3).

Uncertainty Associated with Ageing

During the early decades of the Menhaden Program at the Beaufort Laboratory scales from individual menhaden specimens were read multiple times by several readers. Disagreements on age estimates were decided by an additional reading. By the early 1970s - probably because of budget constraints - only a single reader was retained on staff to age menhaden scales. This employee, Ethel A. Hall (EAH), has been reading menhaden scales for the Beaufort Laboratory from 1969 to the present.

In an effort to estimate contemporary precision of Atlantic menhaden age estimates, EAH was asked to re-read scale samples from the 2008 fishing season. Re-ageing efforts occurred during summer 2009. See **Section 3.1** for results of this study.

4.2 Commercial Bait Fishery

4.2.1 Data Collection Methods

Atlantic menhaden are harvested for bait in almost all Atlantic coast states and are used for bait in commercial (e.g., American lobster and blue crab) and sport fisheries (e.g., striped bass, bluefish). Bait harvest comes from directed bait fisheries, primarily small purse seines, pound nets, gill nets, and cast nets. Menhaden are also landed as bycatch in various food-fish fisheries, such as pound nets, haul seines, and trawls. Systems for reporting bait landings have historically been incomplete, particularly for Atlantic menhaden because of the nature of the fishery and its unregulated marketing. Data limitations also exist because menhaden taken as by-catch in other commercial fisheries are often reported as "bait" together with other fish species. Additionally, menhaden harvested for personal bait use or sold "over-the-side" likely go unreported. As a result, the TC has determined that even though bait landings records date back to 1955, the most reliable bait landings are available since 1985 because of recent improvements made to harvester and dealer reporting programs.

Despite problems associated with estimating menhaden bait landings, data collection has improved in many areas. Some states license directed bait fisheries and require detailed landings records. Most recently, harvest data reporting requirements changed through the implementation of Amendment 2 to the Atlantic Menhaden FMP because of the need for states to monitor in-season harvest relative to their newly implemented state specific quotas. Beginning in 2013, several states went from monthly reporting to weekly or daily reporting to avoid exceeding their allocated quota (Table 4.2.1.1).

Bait landings from 1985-2013 were compiled using state specific landing records by gear type and represent the most accurate dataset (Table 4.2.1.2). Bait landings from 1955-1984 were compiled using the Atlantic Coastal Cooperative Statistics Program’s (ACCSP) data warehouse, which houses historical data but is admittedly incomplete. More specifically, purse seine bait landings from 1955-1984 were not included because bait/reduction disposition is not available

---

[3] “Instructions for menhaden sampling program”, revised May 1995 by J. Smith. Available in PDF format.

prior to 1985 so all the purse seine landings during this time period were included in the reduction landings even though a fraction of those landings may have been for bait purposes. Therefore, bait landings data from 1955-1984 are only from pound nets and “other” gears (Table 4.2.1.2).

Description of Bait Fisheries

In New England, purse-seine landings in Maine, Massachusetts, and Rhode Island account for the majority of the recorded bait landings. In recent years, the main purse seine operation that fishes in Rhode Island state waters lands its harvest in Massachusetts because the menhaden resource is available in Narragansett Bay but the operation is based out of Fall River, MA. An ocean trap net and pound net fishery has historically operated off Rhode Island and Massachusetts. In New Hampshire and Connecticut, smaller directed gill net fisheries are well-regulated and monitored. The bulk of menhaden landings for bait in New England are used in the lobster fishery.

New Jersey dominates current menhaden bait landings among the Mid-Atlantic states. Within New Jersey, purse-seine gear accounts for over 95% of reported bait landings. New Jersey requires reports of catch by fishing area for licensed bait purse-seine vessels. Historically, pound nets and gill nets also contributed to bait landings in New York and New Jersey. Delaware closely regulates its directed gill net fishery, obtaining detailed catch/effort data each year (ASMFC 2001).

Virginia snapper rigs (small purse seines) dominate (about 85%) the reported menhaden bait landings in Chesapeake Bay, as documented by Captain’s Daily Fishing Reports beginning in 1998 (Smith and O’Bier 2011). Pound net landings contribute significantly in Maryland, Virginia, and the Potomac River. Most of the catch is used in the blue crab pot fishery (ASMFC 2001).

Bait harvests in the South Atlantic were historically dominated by landings in Florida and North Carolina. Some landings in North Carolina are reported directly, while the rest are estimated from fishery-dependent sampling. The principal use for menhaden as bait in North Carolina is in the blue crab pot fishery. South Carolina and Georgia have no directed menhaden fisheries; shrimp trawl by-catch and cast nets supply menhaden to crab potters and sport fishermen in those states. Florida's East coast had substantial menhaden landings for bait from gill nets and purse seines prior to the implementation of a net ban in 1995 (ASMFC 2001).

Biological Sampling Methods and Intensity

Sampling of the bait fishery for length and age has generally improved since 1988, especially beginning in 1994 when the Atlantic Menhaden Advisory Committee (precursor to the TC) emphasized greater biological sampling of the bait fishery. A pilot study to sample the menhaden bait fishery was initiated in 1994 based on sampling intensity comparable to that used in the reduction fishery (i.e., one 10-fish sample per 515 mt landed). In particular, bait landings were stratified by state into purse-seine, pound net, and gill net landings. Sampling intensity of one to two 10-fish collections per 515 mt of Atlantic menhaden was recommended. When less than 515 mt of landings were expected, a minimum of at least two to three 10-fish collections were recommended. Bait landings were so low in New Hampshire, Connecticut, South Carolina, and Georgia that no samples were recommended. In 1994, most of the recommended samples targeted Maine (10-20 collections), Rhode Island and Massachusetts (12-24), New Jersey (16-30), Virginia (17-34) and North Carolina (8-14). Most samples recommended were from the purse-seine bait fishery (56-111). Fewer samples were recommended for the pound net (12-22) and gill net (10-16) bait fisheries. Although the goals of these recommendations were not uniformly met at that time, the process was set in motion to begin collecting these data. More specifically, from 1994 to 2006 the average number of fish sampled from the bait fishery was 511. Sampling effort increased to match increased bait harvest from 2007 to 2011 resulting in an average of 1,080 fish sampled over that timeframe.

In 2012, to formalize the bait biological sampling, the TC conducted a power analysis ($\alpha = 0.1$, power=0.9) to statistically determine the level of sampling needed in the bait fishery to adequately represent the age structure in the population (McNamee 2012). Based on the results of the power analysis, and a recommendation by the TC, states implemented length and age sampling as a formal monitoring requirement through Amendment 2 in 2013, as detailed below (ASMFC 2012a):

- Each state in the New England (ME, NH, MA, RI, CT) and Mid-Atlantic (NY, NJ, DE) regions are required to collect one 10-fish sample (age and length) per 300 metric tons landed for bait purposes.
- Each state in Chesapeake Bay (MD, PRFC, VA) and South Atlantic (NC) regions are required to collect one 10-fish sample (age and length) per 200 metric tons landed for bait purposes.
- The TC recommends collecting the samples by gear type. One 10-fish sample consists of 10 fish collected from a distinct landing event (e.g., purse-seine trip, pound-net set). Each collection of 10 fish is an independent sampling event; therefore, multiple 10-fish samples should not be collected from the same landing event.

As a result, in 2013 states sampled 2,090 ages and 3,223 lengths, representing a significant increase from prior sampling efforts.

4.2.2 Commercial Bait Landings

Coastwide bait landings of Atlantic menhaden gradually increased during the period 1985 to 1997, declined slightly over the next decade, and grew rapidly in recent years (Figure 4.2.2.1). During 1985 to 1997 bait landings averaged 36 thousand mt, and landings reached a relative peak of 41 thousand mt in 1997. Landings gradually declined from 1998 to a low of 26.9 thousand mt in 2006. Since 2006 bait landings have doubled, peaking in 2012 at 63.5 thousand mt[4] (Figure 4.2.2.1).

Bait landings during 1985 to 1993 were widely distributed along the coast with major contributions from Maine, Massachusetts, Rhode Island, New Jersey, the Potomac River Fisheries Commission (PRFC), Virginia, North Carolina, and Florida. During the mid-1990s contributions from the New England states and Florida fell sharply. The decline in landings from New England waters was because of the scarcity of fish from Long Island Sound and north after 1993; the decline in landings in Florida was due to the state's 'net ban' in 1995.

---

[4] Growth of the Atlantic coast bait fishery must be tempered by the knowledge that systems for reporting bait landings have historically been incomplete, and recent landings estimates are more accurate.

More recently, the "snapper rig" (small purse seine) fishery in Chesapeake Bay and the purse-seine fishery off New Jersey have dominated the bait landings; these two fisheries account for approximately 80% of the total bait harvest during 2007-2013. Pound net fisheries in Maryland and the Potomac River account for approximately 12% of the total harvest over that same time period with gill nets, cast nets, and trawlers making up the rest in the other states.

In recent years (2007-2013) bait landings have averaged approximately 23% of the total coastwide Atlantic menhaden landings (including landings for reduction). This is up from an average of approximately 11% of total landings for the period 1985-2000. The relative increase of menhaden for bait as a percent of coastal landings since the late 1990s is attributed to better data collection in the Virginia 'snapper rig' bait seine fishery, the relative decline in coastal reduction landings because of plant closures, and increased interest in menhaden for bait purposes because of recent limitations on catch of Atlantic herring, a preferred bait for the lobster fishery.

4.2.3 Commercial Bait Catch-at-Age

Because of the limited age composition data, characterizing the age distribution of the removals by the bait fishery has been done at the region/year level, rather than port/week/area fished used for the reduction fishery. Four regions are defined as follows: (1) New England (Connecticut and north); (2) Mid-Atlantic (coastal Maryland, and Delaware through New York); (3) Chesapeake Bay (including coastal waters of Virginia); and (4) South Atlantic (North Carolina to Florida). Separate catch-at-age matrices were constructed for the northern and southern bait fisheries where the northern region included (1) and (2), while the southern region included (3) and (4). When the number of samples for a given region and year was less than 50, data were pooled across the years available and substituted for that year. For the New England region, data for 1986-2008 were pooled and used for individual years 1986-1993, 1996-2006, and 2009-2013. Data for 1985 was kept separate because these were particularly small fish. For the Mid-Atlantic region, data for 1994-2013 were pooled and substituted for individual years 1985-1993 and 2004-2005. For the Chesapeake Bay region, data for 1995-2013 were pooled and substituted for individual years 1985-1994. For the South Atlantic region, three temporal periods were used to pool data: (1) 1985-1989, (2) 1990-1996, and (3) 1997-2013. Years within the respective temporal periods for which substitution was necessary were 1988-1990, 1993, 1996, and 1999-2013. These three temporal periods were used in the South Atlantic region in order to reflect the changes in size over time with the middle period have the smallest fish and the most recent period having the largest fish sampled. The resultant northern and southern catch-at-age matrices for the bait fishery are shown in Tables 4.2.3.1 and 4.2.3.2. So as not to completely ignore the small amount of recreational catches (see Section 4.3), the catch matrix was inflated to reflect these additional landings. The inflation was calculated on a regional basis.

4.2.4 Commercial Bait Catch Rates (CPUE)

See section 5.1 below.

4.2.5 Potential biases, Uncertainty, and Measures of Precision

Greater uncertainty is expected for the bait fishery as compared to the reduction fishery. Landings reconstructed for 1955-1984 likely underestimate actual bait landings because of a lack of information on purse-seine fishing for bait during this period. Bait landings since 1985 are significantly better, particularly for purse-seine landings for bait. The catch matrix is built from limited sampling for 1985 to present (computed by region and year), and is therefore subject to much greater uncertainty than the catch matrix for reduction landings. However, information on bait size and age has improved in recent years. See ***sections 2.3 and 4.1.6*** for uncertainty associated with ageing.

4.3 Recreational Fishery

4.3.1 Data Collection Methods

The Marine Recreational Fisheries Statistics Survey (MRFSS, 1981-2003) and the Marine Recreational Information Program (MRIP, 2004-2012) data sets were used to derive a time series of recreational landings of Atlantic menhaden. Estimated recreational catches are reported as number/weight of fish harvested (Type A+B1) and number of fish released alive (Type B2). The fundamental cell structure for estimating recreational catches is by state [Maine – Florida], mode of fishing [beach/bank, manmade, shore, private/rental, charter], fishing area [inland, ocean (<=3mi), ocean (>3mi)], and wave [six 2-month periods]. Both MRFSS and MRIP estimates were obtained from the Atlantic Coastal Cooperative Statistics Program (ACCSP) database. The overlapping years of the MRFSS and MRIP data were used to calibrate the MRFSS time-series to the MRIP estimates, following the procedure outlined by the MRFSS/MRIP Calibration Ad Hoc Working Group (Salz et al. 2012). Harvested fish (types A+B1) and released fish (type B2) were reported separately for the two assessment regions (Maryland to south and Delaware to north). The majority of landings from Maryland were assumed to come from Chesapeake Bay; therefore, those landings were allocated to the southern region.

4.3.2 Recreational Landings

The recreational landings estimates of Atlantic menhaden for the two assessment regions are shown in Table 4.3.2.1. These estimates include an assumed 50% mortality of released fish (A+B1+0.5*B2), the same value used in the 2010 benchmark assessment. The average recreational landings in the past ten years was estimated at 207 mt in the north and 230 mt in the south, representing less than 1% of total (combined bait and reduction) landings. Landings were highly variable with an increasing trend in recent years in both regions (Figure 4.3.2.1). Available recreational data were insufficient to calculate recreational catch rates (CPUE).

4.3.3 Recreational Discards/Bycatch

To determine total harvest, an estimate of release mortality to apply to the B2 caught fish is necessary. Under the assumption that many of these recreationally caught fish were caught by cast net, the judgment of the data workshop participants was that a 50% release mortality rate was a reasonable value. Based on this value, the total number of fish dying due recreational fishing (A+B1+0.5*B2) is summarized in Table 4.3.2.1.

4.3.4 Recreational Catch-at-Age

Insufficient biological samples were available to develop a recreational catch at age matrix. As in the 2010 benchmark, recreational landings were combined with bait landings, and the bait catch-at-age matrix was expanded to reflect these additional landings in numbers applied regionally and then combined.

4.3.5 Potential biases, Uncertainty, and Measures of Precision

The MRFSS/MRIP provides estimates of PSE (proportional standard error) as a measure of precision. The PSE values associated with MRFSS/MRIP estimates for Atlantic menhaden were substantial (>50%) in most years. Potential biases are unknown.

5.0 Indices of Abundance

5.1 Fishery-Dependent Indices

The TC initially reviewed 14 fishery-dependent datasets from Atlantic coast states, and 10 were found to be unsuitable for various reasons (see Table 5.1.1). The remaining four datasets (MA pound net, NJ gillnet, MD pound net, and PRFC pound net) were explored more fully and used to create state-specific indices of relative abundance (Table 5.1.2 and Figure 5.1.1).

Due to a high prevalence of zero catches in these data, a delta-GLM approach was used to standardize the data and create annual indices of abundance (i.e., *dglm* function in R). Detailed methods, model diagnostics, and results are available in the document "Fishery_dependent_indices.docx" in supplemental materials.

A review of all possible fishery-independent (FI) and fishery-dependent (FD) datasets revealed that FD indices had significant positive correlations with FI indices, within their respective regions (see Section 5.3 below). Fishery-dependent lacked both age and length data; thus information to determine selectivity were not available. Furthermore, because the FI datasets had longer time series and were generally of a higher quality (i.e., fewer issues of concern; e.g., one data set was one permit holder), all FD indices were removed from consideration in assessment models.

5.2 Fishery-Independent Indices

The TC initially reviewed over 45 fishery-independent surveys (Table 5.2.1). All fishery-independent surveys used in this assessment were evaluated using a standard set of criteria. Indices were removed from consideration for creation of an index for potential use in the assessment if they did not meet all of the following criteria:

1. Absence of hyperstability or gear saturation (unless it could be corrected)
2. Sufficient time series (minimum 10 years)
3. Defined spatial extent
4. Includes trips with zero catches unless evidence can be provided that the lack of zeroes does not impact the index.
5. Consistent data collection over time or ability to account for changes with model or through correction
6. Proper identification of catches to species level
7. Standardization model converges
8. Information on gear selectivity available to determine if the index is YOY or adult

Specific justifications for not considering individual surveys are summarized in Table 5.2.1. The remaining 28 datasets were explored more fully and used to create regional indices of abundance for juveniles and adults (Figure 5.2.1).

All surveys were standardized according to a common decision tree because most surveys displayed a high prevalence of zero catches, were not designed to target menhaden, and used a variety of different gears. Standardization was applied using a generalized linear model to account for factors that might affect catchability of menhaden; see document “FI Index Standardization Guidelines” in supplemental materials for methodology. Detailed model development, diagnostics, and results are available in the document “FI index data standardization.docx” in supplemental materials. Standardization was completed for these data sets in order to account for changes in catchability over time. Specifically, the SAS had concerns about the lack of survey design, fixed stations, and that menhaden were not the target species.

5.3 Index Comparison

Four fishery-dependent data sets were considered in the comparisons amongst indices: Potomac River Fishery Commission pound nets, Maryland pound nets, Massachusetts pound nets, and New Jersey gill nets (Figure 5.3.1). Each time series of the index was compared for the years of overlap using a Pearson correlation test using corr.test from the psych library in R. The only significant correlation was found between the Potomac River Fishery Commission pound net index and the Maryland pound net index (Table 5.3.1; Figure 5.3.2). None of the other correlations were significant; however, the New Jersey gill net index and the Massachusetts pound net index were correlated at 0.53 (p=0.12 before multiple comparison correction). The correlations that were most alike in these analyses were the more northern indices versus the more southern indices, which support the idea of more similar trends in specific areas of the Atlantic Coast.

Young of the Year

Six fishery-independent young of the year (YOY), seine data sets were considered in the comparisons amongst indices: Virginia, Maryland, New Jersey, New York, and the Thames and Connecticut River surveys in Connecticut. Ten fishery-independent YOY, non-seine data sets were considered in the comparisons amongst indices: Delaware inland bay trawl survey, Delaware 16-ft trawl survey, Rhode Island trawl survey, Connecticut Long Island Sound trawl survey, Maryland Chesapeake Bay survey, VIMS trawl survey, South Carolina electrofishing survey, New York Peconic Bay trawl survey, New Jersey trawl survey, and the Georgia trawl survey. Each time series of the index was compared for the years of overlap using a Pearson correlation test using corr.test from the psych library in R.

Several comparisons were positively correlated including Delaware inland bay trawl survey and Maryland seine survey (p=0.02 after correction for multiple comparisons), Rhode Island trawl survey and New Jersey trawl survey (p<0.01 after correction for multiple comparisons), Rhode island trawl and New York seine (p<0.01 after correction for multiple comparisons), and Maryland Chesapeake Bay survey and Virginia seine survey (p<0.01 after correction for multiple comparisons; Tables 5.3.2 and 5.3.3; Figures 5.3.2-5.3.5).

Other correlations - 12 total - were positively correlated when not corrected for multiple comparisons including:

- Delaware inland bay trawl survey with the Maryland Chesapeake Bay survey and Georgia trawl survey (Figure 5.3.6),

- Maryland Chesapeake Bay trawl survey with the Connecticut Long Island Sound Trawl survey, the Connecticut Thames River seine survey, and the Maryland seine survey (Figure 5.3.7),
- Connecticut Thames river seine survey and Connecticut River seine survey (Figure 5.3.8),
- Connecticut River seine survey with the New York seine survey (Figure 5.3.8) and the South Carolina electrofishing survey (Figure 5.3.10),
- New York seine survey with the New Jersey seine survey (Figure 5.3.8) and New Jersey trawl survey (Figure 5.3.4), and
- Delaware 16 ft trawl survey with the Connecticut Thames River seine survey and the New York Peconic Bay trawl survey (Figure 5.3.9).

See tables 5.3.2 and 5.3.3 for correlation coefficients and p-values associated with the correlation coefficients, respectively, among all pairwise comparisons of fishery-independent young of the year indices.

Many of these correlations are for surveys whose study areas are in close proximity. However, some indicate more coastwide congruence. In concert, the recruitment index suite seems to provide supporting evidence of specific year classes having good recruitment. This indication of similar years with large year classes is valuable to the assessment as these indices are being used to create a recruitment index, which influences the estimation of recruitment deviations each year.

Age-1+

Twelve fishery-independent data sets were considered in the comparisons amongst indices: Virginia gill net shad survey, North Carolina gill net survey, South Carolina trammel net survey, Connecticut Long Island Sound trawl survey, New Jersey trawl survey, Delaware 30-ft trawl survey, Delaware 16-ft trawl survey, VIMS trawl survey, Georgia trawl survey, SEAMAP, CHESFIMS, and CHESMAP. Each time series of the index was compared for the years of overlap using a Pearson correlation test using corr.test from the psych library in R.

None of the correlations were significant after correction for multiple comparisons; however, 15 comparisons were positively correlated without the correction. Those comparisons included:

- VIMS trawl survey with the Delaware 30ft trawl survey, the SEAMAP survey and the CHESFIMS survey (Figure 5.3.11),
- Delaware 30ft trawl survey with the CHESMAP survey (Figure 5.3.11),
- Connecticut Long Island Sound Trawl survey with the VIMS trawl survey, the Delaware 30 ft trawl survey, the CHESMAP trawl survey, and the CHESFIMS trawl survey (Figure 5.3.12),
- Georgia trawl survey with the SEAMAP trawl survey, the North Carolina gill net survey, and the South Carolina trammel net survey (Figure 5.3.13),
- North Carolina gill net survey with the South Carolina trammel net survey (Figure 5.3.13),
- New Jersey trawl survey with the SEAMAP trawl survey and the VIMS trawl survey (Figure 5.3.14), and
- CHESFIMS with the Delaware 16ft trawl survey (Figure 5.3.15).

See tables 5.3.4 and 5.3.5 for correlation coefficients and p-values associated with the correlation coefficients, respectively, among all pairwise comparisons of age-1+ fishery-independent indices. (Tables 5.3.4 and 5.3.5; Figures 5.3.11-5.3.15).

Many of the adult or age-1+ indices show common trends in adult abundance across regions. Specifically, the indices show an increasing trend in abundance or larger year classes of older individuals in the most recent part of the time series. Common trends among indices lead to a weight of evidence suggesting that the adult abundance is increasing in the most recent time period.

Comparison among All Indices

Each of the indices was lagged appropriately so that they all matched with the appropriate year and age represented. For instance, all YOY indices were lagged ahead one year (+1); thus, age-0s born in 1989 would match with an age-1 index in 1990. Adult indices that were considered more northern were lagged back one year (-1) in order to reflect that those indices would likely be capturing age-2 fish (which is supported by the commercial reduction age data). Thus, all indices were aligned, and a single large correlation matrix was created. This allowed for comparisons of trends across the entire coast and across age classes represented.

No additional significant correlations were identified in the overall correlation matrix when adjusting p-values for multiple comparisons; however, without adjustment, many comparisons had significant correlations (Tables 5.3.6 and 5.3.7). The large number of significant correlations supports the idea that a similar trend in adult abundance is apparent coastwide. Using lags to account for differences in selectivity, individual cohorts can be tracked as they proceed through the suite of fishery-independent indices.

This corroborating evidence supports the SAS's conclusion that the fishery-independent data are reflecting the true underlying dynamics in the population. The trends seen in the fishery-independent indices are further corroborated by fishery-dependent datasets and powerplant impingement records, which both suggest an increase in abundance in recent years (see document "Powerplant_impingement.doc" in supplemental materials).

5.3.1 Indices Used in the Assessment

YOY Index (1959-2013)

All 16 available fishery-independent YOY data sets that met the above criteria were used to create a coastwide index of recruitment for use in the base run of the Atlantic menhaden assessment model. The individual indices were combined using the hierarchical modeling as described in Conn (2010). This method allows for the combination of indices with the assumption that the survey data sets have similar selectivity. For the YOY index, this assumption should be met because all data sets were censored such that they only included age-0 individuals. The censoring rules for the datasets followed region specific length cutoffs as specified in Table 5.3.8. The resulting index was based on the Maryland striped bass seine survey for 1959-1986, as that was the only index available for that time period. After 1987, several other indices were included. The method used by Conn (2010) applies to indices of different lengths of time, as his example for Spanish mackerel in the paper demonstrates.

The resultant YOY index shows the largest recruitments occurring during the 1970s and 1980s (Figure 5.3.16; Table 5.3.9). Recruitment has since been lower with notable year classes in 2005 and 2010. The CV for the index ranged from 0.4 to 1.02 (Table 5.3.9). This index was used to inform annual recruitment deviations in the model along with the catch at age data.

An additional YOY index was created from these same survey data sets. The coastwide index was an areal extent index in which the size of the survey sampling frame was used to weight the standardized survey information (Figure 5.3.16). This approach was discussed as a possibility with the assumption that area relates to productivity of an area for recruitment of menhaden. Specifically, from 1959-1986, the index was based on MD seine survey and from 1987-2013 the index was based on all of the data sources. This index was used as a sensitivity run and is similar to the index created using the methods in Conn (2010).

Age-1+ Indices

To create a coastwide index of adult abundance, trawl surveys were selected because gear configuration was most similar and because trawl gears had the best spatial coverage along the coast. The SAS expressed concerns about the potential for selectivity differences among the trawl surveys. A Principal Component Analysis (PCA) was run on the length compositions of the nine trawl gears to see which had the most similar sized captures of menhaden. According to the PCA, two groups of indices fell out as having the most consistent selectivities (Figure 5.3.17). A southern adult index (SAD) was created using the method of Conn (2010) that included the SEAMAP trawl survey and the GA trawl survey for the years 1990-2013 (Figure 5.3.18). Also, a northern adult index (NAD) was created using the method of Conn (2010) that included VIMS, CHESMAP, CHESFIMS, NJ, CT, and DE 16- and 30-ft trawls for the years 1980-2013 (Figure 5.3.18). The surveys included in the SAD index captured smaller fish than the surveys included in the NAD index. Given that a majority of the catches for the surveys incorporated into the SAD index occurred on or about mid-May, the SAD index is considered a start of the year index. Given that a majority of the catches for the surveys incorporated into the NAD index occurred on or about early September, the NAD index is considered a mid year index.

The two adult indices for the assessment both indicate an increase in abundance in the most recent years (Table 5.3.9), which is also a trend seen in other fishery-dependent and -independent data sets. The significant correlation between the NAD and SAD with a one-year lag given the smaller sizes of the SAD index length compositions is 0.47 ($p = 0.02$). This agreement provides additional weight of evidence that the age-1+ population is increasing over the latter part of the time period and that both indices provide similar information on stock abundance. The CV associated with the SAD index ranged from 0.33 to 0.79, and the CV associated with the NAD index ranged from 0.27 to 0.85 (Table 5.3.9).

The length compositions for each of the adult indices were combined across surveys. Raw lengths in 10-mm bins from each survey by year were summed and then divided by the total number of length samples for that year. Length compositions with sample sizes over 100 (number of sets, trawls, etc.) were available continuously for 1990-2013 for the SAD and for 1988-2013 for the NAD and were used to determine selectivity of the respective indices.

Comparison of Recruitment and Adult Indices

The adult indices are significantly correlated with a one-year lag, while the recruitment index is not significantly correlated with either the SAD or the NAD given the appropriate lags. Lack of correlation between recruitment indices and adult indices is not surprising for a forage fish species such as Atlantic menhaden and can occur due to a number of reasons, including environment, predation, and density-dependent factors creating a disconnect between adult abundance and recruitment. Substantial natural mortality occurs during the period between ages-0 and -1. Differences in natural mortality over time were addressed in some of the sensitivity runs in Section 6, for example the run with time varying natural mortality from the MSVPA-X.

6.0 Assessment Model

Two modeling statistical catch-at-age approaches were considered during the Assessment Workshops: (1) the Beaufort Assessment Model (BAM) and (2) Stock Synthesis (SS). However, only the BAM was selected as the base (preferred) model. Realistic estimation of growth in the SS model was hindered by the need to account for seasonality. Unfortunately, time constraints did not allow those modifications to be made for this assessment. We anticipate that work on the SS model will continue in the future and that it will be ready for consideration during the next benchmark assessment. A thorough description of the BAM model and a brief overview of the (incomplete) SS model are provided below.

6.1 Beaufort Assessment Model (BAM)

The Beaufort Assessment Model (BAM) is a forward-projecting statistical catch-at-age model. The essence of such a model is to simulate a population that is projected forward in time like the population being assessed. Aspects of the fishing process (e.g., gear selectivity) are also simulated. Quantities to be estimated are systematically varied from starting values until the simulated population's characteristics match available data on the real population as closely as possible. Such data include total catch by year, observed age composition by year, observed indices of abundance, and observed length composition by year. The method of forward projection has a long history in fishery models. It was introduced by Pella and Tomlinson (1969) for fitting production models. Additionally, forward projection was used by Fournier and Archibald (1982) and Deriso et al. (1985) in their CAGEAN model and by Methot (1989) in his stock-synthesis model. Forward-projecting age-structured models share many attributes with ADAPT-style tuned and untuned VPAs. The model developed for this assessment is an elaboration of the CAGEAN and stock-synthesis models and very similar in structure to models used for assessment of Gulf of Mexico cobia (Williams 2001; SEDAR 28 - 2012), South Atlantic red porgy (SEDAR 1 - 2002), South Atlantic black sea bass (SEDAR 2 - 2003; SEDAR Update 2005; SEDAR 25 - 2011; and SEDAR Update 2013), South Atlantic snowy grouper and tilefish (SEDAR 4 – 2004, SEDAR 25 - 2011), South Atlantic red snapper (SEDAR 15 – 2008, SEDAR 24 - 2010), Atlantic menhaden (SEDAR 20 - 2010), and Gulf menhaden (SEDAR 32A - 2013). The BAM was the forward-projecting age-structured model used in the previous Atlantic menhaden assessments, has multiple options for benchmark computation, has many model diagnostics, and can account for uncertainty through sensitivity runs and Monte Carlo bootstrapping.

Treatment of Indices

Several sources of information were used to create three abundance indices for use in the BAM model (See Section 5). Two adult indices were created using trawl time series from a number of state fishery-independent surveys. A single recruitment index was created across several gear types using several different fishery-independent surveys from a number of states. Each of these indices was included in the base run of the BAM along with length compositions for the adult indices because they were deemed as accurate representations of the population over time and best available science.

The two adult surveys included data from southern and northern states separately and were called the southern adult index (SAD) and northern adult index (NAD). These data sets were parsed out using principle components analysis on the length compositions, which clearly showed smaller fish sampled in the south and larger fish sampled in the north. Age-specific selectivity schedules were estimated for each of these indices by fitting to length composition data sampled during the surveys. The SAD index was estimated as a double logistic selectivity as large fish were absent from the length samples. The NAD index was estimated as logistic selectivity as many of these surveys captured some of the largest individuals sampled by either fishery-independent or –dependent gears. The level of error in each index was based on the precision surrounding the annual values produced by the hierarchical method used to standardize and combine the component indices. In the BAM model, the estimates of the product of total numbers of fish at the appropriate time of the year (May 15 for SAD and September 1 for NAD), a single catchability parameter, and the selectivity schedule were fit to the index value in that same year for each respective index. The error in both of these abundance indices was assumed to follow a lognormal distribution.

The recruitment index used in the BAM model comes from a series of state-specific surveys. These surveys, ostensibly designed for other species, capture primarily juvenile or age-0 menhaden. In the model the juvenile abundance index (JAI) was treated as an age-0 CPUE recruitment index, by fitting the product of the model estimated annual age-0 numbers part way through the year (June 1) and a constant catchability parameter to the computed index values. The catchability parameter for this index was blocked in order to accommodate data streams contributing to the index. Therefore, two constant catchability parameters were estimated for this index, one for 1959-1986 and one for 1987-2013. This allowed for changing spatial coverage in the index (the spatial coverage changes as survey time series were added) as well as changes due to habitat with increasing spatial coverage of the index. The error in the JAI index was assumed to follow a lognormal distribution.

Fishery Selectivity

Because of the migratory behavior of Atlantic menhaden (Section 3.7), changes in the spatial distribution of the fishery likely impacted fishery selectivity over time (Sampson and Scott 2011; Sampson 2014; Waterhouse et al. 2014). The use of dome-shaped selectivity to capture these dynamics of the commercial fisheries was thoroughly explored and discussed during the assessment process.

Comparison of fishery-independent and dependent data

Length data are available for Atlantic menhaden from a number of sources including fishery-dependent (1955-2013) and fishery-independent (years vary) data collection. These sources span the majority of the range of the species and provide information to guide the decisions regarding selectivity of both the indices and fisheries within the stock assessment model.

The combined fishery-independent data sets were compared to available fishery-dependent data to determine if larger menhaden are available than have been sampled from the fishery. The presence of larger fish in the fishery-independent data sets indicates that the fishery may not capture the full range of sizes from the population; thus providing evidence for dome-shaped selectivity. Comparisons were completed both for common years among the data sets and across all years of available fishery data. Comparisons among the common years of data between the fishery-dependent and each individual fishery-independent dataset provide information on the overlap of sizes sampled given a specific time frame. Comparisons among the fishery-independent data and all years of the fishery-dependent data provide information on historical sampling relative to collective information on sizes from fishery-independent surveys. Because it was thought that the fishery would be harvesting the entire range of sizes during the 1950s and 1960s, the comparison across all years gives information on the likely shape of the selectivity for those early years.

The comparisons of fishery-independent and fishery-dependent data indicated that the fishery samples do not represent the entire size range of the population for the entire duration of the fishery (1955-2013). Four datasets are available that captured fish larger than those sampled from the fishery. Those datasets include the Northeast Fishery Observer Program (Figure 6.1.1; more specifics on this dataset included below), the Maryland gill net survey (Figure 6.1.2), the New Jersey ocean trawl (Figure 6.1.3), and the Connecticut Long Island Sound trawl survey (Figure 6.1.4). These datasets all demonstrate that lengths are found in the population that have not been sampled from the fishery during the entire history of sampling. These datasets also show that fishery-independent sampling collects larger individuals more frequently than the fishery-dependent sampling. These analyses provide support for dome-shaped selectivity in the fishery during the entire time period (1955-2013).

Comparison of fishery lengths – observer data

Length frequency data of menhaden from the Northeast Fisheries Observer Program (NEFOP) were obtained and compared to the commercial fishery as well as the composite fishery-independent survey indices (NAD, SAD). Over 26,000 individual length observations (from 609 trips) were available from the NEFOP database from 1989 to 2013, covering four gear types (Table 6.1.1).

The majority of NEFOP length data for menhaden were obtained during commercial gillnet trips. Unfortunately, because of inherent mesh-size selectivity of gillnets, data from this gear type were not particularly informative for evaluating fishery selectivity. Likewise, so few observations were available from purse seines and midwater trawls in the northern region that these gear types were also uninformative. Fortunately, sufficient data were available from the northern bottom trawl fishery (767 lengths from 61 trips) that a comparison with the reduction fishery was possible. Despite the presumed extreme low catchability of an epipelagic schooling fish like menhaden in a bottom trawl, it was assumed that the capture process was sufficiently random with respect to size that the resulting length frequencies were representative of the available size of menhaden.

Both the northern bottom trawl fishery (NEFOP) and the NAD index had a distinct mode around 30 cm, which was approximately 10 cm larger than the mode of the northern commercial reduction fishery (Figure 6.1.5). The TC felt that the NAD index and NEFOP datasets corroborated each other in that larger menhaden appeared to be available in the northern region than were harvested by the commercial reduction fishery, supporting the existence of dome-shaped selectivity (Figure 6.1.5).

For the southern region, there were sufficient NEFOP samples in both the purse seine and bottom trawl fishery to compare against the reduction fishery. As expected, the mode of the southern reduction fishery was coincident with the observer data from the same fishery (Figure 6.1.6). However, the primary mode of the bottom trawl fishery was approximately 4 cm greater than that of the reduction fishery, lending support to the possibility of dome-shaped selectivity in the southern region as well (Figure 6.1.6).

Although the TC concluded that fishery selectivities were dome-shaped due to the spatio-temporal overlap of the fish and fishery and potential targeting of the fishery, the TC was unsure as to the extent of the doming and whether the model would have the information to estimate the dome; therefore, likelihood profiling and simulation testing of the model were used to determine that selectivity was estimable.

Support from growth information

Additional information to support selectivity decisions comes from the growth or age and length information collected from the fishery. Specifically, the CV in lengths as age decreases as age increases, which is unexpected (Figure 6.1.7). The expectation with growth curves with adequate sampling is that the CV will remain constant or increase with age. In Figure 6.1.7, there appears to be a size at which the fishery is no longer capturing Atlantic menhaden. Given that the fishery-independent data show that those sized fish are available in the population, again lends support to dome-shaped selectivity (Schueller et al. 2014).

Overall decisions on selectivity

The selectivity for the fishery-independent indices was defined from the length composition data available and specified functional forms. The selectivity of the recruitment index was set at 1.0 for age-0, while all other ages were set at 0.0. The recruitment selectivity was specified as such because it was intended to reflect only the abundance of age-0s (recruitment) over time. The SAD index was considered to have dome-shaped selectivity because its two component indices catch predominantly smaller fish. Finally, selectivity of the NAD index was considered to be flat-topped because some of the largest lengths observed in any of the datasets came from the surveys included in this index.

All fisheries in the model were considered to have dome-shaped selectivity. Support for this conclusion comes from the presence of larger fish in fishery-independent data, and the decreasing variation in length with respect to age (from fishery-dependent data). Several recently published papers demonstrate that dome-shaped selectivity can occur because of heterogeneity in age compositions in the population across space and heterogeneity in fishing that population. Based on the work completed by Sampson and Scott (2011), dome-shaped selectivity is to be expected for a spatially heterogeneous stock such as Atlantic menhaden (Sampson 2014; Waterhouse et al. 2014). Atlantic menhaden undertake extensive migrations throughout the year. Larger individuals migrate farther north as the summer proceeds; therefore, older individuals are less likely to be harvested in a fishery typically centered in Chesapeake Bay (see Section 3.7).

In addition, the fishery-independent data indicate that there are lengths unsampled by the fishery, and the dearth of those sizes in the growth curve information supports that notion. Missing lengths generally imply dome-shaped selectivity even if selectivity is age based because even if the given age is sampled, some proportion of that age remains missing (based on the lack of lengths). However, these observations do not provide information on the extent of the doming, which is unknown and was further explored in other parts of the stock assessment (see Sections 6 and 7).

Menhaden fishery purse seines may have dome-shaped selectivity for several reasons. One reason already discussed is that Atlantic menhaden undertake extensive migrations. Another potential reason is fishery targeting. If the fishery targets the largest schools to set a purse seine on, those schools are likely comprised of the most abundant ages or sizes of fish, which would likely be smaller and younger fish. Thus, even though schools of age-4 to -6 individuals may be present in an area, the schools are not harvested because they are smaller than the optimum school size for the fishery to set on. Finally, larger fish are typically found farther offshore; therefore, if the fishery is located within 3 miles from the coast, they are more likely to encounter smaller fish than sets taken farther offshore.

Parameterization

A summary table of major data sources and time blocks can be found in Table 6.1.2. The ADMB model code and input data file for the base run are attached in Appendix C. All model equations may be found in Appendix C as well. The major characteristics of the model formulation were as follows:

- *Start year and terminal year:* The start year of the model was 1955, and the terminal year of the model was 2013. Alternative start year configurations were explored using sensitivity analyses.
- *Ages:* The model included ages 0 to 6 with age-6 being treated as a plus group.
- *Natural mortality*: The age-specific natural mortality rate was assumed constant. A Lorenzen curve was scaled such that the mortality of the older ages was that estimated in a tagging study (see Section 3).
- *Stock dynamics*: The standard Baranov catch equation was applied. This assumes exponential decay in cohort size because of fishing and natural mortality processes.
- *Sex ratio:* The ratio of males to females was fixed in the model at 1:1 because of the 251,330 fish sampled from the reduction fishery from 1955-1970, 49% were male and 51% were female.

- *Maturity and Fecundity*: The percent of females mature and fecundity were age and time varying, but fixed in the model. Both fecundity and maturity were based on length at age for the population at the start of the fishing year. Annual, cohort-based von Bertalanffy growth parameters (L_∞, K, and t_0) were estimated with a bias correction using the fishery data. These annual growth parameters were then used to estimate mean lengths at age over time. Female fecundity at age (see Section 3) for each year was fixed in the model and was based on a function of mean length by age for the population (Lewis and Roithmayr 1981). Lengths were also used in an estimated logistic regression function for determining maturity each year (see Section 3), which were fixed in the model.
- *Weights at age:* The weight-at-age during spawning and during the middle of the fishery were input into the model and were based on the overall estimates of the parameters for the weight-length equation.
- *Recruitment:* Spawning was assumed to occur on March 1 in the model; hence the spawning time in months was 0.0, as March 1 was the start date for the model. Recruitment to age-0 was estimated in the assessment model for each year with a set of annual deviation parameters, conditioned about a median recruitment, which was estimated in log-space. The SAS tried to fit a Beverton-Holt stock-recruitment curve; however, the steepness parameter always ended up on a bound near 1.0. Given the interim reference points, the panel decided to fix the steepness value at 0.99, which allowed for the estimation of a median recruitment and estimated deviations over time. Estimated deviations were informed by age composition data and a recruitment index.
- *Fishing*: Four fisheries were explicitly modeled. Southern and northern fleets of both the reduction fishery and the bait fishery were explicitly modeled to account for differences in selectivity due to size and age based migratory patterns. Being such a small proportion of the landings in each year, recreational landings were combined with the bait fishery landings. Fishing mortality rates were estimated for each year for each fishery by estimating a mean log fishing mortality rate and annual deviations.
- *Selectivity functions – indices:* Selectivity for the recruitment index was 1.0 for age-0 and 0.0 for all other ages. Selectivity for the NAD and SAD indices was age varying, but constant over time. The NAD index selectivity was estimated as a flat-topped logistic function, while the SAD index selectivity was estimated as a double logistic or dome-shaped function. See Section 3 for further discussion.
- *Selectivity functions - fishery*: Selectivity for each of the fishery fleets was estimated using a functional form of dome-shaped selectivity. Specifically, the selectivity for each fleet was estimated as a four parameter double logistic. Selectivity was dome-shaped for each fishery for all years 1955-2013. Selectivity for both the northern and southern commercial reduction fisheries was time varying using time blocks. For the southern fleet, selectivity was blocked as follows 1955-1971, 1972-2004, and 2005-2013. For the northern fleet, selectivity was blocked as follows 1955-1969, 1970-1993, and 1994-2013. Time blocks were based on the contraction and changes in the fishery over time (Section 4.1). See also *Fishery Selectivity* section above. Selectivity for the bait fishery was constant over time.
- *Discards*: Discards of Atlantic menhaden were believed to be negligible and were therefore ignored in the assessment model.
- *Abundance indices*: The model used three indices of abundance that were each modeled separately: a recruitment (age-0) index series (1959-2013; JAI), a southern adult index

series (1990-2013; SAD), and a northern adult index series (1980-2013; NAD). Each index represents a composite of multiple survey datasets that were standardized/combined using the hierarchical method of Conn (2011).

- *Ageing uncertainty*: Ageing uncertainty was not included in the base run of the assessment due to an absence of information on the true age of sampled fish. However, two sensitivity runs were included which explored different assumed arbitrary levels of ageing uncertainty (see below).
- *Fitting criterion*: The fitting criterion was a total likelihood approach in which catch, the observed age compositions from each fishery, the observed length compositions from each index, and the patterns of the abundance indices were fit based on the assumed statistical error distribution and the level of assumed or measured error (Section 6.1.3).
- *Model testing*: Experiments with a reduced model structure indicated that parameters estimated from the BAM model were unbiased and could be recovered from simulated data with little noise (cf., SEDAR 2007). Simulations were also undertaken for this specific assessment in order to first reproduce results from the assessment and then to determine if selectivity was estimable. Additionally, the general model structure has been extensively peer reviewed. As an additional measure of quality control, code and input data for Atlantic menhaden were examined by multiple analysts to ensure accuracy. This combination of testing and verification procedures suggests that the assessment model has been implemented correctly and provides an accurate assessment of Atlantic menhaden stock dynamics.
- *Biological benchmarks*: Current interim benchmarks adopted for Atlantic menhaden are SPR based benchmarks, specifically $F_{15\%}$, $F_{30\%}$, $FEC_{15\%}$, and $FEC_{30\%}$. Further discussion of benchmarks are in Section 6.2.

Weighting of Likelihoods

The likelihood components in the BAM model include northern and southern reduction landings, northern and southern bait landings, northern and southern reduction catch-at-age, northern and southern bait catch-at-age, the NAD index, the SAD index, a recruitment index, NAD length compositions, and SAD length compositions. For each of these components, a statistical error distribution was assumed as follows:

Likelihood Component	Error Distribution	Error Levels
N & S reduction landings	Lognormal	Constant CV = 0.03
N & S bait landings	Lognormal	Constant CV = 0.15 (1955-1984) and Constant CV = 0.05 (1985-2013)
N & S reduction catch at age	Multinomial	Annual number of trips sampled
N & S bait catch at age	Multinomial	Annual number of trips sampled
NAD length compositions	Multinomial	Annual number of sampling events
SAD length compositions	Multinomial	Annual number of sampling events
NAD index	Lognormal	Annual CV values from 0.27 to 0.85
SAD index	Lognormal	Annual CV values from 0.33 to 0.79
Recruitment index (JAI)	Lognormal	Annual CV values from 0.40 to 1.02

In addition to these components, the likelihood also contained some penalty terms and prior probability distributions. The penalties were on recruitment deviations and the deviations in the initial age structure from equilibrium. The priors were on the two parameters of the descending limb of the double logistic selectivity for the SAD index and the A_{50} of the descending limb of the southern commercial reduction fishery selectivity. For formal configuration of these priors see Appendix C.

Iterative reweighting was first used to weight the data components by setting the weights to a value that allowed for the standard deviation of the normalized residuals (SNDR) to be equal to 1.0 (Francis 2011). However, when this was done, the model achieved only marginal fit to the indices; therefore, per the recommendations of Francis (2011) the indices were upweighted such that the SDNRs were equal to 2.0. A series of SDNR values were explored and are included in the sensitivity analyses in Section 6.1.5 below.

Estimating Precision

The BAM model was implemented using the AD Model Builder software, which allowed for easy calculation of the inverse Hessian matrix, which provides approximate precision of estimated parameters. However, in this case where some key values were fixed (e.g., natural mortality), it is believed that precision measures from the inverse Hessian matrix are underestimates of the true precision. Instead, the BAM model employed a parametric Monte Carlo bootstrap (MCB) procedure in which the input data sources were re-sampled using the measured or assumed statistical distribution and error levels provided. The data sources that were re-sampled in 1,000 bootstrap iterations included northern and southern reduction and bait landings; the NAD, SAD, and recruitment index; natural mortality; NAD and SAD length compositions; northern and southern commercial reduction and bait age compositions; and maturity. The landings and indices were all re-sampled using multiplicative lognormal error using the CVs specified in the model input for each respective component. To implement this approach in the MCB runs, random variables (x_s,y) were drawn for each year y of time series s from a normal distribution with a mean of 0 and a variance of $\sigma^{2s,y}$. Each observation was then perturbed from the original values ($O_{s,y}$) using the equation:

$$O_{s,y} = \hat{O}_{s,y}(\exp(x_{s,y}) - \sigma^2_{s,y}/2)$$

where $\sigma^2_{s,y}/2$ is a bias correction that centers the multiplicative error on the value of 1.0. Standard deviations in log space were computed from *CV*s in arithmetic space:

$$\sigma_{s,y} = \sqrt{\log(1 + CV^2_{s,y})}$$

The age and length compositions were recreated for each year by distributing the number of fish sampled for each year to each age or length based on the probability observed. Variability in natural mortality was included based on variability in natural mortality for age-0 from the MSVPA-X model. Specifically, an age-0 natural mortality was randomly selected from the annual values provided by the MSVPA-X with replacement for each of the individual bootstrap runs. The Lorenzen curve for natural mortality was then scaled such that the age-0 value was equal to the value randomly sampled. This vector was then used as the time invariant value of natural mortality for that model run. Finally, maturity varied over time in the model based on a logistic regression of length. In order to include the uncertainty surrounding that logistic regression into the bootstrap runs, the 95% confidence intervals for the slope and intercept parameters were used as a uniform distribution. A slope and intercept were randomly selected from the respective uniform distributions and then applied to the mean length at age to produce a matrix for maturity for each run. The bootstrap runs incorporated the major sources of uncertainty in the data and model choices.

Sensitivity Analyses

A total of 29 sensitivity runs were completed with the BAM model. These sensitivity runs represent those involving input data, those involving changes to the model configuration, and those included as part of the retrospective analyses.

Sensitivity to Input Data

Several sensitivity runs were conducted to examine various effects to changes in the input data. These runs are related to uncertainty in index choice, growth or life history values, and ageing uncertainty. The following is a list of these sensitivity runs:

Run Number	Sensitivity Examined
am-023	Excluded the recruitment index
am-024	Excluded the SAD index and SAD length compositions
am-025	Excluded the NAD index and NAD length compositions
am-026	Excluded the NAD and SAD indices and the NAD and SAD length compositions
am-027	Constant maturity
am-028	Included ageing uncertainty from agemat (based on scale:scale comparison)
am-029	Included ageing uncertainty; half of values provided by agemat
am-044	Replaced recruitment index with an areal extent recruitment index
am-046	Lower CI from Lorenzen for M
am-047	Upper CI from Lorenzen for M
am-048	Constant growth throughout the model
am-049	No bias correction on the population growth throughout the model

In order to explore the uncertainty related to the inclusion of indices of abundance, several sensitivity runs were completed with data sources excluded or replaced. First, a run was done without the recruitment index (am-023). For this run, priors were required for convergence and Hessian inversion. Priors included were on the slope of the ascending limb of the SAD index selectivity, the A_{50} of the descending limb and slope of the ascending limb of the southern commercial reduction fishery selectivity for the first time block, the A_{50} of the descending limb of the commercial reduction fishery selectivity for time blocks two and three, and the A_{50} of the descending limb of the commercial bait fishery selectivity. Second, runs were completed without the SAD index and SAD length compositions (am-024) and without the NAD index and NAD length compositions (am-025). Run am-025 required several loose priors for convergence of the Hessian. Priors were included on the ascending slope of the SAD index selectivity, the ascending slope of the southern commercial reduction fishery selectivity in the third time block, the descending slope of the southern commercial reduction fishery selectivity in the second time block, and the A_{50} of the descending limb of selectivity for the southern commercial reduction selectivity in time periods two and three. Then, a run was done excluding both the SAD and NAD indices as well as the SAD and NAD length compositions (am-026). This run included priors on the A_{50} of the descending limb of the southern commercial reduction fishery selectivity in the second and third time periods. Finally, a run was done where the recruitment index was replaced with an index that weighted the component surveys using the areal extent of the sampling frame of each survey (am-044). One additional prior was required for this run on the A_{50} of the descending limb of the southern commercial reduction fishery selectivity in time block three. Each of these runs explored the effects of indices on the overall results of the model.

In order to explore the uncertainty related to growth and life history values, several sensitivities were completed related to changes in maturity, natural mortality, and growth. First, to determine the influence of time-varying maturity, a sensitivity run with time invariant maturity was completed (am-027). This run included priors on the A_{50} of the descending limb of the southern commercial reduction fishery selectivity in the second and third time periods. Natural mortality is typically a primary source of uncertainty in stock assessments. To test the sensitivity of the model output to assumptions about natural mortality, sensitivity run numbers am-046 and am-047 were completed. In these runs, natural mortality values used were the upper and lower confidence limits from the Lorenzen curve. Several priors were required for these two runs with higher and lower natural mortality; these include priors on the slope of the ascending limb of the SAD index selectivity and the A_{50}s for the southern commercial reduction fishery selectivity in each time period. Finally, two runs were completed to look at assumptions related to growth. For the run with higher M, priors were also needed on the slopes of the descending limbs of the southern commercial reduction fishery selectivities for all time blocks. First, constant growth throughout the model replaced time varying growth (am-048) to assess the impact of the assumption of time-varying growth that is apparent throughout the data. Finally, a run was completed that did not bias correct growth and all related quantities (am-049). This run was to assess the impact of the bias correction on population growth given sampling is missing some of the largest individuals. In order for this run to converge and for the Hessian to invert, priors were required on the slope of the ascending limb of the SAD index selectivity and on the A_{50} of the descending limb of southern reduction fleet selectivity in time period three.

Two additional sensitivity runs were completed to look at the uncertainty surrounding ageing. Because no validated age data are available, ageing uncertainty was incorporated for these sensitivity runs based on within reader error (am-028) and then halving that within reader error (am-029). Both runs with age reader error (am-028 and am-029) did not fully converge and the Hessian did not invert. This model was likely having difficulty estimating selectivity parameters while including ageing uncertainty. These runs assume that the true age is uncertain, but we have no data to support that assumption. Therefore, these runs are only explorations of the potential effects of true ageing uncertainty. In the end, the SAS decided to use the information in the age composition data and allow the estimation of dome-shaped selectivity in the base run.

Sensitivity to Model Configuration

Several sensitivity runs were conducted to examine the effects of various model configurations. These runs are related to uncertainty in weighting or SDNRs of likelihood components, selectivity, model start year, recruitment index catchability, and choice of ages to model. The following is a list of these sensitivity runs:

Run Number	Sensitivity Examined
am-022	SDNRs of indices = 3
am-022a	SDNRs of indices = 1
am-022c	SDNRs of indices = 4
am-030	All weights = 1.0
am-040	No time blocks for northern and southern commercial reduction selectivity
am-041	All fishery selectivities estimated as logistic (flat-topped)
am-042	Start year of the model = 1982; Use MSVPA-X estimated M
am-043	Start year of the model = 1988
am-045	One estimated catchability for the recruitment index
am-050	Models ages 0 to 4+
am-053	Steepness fixed at 0.9
am-054	Steepness fixed at 0.7
am-055	Steepness fixed at 0.5

In order to explore the effect that weighting the likelihood components had on the fit to the various data components as well as estimated parameters, a series of sensitivity analyses were run. First, in order to determine how much to upweight indices, weights were increased to attain SDNRs of 1 (am-022a), 2 (base run), 3 (am-022), and 4 (am-022c). A runs test, which tests for residual patterns (positives versus negatives), and the sum of squared residuals were explored to determine the best choice related to fits of indices and other data components while eliminating poor residual patterns. Finally, a sensitivity run with all data component weights set to 1.0 was run (am-030). This run required some priors for convergence of the Hessian. The priors were included on the A_{50} of the descending limb of the selectivity for the northern and southern commercial reductions fisheries in the third time block, as well as the A_{50} of the ascending limb of the SAD index selectivity.

Selectivity is always an uncertainty in stock assessments, and that uncertainty was explored with two sensitivity runs related to time blocks and functional form of selectivity. The first was to eliminate time blocks from the northern and southern commercial reduction fishery fleets (am-040). The second was to estimate the selectivity for all fisheries as logistic or flat-topped (am-041).

In order to explore the effects of the start year of the model, two sensitivity runs were completed. The first sensitivity was with a start year of 1982 and used the M estimated from the MSVPA-X (see Appendix A). This run was meant to look at both a time-varying M and starting in a more recent time period after which the recruitment index is more stable (am-042). The second run used a start year later in the time series to reflect more recent recruitment and used the year 1988 as a PCA based decision (am-043). Both of these runs required a series of priors for inversion of the Hessian.

To explore the assumption of steepness of 0.99, which assumes a median recruitment with yearly deviations estimated, the SAS ran sensitivity runs with different assumptions about steepness. Specifically, steepness was fixed at 0.9, 0.7, and 0.5. This allowed for an inspection of the effect of productivity levels on stock status results. In addition, the SAS wanted to explore the implications of the potential for a reduced stock size given that a stock-recruitment relationship exists and the steepness value is one where a population would be less productive at low stock sizes.

Finally, two additional runs were completed to look at the effects of the time block for catchability for the recruitment index and the ages which are modeled. First, a run was completed that estimated only a single catchability for the recruitment index (am-45). This run required a prior on the A_{50} of the descending limb of the southern commercial reduction fishery selectivity during the second time block. Second, a run was completed that used the ages 0 to 4+ (am-050). Each of these addressed a structural model choice or assumption. This run required a priors on the A_{50} of the descending limbs of the northern and southern commercial reduction fishery selectivity during the second and third time blocks, respectively.

Retrospective Analyses

Retrospective analyses were completed by running the BAM model in a series of runs sequentially omitting years 2013 to 2010, as indicated below:

Run Number	Sensitivity Examined
am-031	Retrospective analysis with modeling ending in 2012
am-032	Retrospective analysis with modeling ending in 2011
am-033	Retrospective analysis with modeling ending in 2010
am-034	Retrospective analysis with modeling ending in 2009

The retrospective analysis was limited to these years in order to avoid changing model assumptions that would impact the retrospective analysis. For example, the last selectivity block for the southern commercial reduction fishery started in 2005. If further data would be removed, then little to no data would be available to estimate the selectivity for that fishery and time period.

For this retrospective analysis, the run with the terminal year of 2011 required priors to obtain Hessian inversion. Priors were included on the slope of the ascending limb of the SAD selectivity and on the A_{50} of the descending limbs of the southern commercial reduction fleet in time periods two and three.

Retrospective analyses are meant to demonstrate the behavior of the model to additional years of data. If additional years of data are outside the range of data observed in the past, sometimes patterns may exist in the retrospective runs. This is a natural behavior for a model when data outside the bounds of those observed are included.

Likelihood profiling and simulation analyses

Prior to estimating dome-shaped selectivity for each of the fisheries, the SAS panel wanted to determine if the extent of the dome was estimable. Thus, selectivity was estimated for each fishery as an age-specific value. For each age specific value, a likelihood profile was run across a range of plausible selectivity options. This allowed the panel to determine if there was a value that would be estimated based on the other data that clearly had a better likelihood. The best likelihood was determined by graphing the change in the negative log-likelihood over the values for the age-based selectivity. In addition to running likelihood profiles, the assessment model was rebuilt as a simulation model by another analyst. This was done for two reasons: 1) to make sure that the assessment model was performing as expected (which it was) and to have another review of the code and 2) to determine if the model can estimate selectivity with simulated variability in the model. These two analyses indicated the notion that there was enough information in the available data to estimate the descending limb of the dome-shaped selectivity curves.

Reference Point Estimation – Parameterization, Uncertainty, and Sensitivity Analysis

The current fishing mortality reference points for Atlantic menhaden are $F_{30\%}$ (target) and $F_{15\%}$ (limit) based on SPR. Population fecundity (*FEC*, number of maturing or ripe eggs) is the other current reference point and is a measure of reproductive capacity. The reference points for reproductive output include $FEC_{30\%}$ (target) and $FEC_{15\%}$ (limit). All benchmark calculations were based upon landings weighted selectivity across all fleets and areas, *M*-at-age (which was constant), mean maturity at age, a 1:1 sex ratio, and mean fecundity-at-age from the model inputs. All means are across the entire time series of 1955 to 2013. Also included was the $F_{X\%}$ of the current fishing mortality rate and a plot of the biomass over time divided by the biomass at $F = 0$. Uncertainty in the benchmark estimates was provided by the bootstrap runs; whereby for each run, the current reference points were calculated and a distribution of the benchmarks was provided.

Projections

Projections will be conducted following the Peer Review Workshop pending requests for specific scenarios from the Atlantic Menhaden Management Board. The overall methodology and example results assuming a constant landings scenario are provided in Appendix D.

6.2 Stock Synthesis

In preparation for the 2014 benchmark assessment for Atlantic menhaden, an "integrated" age- and length-structured model for menhaden was constructed using Stock Synthesis (SS) version 3.24 (Methot and Wetzel 2013). The SS model was configured as closely to the base run of BAM as possible, with the notable exceptions of 1) the estimation of time-varying growth, 2) the associated fitting of fishery length and conditional age-at-length composition data, 3) no temporal blocking of catchability estimates for the juvenile abundance index, and 4) exclusion of the southern adult abundance index.

The TC determined that seasonality must be added to accurately characterize growth and incorporate the SAD index in the SS model given the timing of the growth and survey data collected. This model will be revisited and further developed in the future as the assessment is expanded to include additional spatial and seasonal components.

7.0 Model Results

7.1 Goodness of Fit

Goodness-of-fit was governed in the BAM assessment model by the likelihood components in the objective function. The relative fit among the likelihood components was governed by the weighting terms and the assumed error levels for each data source (see Section 6). During the Assessment Workshop, goodness of fit was also judged for each data source through examination of the model residuals.

Observed and model-predicted removals for the northern and southern reduction and bait fisheries (1955–2013; Figures 7.1.1-7.1.4) were compared for the base model run. Reduction fishery removals, which are known fairly precisely, fit very well, as do bait fishery removals. Patterns in the annual comparisons of observed and predicted proportion catch-at-age for the northern and southern reduction and bait fisheries (Figures 7.1.5-7.1.8) indicate a good overall model fit to the observed data. The bubble plots for the northern and southern reduction and bait fisheries (Figures 7.1.9-7.1.12) indicate that the model fit does fairly well at estimating catch-at-age during the time series. There is no patterning observed in the bubble plot that caused concern.

Observed and predicted coastwide recruitment indices were compared for the base model run (1959–2013; Figure 7.1.13). The residual pattern suggests that the recruitment index data did not fit well for relatively large year classes, especially those that occurred in the 1970s and 1980s. Visual examination of the fit suggests that the overall pattern fit reasonably well for the most recent time period with the BAM model capturing some of the lows and highs observed in the index values.

The observed and predicted NAD index (1980–2013; Figure 7.1.14) and SAD index (1990-2013; Figure 7.1.15) values fit well. The general patterns are captured. However, the model has a difficult time fitting estimates to the highest observed values in the 1980s for the NAD and in 1990, 2006, 2009, and 2011 for the SAD. Patterns in the annual comparisons of observed and predicted proportion NAD and SAD measurements at length for the NAD and SAD indices (Figures 7.1.16-7.1.17) indicate good fit to the observed data in some years, but problems in fitting to data in other years. Given the nature of these indices as a conglomeration of data from different state fishery-independent data sources, changing patterns in the data are expected, yet are difficult to discern with model specifications. Therefore, although the fits to the data could be better, the SAS only used the length data to get an idea of ages represented by each index, nothing more. Some of the problems include an accumulation of predicted values at larger lengths for the NAD index, a mismatch in size for given years for the SAD index, and bi-modality in the NAD index, all of which would be difficult to capture by addressing them with selectivity within the model. The bubble plots for the NAD and SAD index length compositions (Figures 7.1.18-7.1.19) show patterns, as would be expected from the annual length composition plots. The SAD index generally underestimated lengths of 130-150 mm fork length (FL), while overestimating sizes larger than that. The index has steep changes in slope surrounding age-1 and this species has broad distributions of sizes at age, which lead the SAS to believe that these lengths compositions may not fit well under a variety of selectivity configurations. The NAD index has an arch-shaped pattern of underestimation over time, likely because of lengths being added over the time series by the different state surveys included in the index. Chasing the fits to the length composition data would not improve the information being estimated in the stock assessment model on the overall trends in the population over time. The primary role of the length composition data was to inform selectivity for the indices.

7.2 Parameter Estimates

7.2.1 Selectivities and Catchability

Fishery removals were related to an overall level of fishing mortality and the selectivity (or availability) of Atlantic menhaden to the fishery. Model estimates of selectivity for the reduction and bait fisheries are shown graphically in Figures 7.2.1.1-7.2.1.8. Selectivity parameters were estimated for each fishery and time period as four-parameter, double-logistic models with the parameters being the ascending slope and A_{50} and the descending slope and A_{50} (Table 7.2.1.1). The application of fishery-specific dome-shaped selectivities is meant to account for varying degrees of availability of menhaden, given the heterogeneity in both the population and fishing effort.

Selectivity for the NAD index was estimated as a two-parameter logistic function as shown in Figure 7.2.1.9 and Table 7.2.1.1. Selectivity for the NAD index was used to fit the NAD length composition data and represents the ages of fish that were captured by the NAD index.

Selectivity for the SAD index was estimated as a four-parameter, double-logistic function as shown in Figure 7.2.1.10 and Table 7.2.1.1. Selectivity for the SAD index was used to fit the SAD length composition data and represents the ages of fish that were captured by the SAD index. Some of these values have large SEs, but the uncertainties in selectivity were addressed using sensitivity analyses, likelihood profiling, and simulations.

The base BAM model estimated a single, constant catchability parameter for the NAD and SAD abundance indices, reflecting the assumption that expected catchability for these indices is believed to be constant through time. This is a good assumption for the NAD and SAD fishery-independent indices since they are based on consistent, scientific survey collections, albeit the surveys are a mix of state surveys and do not target menhaden and because the indices used to create the NAD and SAD were standardized to account for catchability differences. Log-catchability was estimated as -0.85 (0.43 back transformed) for the NAD index with a 0.15 SE, while the log-catchability of the SAD index was -1.54 (0.21 back transformed) with a 0.09 SE.

The base BAM model estimated two constant catchability parameters for the recruitment index using two time blocks: 1959-1986 and 1987-2013. The time blocks represent a change in the combined spatial extent of the component seine surveys that comprise the index, with the addition of several state fishery-independent surveys after 1987. Log-catchability was estimated as -2.42 (0.09 back transformed) for the first time period with a SE of 0.08, while the log-catchability of the second time period was -2.95 (0.05 back transformed) with a SE of 0.06.

7.2.2 Fishing Mortality Rates

Highly variable fishing mortalities were noted throughout the entire time series and dependent upon the fishing. The highest fishing mortalities for the commercial reduction fishery in the north were in the 1950s (Figure 7.2.2.1), while the highest fishing mortality rates for the commercial reduction fishery in the south were during the 1970s to 1990s (Figure 7.2.2.2). The highest fishing mortalities for the commercial bait fishery in the north were in the 1950s and 1990s (Figure 7.2.2.3), while the highest fishing mortality rates for the commercial bait fishery in the south were during the late 1990s and early 2000s (Figure 7.2.2.4).

Fishing mortality rate over time was reported as the fishing mortality rate at age-2 and at age-3 (Table 7.2.2.1; Figure 7.2.2.5). In the most recent decade, the full fishing mortality rate has ranged between 0.23 and 0.63 for age-2 and between 0.27 and 0.53 for age-3 (Table 7.2.2.1; Figure 7.2.2.5). However, not all ages are fully selected, thus the fishing mortality rate on other ages can be much smaller. In the most recent decade, full fishing mortality on age-1 has ranged from 0.03 to 0.13 (Table 7.2.2.1). The estimate of fishing mortality rate for 2013 for age-2 is 0.24 and for age-3 is 0.27 (Table 7.2.2.1).

7.2.3 Abundance, Fecundity, Biomass, and Recruitment Estimates

The base BAM model estimated population numbers-at-age (ages 0-6+) for 1955–2013 (Figure 7.2.3.1 and Table 7.2.3.1). From these estimates, along with growth and reproductive data, different estimates of reproductive capacity were computed. Population fecundity (i.e., Total Egg Production) was the measure of reproductive output used as that is what has been used in the past. Population fecundity (*FEC*, number of maturing ova) was highest in the early 1960s, early 1970s, and during the present decade and has generally been higher with older age classes making up a larger proportion of the *FEC* (Figure 7.2.3.2 and Table 7.2.3.2). The largest values of population fecundity were present in 2012 and 2013, which were the last two years of the model, but were similar in magnitude to historical values of population fecundity. The time period 1955-2013 produced a median population fecundity of 93×10^{12} ova with a minimum of 43×10^{12} and a maximum of 170×10^{12} and an interquartile range of 68×10^{12} to 112×10^{12}. The estimate for population fecundity in 2013 was 156×10^{12}, which is near the 95th quantile. Throughout the time series, age-2 and age-3 fish have produced most of the total estimated number of eggs spawned annually (Table 7.2.3.2); however, in more recent years, ages-4+ have contributed more significantly to the overall number of eggs.

Biomass has fluctuated over time from an estimated high of over 2,284,000 mt in 1958 to a low of 667,000 mt in the mid-1990s (Figure 7.2.3.3; Figure 7.2.3.4; Table 7.2.3.3). Biomass was estimated to have been largest during the late-1950s and late-2000s, with lows occurring during the mid-1990s to mid-2000s, and was relatively stable through much of the 1970s and 1980s. The oldest age classes compose the smallest proportion of the population, but that proportion has increased in recent years. Biomass is likely increasing at a faster rate than abundance because of the increase in the number of older fish at age and an increase in weight at age.

Age-0 recruits of Atlantic menhaden (Figure 7.2.3.5 and Table 7.2.3.1) were highest during the 1970s and 1980s. An extremely large year class was also predicted for 1958. More recently, larger year-classes have also been estimated in 2005 and 2010. The annual estimated recruitment values relative to the median are shown in Figure 7.2.3.6. The only recruitment parameter estimated in the model was log of R_0, which was estimated at 2.74 with a standard deviation of 0.044.

7.3 Weighting of the Data Components

Initially, the likelihood components of NAD index, SAD index, recruitment index, SAD length compositions, NAD length compositions, northern commercial reduction fishery age compositions, southern commercial reduction fishery age compositions, northern bait fishery age compositions, and southern bait fishery age compositions were weighted such that the standard deviations of the normalized residuals (SDNR) equaled ~1.0 (Francis 2011). With SDNRs near 1.0, the index fits were still quite poor. Therefore, the SAS decided to upweight indices such that the SDNR values were ~2, ~3, and ~4 at the same time using a runs test and the sum of squared residuals to look at overall improvement in fit to the indices. The runs test is a statistical test that indicates if residuals are randomly positive and negative over the time series. Under all weighting scenarios, the runs test indicated that the SAD index was always random, while the JAI or recruitment index was always significantly different than random (Table 7.3.1). The JAI had runs in the residuals for the 1970s and 1980s, which were consistently high years of recruitment. For the NAD index, an increase in the weights such that the SDNR was ~2 resulted in the runs test indicating randomized residuals (Table 7.3.1). With each increase in weight, the sum of squared residuals for the NAD and SAD indices decreased except for values at SDNR = 4 (Table 7.3.2). These increasing index weights also resulted in decreased fits to other likelihood components. Thus, there was a diminishing marginal benefit from increasing the weight of an index. In order to balance improved index fit with diminished fit to the other likelihood components, the SAS determined that setting index weights such that SDNRs were ~2 was the best option. See sensitivity runs below for more information and outputs for the runs with differing SDNR values.

7.4 Sensitivity Analyses

7.4.1 Alternate model runs

The results of the sensitivity runs suggest that the base BAM model trends and stock status are fairly robust to model choices made in the base run and data choices made by the SAS (Figures 7.4.1.1-7.4.1.77).

Sensitivity runs were completed to evaluate model robustness to decisions related to growth and life history parameters. Fishing mortality rate did not vary much overall for this series of runs with the largest difference in F being for the run with an increase in M. Smaller changes in F were also observed for the run with a decrease in M and the run with no bias correction on the growth curve parameter estimates. Biomass and recruitment were greatly influenced by M with increased (upper) M values causing dramatically increased biomass and recruitment, which is to be expected. Fecundity is a much more complicated picture with each sensitivity run having large differences in fecundity from the base run over the entire time series depending on data decisions. However, each run has increasing fecundity in the most recent time period from a low prior to 2000. Fits to the individual indices were similar across all of the runs. Even with large differences in fecundity between the runs, all were above the threshold and target fecundity levels in the most recent time period. In addition, all runs were below the fishing mortality target and threshold in the most recent time period.

Several sensitivity runs were completed to look at the effects of index choice on model outcomes. The largest differences in model outcomes were for those runs that excluded the NAD index. When the NAD index was removed from the model, the biomass and fecundity from the 1990s forward increased dramatically and recruitment increased, while the F decreased. In short, the removal of the NAD index resulted in a larger population. With a loss of the NAD index, the model also lost its one logistic selectivity. In addition, the R_0 estimate was larger and the catchability estimates were lower, which in turn would lead to larger population sizes. The rest of the runs resulted in small changes to the outputs. Overall, all of the sensitivity runs with removed or altered indices resulted in a population that is currently fished below both the target and threshold and has a reproductive capacity above both the target and threshold.

The sensitivity runs that explored changes in selectivity had some effect on the overall results from the model. The run in which all of the fishery selectivities were estimated as logistic had the largest effect. In this run, the full F at age-2 and age-3 was increased over the entire time series, with decreased levels of fecundity and biomass. The index fits under these sensitivity runs were similar to the base run. Overall, the behaviors observed from the sensitivity runs changing the selectivity for the fisheries were as expected, and the fishing mortality rate was below the target and threshold while the fecundity was above the target and threshold for the most recent time period.

Removal of time blocks on catchability for the recruitment index had very little influence on estimates of fishing mortality, especially in the most recent time period. With one constant catchability for the recruitment index, the biomass and fecundity in the 1970s was much higher than the base run. However, both the biomass and fecundity from 1990 to the present are almost exactly the same as the base run. Recruitment was similar to the base run, as were the fits to the NAD and SAD indices. The fit to the recruitment index was different from the base run with a poorer fit for the sensitivity run. This was expected as the additional q parameter would allow for better fit to the recruitment index. Overall, the behaviors observed from the sensitivity run with one q were as expected, and the fishing mortality rate was below the target and threshold while the fecundity was above the target and threshold for the most recent time period.

Incorporating ageing uncertainty into the model had little influence on estimates of fishing mortality, especially in the most recent time period. The addition of ageing uncertainty resulted in slightly smaller biomass and fecundity over the entire time period. Recruitment was similar to the base run, as were the fits to the indices. Overall, the behaviors observed from the sensitivity runs incorporating ageing uncertainty were as expected, and the fishing mortality rate was below the target and threshold while the fecundity was above the target and threshold for the most recent time period.

Altering the ages included in the model had very little influence on estimates of fishing mortality, especially in the most recent time period. Restricting the modeled ages to 0-4+ resulted in slightly higher biomass and fecundity over the entire time period compared to the base run. Recruitment was similar to the base run, as were the fits to the indices. Overall, the behaviors observed from the sensitivity run including ages 0-4+ were as expected, and the fishing mortality rate was below the target and threshold while the fecundity was above the target and threshold for the most recent time period.

Starting the model in 1988 had little to no effect on the estimated fishing mortality rate, biomass, and recruitment. Starting the model in 1982 with time varying M resulted in a slightly increased estimated fishing mortality rate and slightly decreased recruitment and biomass after 1987. The fecundity for the start year of 1982 with time varying mortality was significantly reduced compared to the base run. The indices were fit similarly to the base run for these runs. Overall, the fishing mortality rate was below the target and threshold values, while the fecundity was above the target and threshold values for these runs.

Several runs were completed that changed weighting of data inputs including setting all weights to 1.0 and setting weights such that SDNRs were equal to ~1, ~3, and ~4. The run that resulted in the most significant differences from the base run was the run with all weights set to 1.0. In general, full *F* was lower for this run, and fecundity, biomass, and recruitment were much higher. This run did not fit the indices well and basically assumes that the catch-at-age data have the most information, which is contrary to the final decisions made by the SAS for the base run and contrary to the data content available for the assessment (see data sections). For runs with increased SDNRs, the indices fit better with increasing SDNRs as would be expected. Overall, these runs resulted in expected model behaviors. Fishing mortality was below the target and threshold values, while fecundity was above the target and threshold values. Finally, these runs were used to help chose the base run in addition to data shown above (see runs test and residual sum of squares in Section 7.3).

Steepness values were explored in the sensitivity runs. The steepness of 0.9 was very similar in outcomes to the base run, which was not surprising given that the base run had a value fixed at 0.99. The run with a steepness value of 0.7 was also not much different, yet did require several priors in order for it to converge and invert the Hessian. Specifically, weak priors were included on the age at 50% selectivity for the ascending limb of the SAD, the age at 50% selectivity for the descending limb of the southern commercial reduction fishery in the second and third time period, the slope of the descending limb of the northern commercial reduction fishery in the first time period and the southern commercial reduction fishery in the second time period, the slope of the NAD selectivity, and ascending slope of the southern commercial reduction fishery in the third time period. Finally, the steepness value of 0.5 was somewhat different; although, not as different as would be expected. This run had difficulty providing a reasonable benchmark given that recruitment was near zero when fishing mortality was higher. The largest differences in all three of these runs were for the earliest part of the time series, which makes sense given that part of the time series was when the population was most likely on the descending curve of the stock-recruitment function.

In general, a common trend in the results from 1955-2013 were seen in many of the sensitivity runs. Some sensitivity runs resulted in differing year-to-year values depending upon the data sources used and modeling choices that were made, which was expected. Some sensitivity runs did change the overall scale of the assessment. For example, changes to natural mortality scaled other model components, which is a typical stock assessment result. This is a typical stock assessment result. Overall, the final stock status using current reference points was the same across all sensitivity runs.

The sensitivity runs when compared to the MCB runs discussed below (Section 7.5) are generally within the bounds of uncertainty explored for this assessment. Likelihood values, SDNRs, and some of the estimated parameters (Tables 7.4.1.1-7.4.1.3) can be compared below. The output distributions from the estimated parameters from the MCBs are fairly smooth distributions, which suggests that these runs are simply the bounds on the uncertainty of the assessment given the assumptions and data inputs (see Section 7.5 below).

7.4.2 Retrospective Analyses

The retrospective was run peeling off data back to 2009 (Figures 7.4.2.1-7.4.2.18; Tables 7. 4.2.1-7.4.2.3). The fits to the indices remained consistently good with the removal of years of data. For example, the JAI index fit better with some years of data removed than in the base run; however, the percent relative change would be considered concerning as it has a pattern. Overall, the index fits are reasonable with the removal of data and even improve in some cases. In addition, predicted recruitment would be effected by the fit to the JAI index. The predicted recruitment does have some differences compared to the base run, but with increased fit to the JAI index as years of data are removed, cause for concern is minimized.

The retrospective exhibits consistent yet small relative change in fishing mortality at age-3 when compared to the base run. However, this pattern is not apparent in the fishing mortality at age-2. Thus, there is a possibility that the model is slightly overestimating fishing mortality rate in the more terminal years for some ages.

Biomass and fecundity exhibit similar behaviors for the retrospective analysis. Biomass seems to be estimated fairly well in the retrospective analysis. Fecundity also seems to be estimated fairly well in the retrospective analysis albeit with a consistently small difference from the base run.

There are always trade-offs in fitting data components, and those tradeoffs change over time; these trade-offs have an impact on the appearance of retrospective analyses. For example, the second catchability parameter estimated for the JAI index is consistently estimated, but the catchability for the other indices and R_0 are changing with respect to the number of years of data included (Table 7.4.2.3). Some additional runs were done to determine the influence of data components on the overall shape of the model outputs. Patterns in retrospective analysis can emerge from data trade-offs; the addition of data in a data space with no historical information can create patterns where parameter estimates are influenced and the fit to the indices is influenced.

In addition to the increase in quality of data, there are also some model assumptions that change near to the end of the time period. For example, the selectivity block in the final time period for the southern commercial reduction fleet starts in 2005. Therefore, retrospective analyses were only completed for years going back to 2009.

The stock status outcome did not vary in this set of retrospective model runs. In particular, the ratio of fishing mortality at age-2 and age-3 to the benchmarks in the terminal year showed no variation in stock status (Figures 7.4.2.15-7.4.2.18), nor did the ratio of *FEC* to the *FEC* benchmarks in the terminal year.

7.4.3 Likelihood profiling and simulation analyses

NOTE: Likelihood profiling and simulation analyses were used as supplemental analyses in support of decisions made by the SAS regarding the estimability of dome-shaped selectivity given the data contained in the model. The figures included in this document are from previous iterations of the model during development of a base run.

Likelihood profiling demonstrated that the descending limb of the fishery selectivity curves were estimable and supported by the data contained within the model. Some of the oldest ages had smaller changes in the negative log–likelihood values. However, in the final base run, the panel decided to use a functional form for selectivity, thus this was not a concern. See Figures 7.4.3.1-7.4.3.4 for examples of likelihood profiles on selectivity.

Simulation analyses were also used in support of the decision to freely estimate dome-shaped selectivity. Simulation analyses confirmed that data could be reproduced as "truth" in an operating model and that the assessment model could provide the correct parameter estimates for selectivity. Then, simulations were run with variability observed in the assessment model to see if selectivity could still be reproduced, which will of course have uncertainty (Figure 7.4.3.5). This analysis also supported estimability of dome-shaped selectivity.

7.5 Uncertainty Analysis

Uncertainty was examined in our results in two distinct ways: by considering each data source, in turn, in a series of sensitivity runs (Section 7.4.1), and by using a MCB procedure. This parametric bootstrap procedure was run for 1,000 iterations. For some iterations, the model did not converge; where this was true, then that particular iteration was not included in the results. In addition, some iterations estimated fairly high values for R_0 or other parameters. Thus, some additional runs were excluded. In the end, about 15% of runs did not converge or were excluded for unrealistic parameter estimates.

The resulting estimates from the MCB runs have been summarized in Figures 7.5.1-7.5.4, showing the 95% confidence region. In general, the MCB results are not symmetrical distributions about the base run results because some of the uncertainty specifications were not symmetrical. Uncertainty was large in some years, especially for biomass and fecundity.

8.0 Stock Status

8.1 Current Overfishing, Overfished/Depleted Definitions

As established in Amendment 2 to the Interstate Fisheries Management Plan for Atlantic Menhaden, the current overfishing definition is a fecundity-per-recruit threshold of $F_{15\%}$ and a target of $F_{30\%}$. F-based reference points should be compared to the full fishing mortality rate, which is the maximum fishing morality rate for a year across ages. The current fecundity-based overfished definition is a threshold of $FEC_{15\%}$ and a target of $FEC_{30\%}$.

The maximum spawning potential (MSP) or spawner per recruit (SPR) based reference points are intended to be interim reference points while the ASMFC's Multispecies Technical Committee develops ecological-based reference points (ERP). The ERPs will take time to develop because of the complexity of modeling the predator-prey relationships for marine species that rely on Atlantic menhaden for forage (e.g., striped bass, bluefish, and weakfish). In either case (biological or ecological reference points), the intent is to manage Atlantic menhaden at sustainable levels to support fisheries and meet predator demands by maintaining sufficient reproductive capacity to prevent stock depletion and protect against recruitment failure.

8.2 Recommended Overfishing, Overfished/Depleted Definitions

The TC does not recommend that the current, interim SPR-based overfishing and overfished definitions continue to be used for management. Specifically, the values for the SPR-based reference points seem unreasonable given the choices were based on the last stock assessment during which the population was thought to be at $F_{8\%}$. Given the new assessment, the TC does not feel that the reference points provide a measure of sustainability.

The TC recommends that the Atlantic Menhaden Management Board adopt SPR reference points based on the maximum F value experienced at age-2 during the 1960-2012 time period as the threshold and the median F value experienced at age-2 during the 1960-2012 time period as the target along with the associated FEC values. The 1960-2012 time period represents a time with little to no restrictions on total harvest in which the population appears to have been sustainable given that the population did not experience collapse. Age-2 fishing mortality rate was chosen for consistency over time. Because the fisheries have dome-shaped selectivity, which varies by fleet over time, the age at full fishing mortality changes over time. The majority of the removals come from the southern commercial reduction fishery, which is fully selected at age-2; thus, age-2 was chosen as the reference age for comparisons. Using these metrics, the maximum F experienced was $F_{20\%} = 2.01$, and the median was $F_{36\%} = 0.82$. The associated ***FEC*** reference points would be $FEC_{20\%} = 61{,}401$ and $FEC_{36\%} = 111{,}077$ (billions of eggs); FEC_{2013} was 156,495 (billions of eggs). At the fishing mortality rate in the terminal year (age-2: 0.24), the fishing mortality rate is at $F_{69\%}$ (Table 8.2.1). With these suggested reference points, the stock status for the base run is still not overfished and overfishing is not occurring (Figures 8.2.1-8.2.2). In addition, the current stock would still be below the suggested fishing mortality target and above the suggested ***FEC*** target.

The menhaden stock is unlikely to experience unsustainable harvest rates or drop to depleted biomass levels in the short term under the current management plan. The TC noted, however, that the stock-recruitment relationship observed to date is weak at best; therefore, the current fecundity-based reference points used to identify overfished conditions may not be useful for management of menhaden in general. In other words, at this time the TC cannot reliably predict the magnitude of a recruitment response to increased biomass under any harvest scenario.

Alternative SPR configurations, alternative SPR levels (different %SPR), and other single species reference point options were discussed by the TC during the benchmark assessment process. Those options included the use of Spawning Stock Biomass (weight)-based SPR reference points, different %SPR levels, different time periods across which to calculate SPR reference points, and new historical reference points that would identify a threshold based on the historical response of the stock to differing levels of harvest pressure (i.e., the minimum biomass or abundance from which the stock recovered under high harvest pressure). However, the TC cannot comment on the relative performance of these reference points until a formal Management Strategy Evaluation (MSE) is conducted. An MSE is tentatively scheduled to be conducted by the Beaufort Laboratory in 2015.

The TC's conclusions and recommendations regarding the development and adoption of ecological reference points are outlined in Section 3 of Appendix E.

8.3 Stock Status Determination

8.3.1 Overfished and Overfishing Status

Current benchmarks for Atlantic menhaden are $F_{30\%}$, $F_{15\%}$, $FEC_{30\%}$, and $FEC_{15\%}$. The current benchmarks are calculated through spawner-per-recruit analysis using the mean values of any time-varying components (i.e., growth, maturity) over the time series 1955-2013 and full fishing mortality rate defined as the maximum rate across ages for each year (Figure 8.3.1.1). The base BAM model benchmark estimates and terminal year stock status are indicated in Table 8.2.1. Based on the current adopted benchmarks, **the Atlantic menhaden stock status is not overfished and overfishing is not occurring** (Table 8.2.1). In addition, the current stock is below the current fishing mortality target and above the current *FEC* target (Table 8.2.1).

8.3.2 Uncertainty

The MCB runs and sensitivity runs support the stock status determination using the formally adopted benchmarks. For each MCB run, the benchmarks were calculated (see Figures 8.3.2.1 and 8.3.2.2 for the distribution of benchmarks calculated across the MCB runs). The entire time series of estimates of fishing mortality at age-2 and age-3 over $F_{15\%}$ and $F_{30\%}$ are shown in Figures 8.3.2.3 and 8.3.2.4, which include the 95% confidence intervals for the MCB runs. The entire time series of estimates of fecundity over $FEC_{15\%}$ and $FEC_{30\%}$ are shown in Figures 8.3.2.5 and 8.3.2.6, which also include the 95% confidence intervals for the MCB runs. Phase plots of base run and each MCB run versus the threshold and target benchmarks are shown in Figures 8.3.2.7 and 8.3.2.8, respectively. Densities and cumulative probability densities for each of the benchmarks are shown in Figures 8.3.2.9 -8.3.2.12. In addition, each of the sensitivity and retrospective runs indicated the same stock status as the base run and most of the MCB runs (Tables 8.3.2.1-8.3.2.2; Figures 7.4.1.50-7.4.1.77). The history of fishing mortality rates in these figures suggests that overfishing likely occurred in the 1950s, but generally, overfishing is unlikely to be occurring at present. The history of fecundity over the time series suggests that the population was overfished as recent as the late 1990s, but is not currently overfished.

The uncertainty in the terminal year stock status indicators were expressed using the results of the bootstrap runs of the base BAM model and sensitivity runs. The results indicate that the fecundity estimates for the terminal year are generally above both the target and threshold with 8% of runs falling below 1.0 for $FEC_{15\%}$ and 19% of runs falling below 1.0 for $FEC_{30\%}$. The results for the 2013 fishing mortality rate suggests that the base run estimate is below the target and threshold with only a handful of the bootstrap runs exceeding the threshold values in the terminal year and very few of the boostrap runs exceeding the target values in the terminal recent year.

8.4 Plan for Development of Ecological Reference Points

See Appendix E.

9.0 Research and Modeling Recommendations for Benchmark

Many of the research and modeling recommendations from the last benchmark stock assessment remain relevant for this update stock assessment. Research recommendations are broken down into two categories: data and modeling. While all recommendations are high priority, the first recommendation is the highest priority. Each category is further broken down into recommendations that can be completed in the short term and recommendations that will require long term commitment.

Annual Data Collection

Short term (next 3-6 years):

1. Continue current level of sampling from bait fisheries, particularly in the Mid-Atlantic and New England. Analyze sampling adequacy of the reduction fishery and effectively sample areas outside of that fishery (e.g., work with industry and states to collect age structure data and biological data outside the range of the fishery).
2. Ageing:
    a. Conduct ageing validation study (e.g., scale : otolith comparison), making sure to sample older age classes. Use archived scales to do radio isotope analysis.
    b. Ageing precision: conduct an ageing workshop to assess precision and error among readers (currently planned for January 2015).
3. Conduct a comprehensive fecundity study.
4. Place observers on boats to collect at-sea samples from purse-seine sets, or collect samples at dockside during vessel pump-out operations (as opposed to current top of hold sampling) to address sampling adequacy.
5. Investigate relationship between fish size and school size in order to address selectivity (specifically addressing fisher behavior related to harvest of specific school sizes).
6. Investigate relationship between fish size and distance from shore (addressing selectivity).
7. Evaluate alternative fleet configurations for the removal and catch-at-age data.

Long term (6+ years):

1. Develop a menhaden specific coastwide fishery-independent index of adult abundance at age. One possible methodology is an air spotter survey complemented with ground truthing for biological information (e.g., size and age composition). In all cases, a sound statistical design is essential (involving statisticians in the development and review of the design; some trial surveys may be necessary). **[Highest Priority]**
2. Conduct studies on spatial and temporal dynamics of spawning (how often, how much of the year, batch spawning, etc.)
3. Conduct studies on productivity of estuarine environments related to recruitment.
4. Investigation of environmental covariates related to recruitment.

Assessment Methodology

Short term (3-6 year):

1. Conduct management strategy evaluation (MSE). **[Highest Priority]**
2. Conduct multi-objective decision analysis (MODA). **[Highest Priority]**
3. Continue to develop an integrated length and age based model (e.g., SS3).
4. Continue to improve methods for incorporation of natural mortality (e.g., multi-species statistical catch-at-age model). See Appendix E.

Long term (6+ years):

1. Develop a seasonal spatially-explicit model, once sufficient age-specific data on movement rates of menhaden are available.

10.0 Literature Cited

Ahrenholz, D.W. 1991. Population biology and life history of the North American menhadens, *Brevoortia* spp. Marine Fisheries Review 55(4)3-19.

Ahrenholz, D.W., W.R. Nelson, and S.P. Epperly. 1987. Population characteristics of Atlantic menhaden, *Brevoortia tyrannus*. Fishery Bulletin 85:569-600.

Atlantic States Marine Fisheries Commission (ASMFC). 1981. Fishery Management Plan for Atlantic Menhaden. 146p.

_______. 1981. Fishery Management Plan for Atlantic Menhaden – 1992 Revision (September 1992). 170p.

_______. 1992. Fishery Management Plan for Atlantic Menhaden: 1992 revision. Atlantic States Marine Fisheries Commission, Fishery Management Report No. 22. 159 p.

_______. 2001. Amendment 1 to the Interstate Fishery Management Plan for Atlantic Menhaden. Atlantic States Marine Fisheries Commission, Fishery Management Report No. 37. 127 p.

_______. 2004a. Addendum I to Amendment I to the Interstate Fishery Management Plan for Atlantic menhaden. 52 p.

_______. 2004b. Atlantic menhaden stock assessment report for peer review. Atlantic States Marine Fisheries Commission, Stock Assessment Report No. 04-01 (Supplement), 145 p.

_______. 2005. Addendum II to Amendment 1 to the Interstate Fishery Management Plan for Atlantic menhaden.

_______. 2006. Addendum III to Amendment 1 to the Interstate Fishery Management Plan for Atlantic menhaden.

_______. 2009. Addendum IV to Amendment 1 to the Interstate Fishery Management Plan for Atlantic menhaden. 5 p.

_______. 2010. Atlantic menhaden stock assessment for peer review. Stock Assessment Rep. No. 10-02, 268 p.

_______. 2011. Addendum V to Amendment 1 to the Interstate Fishery Management Plan for Atlantic menhaden. 17 p.

_______. 2012a. Amendment 2 to the Interstate Fishery Management Plan for Atlantic menhaden. 114 p.

_______. 2012b. Atlantic menhaden stock assessment update. 213 p.

_______. 2013. Technical Addendum I to Amendment 2 to the Interstate Fishery Management Plan for Atlantic Menhaden. 4 p.

Alverson, D.L., and M.J. Carney. 1975. A graphic review of the growth and decay of population cohorts. Journal Conseil International pour l'Exploration de la Mer 36:133-143.

Anderson, J.D. 2007. Systematics of the North American menhadens: molecular evolutionary reconstructions in the genus *Brevoortia* (Clupeiformes: Clupeidae). Fishery Bulletin 205:368-378.

Beamish, R.J., and D.A. Fournier. 1981. A method for comparing the precision of a set of age determinations. Canadian Journal of Fisheries and Aquatic Sciences 38: 982-983.

Bonzek, C.F., J. Gartland, D.J. Gauthier, R.J. Latour. 2012. Data collection and analysis in support of single and multispecies stock assessments in the Mid-Atlantic: Northeast Area Monitoring and Assessment Program Near Shore Trawl Report. Final Report March 2012. 290 pp. http://www.neamap.net/publications/NEAMAP%20Report%20thru%20Fall2011.pdf

Boudreau, P.R., and L.M. Dickie. 1989. Biological model of fisheries production based on physiological and ecological scalings of body size. Canadian Journal of Fisheries and Aquatic Sciences 46:614-623.

Charnov, E., Gislason, H., Pope, J.G. 2013. Evolutionary assembly rules for fish life histories. Fish and Fisheries 14: 213–224

Chester, A.J. 1984. Sampling statistics in the Atlantic menhaden fishery. NOAA Tech. Rep. NMFS 9, 16 p.

Chester, A.J. and J.R.Waters. 1985. Two-stage sampling for age distribution in the Atlantic menhaden fishery, with comments on optimal survey design. North American Journal of Fisheries Management 5: 449-456

Clark, C.W., and M. Mangel. 1979. Aggregation and fishery dynamics: A theoretical study of schooling and the purse seine tuna fishery. Fishery Bulletin 77:317-337.

Conn, P. B. 2010. Hierarchical analysis of multiple noisy abundance indices. Canadian Journal of Fisheries and Aquatic Sciences 67: 108-120.

Cooper, R.A. 1965. An unusually large menhaden *Brevoortia tyrannus* (Latrobe), from Rhode

Island. Transactions of the American Fisheries Society 94: 412.

Dietrich Jr., C.S. 1979. Fecundity of the Atlantic menhaden, *Brevoortia tyrannus*. Fishery Bulletin 77: 308–311.

Deriso, R.B., T.J. Quinn, II, and P.R. Neal. 1985. Catch-age analysis with auxiliary information. Canadian Journal of Fisheries and Aquatic Sciences 42: 815–824.

Deroba, J. J, and A. M. Schueller. 2013. Performance of stock assessments with misspecified age- and time-varying natural mortality. Fisheries Research 146:27-40.

Dryfoos, Robert L., Randall P. Cheek, and Richard L. Kroger. 1973. Preliminary analyses of Atlantic menhaden, *Brevoortia tyrannus*, migrations, population structure, survival and exploitation rates, and availability as indicated from tag returns. Fishery Bulletin 71(3):719-734.

Fournier, D., and C.P. Archibald. 1982. A general theory for analyzing catch at age data. Canadian Journal of Fisheries and Aquatic Sciences 39: 1195–1207.

Francis, R.I.C.C. 2011. Data weighting in statistical fisheries stock assessment models. Canadian Journal of Fisheries and Aquatic Sciences 68:1124-1138.

Garrison, L. P., Link, J. S., Kilduff, D. P., Cieri, M. D., Muffley, B., Vaughan, D. S., Sharov, A., Mahmoudi, B., and 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: 856–870.

Greer, R.L., 1915. The menhaden industry of the Atlantic coast. U.S. Bur. Fisheries Doc. No. 811. 27 p.

Heimbuch, D.G., E. Lorda, D. Vaughan, L.W. Barnthouse, J. Uphoff, W. Van Winkle, A. Kahnle, B. Young, J. Young, and L. Kline. 2007. Assessing coastwide effects of power plant entrainment and impingement on fish populations: Atlantic menhaden example. North American Journal of Fisheries Management 27:569-577.

Hewitt, D.A., and J.M. Hoenig. 2005. Comparison of two approaches for estimating natural mortality based on longevity. Fishery Bulletin 103:433-437.

Higham, J.R., and W.R. Nicholson. 1964. Sexual maturation and spawning of Atlantic menhaden. Fishery Bulletin 63: 255–271.

Hoenig, J.M. 1983. Empirical use of longevity data to estimate mortality rates. Fishery Bulletin 82:898-903.

Huntsman, G.R., and R.B. Chapoton. 1973. Biostatistical data acquisition in the menhaden fisheries. Transactions of the American Fisheries Society 102 (2): 452-456.

Jensen, A.L. 1996. Beverton and Holt life history invariants result from optimal trade-off of reproduction and survival. Canadian Journal of Fisheries and Aquatic Sciences 53:820-822.

June, F.C., and J.W. Reintjes. 1959. Age and size composition of the menhaden catch along the Atlantic coast of the United States, 1952-1955; with a brief review of the commercial fishery. U.S. Fish Wildl. Serv., Spec. Sci. Rep., Fisheries No. 317, 65 p.

June, F.C., and C.M. Roithmayr. 1960. Determining age of Atlantic menhaden from their scales. Fishery Bulletin 60:323-342.

June, F.C. 1965. Comparision of vertebral counts of Atlantic menhaden. U.S. Fish Wildl. Serv. Spec. Sci. Rep. Fish. 513: 12.

Kroger, J.F. Guthrie, and M.H. Judy. 1974. Growth and first annulus formation of tagged and untagged Atlantic menhaden. Transactions of the American Fisheries Society 103(2): 292-296.

Lewis, R.M., D.W. Ahrenholz, and S.P. Epperly. 1987. Fecundity of Atlantic menhaden, *Brevoortia tyrannus*. Estuaries 10(4):347-350.

Lorenzen, K. 1996. The relationship between body weight and natural mortality in juvenile and adult fish: A comparison of natural ecosystems and aquaculture. Journal of Fish Biology 49:627-647.

Lynch, A. J., J. R. McDowell, J. E. Graves. 2010. A molecular genetic investigation of the population structure of Atlantic menhaden (*Brevoortia tyrannus*). Fishery Bulletin 108:87-97.

Methot, R.M. 1989. Synthetic estimates of historical abundance and mortality for northern anchovy. *In*: Edwards, E. and B. Megrey (eds) "Mathematical Analysis of Fish Stock dynamics: Reviews and Current Applications". American Fisheries Society Symposium No. 6. pp. 66-82.

Methot, R.D., Jr. and C. R. Wetzel. 2013. Stock synthesis: A biological and statistical framework for fish stock assessment and fishery management. Fisheries Research 142: 86-99.

Nicholson, W.R. 1971. Changes in catch and effort in the Atlantic menhaden purse-seine fishery 1940-1968. Fishery Bulletin 69: 765-781.

_____. 1972. Population structure and movements of Atlantic menhaden, *Brevoortia tyrannus*, as inferred from back-calculated length frequencies. Chesapeake Science 13: 161-174.

_____. 1975. Age and size composition of the Atlantic menhaden, *Brevoortia tyrannus*, purse seine catch, 1963-71, with a brief discussion of the fishery. NOAA Tech. Rep. NMFS SSRF-684, 28 p.

_____. 1978. Movements and population structure of Atlantic menhaden indicated by tag returns. Estuaries 1(3): 141-150.

Northeast Fisheries Science Center (NEFSC). 2006. 42nd Northeast Regional Stock Assessment Workshop (42nd SAW) stock assessment report, part B: Expanded Multispecies Virtual Population Analysis (MSVPA-X) stock assessment model. *U.S. Dep. Commer., Northeast Fish. Sci. Cent. Ref. Doc.* 06-09b; 308 p. [Available from: National Marine Fisheries Service, 166 Water Street, Woods Hole, MA 02543-1026.]

Pauly, D. 1980. On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. Journal Conseil International pour l'Exploration de la Mer 39:175-192.

Pella, J.J., and P.K. Tomlinson. 1969. A generalized production model. Inter-Am. Trop. Tuna Commission Bulletin 13:421-496.

Peterson, I., and J.S. Wroblewski. 1984. Mortality rate of fishes in the pelagic ecosystem. Canadian Journal of Fisheries and Aquatic Sciences 41:1117-1120.

Punt, A.E., D.C. Smith, K. Krusic Golub, and S. Robertson. 2008. Quantifying age-reading error for use in fisheries stock assessments, with application to species in Australia's southern and eastern scalefish and shark fishery. Canadian Journal of Fisheries and Aquatic Sciences 65: 1991-2005.

Quinn, T.J. II, and R.B. Deriso. 1999. Quantitative Fish Dynamics. Oxford Press, 542 p.

Reintjes, J.W. 1969. Synopsis of biological data on the Atlantic menhaden, *Brevoortia tyrannus*. FAO Species Synopsis 42. 30 p.

Reish, R.L., R.B. Deriso, D. Ruppert, and R.J. Carroll. 1985. An investigation of the population dynamics of Atlantic menhaden (*Brevoortia tyrannus*). Canadian Journal of Fisheries and Aquatic Sciences 42 (Suppl 1):147-157.

Roithmayr, C.M. 1963. Distribution of fishing by purse seine vessels for Atlantic menhaden, 1955-59. U.S. Fish. Wildl. Serv., Spec. Sci. Rep. Fish. 434, 22 p.

Salz, R., T. Miller, E. Williams, J. Walter, K. Drew, G. Bray 2012. MRFSS/MRIP Calibration Workshop Ad-hoc Working Group Report. Available at:
http://www.sefsc.noaa.gov/sedar/Sedar_Workshops.jsp?WorkshopNum=002

Sampson, D.B. 2014. Fishery selection and its relevance to stock assessment and fishery management. Fisheries Research 158: 5-14.

Sampson, D.B. and R.D. Scott. 2011. A spatial model for fishery age-selection at the population level. Canadian Journal of Fisheries and Aquatic Sciences 68: 1077-1086.

Schaaf, W.E., and G.R. Hunstman. 1972. Effects of fishing on the Atlantic menhaden stock, 1955-1969. Transactions of the American Fisheries Society. 101(2):290-297.

Schueller, A.M., E.H. Williams, and R.T. Cheshire. 2014. A proposed, tested, and applied adjustment to account for bias in growth parameter estimates due to selectivity. Fisheries Research 158: 26-39.

Smith, J.W. 1999. A large fish kill of Atlantic menhaden, Brevoortia tyrannus, on the North Carolina coast. Journal of the Elisha Mitchell Scientific Society 115:157-163.

Smith, J.W. 1999. Distribution of Atlantic menhaden, *Brevoortia tyrannus*, purse-seine sets and catches from southern New England to North Carolina, 1985-96. NOAA Tech. Rep. NMFS 144, 22 p.

Smith, J.W. and W.B. O'Bier. 1996. An exceptionally large Atlantic menhaden, Brevoortia tyrannus, from Chesapeake Bay. Journal of the Elisha Mitchell Scientific Society 112(3): 121-123

Southeast Data, Assessment, and Review (SEDAR). 2011. SEDAR 27 - Gulf of Mexico menhaden stock assessment report. SEDAR, North Charleston SC. 446 p.

Sutherland, D.F. 1963. Variation in vertebral numbers of juvenile Atlantic menhaden. U.S. Fish Wildl. Serv. Spec. Sci. Rep. Fish. 435: 1-21.

Vaughan, D.S., K.W. Shertzer, and J.W. Smith. 2007. Gulf menhaden (*Brevoortia patronus*) in the U.S. Gulf of Mexico: Fishery characteristics and biological reference points for management. Fisheries Research 83:263-275.

_____, and J.W. Smith. 1988. Stock assessment of the Atlantic menhaden, *Brevoortia tyrannus*, fishery. NOAA Tech. Rep. NMFS 63, 18 p.

Waterhouse, L., D.B. Sampson, M. Maunder, and B.X. Semmens. 2014. Using areas-as-fleets selectivity to model spatial fishing: asymptotic curves are unlikely under equilibrium conditions. Fisheries Research 158: 15-25.

Williams, A.B., G.S. Posner, W.J. Woods, and E.E. Deubler. 1973. A hydrographic atlas of larger North Carolina sounds. University of North Carolina, Institute of Marine Science, Report UNC-SG-73-02, Morehead City.

Williams, E.H. 2001. Assessment of cobia, *Rachycentron canadum*, in the waters of the U.S. Gulf of Mexico. NOAA Tech. Memo. NMFS-SEFSC-469.

11.0 Appendix A. 2014 MSVPA-X update report.

12.0 Appendix B. Atlantic menhaden tagging report.

13.0 Appendix C. Atlantic menhaden Beaufort Assessment Model (BAM) equations and code.

14.0 Appendix D. Projections methodology and example assuming constant landings.

15.0 Appendix E. Ecological Reference Points for Atlantic menhaden: Plan of Action.

2014 Atlantic Menhaden Benchmark Stock Assessment Tables

Table 3.2.1. Ageing error matrix used for a sensitivity run of the stock assessment based on a within reader comparison as estimated by the program agemat (Punt et al. 2008).

Ages	0	1	2	3	4	5	6
0	0.98	0.02	0.00	0.00	0.00	0.00	0.00
1	0.02	0.97	0.02	0.00	0.00	0.00	0.00
2	0.00	0.03	0.93	0.03	0.00	0.00	0.00
3	0.00	0.00	0.09	0.82	0.09	0.00	0.00
4	0.00	0.00	0.00	0.19	0.62	0.19	0.00
5	0.00	0.00	0.01	0.06	0.24	0.39	0.31
6	0.00	0.01	0.02	0.06	0.12	0.18	0.60

Table 3.3.1 The estimated annual, cohort based von Bertalanffy growth curves without and with the bias correction as detailed in Schueller et al. (2014). Those t_0 values with a * indicated values were fixed at the non-bias corrected values.

		Non-bias corrected values			Bias corrected values		
	n	L_∞	K	t_0	L_∞	K	t_0
1947	28	337.7	3.95	7.51	380.7	0.23	0.00
1948	101	335.5	2.76	5.84	335.2	0.69	0.00
1949	355	323.3	4.73	5.48	322.8	0.75	-0.71
1950	1202	340.2	0.45	0.49	342.2	0.39	-0.25
1951	6574	341.9	0.48	0.53	344.7	0.42	0.00
1952	3596	350.7	0.35	-1.02	354.8	0.34	-1.02*
1953	9362	340.3	0.51	-0.06	356.5	0.39	-0.58
1954	9216	353.2	0.40	-0.50	366.1	0.39	-0.43
1955	18271	363.5	0.34	-0.57	544.9	0.15	-1.13
1956	20357	350.3	0.39	-0.27	393.0	0.28	-0.68
1957	9581	373.9	0.30	-0.79	487.3	0.17	-1.37
1958	34120	397.4	0.27	-0.52	459.1	0.19	-0.85
1959	6880	422.5	0.22	-1.30	443.7	0.21	-1.30*
1960	9016	343.9	0.44	-0.32	374.6	0.33	-0.63
1961	8220	328.5	0.41	-0.68	334.6	0.39	-0.74
1962	11242	324.2	0.45	-0.65	349.6	0.35	-0.88
1963	9324	345.7	0.37	-0.84	368.6	0.32	-0.95
1964	17597	389.7	0.29	-1.01	469.8	0.23	-1.01*
1965	17274	469.5	0.20	-1.17	627.4	0.14	-1.17*
1966	25575	362.6	0.38	-0.76	440.1	0.29	-0.76*
1967	13397	706.3	0.09	-1.95	675.2	0.12	-1.50*
1968	9459	563.0	0.13	-1.92	620.2	0.13	-1.50*
1969	11442	386.2	0.35	-0.84	503.3	0.25	-0.84*
1970	4373	343.7	0.52	-0.36	392.2	0.45	-0.36*
1971	7721	385.3	0.31	-0.75	539.8	0.15	-1.36
1972	6292	304.4	0.66	0.03	327.1	0.54	-0.11
1973	6366	343.6	0.34	-0.72	401.5	0.27	-0.72*
1974	6796	335.5	0.35	-0.54	562.3	0.13	-1.29
1975	8832	377.2	0.22	-0.95	426.5	0.19	-0.95*
1976	6814	333.6	0.34	-0.35	537.4	0.13	-1.06
1977	7168	347.1	0.31	-0.48	592.9	0.12	-1.05
1978	5200	374.9	0.21	-1.08	480.4	0.14	-1.34
1979	9437	510.9	0.12	-1.47	565.5	0.10	-1.47*
1980	7302	333.2	0.33	-0.49	393.7	0.22	-0.84
1981	13566	330.8	0.36	-0.36	472.5	0.16	-1.10
1982	6564	361.5	0.27	-0.70	429.1	0.22	-0.70*
1983	9446	416.4	0.17	-1.31	541.3	0.12	-1.31
1984	10173	333.8	0.30	-0.63	427.9	0.19	-0.98
1985	8361	328.1	0.32	-0.54	544.8	0.13	-1.15
1986	6350	316.3	0.35	-0.55	397.8	0.21	-0.92
1987	4215	349.5	0.27	-0.76	420.2	0.21	-0.76*

		Non-bias corrected values			**Bias corrected values**		
	n	L_∞	K	t_0	L_∞	K	t_0
1988	9608	314.2	0.46	-0.29	384.6	0.29	-0.59
1989	3806	307.0	0.48	-0.46	332.8	0.40	-0.56
1990	5668	342.9	0.32	-0.79	393.6	0.26	-0.79*
1991	7743	329.0	0.41	-0.70	461.4	0.20	-1.25
1992	5775	357.0	0.35	-0.46	626.9	0.13	-1.01
1993	3567	353.6	0.34	-0.82	417.4	0.27	-0.82*
1994	5693	335.2	0.55	-0.03	405.2	0.35	-0.25
1995	3201	344.6	0.44	-0.16	414.8	0.34	-0.16*
1996	3329	331.9	0.48	-0.05	455.6	0.23	-0.46
1997	3364	363.8	0.34	-0.46	396.3	0.30	-0.46*
1998	4574	392.0	0.27	-1.09	426.3	0.24	-1.09*
1999	3797	331.9	0.52	-0.26	392.5	0.41	-0.26*
2000	2182	316.5	0.63	-0.01	325.7	0.62	0.00
2001	3377	291.8	0.63	-0.39	295.2	0.59	-0.47
2002	4238	312.9	0.50	-0.34	363.0	0.35	-0.63
2003	3326	339.9	0.35	-0.83	376.3	0.30	-0.83*
2004	2293	308.5	0.47	-0.25	367.3	0.36	-0.25*
2005	4356	297.0	0.57	-0.26	296.1	0.60	-0.19
2006	4009	298.9	0.58	-0.31	302.2	0.55	-0.38
2007	1875	295.3	0.55	-0.51	296.3	0.57	-0.43
2008	3544	383.6	0.23	-1.46	402.5	0.22	-1.46*
2009	3325	287.7	0.59	-0.47	292.1	0.58	-0.46
2010	4171	303.3	0.47	-0.70	302.7	0.48	-0.68

Table 3.3.2. Fork length (mm) at age on March 1 (beginning of fishing year) estimated from year class von Bertalanffy growth parameters with a bias correction. Shaded cells are the average from the three preceding years.

Year	1	2	3	4	5	6+
1955	155.1	226.3	263.8	280.2	298.5	320.7
1956	151.5	222.7	268.3	290.0	302.3	312.7
1957	147.3	207.3	268.6	296.8	308.6	316.8
1958	157.6	207.3	255.2	299.8	316.1	321.9
1959	138.7	207.7	252.7	296.3	321.1	329.2
1960	169.9	195.2	250.3	287.0	331.6	335.5
1961	156.4	221.8	241.8	286.3	312.9	361.8
1962	164.5	218.1	263.8	280.1	316.9	332.4
1963	169.1	219.5	262.3	297.9	311.7	342.8
1964	171.7	222.7	256.6	294.0	325.5	337.7
1965	171.0	225.8	260.3	281.8	316.8	347.9
1966	162.1	231.2	265.0	286.8	298.9	333.1
1967	175.4	222.0	279.3	293.4	305.4	310.4
1968	168.7	241.8	274.3	317.7	314.1	318.5
1969	174.3	223.7	291.6	319.8	348.3	329.0
1970	184.5	229.5	272.8	328.8	359.5	372.8
1971	179.4	254.5	277.8	316.5	356.8	394.0
1972	161.6	256.5	309.1	320.1	355.5	377.7
1973	147.3	214.6	305.7	351.8	357.2	390.2
1974	149.9	222.3	260.2	337.1	385.1	389.8
1975	141.0	209.8	266.1	299.4	357.0	411.0
1976	132.1	190.9	255.4	291.5	333.1	369.8
1977	127.7	183.1	234.9	290.2	306.4	362.1
1978	129.1	178.4	225.2	273.6	316.7	315.1
1979	134.4	181.5	222.8	260.0	307.8	336.9
1980	128.2	179.6	228.1	261.7	288.8	337.9
1981	131.0	171.4	218.9	269.3	295.8	312.6
1982	136.4	182.9	210.3	253.1	305.9	325.7
1983	132.1	186.6	224.5	245.4	282.8	338.4
1984	134.6	190.0	229.4	257.9	277.0	308.6
1985	131.4	182.0	236.6	265.7	284.7	305.5
1986	129.3	181.5	223.9	274.2	296.7	306.2
1987	133.8	178.5	223.1	260.9	304.4	323.0
1988	130.1	184.7	221.9	257.7	293.6	328.7
1989	140.4	185.0	225.7	260.1	286.4	322.5
1990	154.9	200.9	229.6	258.9	293.8	310.3
1991	147.9	213.8	246.5	265.7	285.6	323.5
1992	163.6	204.7	253.2	280.7	294.9	307.2
1993	143.2	216.4	248.4	279.6	306.5	318.7
1994	162.2	201.7	259.8	282.0	297.2	325.9

Year	1	2	3	4	5	6+
1995	142.8	222.6	253.2	295.5	307.8	309.0
1996	134.3	219.7	268.7	298.4	324.9	327.6
1997	131.9	214.7	274.1	303.9	338.2	349.1
1998	141.7	199.5	272.1	312.6	330.7	373.1
1999	169.9	208.2	252.9	313.0	339.7	351.2
2000	158.2	225.2	257.4	295.2	342.2	358.9
2001	150.1	237.0	268.6	293.7	328.6	363.1
2002	170.9	231.1	289.3	302.6	320.5	355.1
2003	156.7	226.2	274.7	324.0	329.3	340.3
2004	158.1	217.0	256.9	298.2	347.1	350.2
2005	134.0	214.3	259.7	273.9	310.9	362.3
2006	151.6	204.8	256.1	289.9	283.4	317.7
2007	160.5	216.9	254.2	287.1	311.3	288.6
2008	164.8	220.3	252.6	288.5	310.1	326.4
2009	165.5	221.9	254.8	272.3	312.4	327.1
2010	166.4	211.3	254.2	274.8	283.0	329.1
2011	168.1	221.4	248.3	272.5	286.4	288.9
2012	166.6	219.6	252.4	278.1	282.8	293.0
2013	166.6	217.4	251.3	269.8	302.2	288.7

Table 3.3.3. Weight (g) at age on September 1 (middle of fishing year) estimated from overall weight-length parameters and annual lengths at age. Shaded cells are the average from the three preceding years.

Year	0.5	1	2	3	4	5	6+
1955	36.7	126.2	279.1	397.5	459.9	533.3	622.6
1956	25.3	105.8	269.1	431.5	502.2	563.4	606.7
1957	43.2	94.0	232.5	410.6	545.5	586.4	634.6
1958	24.0	110.2	227.0	368.9	530.1	622.7	651.3
1959	62.8	77.5	230.6	367.0	494.1	622.4	672.2
1960	35.3	132.3	189.8	363.2	488.8	599.3	690.3
1961	51.6	118.9	254.9	328.0	489.7	585.0	683.1
1962	57.5	128.0	265.9	396.4	471.3	600.8	656.5
1963	62.0	140.9	248.2	407.2	542.2	606.4	693.4
1964	63.7	142.7	266.4	360.2	520.9	682.4	726.0
1965	52.8	143.7	270.0	377.5	450.9	604.4	810.9
1966	65.6	121.0	280.1	392.7	462.8	518.8	662.5
1967	63.8	158.4	251.0	426.5	496.4	523.7	567.4
1968	73.0	124.8	307.7	411.7	565.3	577.8	565.3
1969	75.6	138.4	243.6	452.7	587.6	687.3	638.9
1970	55.7	177.6	258.8	404.1	575.4	766.0	789.5
1971	48.4	167.4	344.6	411.4	603.0	671.5	937.8
1972	24.8	125.4	339.9	511.8	588.8	834.8	743.4
1973	40.5	118.0	263.8	486.2	658.5	783.1	1093.6
1974	28.6	104.0	266.0	414.5	591.5	777.6	986.9
1975	27.1	84.2	213.8	377.5	556.6	661.3	870.0
1976	18.0	67.4	186.2	328.0	445.9	679.7	705.5
1977	21.2	64.2	145.2	294.9	430.8	484.3	781.1
1978	28.9	68.1	157.4	240.2	393.5	516.1	504.9
1979	25.3	67.8	161.4	262.4	341.6	475.4	583.3
1980	22.1	55.7	141.2	269.1	361.0	441.2	539.7
1981	20.8	69.0	117.5	230.4	373.8	444.8	534.0
1982	24.9	71.9	159.3	202.1	325.7	466.2	511.8
1983	30.6	69.9	171.6	260.0	306.0	420.0	543.2
1984	23.8	67.7	157.8	279.9	354.8	425.0	508.6
1985	21.9	67.5	138.9	262.0	378.1	436.1	554.5
1986	25.5	65.9	150.3	228.9	367.8	458.8	502.1
1987	25.9	73.7	149.9	243.7	330.5	466.1	521.5
1988	27.3	69.0	160.6	243.7	333.8	437.1	552.5
1989	41.2	93.2	150.8	252.2	332.5	413.4	543.4
1990	37.5	114.7	207.7	246.0	334.3	409.3	479.9
1991	52.5	94.0	228.2	315.9	341.6	401.8	472.1
1992	30.1	128.3	192.9	327.1	401.2	429.6	454.3
1993	51.0	95.3	247.2	298.8	400.7	462.7	506.4
1994	25.2	122.8	218.5	358.6	397.3	451.5	504.8

Year	0.5	1	2	3	4	5	6+
1995	23.5	118.6	243.0	351.9	449.3	481.7	484.8
1996	18.2	98.5	286.6	366.4	473.6	517.7	550.5
1997	29.7	88.3	243.1	435.1	477.0	574.9	567.0
1998	61.1	94.7	227.0	388.4	541.6	568.5	654.4
1999	40.3	134.7	219.5	363.3	507.8	610.8	640.7
2000	28.2	136.2	261.3	357.0	471.4	596.4	653.6
2001	55.4	128.0	291.6	400.2	484.6	548.7	658.6
2002	37.8	145.9	289.3	426.1	535.1	592.5	600.9
2003	48.1	116.9	262.8	414.7	523.7	656.8	678.6
2004	24.8	114.4	242.1	345.9	494.5	588.5	761.4
2005	35.3	88.3	224.0	350.8	397.0	540.9	629.6
2006	43.6	114.2	199.2	334.7	430.7	426.2	566.7
2007	53.7	129.6	233.0	303.1	432.7	484.5	442.5
2008	59.7	134.8	252.5	328.1	384.1	512.8	519.3
2009	53.4	117.6	245.6	347.3	392.2	441.6	575.2
2010	57.7	134.6	215.1	331.7	409.4	432.1	480.5
2011	56.9	132.7	241.5	324.0	389.7	447.2	455.8
2012	56.9	128.1	239.1	320.4	433.7	426.1	469.2
2013	56.9	128.1	231.7	328.5	371.1	537.1	448.1

Table 3.4.1. Percentage of Atlantic menhaden mature at age as determined by using the NEAMAP and commercial reduction fishery data sets. Also included is the maturity ogive used in the last assessment.

Age	Last assessment	NEAMAP	Reduction fishery
0	0%	0%	0%
1	0%	13%	8%
2	12.5%	53%	52%
3	85.1%	83%	87%
4	100%	98%	97%
5	100%	100%	99%
6	100%	100%	100%
7	100%	100%	100%
8	100%	100%	100%

Table 3.4.2. Percentage of Atlantic menhaden mature at age over time as determined by using the logistic regression from the commercial reduction fishery data sets and the time-varying population lengths at age.

				Age			
Year	0	1	2	3	4	5	6+
1955	0.00	0.07	0.70	0.93	0.97	0.99	1.00
1956	0.00	0.06	0.66	0.95	0.98	0.99	0.99
1957	0.00	0.05	0.49	0.95	0.99	0.99	0.99
1958	0.00	0.08	0.49	0.90	0.99	0.99	1.00
1959	0.00	0.03	0.49	0.89	0.98	1.00	1.00
1960	0.00	0.14	0.35	0.88	0.98	1.00	1.00
1961	0.00	0.08	0.65	0.83	0.98	0.99	1.00
1962	0.00	0.11	0.61	0.93	0.97	0.99	1.00
1963	0.00	0.13	0.63	0.93	0.99	0.99	1.00
1964	0.00	0.15	0.66	0.91	0.98	1.00	1.00
1965	0.00	0.14	0.69	0.92	0.97	0.99	1.00
1966	0.00	0.10	0.75	0.94	0.98	0.99	1.00
1967	0.00	0.17	0.66	0.97	0.98	0.99	0.99
1968	0.00	0.13	0.83	0.96	0.99	0.99	0.99
1969	0.00	0.16	0.67	0.98	1.00	1.00	1.00
1970	0.00	0.24	0.73	0.96	1.00	1.00	1.00
1971	0.00	0.20	0.90	0.96	0.99	1.00	1.00
1972	0.00	0.10	0.91	0.99	1.00	1.00	1.00
1973	0.00	0.05	0.57	0.99	1.00	1.00	1.00
1974	0.00	0.06	0.66	0.92	1.00	1.00	1.00
1975	0.00	0.04	0.52	0.94	0.99	1.00	1.00
1976	0.00	0.03	0.30	0.90	0.98	1.00	1.00
1977	0.00	0.02	0.23	0.78	0.98	0.99	1.00
1978	0.00	0.02	0.19	0.69	0.96	0.99	0.99
1979	0.00	0.03	0.22	0.66	0.92	0.99	1.00
1980	0.00	0.02	0.20	0.72	0.93	0.98	1.00
1981	0.00	0.02	0.15	0.62	0.95	0.98	0.99
1982	0.00	0.03	0.23	0.52	0.89	0.99	1.00
1983	0.00	0.03	0.26	0.68	0.85	0.97	1.00
1984	0.00	0.03	0.29	0.73	0.91	0.96	0.99
1985	0.00	0.02	0.22	0.79	0.94	0.97	0.99
1986	0.00	0.02	0.22	0.68	0.96	0.99	0.99
1987	0.00	0.03	0.19	0.67	0.92	0.99	1.00
1988	0.00	0.02	0.24	0.65	0.91	0.98	1.00
1989	0.00	0.04	0.25	0.69	0.92	0.98	1.00
1990	0.00	0.07	0.41	0.73	0.92	0.98	0.99
1991	0.00	0.05	0.56	0.86	0.94	0.98	1.00
1992	0.00	0.11	0.45	0.89	0.97	0.98	0.99
1993	0.00	0.04	0.59	0.87	0.97	0.99	0.99
1994	0.00	0.10	0.42	0.92	0.97	0.99	1.00
1995	0.00	0.04	0.66	0.89	0.98	0.99	0.99

	Age						
Year	0	1	2	3	4	5	6+
1996	0.00	0.03	0.63	0.95	0.99	1.00	1.00
1997	0.00	0.03	0.57	0.96	0.99	1.00	1.00
1998	0.00	0.04	0.39	0.95	0.99	1.00	1.00
1999	0.00	0.14	0.50	0.89	0.99	1.00	1.00
2000	0.00	0.08	0.69	0.91	0.98	1.00	1.00
2001	0.00	0.06	0.80	0.95	0.98	1.00	1.00
2002	0.00	0.14	0.75	0.98	0.99	1.00	1.00
2003	0.00	0.08	0.70	0.96	1.00	1.00	1.00
2004	0.00	0.08	0.60	0.91	0.99	1.00	1.00
2005	0.00	0.03	0.57	0.92	0.96	0.99	1.00
2006	0.00	0.06	0.46	0.91	0.98	0.97	0.99
2007	0.00	0.09	0.60	0.90	0.98	0.99	0.98
2008	0.00	0.11	0.64	0.89	0.98	0.99	1.00
2009	0.00	0.11	0.65	0.90	0.95	0.99	1.00
2010	0.00	0.12	0.53	0.90	0.96	0.97	1.00
2011	0.00	0.13	0.65	0.87	0.95	0.98	0.98
2012	0.00	0.12	0.63	0.89	0.96	0.97	0.98
2013	0.00	0.12	0.60	0.88	0.95	0.99	0.98

Table 3.5.1. Fecundity (number of ova) at age on March 1 (beginning of fishing year) estimated from annual lengths.

Year	1	2	3	4	5	6+
1955	26267	76356	134072	171499	225574	314702
1956	24883	72366	143502	198473	238833	279006
1957	23368	57467	144117	219979	262471	296958
1958	27254	57476	117858	230192	293759	320304
1959	20527	57823	113474	218295	316474	357302
1960	32777	47911	109417	189742	370470	392930
1961	26775	71349	96300	187906	279836	583275
1962	30235	67500	134037	171141	297215	375348
1963	32403	68920	131049	223455	274818	438442
1964	33692	72330	120396	210941	338151	405941
1965	33326	75794	127224	175648	296815	473099
1966	29143	82221	136478	189256	226831	379233
1967	35572	71658	169108	209101	250238	269709
1968	32194	96373	156906	300776	284953	304553
1969	35028	73488	203311	310553	476360	356683
1970	40785	80098	153362	355629	562879	687690
1971	37767	116588	165349	295467	540609	944933
1972	28938	120135	264616	312075	530105	739806
1973	23352	64090	251253	501646	544506	892560
1974	24271	71970	126973	402194	826354	886857
1975	21245	59625	138682	228571	542898	1219898
1976	18604	44895	118252	203248	378919	657341
1977	17400	39935	86830	199236	253960	585202
1978	17768	37208	75112	155318	296465	289161
1979	19244	39023	72427	126644	259346	401304
1980	17524	37913	78409	129836	195075	407546
1981	18298	33502	68360	145595	216542	278839
1982	19817	39834	60076	114123	252076	339017
1983	18579	42124	74366	101690	178182	410168
1984	19306	44310	79989	122730	163410	262470
1985	18410	39323	89194	137999	183470	250572
1986	17838	39010	73718	156641	219434	253334
1987	19072	37306	72816	128431	246471	325540
1988	18035	40898	71494	122319	209725	354998
1989	21041	41123	75715	126859	188243	323439
1990	26177	52198	80213	124490	210324	269352
1991	23564	63325	103370	137864	185986	328444
1992	29834	55250	114350	172802	213846	257181
1993	21955	65819	106374	169801	254310	305240
1994	29190	52835	126214	176012	221209	340065

Year	1	2	3	4	5	6+
1995	21827	72214	114326	215661	259222	264026
1996	19204	69223	144185	225319	335133	349075
1997	18541	64206	156512	244434	409063	481664
1998	21465	51057	151852	278590	365730	690935
1999	32798	58256	113812	280572	418758	497451
2000	27487	75179	121790	214629	434711	558555
2001	24369	89659	144090	209972	354575	594044
2002	33274	82031	196498	240004	313961	527521
2003	26878	76273	157805	330756	358097	422592
2004	27465	66446	120859	224531	467296	490110
2005	19130	63834	126059	156028	271539	587754
2006	24912	55360	119383	198305	179784	300837
2007	28460	66301	116016	190006	273240	194493
2008	30382	69774	113395	194201	268277	342797
2009	30670	71500	117175	152188	277993	346570
2010	31077	61013	116070	158122	178830	356863
2011	31910	70991	106252	152698	188034	195368
2012	31215	69046	112949	166207	178345	207843
2013	31215	66874	111211	146641	238433	194730

Table 3.6.1. Constant ***M*** from life history approaches, using ***K*** and L_∞ averaged across annual values, either full period of 1955-2012 or recent period of 2011-2013. Maximum age, t_{max}, is 10 years, and water temperature, T°C, is 19. For comparison, we have included the average estimates of ***M*** from age-varying approaches for ages 1-10.

Life History	**Parameters**	**Recent (2011-2013)**	**Overall (1955-2012)**
Fixed M Approaches:	$t_{max} = 10$ $T = 19^{o}C$	$L_\infty = 32.6$ cm, $K = 0.466$	$L_\infty = 36.5$ cm, $K = 0.363$
Alverson & Carney	K, t_{max}	0.28	0.36
Hoenig	t_{max}	0.42	0.42
Jensen	K	0.7	0.55
Pauly	K, L_∞, T°C	0.88	0.74
Rule of thumb	t_{max}	0.30	0.30
Age Varying Approaches:		***M Averaged over Ages 1-10 and then over years***	
Peterson & Wroblewski	W_a^{-1}	0.58	0.61
Boudreau & Dickie	W_a^{-1}	0.47	0.50
Lorenzen	W_a^{-1}	0.54	0.57
Charnov et al	$W\alpha/W_\infty$	0.46	0.53
MSVPA-X (1982-2012)	MSVPA-X	0.53	0.56

Table 3.6.2. Summaries of various age-specific estimates of ***M*** including those as inverse function of size at age [Petersen and Wroblewski 1984, Boudreau and Dickie 1989, Lorenzen 1996, Charnov et al. 2013] and the predator-prey approach used in MSVPA-X.

Age	P&W	B&D	L	CGP	MSVPA
0	1.166	1.147	1.231	1.651	1.115
1	0.899	0.813	0.896	0.955	0.872
2	0.746	0.635	0.713	0.656	0.674
3	0.669	0.550	0.624	0.532	0.576
4	0.625	0.503	0.575	0.468	0.522
5	0.597	0.474	0.544	0.431	0.478
6	0.579	0.455	0.524	0.408	0.443

Table 3.6.3. Observed year- and age-varying estimates of ***M*** from MSVPA-X for 1982-2012.

Year	Age 0	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6+
1982	1.69	1.31	0.99	0.85	0.67	0.52	0.46
1983	1.53	1.24	0.92	0.75	0.67	0.53	0.45
1984	1.36	1.11	0.81	0.67	0.60	0.52	0.44
1985	1.30	1.07	0.82	0.63	0.56	0.51	0.45
1986	1.25	1.05	0.81	0.66	0.54	0.50	0.46
1987	1.15	0.92	0.74	0.62	0.53	0.47	0.45
1988	1.01	0.85	0.67	0.58	0.52	0.46	0.43
1989	0.93	0.78	0.66	0.57	0.51	0.46	0.43
1990	0.92	0.72	0.60	0.55	0.51	0.46	0.43
1991	0.85	0.75	0.58	0.52	0.50	0.46	0.43
1992	0.84	0.64	0.56	0.50	0.47	0.45	0.43
1993	0.83	0.73	0.56	0.51	0.48	0.45	0.43
1994	0.95	0.68	0.59	0.50	0.48	0.46	0.43
1995	1.08	0.76	0.57	0.52	0.47	0.46	0.44
1996	1.07	0.78	0.57	0.50	0.46	0.45	0.45
1997	1.04	0.82	0.58	0.49	0.46	0.44	0.44
1998	0.94	0.84	0.65	0.50	0.46	0.44	0.42
1999	1.14	0.76	0.64	0.54	0.46	0.44	0.42
2000	1.18	0.76	0.59	0.53	0.48	0.44	0.42
2001	1.01	0.81	0.57	0.52	0.49	0.45	0.42
2002	1.20	0.85	0.64	0.51	0.50	0.47	0.43
2003	1.06	0.83	0.63	0.53	0.46	0.45	0.43
2004	1.25	0.86	0.66	0.59	0.51	0.45	0.44
2005	1.24	1.00	0.70	0.58	0.57	0.48	0.44
2006	1.21	0.95	0.73	0.60	0.54	0.53	0.44
2007	1.08	0.85	0.67	0.58	0.52	0.50	0.48
2008	1.06	0.85	0.67	0.60	0.52	0.50	0.49
2009	1.10	0.88	0.68	0.60	0.57	0.49	0.48
2010	1.09	0.87	0.72	0.61	0.57	0.52	0.46
2011	1.09	0.86	0.69	0.61	0.57	0.53	0.48
2012	1.11	0.88	0.70	0.60	0.56	0.54	0.50

Table 4.1.1. Years of activity for individual menhaden reduction plants along the U.S. Atlantic coast, 1955-2013.

Year/																																				Total	Numbe
Plant	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	32	33	34	35	36	Plants	Vessels
1955	+	+	+	+	+	+		+		+	+	+	+		+	+	+	+	+	+	+	+	+	+	+	+										23	150
1956	+	+	+	+	+	+		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+											24	149
1957	+	+	+	+	+	+		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+										25	144
1958	+	+	+	+	+			+	+	+	+	+	+	+	+	+	+	+		+	+		+	+	+	+										22	130
1959	+	+	+	+	+	+		+	+	+	+	+	+	+	+	+	+	+		+	+		+	+	+	+										23	144
1960	+	+	+	+	+	+		+	+	+	+	+	+	+	+	+	+	+		+			+		+											20	115
1961	+	+	+	+	+	+		+	+	+	+	+	+	+	+	+	+	+		+			+		+											20	117
1962	+	+	+	+	+	+		+	+	+	+	+	+	+	+	+	+			+			+		+											19	112
1963	+	+	+	+	+			+	+	+	+	+	+	+	+	+	+	+		+																17	112
1964	+	+	+	+	+	+		+	+	+	+	+	+	+	+	+	+	+		+																18	111
1965	+	+		+	+			+		+	+	+	+	+		+	+	+	+	+							+	+								17	84
1966	+	+		+	+		+	+	+	+	+	+	+	+	+	+	+		+	+							+	+	+							20	76
1967		+		+			+	+	+	+	+	+	+	+	+	+	+		+	+							+	+	+							18	64
1968	+	+		+			+			+	+	+	+	+	+	+	+		+	+							+	+	+							17	59
1969	+	+		+			+			+		+	+	+	+	+	+			+							+	+	+							15	51
1970		+					+			+		+	+	+	+	+	+			+			+		+		+	+	+							15	54
1971		+					+			+		+	+	+	+	+	+			+			+		+		+	+								14	51
1972		+					+			+			+	+			+			+			+		+		+	+								11	51
1973		+					+			+			+	+			+			+		+	+		+			+								11	58
1974		+					+			+			+	+			+			+			+		+			+								10	63
1975		+					+			+			+	+			+			+		+	+		+			+		+						12	61
1976		+					+			+			+	+			+			+			+		+			+		+						11	62
1977		+					+			+			+	+			+			+		+	+		+			+		+						12	64
1978		+					+			+			+	+			+			+		+	+		+			+		+						12	53
1979		+					+			+			+	+			+			+		+	+		+			+		+						12	54
1980		+					+			+			+	+			+			+		+	+					+		+						11	51
1981		+					+			+			+	+			+			+		+	+					+		+						11	57
1982							+			+			+	+			+			+		+	+					+		+						10	47
1983							+			+			+	+			+			+			+					+		+						9	41
1984							+			+			+	+						+			+					+		+						8	38
1985							+			+			+							+								+		+						6	24
1986							+			+			+							+								+		+						6	16
1987							+			+			+							+										+	+					6	23
1988							+			+			+																	+	+	+				6	30
1989							+			+			+																		+	+				5	37
1990							+			+			+																		+	+				5	35
1991							+			+			+																		+	+				5	37
1992							+			+			+																		+	+	+	+	+	8	37
1993							+			+			+																		+	+		+	+	7	31
1994							+			+			+																							3	20
1995							+			+			+																							3	20
1996							+			+			+																							3	21
1997							+			+			+																							3	23
1998										+			+																							2	15
1999										+			+																							2	15
2000										+			+																							2	12
2001										+			+																							2	12
2002										+			+																							2	12
2003										+			+																							2	12
2004										+			+																							2	13
2005										+																										1	11
2006										+																										1	11
2007										+																										1	10
2008										+																										1	10
2009										+																										1	10
2010										+																										1	11
2011										+																										1	10
2012										+																										1	9
2013										+																										1	7

Table 4.1.1. Continued.

Port	Plant	Name	Location
3	1	Atlantic Processing Co.	Amagansett, NY
4	2	J. Howard Smith (Seacoast Products)	Port Monmouth, NJ
4	3	Fish Products Co.	Tuckerton, NJ
8	4	New Jersey Menhaden Products Co.	Wildwood, NJ
0	5	Fish Products Co. (Seacoast Products Co.)	Lewes, DE
0	6	Consolidated Fisheries	Lewes, DE
5	7	AMPRO (Standard Products Co.)	Reedville, VA
5	8	McNeal-Edwards (Standard Products Co.)	Reedville, VA
5	9	Menhaden Co. (Standard Products Co.)	Reedville, VA
5	10	Omega Protein (Zapata Haynie Co.)	Reedville, VA
5	11	Standard Products Co.	White Stone, VA
6	12	Fish Meal Co.	Beaufort, NC
6	13	Beaufort Fisheries, Inc.	Beaufort, NC
6	14	Standard Products Co.	Beaufort, NC
6	15	Standard Products Co.	Morehead City, NC
6	16	Haynie Products, Inc.	Morehead City, NC
7	17	Standard Products Co.	Southport, NC
7	18	Southport Fisheries Menhaden	Southport, NC
9	19	Quinn Menhaden Fisheries, Inc.	Fernandina Beach, FL
9	20	Nassau Oil and Fertilizer Co.	Fernandina Beach, FL
9	21	Mayport Fisheries	Mayport, FL
1	22	Maine Marine Products (Pine State Products)	Portland, ME
2	23	Lipman Marine Products (Gloucester Marine Protein)	Gloucester, MA
2	24	Gloucester Dehydration Co.	Gloucester, MA
11	25	Point Judith By Products Co.	Point Judith, RI
9	26	Quinn Fisheries	Younges Island, SC
5	27	Haynie Products (Cockerall's Ice & Seafood)	Reedville, VA
6	28	Sea and Sound Processing Co.	Beaufort, NC
12	29	Cape Charles Processing Co.	Cape Charles, VA
13	30	Sea Pro, Inc.	Rockland, ME
15	32	Connor Bros.	New Brunswick, Canada
14	33	Riga (IWP)	Maine
14	34	Vares (IWP)	Maine
14	35	Dauriya (IWP)	Maine
15	36	Comeau	Nova Scotia, Canada

Table 4.1.3.1.1. Menhaden reduction landings (1000s mt), nominal fishing effort (vessel-weeks), and CPUE (landings per vessel-week), 1940-2013.

	Reduction Fishery		
Year	Landings (1000 t)	Effort (v-w)	CPUE
1940	217.7	967	0.225
1941	277.9	1291	0.215
1942	167.2	991	0.169
1943	237.2	889	0.267
1944	257.9	1167	0.221
1945	295.9	1271	0.233
1946	362.4	1365	0.265
1947	378.3	1582	0.239
1948	346.5	1781	0.195
1949	363.8	2076	0.175
1950	297.2	1650	0.180
1951	361.4	1686	0.214
1952	409.9	1653	0.248
1953	593.2	1972	0.301
1954	608.1	2094	0.290
1955	641.4	2748	0.233
1956	712.1	2878	0.247
1957	602.8	2775	0.217
1958	510.0	2343	0.218
1959	659.1	2847	0.232
1960	529.8	2097	0.253
1961	575.9	2371	0.243
1962	537.7	2351	0.229
1963	346.9	2331	0.149
1964	269.2	1807	0.149
1965	273.4	1805	0.151
1966	219.6	1386	0.158
1967	193.5	1316	0.147
1968	234.8	1209	0.194
1969	161.6	995	0.162
1970	259.4	906	0.286
1971	250.3	897	0.279
1972	365.9	973	0.376
1973	346.9	1099	0.316
1974	292.2	1145	0.255
1975	250.2	1218	0.205

Table 4.1.3.1.1 Continued.

	Reduction Fishery		
Year	Landings (1000 t)	Effort (v-w)	CPUE
1976	340.5	1163	0.293
1977	341.1	1239	0.275
1978	344.1	1210	0.284
1979	375.7	1198	0.314
1980	401.5	1158	0.347
1981	381.3	1133	0.337
1982	382.4	948	0.403
1983	418.6	995	0.421
1984	326.3	892	0.366
1985	306.7	577	0.532
1986	238.0	377	0.631
1987	327.0	531	0.616
1988	309.3	604	0.512
1989	322.0	725	0.444
1990	401.2	826	0.486
1991	381.4	926	0.412
1992	297.6	794	0.375
1993	320.6	626	0.512
1994	260.0	573	0.454
1995	339.9	600	0.567
1996	292.9	528	0.555
1997	259.1	618	0.419
1998	245.9	437	0.563
1999	171.2	382	0.448
2000	167.2	311	0.538
2001	233.7	334	0.700
2002	174.0	318	0.547
2003	166.1	302	0.550
2004	183.4	345	0.532
2005	146.9	291	0.505
2006	157.4	322	0.489
2007	174.5	333	0.524
2008	141.1	262	0.539
2009	143.8	300	0.479
2010	183.1	356	0.514
2011	174.0	324	0.537
2012	160.6	279	0.576
2013	131.0	196	0.668

Table 4.1.3.3.1. Sample size (n), landings in numbers of fish, landings in biomass (C), sampling “intensity” (landings in metric tons per 100 fish measured), and mean weight of fish landed from the Atlantic menhaden reduction fishery, 1955-2013.

Year	Sample Size (n)	Landings (millions)	Landings (1000 t)	Intensity (C/100n)	Mean Weight (g)
1955	16037	3118.4	641.4	3999.5	205.7
1956	19873	3564.8	712.1	3583.3	199.8
1957	19674	3511.7	602.8	3063.9	171.7
1958	15315	2719.2	510.0	3330.1	187.6
1959	17935	5353.6	659.1	3674.9	123.1
1960	13505	2775.1	529.8	3923.0	190.9
1961	13184	2598.3	575.9	4368.2	221.6
1962	15771	2099.9	537.7	3409.4	256.1
1963	13001	1764.5	346.9	2668.3	196.6
1964	10438	1729.1	269.2	2579.0	155.7
1965	19518	1519.5	273.4	1400.8	179.9
1966	15633	1340.6	219.6	1404.7	163.8
1967	15426	984.2	193.5	1254.4	196.6
1968	26830	1148.0	234.8	875.1	204.5
1969	15114	868.2	161.6	1069.2	186.1
1970	8426	1403.0	259.4	3078.6	184.9
1971	8269	969.1	250.3	3027.0	258.3
1972	6552	1713.9	365.9	5584.6	213.5
1973	6351	1843.4	346.9	5462.1	188.2
1974	5421	1990.6	292.2	5390.1	146.8
1975	7278	2162.3	250.2	3437.8	115.7
1976	6725	3283.5	340.5	5063.2	103.7
1977	7276	3673.7	341.1	4688.0	92.8
1978	7094	3085.2	344.1	4850.6	111.5
1979	6365	3870.1	375.7	5902.6	97.1
1980	7291	3332.3	401.5	5506.8	120.5
1981	9201	3984.0	381.3	4144.1	95.7
1982	9066	3175.7	382.4	4218.0	120.4
1983	11533	3942.1	418.6	3629.6	106.2
1984	11689	3548.0	326.3	2791.5	92.0
1985	8498	3025.3	306.7	3609.1	101.4
1986	5828	1912.4	238.0	4083.7	124.5
1987	7618	2315.2	327.0	4292.5	141.2
1988	7349	2158.0	309.3	4208.7	143.3
1989	7027	2630.5	322.0	4582.3	122.4

Table 4.1.3.3.1. Continued.

	Sample Size	Landings		Intensity	Mean
Year	(n)	(millions)	(1000 mt)	(C/100n)	Weight (g)
1990	6838	2157.9	401.2	5867.2	185.9
1991	7770	3166.6	381.4	4908.6	120.4
1992	5680	2052.5	297.6	5239.4	145.0
1993	5488	1594.0	320.6	5841.8	201.1
1994	5278	1492.0	260.0	4926.1	174.3
1995	4996	1643.3	339.9	6803.4	206.8
1996	4628	1091.9	292.9	6328.9	268.2
1997	4465	995.9	259.1	5802.9	260.2
1998	4558	1007.5	245.9	5394.9	244.1
1999	4279	1056.3	171.2	4000.9	162.1
2000	3669	657.4	167.2	4557.1	254.3
2001	5012	669.2	233.7	4662.8	349.2
2002	4370	803.1	174.0	3981.7	216.7
2003	3945	698.3	166.1	4210.3	237.9
2004	4600	978.0	183.4	3987.0	187.5
2005	3940	648.5	146.9	3727.4	226.4
2006	4209	754.0	157.4	3739.6	208.8
2007	5320	932.6	174.5	3280.1	187.1
2008	4438	577.4	141.1	3179.4	244.4
2009	2461	738.3	143.8	5843.2	199.4
2010	2710	1023.1	183.1	6756.5	192.5
2011	2721	987.3	174.0	6394.7	187.1
2012	2412	796.4	160.6	6658.4	204.4
2013	1873	633.6	131.0	6994.1	212.8

Table 4.1.3.3.2. Estimated reduction landings of Atlantic menhaden in numbers at age (in millions), 1955-2013.

Year	0	1	2	3	4	5	6	7	8
1955	761.01	674.15	1057.68	267.31	307.21	38.07	10.53	1.84	0.64
1956	36.37	2073.26	902.72	319.60	44.78	150.68	28.70	6.72	1.99
1957	299.58	1599.98	1361.77	96.73	70.80	40.52	36.93	4.26	1.10
1958	106.06	858.16	1635.35	72.05	17.25	15.94	9.09	4.88	0.43
1959	11.40	4038.72	851.29	388.27	33.41	11.87	12.36	4.55	1.77
1960	72.17	281.01	2208.63	76.37	102.20	23.77	7.95	2.36	0.65
1961	0.25	832.42	503.60	1209.57	19.18	29.38	2.86	0.81	0.24
1962	51.58	514.11	834.52	217.25	423.37	30.75	24.60	2.98	0.70
1963	96.89	724.23	709.20	122.53	44.97	52.38	10.42	3.33	0.56
1964	302.59	703.95	604.98	83.50	17.94	7.85	6.62	1.31	0.32
1965	259.12	745.21	421.40	77.76	12.17	1.81	1.22	0.75	0.07
1966	349.45	550.82	404.14	31.70	3.89	0.36	0.11	0.11	0.04
1967	6.95	633.20	265.67	72.78	5.09	0.49	0.01	0.00	0.00
1968	154.26	377.36	538.95	65.69	10.68	0.98	0.06	0.00	0.00
1969	158.13	372.33	284.31	47.81	5.44	0.15	0.01	0.00	0.00
1970	21.42	870.85	473.92	32.63	4.02	0.11	0.00	0.00	0.00
1971	72.85	263.29	524.32	88.29	17.84	2.51	0.00	0.00	0.00
1972	50.16	981.27	488.47	173.06	19.12	1.86	0.00	0.00	0.00
1973	55.98	588.47	1152.94	38.63	7.00	0.34	0.00	0.00	0.00
1974	315.55	636.68	985.97	48.59	2.49	1.35	0.00	0.00	0.00
1975	298.64	719.96	1086.53	50.24	6.63	0.20	0.10	0.00	0.00
1976	274.23	1611.96	1341.09	47.97	7.95	0.28	0.00	0.00	0.00
1977	484.62	1004.54	2081.77	83.46	17.80	1.41	0.11	0.00	0.00
1978	457.41	664.09	1670.91	258.12	31.19	3.48	0.00	0.00	0.00
1979	1492.46	623.14	1603.29	127.93	21.76	1.47	0.09	0.00	0.00
1980	88.29	1478.09	1458.23	222.71	69.23	14.36	1.43	0.00	0.00
1981	1187.57	698.66	1811.46	222.20	47.47	15.37	1.27	0.00	0.00
1982	114.12	919.44	1739.55	379.67	16.33	5.78	0.53	0.32	0.00
1983	964.41	517.22	2293.06	114.35	47.37	5.01	0.23	0.00	0.46
1984	1294.22	1024.17	892.09	271.50	50.34	15.21	0.51	0.00	0.00
1985	637.19	1075.85	1224.62	44.06	35.63	6.25	1.68	0.00	0.00
1986	98.39	224.21	1523.13	49.07	10.47	6.08	1.06	0.00	0.00
1987	42.87	504.70	1587.66	151.88	25.17	2.19	0.70	0.00	0.00
1988	338.82	282.65	1157.65	301.37	69.79	7.11	0.33	0.25	0.00
1989	149.72	1154.59	1158.54	108.36	47.47	11.63	0.21	0.00	0.00

Table 4.1.3.3.2. Continued.

Year	0	1	2	3	4	5	6	7	8
1990	308.07	132.80	1553.12	108.96	42.18	12.34	0.43	0.00	0.00
1991	881.77	1033.94	946.07	253.98	37.95	10.70	2.03	0.13	0.00
1992	399.65	727.22	795.44	66.06	51.30	10.89	1.39	0.51	0.00
1993	67.91	379.02	983.07	148.90	10.91	3.88	0.30	0.00	0.00
1994	88.61	274.51	888.86	165.07	67.24	7.52	0.23	0.00	0.00
1995	56.76	533.65	671.85	309.13	67.53	4.36	0.00	0.00	0.00
1996	33.72	209.14	679.13	138.95	28.96	2.04	0.00	0.00	0.00
1997	25.22	246.91	424.54	237.43	51.59	8.97	1.21	0.00	0.00
1998	72.84	184.99	540.56	126.32	72.98	9.00	0.76	0.00	0.00
1999	193.87	301.12	450.82	81.84	25.00	3.24	0.36	0.00	0.00
2000	77.75	114.15	340.62	111.89	11.06	1.94	0.00	0.00	0.00
2001	22.97	43.52	369.48	217.60	14.93	0.67	0.00	0.00	0.00
2002	178.19	211.74	259.79	135.80	17.05	0.48	0.00	0.00	0.00
2003	60.74	127.51	447.28	53.76	7.79	0.93	0.27	0.00	0.00
2004	17.97	213.95	652.09	75.70	17.41	0.90	0.00	0.00	0.00
2005	12.10	78.86	382.89	154.19	18.68	1.82	0.00	0.00	0.00
2006	9.16	298.91	300.13	121.65	23.62	0.48	0.00	0.00	0.00
2007	1.14	239.20	609.24	69.43	12.97	0.68	0.00	0.00	0.00
2008	7.90	52.37	394.87	106.64	14.65	1.03	0.00	0.00	0.00
2009	4.39	352.41	228.95	130.82	19.92	1.84	0.00	0.00	0.00
2010	15.48	409.50	501.11	68.10	28.31	0.57	0.00	0.00	0.00
2011	0.00	418.47	493.06	65.14	8.86	1.72	0.00	0.00	0.00
2012	4.67	127.24	626.95	33.61	3.89	0.00	0.00	0.00	0.00
2013	22.13	240.01	284.84	76.26	10.11	0.25	0.00	0.00	0.00

Table 4.1.3.4.1. Northern and southern reduction fishery landings in 1000s of mt from 1955-2013.

Year	North	South
1955	402.7	241.7
1956	478.9	236.4
1957	389.8	215.8
1958	248.3	264.0
1959	318.4	343.7
1960	323.9	208.4
1961	334.8	243.9
1962	321.4	219.3
1963	147.5	200.9
1964	50.6	219.8
1965	58.0	216.6
1966	7.9	212.8
1967	17.2	177.2
1968	33.1	202.8
1969	15.4	146.9
1970	15.8	243.6
1971	33.4	216.9
1972	69.1	296.8
1973	90.7	256.2
1974	77.9	214.3
1975	48.4	201.8
1976	86.8	253.7
1977	53.3	287.8
1978	63.5	280.5
1979	70.2	305.6
1980	83.0	318.5
1981	68.1	313.2
1982	35.1	347.4
1983	39.4	379.3
1984	35.0	291.3
1985	111.3	195.4
1986	42.6	195.4
1987	83.0	243.9
1988	73.6	235.6
1989	98.8	223.2
1990	144.1	257.1
1991	104.6	276.9
1992	99.1	198.5
1993	58.4	262.2
1994	33.4	226.6
1995	96.3	243.6
1996	61.6	231.4
1997	25.2	234.0
1998	12.3	233.6
1999	8.4	162.8
2000	43.2	124.1
2001	39.6	193.9
2002	27.2	146.9
2003	4.1	162.0
2004	25.9	152.6
2005	15.4	137.5
2006	60.1	97.2
2007	36.6	137.8
2008	39.3	101.8
2009	18.7	125.1
2010	28.7	154.4
2011	29.6	144.5
2012	23.9	136.7
2013	32.7	98.3

Table 4.1.3.4.2. Catch-at-age for the northern commercial reduction fishery from 1955-2013.

Year	0	1	2	3	4	5	6+
1955	0.000	0.015	0.471	0.217	0.253	0.032	0.012
1956	0.000	0.133	0.555	0.195	0.025	0.072	0.020
1957	0.000	0.270	0.610	0.051	0.033	0.017	0.020
1958	0.000	0.025	0.908	0.042	0.010	0.008	0.009
1959	0.000	0.531	0.291	0.159	0.009	0.004	0.007
1960	0.000	0.009	0.892	0.037	0.049	0.009	0.004
1961	0.000	0.003	0.160	0.803	0.012	0.018	0.003
1962	0.000	0.015	0.245	0.218	0.457	0.033	0.032
1963	0.000	0.296	0.438	0.095	0.068	0.080	0.023
1964	0.000	0.034	0.357	0.345	0.128	0.065	0.072
1965	0.000	0.160	0.370	0.373	0.071	0.013	0.014
1966	0.000	0.201	0.467	0.212	0.100	0.009	0.012
1967	0.000	0.055	0.296	0.567	0.072	0.009	0.000
1968	0.000	0.007	0.479	0.388	0.116	0.009	0.001
1969	0.000	0.001	0.251	0.594	0.149	0.005	0.000
1970	0.000	0.150	0.793	0.050	0.007	0.000	0.000
1971	0.000	0.126	0.288	0.433	0.137	0.017	0.000
1972	0.000	0.169	0.286	0.452	0.085	0.008	0.000
1973	0.000	0.021	0.821	0.133	0.024	0.001	0.000
1974	0.000	0.028	0.844	0.117	0.006	0.004	0.000
1975	0.000	0.000	0.798	0.175	0.025	0.001	0.000
1976	0.000	0.092	0.823	0.071	0.013	0.000	0.000
1977	0.000	0.022	0.567	0.326	0.079	0.006	0.001
1978	0.000	0.000	0.298	0.567	0.120	0.015	0.000
1979	0.000	0.007	0.579	0.332	0.076	0.006	0.000
1980	0.000	0.002	0.237	0.462	0.243	0.051	0.004
1981	0.000	0.001	0.357	0.357	0.210	0.070	0.006
1982	0.000	0.042	0.393	0.473	0.063	0.025	0.004
1983	0.000	0.012	0.826	0.120	0.037	0.005	0.000
1984	0.000	0.024	0.343	0.506	0.097	0.029	0.001
1985	0.000	0.020	0.760	0.089	0.111	0.017	0.003
1986	0.000	0.010	0.795	0.107	0.050	0.031	0.006
1987	0.000	0.005	0.652	0.277	0.058	0.006	0.002
1988	0.000	0.000	0.225	0.486	0.260	0.026	0.003
1989	0.000	0.081	0.623	0.173	0.097	0.025	0.000
1990	0.000	0.011	0.788	0.134	0.049	0.018	0.001
1991	0.000	0.085	0.430	0.385	0.072	0.023	0.005
1992	0.000	0.058	0.687	0.107	0.118	0.026	0.004
1993	0.000	0.045	0.675	0.226	0.036	0.017	0.002
1994	0.000	0.017	0.420	0.333	0.183	0.047	0.000
1995	0.000	0.020	0.567	0.329	0.079	0.006	0.000
1996	0.000	0.000	0.579	0.320	0.092	0.008	0.000
1997	0.000	0.000	0.495	0.293	0.158	0.055	0.000
1998	0.000	0.000	0.657	0.281	0.062	0.000	0.000
1999	0.000	0.000	0.389	0.428	0.168	0.015	0.000
2000	0.000	0.005	0.559	0.406	0.019	0.011	0.000

Year	0	1	2	3	4	5	6+
2001	0.000	0.000	0.150	0.796	0.055	0.000	0.000
2002	0.000	0.040	0.347	0.491	0.120	0.002	0.000
2003	0.000	0.000	0.474	0.378	0.139	0.010	0.000
2004	0.000	0.004	0.615	0.320	0.061	0.000	0.000
2005	0.000	0.000	0.219	0.605	0.174	0.002	0.000
2006	0.000	0.022	0.456	0.422	0.099	0.001	0.000
2007	0.000	0.022	0.761	0.174	0.041	0.002	0.000
2008	0.000	0.002	0.216	0.668	0.106	0.008	0.000
2009	0.000	0.123	0.299	0.463	0.102	0.013	0.000
2010	0.000	0.000	0.456	0.348	0.193	0.003	0.000
2011	0.000	0.058	0.726	0.190	0.023	0.003	0.000
2012	0.000	0.001	0.778	0.192	0.029	0.000	0.000
2013	0.000	0.028	0.724	0.233	0.015	0.000	0.000

Table 4.1.3.4.3. Catch-at-age for the southern commercial reduction fishery from 1955-2013.

Year	0	1	2	3	4	5	6+
1955	0.374	0.323	0.269	0.016	0.016	0.002	0.000
1956	0.017	0.885	0.049	0.018	0.004	0.022	0.004
1957	0.151	0.598	0.217	0.010	0.011	0.007	0.006
1958	0.059	0.466	0.443	0.018	0.005	0.005	0.004
1959	0.003	0.855	0.099	0.034	0.005	0.002	0.002
1960	0.052	0.192	0.701	0.018	0.025	0.008	0.004
1961	0.000	0.538	0.217	0.234	0.004	0.007	0.000
1962	0.040	0.387	0.491	0.033	0.044	0.003	0.002
1963	0.079	0.460	0.386	0.059	0.007	0.008	0.002
1964	0.187	0.433	0.349	0.028	0.002	0.000	0.000
1965	0.184	0.528	0.269	0.018	0.001	0.000	0.000
1966	0.265	0.414	0.299	0.020	0.001	0.000	0.000
1967	0.007	0.663	0.269	0.057	0.003	0.000	0.000
1968	0.143	0.349	0.468	0.037	0.003	0.000	0.000
1969	0.188	0.442	0.330	0.038	0.002	0.000	0.000
1970	0.016	0.650	0.309	0.022	0.003	0.000	0.000
1971	0.083	0.288	0.569	0.054	0.005	0.001	0.000
1972	0.033	0.618	0.285	0.061	0.003	0.000	0.000
1973	0.036	0.372	0.591	0.001	0.000	0.000	0.000
1974	0.196	0.388	0.413	0.003	0.000	0.000	0.000
1975	0.154	0.371	0.469	0.006	0.001	0.000	0.000
1976	0.101	0.572	0.324	0.003	0.000	0.000	0.000
1977	0.140	0.289	0.567	0.003	0.000	0.000	0.000
1978	0.158	0.230	0.558	0.050	0.003	0.000	0.000
1979	0.413	0.172	0.403	0.012	0.001	0.000	0.000
1980	0.028	0.476	0.452	0.038	0.004	0.001	0.000
1981	0.316	0.186	0.460	0.038	0.000	0.000	0.000
1982	0.038	0.306	0.558	0.096	0.001	0.000	0.000
1983	0.279	0.148	0.547	0.016	0.008	0.001	0.000
1984	0.396	0.311	0.244	0.040	0.007	0.002	0.000
1985	0.235	0.394	0.364	0.006	0.000	0.000	0.000
1986	0.056	0.126	0.797	0.019	0.002	0.001	0.000
1987	0.022	0.253	0.691	0.031	0.003	0.000	0.000
1988	0.175	0.146	0.573	0.099	0.006	0.001	0.000
1989	0.069	0.514	0.402	0.014	0.001	0.000	0.000
1990	0.190	0.078	0.697	0.023	0.010	0.002	0.000
1991	0.317	0.360	0.281	0.038	0.004	0.001	0.000
1992	0.243	0.428	0.313	0.014	0.002	0.000	0.000
1993	0.049	0.266	0.608	0.074	0.003	0.000	0.000
1994	0.064	0.197	0.609	0.094	0.035	0.002	0.000
1995	0.044	0.408	0.366	0.150	0.031	0.002	0.000
1996	0.036	0.226	0.630	0.092	0.015	0.001	0.000
1997	0.027	0.260	0.423	0.236	0.047	0.007	0.001
1998	0.073	0.187	0.535	0.123	0.073	0.009	0.001
1999	0.188	0.292	0.428	0.069	0.020	0.003	0.000
2000	0.140	0.205	0.510	0.127	0.016	0.002	0.000

Year	0	1	2	3	4	5	6+
2001	0.039	0.073	0.604	0.265	0.018	0.001	0.000
2002	0.242	0.284	0.321	0.140	0.012	0.000	0.000
2003	0.088	0.185	0.643	0.073	0.010	0.001	0.000
2004	0.020	0.234	0.670	0.060	0.015	0.001	0.000
2005	0.020	0.131	0.618	0.210	0.018	0.003	0.000
2006	0.016	0.525	0.378	0.072	0.008	0.000	0.000
2007	0.001	0.306	0.631	0.054	0.008	0.000	0.000
2008	0.017	0.115	0.812	0.053	0.003	0.000	0.000
2009	0.007	0.515	0.311	0.147	0.019	0.001	0.000
2010	0.017	0.447	0.494	0.034	0.008	0.000	0.000
2011	0.000	0.477	0.467	0.048	0.007	0.002	0.000
2012	0.007	0.183	0.789	0.020	0.001	0.000	0.000
2013	0.043	0.457	0.388	0.095	0.016	0.000	0.000

Table 4.2.1.1. State quota reporting timeframes in 2013. The **bold** text indicates which reporting program (dealer or harvesters) the states used in 2013 to monitor its quota.

State	Dealer Reporting	Harvester Reporting	Notes
ME	**monthly**	monthly/daily	Harvesters landing greater than 6,000 lbs will report daily
NH	**weekly**	monthly	Exempt from timely reporting. Implementing weekly reporting for state dealers.
MA	**weekly**	monthly/daily	Harvesters landing greater than 6,000 lbs will report daily
RI	**twice weekly**	quarterly/daily	Harvesters using purse seines will report daily
CT	**monthly**	monthly	No directed fisheries for Atlantic menhaden
NY	**monthly**	monthly/weekly	Capability to require weekly harvester reporting if needed
NJ	**weekly**	monthly	All menhaden sold or bartered must be done through a licensed dealer
DE	—	**monthly/daily**	Harvesters landing menhaden will daily using IVR
MD	monthly	**monthly/daily**	Currently monthly harvester reporting, but implementing weekly in 2013
PRFC	—	**weekly**	Trip level harvester reports submitted weekly
VA	—	**monthly/weekly/daily**	Purse seines submit weekly reports until 97% of quota, then daily reports. Monthly for all other gears until 90% of quota, then reporting every 10 days.
NC	**monthly (combined reports)**		Single trip ticket with dealer and harvester information submitted monthly
SC	**monthly (combined reports)**		Exempt from timely reporting. Single trip ticket with dealer and harvester information
GA	**monthly (combined reports)**		Exempt from timely reporting. Single trip ticket with dealer and harvester information
FL	**monthly/weekly (combined reports)**		Monthly until implementation of weekly expected in September 2013. For 2013 at 50% of quota FL will call dealers weekly and close the fishery when at 70% of quota.

Table 4.2.1.2. Atlantic menhaden historical bait landings from 1950-1984 and recent bait landings (1000 mt) from 1985-2013.

Year	Historical Bait (1000mt)	Year	Recent Bait (1000mt)
1950	11.3	1985	30.1
1951	20.4	1986	35.1
1952	14.2	1987	34.6
1953	25.8	1988	37.6
1954	19.3	1989	31.7
1955	14.6	1990	30.3
1956	23.3	1991	36.9
1957	24.7	1992	40.2
1958	14.7	1993	39.8
1959	20.6	1994	34.6
1960	19.4	1995	39.7
1961	25.1	1996	36.2
1962	26.6	1997	41.0
1963	24.4	1998	39.3
1964	20.2	1999	34.6
1965	23.6	2000	33.4
1966	13.7	2001	35.4
1967	11.6	2002	36.6
1968	9.5	2003	33.2
1969	10.6	2004	33.8
1970	21.6	2005	38.0
1971	13.5	2006	26.9
1972	10.3	2007	41.9
1973	14.8	2008	48.1
1974	14.5	2009	38.8
1975	21.7	2010	43.9
1976	19.6	2011	51.3
1977	23.1	2012	63.5
1978	25.9	2013	38.0
1979	13.0		
1980	26.2		
1981	22.4		
1982	19.9		
1983	19.1		
1984	14.3		

Table 4.2.3.1. Catch-at-age for the northern commercial bait fishery (includes small amount of recreational catch).

Year	0	1	2	3	4	5	6+
1985	0.000	0.000	0.660	0.189	0.119	0.025	0.006
1986	0.000	0.000	0.072	0.619	0.281	0.026	0.003
1987	0.000	0.000	0.073	0.619	0.280	0.026	0.003
1988	0.000	0.000	0.069	0.621	0.282	0.026	0.003
1989	0.000	0.000	0.085	0.612	0.275	0.025	0.003
1990	0.000	0.000	0.113	0.597	0.262	0.025	0.003
1991	0.000	0.000	0.125	0.591	0.256	0.025	0.003
1992	0.000	0.000	0.152	0.576	0.244	0.025	0.003
1993	0.000	0.000	0.160	0.571	0.240	0.025	0.003
1994	0.000	0.000	0.111	0.495	0.341	0.049	0.003
1995	0.000	0.000	0.088	0.476	0.435	0.001	0.000
1996	0.000	0.000	0.411	0.452	0.130	0.007	0.000
1997	0.000	0.000	0.146	0.345	0.382	0.110	0.017
1998	0.004	0.000	0.106	0.413	0.390	0.075	0.012
1999	0.005	0.000	0.149	0.482	0.312	0.041	0.010
2000	0.000	0.004	0.414	0.318	0.228	0.029	0.007
2001	0.000	0.000	0.113	0.732	0.137	0.014	0.004
2002	0.000	0.000	0.058	0.570	0.318	0.054	0.000
2003	0.000	0.000	0.126	0.665	0.198	0.010	0.000
2004	0.000	0.000	0.260	0.517	0.195	0.025	0.003
2005	0.000	0.000	0.238	0.529	0.205	0.025	0.003
2006	0.000	0.004	0.279	0.570	0.140	0.007	0.000
2007	0.000	0.000	0.391	0.492	0.108	0.007	0.002
2008	0.000	0.000	0.248	0.607	0.131	0.014	0.000
2009	0.000	0.000	0.182	0.614	0.186	0.017	0.000
2010	0.000	0.000	0.367	0.389	0.217	0.024	0.002
2011	0.000	0.000	0.143	0.487	0.326	0.045	0.000
2012	0.000	0.000	0.393	0.472	0.125	0.008	0.002
2013	0.000	0.000	0.259	0.560	0.155	0.026	0.000

Table 4.2.3.2. Catch-at-age for the southern commercial bait fishery (includes small amount of recreational catch).

Year	0	1	2	3	4	5	6
1985	0.003	0.172	0.654	0.141	0.027	0.003	0.000
1986	0.002	0.123	0.704	0.147	0.021	0.002	0.000
1987	0.003	0.124	0.698	0.143	0.028	0.003	0.000
1988	0.003	0.147	0.654	0.163	0.030	0.003	0.000
1989	0.003	0.148	0.653	0.163	0.030	0.003	0.000
1990	0.005	0.327	0.530	0.114	0.021	0.002	0.000
1991	0.002	0.243	0.606	0.123	0.023	0.002	0.000
1992	0.005	0.317	0.532	0.120	0.023	0.002	0.000
1993	0.010	0.400	0.415	0.143	0.029	0.003	0.000
1994	0.003	0.199	0.623	0.147	0.027	0.003	0.000
1995	0.000	0.391	0.373	0.219	0.017	0.000	0.000
1996	0.001	0.049	0.739	0.179	0.033	0.000	0.000
1997	0.000	0.083	0.521	0.303	0.074	0.012	0.006
1998	0.038	0.069	0.538	0.234	0.106	0.012	0.003
1999	0.000	0.053	0.722	0.169	0.050	0.006	0.000
2000	0.008	0.234	0.640	0.118	0.001	0.000	0.000
2001	0.003	0.062	0.685	0.233	0.014	0.003	0.000
2002	0.000	0.043	0.259	0.500	0.176	0.020	0.002
2003	0.006	0.101	0.751	0.129	0.013	0.000	0.000
2004	0.000	0.070	0.735	0.162	0.030	0.003	0.000
2005	0.000	0.018	0.532	0.423	0.024	0.003	0.000
2006	0.000	0.286	0.494	0.196	0.023	0.000	0.000
2007	0.000	0.272	0.689	0.029	0.011	0.000	0.000
2008	0.000	0.045	0.860	0.080	0.012	0.003	0.000
2009	0.004	0.266	0.409	0.292	0.030	0.000	0.000
2010	0.000	0.348	0.564	0.067	0.021	0.000	0.000
2011	0.000	0.406	0.500	0.080	0.015	0.000	0.000
2012	0.000	0.090	0.892	0.018	0.000	0.000	0.000
2013	0.009	0.609	0.287	0.091	0.003	0.000	0.000

Table 4.3.2.1. MRFSS/MRIP recreational landings estimates of Atlantic menhaden for the two assessment regions.

Area_North (Delaware and North), Harvest (A+B1, mt)

	Jan_Feb	Mar_Apr	May_Jun	Jul_Aug	Sep_Oct	Nov_Dec		A+B1 (mt)	B2*0.5 (mt)	Total Harvest (mt)
1981	0	0	0	34.446	19.099	0		53.5	26.8	80.3
1982	0	0	14.617	65.427	0.21	0		80.3	40.1	120.4
1983	0	0	0	27.069	44.76	0		71.8	35.9	107.7
1984	0	0	0	37.094	16.311	0		53.4	26.7	80.1
1985	0	0	0	99.905	60.427	0.405		160.7	80.4	241.1
1986	0	0	1.568	71.213	93.021	3.012		168.8	84.4	253.2
1987	0	0	1.664	70.862	63.504	8.009		144.0	72.0	216.1
1988	0	0	64.519	135.974	2.862	0		203.4	101.7	305.0
1989	0	0	22.64	57.651	24.473	0		104.8	52.4	157.1
1990	0	0	5.21	55.991	11.995	0		73.2	36.6	109.8
1991	0	0	34.131	242.309	99.624	0.251		376.3	188.2	564.5
1992	0	0	130.189	183.113	239.971	0.486		553.8	276.9	830.6
1993	0	0	37.712	90.997	36.438	0		165.1	82.6	247.7
1994	0	0.508	4.458	40.912	0	0		45.9	22.9	68.8
1995	0	0	25.578	71.67	0	0		97.2	48.6	145.9
1996	0	0	0	82.155	0	0		82.2	41.1	123.2
1997	0	0	6.72	0	20.097	0		26.8	13.4	40.2
1998	0	0	40.899	0	0	2.394		43.3	21.6	64.9
1999	0	0	8.97	0.053	0	0		9.0	4.5	13.5
2000	0	0	2.738	8.111	0	0		10.8	5.4	16.3
2001	0	4.554	0	0.083	0	2.102		6.7	3.4	10.1
2002	0	0	13.941	1.024	181.193	0		196.2	98.1	294.2
2003	0	0	0	25.59	1.801	0		27.4	13.7	41.1
2004	0	0	20.061	4.639	3.531	0		28.2	14.1	42.3
2005	0	0	0	1.259	8.392	4.638		14.3	7.1	21.4
2006	0	3.122	36.052	15.298	43.88	9.757		108.1	54.1	162.2
2007	0	7.408	159.317	71.022	48.709	9.519		296.0	148.0	444.0
2008	0	72.413	89.255	103.327	66.36	0		331.4	165.7	497.0
2009	0	0	54.092	17.157	2.157	0.7		74.1	37.1	111.2
2010	0	0.307	20.328	75.802	15.187	0		111.6	55.8	167.4
2011	0	0	17.635	0.202	6.717	0.174		24.7	12.4	37.1
2012	0	1.17	69.119	68.419	129.504	0		268.2	134.1	402.3
2013	0	0	19.681	77.691	28.12	0		125.5	62.7	188.2

Area_South (Maryland and South), Harvest (A+B1, mt)

	Jan_Feb	Mar_Apr	May_Jun	Jul_Aug	Sep_Oct	Nov_Dec		A+B1 (mt)	B2*0.5 (mt)	Total Harvest (mt)
1981	0	0	0	1.176	7.196	0		8.4	4.2	12.6
1982	0	0	25.66	20.179	0.443	2.53		48.8	24.4	73.2
1983	0	0	0	0.219	0	0.169		0.4	0.2	0.6
1984	0	0	29.015	0	0.371	0		29.4	14.7	44.1
1985	0	0	0	1.196	4.801	0.03		6.0	3.0	9.0
1986	0	102.012	0	0.312	0	0		102.3	51.2	153.5
1987	0	0	0	3.996	4.404	0		8.4	4.2	12.6
1988	0	0	0.88	18.722	0	0		19.6	9.8	29.4
1989	0	0	4.273	3.865	0.052	0		8.2	4.1	12.3
1990	0	0	1.618	34.263	1.134	0		37.0	18.5	55.5
1991	0	0	0	22.545	0	7.878		30.4	15.2	45.6
1992	0	0	0	118.501	0	0		118.5	59.3	177.8
1993	0	0	0.039	2.765	0	0		2.8	1.4	4.2
1994	0	0.115	0.82	8.194	0	0		9.1	4.6	13.7
1995	0	0.205	0	1.52	0	0		1.7	0.9	2.6
1996	0	0	1.488	0	0	0		1.5	0.7	2.2
1997	0	0	3.724	0	0	0		3.7	1.9	5.6
1998	0	0	0	2.156	0	0		2.2	1.1	3.2
1999	0	0	0	12.53	0	0		12.5	6.3	18.8
2000	0	0	1.322	0	0	0		1.3	0.7	2.0
2001	0	0.348	0	0	15.072	0		15.4	7.7	23.1
2002	0	0	0	0.044	0	0		0.0	0.0	0.1
2003	0	0	0	16.4	0	0		16.4	8.2	24.6
2004	0	0	92.992	50.754	34.451	0.791		179.0	89.5	268.5
2005	0	0	44.471	100.879	6.217	0		151.6	75.8	227.4
2006	0	10.166	164.542	32.304	27.918	7.486		242.4	121.2	363.6
2007	0	9.958	152.412	29.407	25.528	0.744		218.0	109.0	327.1
2008	0	0.272	19.013	36.773	19.053	0		75.1	37.6	112.7
2009	0	0	98.771	43.604	6.281	1.013		149.7	74.8	224.5
2010	0	0.05	43.904	52.174	5.637	0		101.8	50.9	152.6
2011	0	1.067	77.074	9.91	23.392	0.031		111.5	55.7	167.2
2012	0	2.801	14.69	81.216	31.024	0		129.7	64.9	194.6
2013	0	0	25.863	113.259	38.127	0.103		177.4	88.7	266.0

Table 5.1.1. Fishery-dependent datasets reviewed, but excluded from analysis.

State	Gear	Years	Reason for exclusion
NH	Gillnet	1989-2012	targeted menhaden in 1990s, but switched to other spp in 2000s
RI	Fish Trap	2007-2012	short time series
NY	Gillnet	2004-2012	paper format only; ~30% reporting compliance pre-2012
NY	Pound Net	2004-2012	paper format only; ~30% reporting compliance pre-2012
DE	Gillnet	1985-2012	target spp switches between bass and menhaden seasonally
VA	Pound Net	1993-2012	~50% of landings reported as "bait" (i.e. no species info)
NC	Pound Net	1994-2012	no effort data
NC	Pound Net	1994-2012	no effort data
NC	Gillnet	1994-2012	no effort data
VTR	Gillnet/Pound Net	1994-2012	low data quality (i.e., abundant misreporting)

Table 5.1.2. Fishery-dependent datasets reviewed, and retained for analysis.

State	Gear	Years	Season (Peak CPUE)	Effort	Soak time	Ages/Lengths	Avg n/yr	% Zeros
MA	Pound Net	2002-2012	Apr-Sep (May)	hauls	Yes*	No	43	64%
NJ	Gillnet	1997-2012	Jan-Dec (August)	net-feet	Yes	No	143	2%
MD	Pound Net	1992-2012	Jan-Dec (Apr-May)	hauls	Yes*	Yes (2005 on)	235**	51%
PRFC	Pound Net	1989-2012	Feb-Dec (Mar)	net-days	No	Yes (2009 on)	6	?

**soak time calculated based on interval between consecutive trips*

***This is the number of monthly summarized records per year. Avg number of trips/yr ~3000.*

Table 5.2.1. Surveys considered for inclusion in assessment. Yellow highlighted cells indicate if a survey was used to generate the juvenile index of abundance (JAI) or the northern/southern adult indices (NAD/SAD) and was therefore used in the base run of the stock assessment.

Survey	Use in Assessment or Justification for Exclusion
MA Seine	Extremely low occurrence of menhaden
MA Trawl	Extremely low occurrence of menhaden
RI Trawl	JAI
RI NB Seine	Mistakenly dropped from final index generation
RI Seine - Lagoons	Extremely low occurrence of menhaden
URI Trawl	Only one sampling site
CT LCR Seine	JAI
CT Thames River	JAI
CT LIS Seine	Extremely low occurrence of menhaden
CT LIS Trawl	JAI and adult (NAD) indices
NY Peconic Bay Trawl	JAI
NY WLIS Seine	JAI
NY LHR Seine	Prior to 2000, YOY/adult distinction could not bemade. No associated lengths.
NJ DB Trawl	Negatively correalated with NJ SB Seine
NJ Ocean Trawl	JAI and adult (NAD) indices
NJ Juv Sbass Seine	JAI
Rutgers Trawl	Only one inland sampling site
Rutgers IP	~60% of menhaden larvae from survey were caught on single night
Salen/PSEF DB Seine	Data not available
DE YOY Midwater Trawl	Index generated but not included in NAD. Same trend as (and significant correlation with) nearby DE IB Trawl.
DE DB Juv 30ft Trawl	Adult Index (NAD)
DE DB Juv 16ft Trawl	JAI and adult (NAD) indices
DE IB Juv Trawl	JAI
MD Juv SB Seine	JAI
MD Coastal Trawl	JAI
MD Coastal Seine	Correlated with nearby MD Coastal Trawl
MD SB Gillnet	Extremely low occurrence of menhaden
CHESFIMS	Adult Index (NAD)
ChesMMAP	Adult Index (NAD)
VA Shad Gillnet	Index generated but not included in NAD/SAD. Trawl gears only used for adult index.
VA SB Seine	JAI
VIMS Juv Trawl	JAI and adult (NAD) indices
NC Gillnet	Index generated but not included in SAD. Trawl gears only used for adult index.
SC Electrofishing	JAI
SC Trammel Net	Index generated but not included in SAD. Trawl gears only used for adult index.
GA Trawl	JAI and adult (SAD) indices
FL Trawl	Fish only identified to genus (tyrannus + smithii caught but not distinguishable).
FL Seine	Fish only identified to genus (tyrannus + smithii caught but not distinguishable).
SEAMAP Trawl	Adult Index (SAD)
NEFSC Trawl	Extremely low occurrence of menhaden. Concerned not nearshore enough for JAI.
NEAMAP	Time series limited (<10 years). Only spring survey caught sufficient number of fish. Consider in future assessments.
MARMAP	More work needed on modeling larval mortality, spawning seasonality, and timing of sampling.
ECOMON	More work needed on modeling larval mortality, spawning seasonality, and timing of sampling.
Powerplant impingement	Difficult to obtain all the data and sa,pling may have changed with permitting requirements.

Table 5.3.1. Correlation coefficients are below the diagonal for the pairwise comparisons of the fishery-dependent indices. The associated p-values are in parentheses, while p-values corrected for multiple comparisons are above the diagonal.

	PRFC	MD	NJ	MA
PRFC	1.00	<0.01	1.00	1.00
MD	0.71 (<0.01)	1.00	0.94	1.00
NJ	-0.21 (0.44)	-0.31 (0.24)	1.00	0.59
MA	-0.20 (0.58)	0.28 (0.44)	0.53 (0.12)	1.00

Table 5.3.2. Correlation coefficients for the pairwise comparisons of the fishery-independent young of the year indices.

	DE.ib	RI.t	MD.cb	VIMS.t	SC.el	NY.t	GA.t	CT.t	DE.tj	NJ.t	CT.th.s	CT.r.s	NY.s	NJ.s	VA.s	MD.s
DE.ib	1															
RI.t	-0.16	1														
MD.cb	0.54	-0.04	1													
VIMS.t	-0.01	-0.23	0.02	1												
SC.el	-0.12	-0.1	-0.13	-0.22	1											
NY.t	-0.1	0.26	0.09	-0.2	-0.21	1										
GA.t	0.6	-0.25	-0.06	0.31	-0.24	-0.25	1									
CT.t	0.42	0.12	0.55	-0.19	-0.03	0.27	0.15	1								
DE.tj	-0.1	0.24	0.28	0.04	0.02	0.63	0.04	-0.1	1							
NJ.t	-0.16	0.8	-0.14	-0.21	0.1	-0.04	-0.11	0.35	-0.14	1						
CT.th.s	-0.1	0.34	0.55	-0.14	0.4	0.5	-0.33	0.06	0.76	0.04	1					
CT.r.s	-0.07	0.25	0.06	-0.07	0.7	0.17	-0.28	0.19	0.21	0.28	0.74	1				
NY.s	-0.18	0.83	-0.1	-0.18	0.28	0.18	-0.28	0.09	0.33	0.63	0.49	0.4	1			
NJ.s	0.04	0.22	0.05	0.11	-0.04	-0.2	0.24	-0.22	0.23	0	0.01	-0.18	0.48	1		
VA.s	0.23	-0.27	0.73	0.12	-0.22	-0.32	0.27	-0.21	-0.1	-0.24	-0.28	-0.27	-0.33	0.15	1	
MD.s	0.66	-0.18	0.45	-0.17	-0.54	-0.42	0.25	-0.35	-0.05	-0.13	-0.52	-0.17	-0.16	0.11	0.29	1

Table 5.3.3. P-values associated with the correlation coefficients for the pairwise comparisons of the fishery-independent young of the year indices (correlation values are in Table 5.3.2). Values above the diagonal are corrected for multiple comparisons.

	DE.ib	RI.t	MD.cb	VIMS.t	SC.el	NY.t	GA.t	CT.t	DE.tj	NJ.t	CT.th.s	CT.r.s	NY.s	NJ.s	VA.s	MD.s
DE.ib	0	1	0.60	1	1	1	1	1	1	1	1	1	1	1	1	0.02
RI.t	0.46	0	1	1	1	1	1	1	1	<0.01	1	1	<0.01	1	1	1
MD.cb	0.01	0.84	0	1	1	1	1	1	1	1	1	1	1	1	<0.01	1
VIMS.t	0.94	0.29	0.93	0	1	1	1	1	1	1	1	1	1	1	1	1
SC.el	0.69	0.74	0.67	0.48	0	1	1	1	1	1	1	0.87	1	1	1	1
NY.t	0.68	0.28	0.73	0.4	0.56	0	1	1	0.60	1	1	1	1	1	1	1
GA.t	0.02	0.38	0.84	0.29	0.47	0.46	0	1	1	1	1	1	1	1	1	1
CT.t	0.09	0.63	0.02	0.46	0.93	0.35	0.65	0	1	1	1	1	1	1	1	1
DE.tj	0.63	0.29	0.2	0.85	0.94	0.01	0.88	0.7	0	1	0.10	1	1	1	1	1
NJ.t	0.43	<0.01	0.51	0.3	0.76	0.86	0.71	0.17	0.52	0	1	1	0.09	1	1	1
CT.th.s	0.72	0.2	0.03	0.6	0.18	0.08	0.32	0.84	<0.01	0.88	0	0.12	1	1	1	1
CT.r.s	0.73	0.23	0.79	0.74	0.01	0.48	0.33	0.45	0.32	0.16	<0.01	0	1	1	1	1
NY.s	0.38	<0.01	0.64	0.39	0.35	0.49	0.36	0.74	0.13	<0.01	0.06	0.04	0	1	1	1
NJ.s	0.86	0.31	0.8	0.58	0.9	0.41	0.4	0.4	0.25	1	0.96	0.38	0.01	0	1	1
VA.s	0.24	0.21	<0.01	0.56	0.47	0.18	0.34	0.41	0.6	0.24	0.29	0.18	0.1	0.45	0	1
MD.s	<0.01	0.41	0.02	0.41	0.06	0.07	0.38	0.17	0.77	0.53	0.04	0.39	0.44	0.58	0.09	0

Table 5.3.4. Correlation coefficients for the pairwise comparisons of the fishery-independent adult indices.

	vims.t	de.30	seamap	va.ss	nc.gn	sc.tr	chesmap	chesfims	ga.tr	ct.tr	de.jay	nj.tr
vims.t	1											
de.30	0.41	1										
seamap	0.57	-0.09	1									
va.ss	-0.16	-0.25	-0.18	1								
nc.gn	-0.19	-0.36	0.52	-0.04	1							
sc.tr	-0.39	-0.36	0.23	0.24	0.79	1						
chesmap	0.56	0.68	0.29	-0.26	-0.06	0.15	1					
chesfims	0.8	0.13	0.28	-0.14	0.05	-0.29	0.52	1				
ga.tr	0.42	-0.06	0.9	-0.4	0.73	0.64	0.28	0.18	1			
ct.tr	0.58	0.63	0.01	-0.14	-0.36	-0.47	0.71	0.7	-0.1	1		
de.jay	0.18	0.27	-0.08	-0.25	-0.48	-0.17	0.05	0.75	-0.17	0.06	1	
nj.tr	0.61	0.21	0.43	0	-0.18	-0.17	0.22	0.41	0.32	0.32	0.04	1

Table 5.3.5. P-values associated with the correlation coefficients for the pairwise comparisons of the fishery-independent adult indices (correlation values are in Table 5.4). Values above the diagonal are corrected for multiple comparisons.

	vims.t	de.30	seamap	va.ss	nc.gn	sc.tr	chesmap	chesfims	ga.tr	ct.tr	de.jay	nj.tr
vims.t	0	1	0.23	1	1	1	1	0.07	1	0.68	1	0.06
de.30	0.05	0	1	1	1	1	0.8	1	1	0.28	1	1
seamap	<0.01	0.69	0	1	1	1	1	1	0	1	1	1
va.ss	0.54	0.35	0.51	0	1	1	1	1	1	1	1	1
nc.gn	0.58	0.28	0.1	0.9	0	0.21	1	1	0.59	1	1	1
sc.tr	0.09	0.11	0.32	0.37	<0.01	0	1	1	0.72	1	1	1
chesmap	0.06	0.01	0.37	0.41	0.86	0.65	0	1	1	0.58	1	1
chesfims	<0.01	0.66	0.36	0.69	0.93	0.33	0.29	0	1	0.68	0.2	1
ga.tr	0.14	0.84	<0.01	0.22	0.01	0.01	0.4	0.68	0	1	1	1
ct.tr	0.01	<0.01	0.98	0.61	0.27	0.05	0.01	0.01	0.74	0	1	1
de.jay	0.4	0.21	0.72	0.36	0.16	0.49	0.89	<0.01	0.58	0.82	0	1
nj.tr	<0.01	0.32	0.04	1	0.59	0.47	0.49	0.17	0.27	0.19	0.83	0

Table 5.3.6. Correlations of all indices from all data sources including fishery-dependent, fishery-independent, adult, and recruitment with appropriate lags.

	fd.ma.pn	fi.yoy.ri.tr	fi.ct.tr	fi.yoy.ct.tr	fi.yoy.ct.t.s	fi.yoy.ct.r.s	fi.yoy.ny.pb	fi.yoy.ny.s	fd.nj.gn	fi.nj.tr	fi.yoy.nj.tr	fi.yoy.nj.s	fi.de.30	fi.de.j	fi.yoy.de.ib	fi.yoy.de.j	fd.md.pn
fd.ma.pn	1																
fi.yoy.ri.tr	0.46	1															
fi.ct.tr	-0.01	-0.38	1														
fi.yoy.ct.tr	0.17	0.29	0.28	1													
fi.yoy.ct.t.s	0.05	0.84	-0.39	0.41	1												
fi.yoy.ct.r.s	0	0.62	-0.38	0.3	0.78	1											
fi.yoy.ny.pb	0.46	0.05	0.38	0.38	0.17	-0.1	1										
fi.yoy.ny.s	0.27	0.63	-0.31	0.42	0.78	0.7	0.27	1									
fd.nj.gn	0.5	0.47	-0.41	0.02	0.47	0.49	0.3	0.41	1								
fi.nj.tr	0.22	-0.1	0.78	0.33	-0.28	-0.43	0.27	-0.13	-0.42	1							
fi.yoy.nj.tr	-0.22	0.29	-0.18	0.5	0.53	0.39	-0.12	0.55	-0.31	0.05	1						
fi.yoy.nj.s	0.2	-0.05	-0.49	-0.25	0.14	0.04	-0.2	0.19	0.37	-0.24	-0.03	1					
fi.de.30	0.44	-0.13	0.12	-0.46	-0.47	-0.53	0.15	-0.31	0.1	0.25	-0.45	0.04	1				
fi.de.j	0.18	-0.33	0.29	0.04	-0.81	-0.63	-0.34	-0.49	-0.38	0.39	-0.08	-0.17	0.34	1			
fi.yoy.de.ib	0.39	0.05	0.3	0.53	-0.08	-0.01	-0.17	0.18	0.11	0.21	0.16	0.16	-0.23	0.25	1		
fi.yoy.de.j	0.41	0.3	-0.24	-0.16	0.03	0.1	-0.08	0.19	0.52	0	-0.17	0.28	0.29	-0.04	0	1	
fd.md.pn	0.21	-0.01	0.51	0.01	-0.67	-0.57	-0.1	-0.21	-0.39	0.62	-0.17	-0.15	0.55	0.74	0.3	0.1	1
fi.yoy.md.cb	0.3	0.01	0.24	0.55	0.12	-0.02	-0.02	-0.01	-0.16	0.39	0.37	0.09	-0.21	0.33	0.5	0.29	0.21
fi.yoy.md.s	0.02	-0.32	-0.08	-0.2	-0.47	-0.25	-0.46	-0.27	-0.11	0.11	-0.19	0.33	0.01	0.35	0.31	-0.02	0.24
fd.prfc	0.01	-0.12	0.39	0.05	-0.48	-0.52	0.34	-0.25	-0.2	0.54	-0.06	-0.21	0.54	0.46	0.04	-0.13	0.68
fi.seamap	-0.17	-0.16	0.06	-0.29	-0.2	-0.45	-0.26	-0.23	-0.38	0.27	-0.06	-0.05	0.07	0.18	0.2	0.19	0.24
fi.chesmap	0.17	-0.4	0.45	-0.29	-0.53	-0.78	0.14	-0.55	-0.2	0.61	-0.53	-0.13	0.68	0.59	0.17	0.01	0.77
fi.chesfims	0.71	-0.03	0.07	0.74	-0.39	-0.12	0.27	0.26	-0.51	0.23	0.44	-0.13	-0.14	0.75	0.28	0.01	0.23
fi.vims.t	-0.14	-0.16	0.52	-0.02	-0.49	-0.56	-0.04	-0.38	-0.62	0.64	0.04	-0.18	0.39	0.69	0.1	-0.01	0.73
fi.yoy.vims.tr	-0.16	-0.06	0.02	-0.25	-0.38	0.11	-0.4	0.26	-0.06	-0.05	0.18	-0.04	-0.15	0.08	0.25	0.33	0.1
fi.va.ss	-0.29	-0.03	0.25	0.32	-0.15	0.08	-0.07	0.07	-0.01	0.22	-0.09	0.17	-0.23	-0.19	0.33	-0.22	0.18
fi.yoy.va.s	-0.07	-0.26	0.26	-0.13	-0.52	-0.23	-0.52	-0.47	-0.38	0.08	-0.2	0.15	-0.27	0.45	0.25	-0.06	0.09
fi.nc.gn	0.26	0.48	-0.42	0.15	0.5	0.06	0.17	0.32	-0.23	-0.26	0.21	0.16	-0.24	-0.62	-0.09	-0.18	-0.3
fi.sc.tr	0.37	0.24	-0.38	-0.05	0.36	0.21	-0.03	0.14	0.43	-0.33	-0.3	0.11	-0.28	-0.39	0.25	0.02	-0.36
fi.yoy.sc.el	0.07	0.23	-0.67	0.1	0.34	0.36	-0.17	0.17	0.15	-0.43	0.09	0.1	-0.52	-0.59	-0.02	0.05	-0.77
fi.ga.tr	-0.11	0.06	-0.12	-0.43	0.21	-0.29	-0.32	-0.1	-0.24	0.31	-0.04	-0.33	0.09	-0.04	-0.16	0.13	0.05
fi.yoy.ga.tr	0.16	-0.37	-0.04	0.36	-0.61	-0.2	-0.21	-0.28	-0.07	-0.03	0.06	0.26	-0.16	0.47	0.59	-0.09	0.13

Table 5.3.6. (cont'd)

	fi.yoy.md.cb	fi.yoy.md.s	fd.prfc	fi.seamap	fi.chesmap	fi.chesfims	fi.vims.t	fi.yoy.vims.tr	fi.va.ss	fi.yoy.va.s	fi.nc.gn	fi.sc.tr	fi.yoy.sc.el	fi.ga.tr	fi.yoy.ga.tr
fd.ma.pn															
fi.yoy.ri.tr															
fi.ct.tr															
fi.yoy.ct.tr															
fi.yoy.ct.t.s															
fi.yoy.ct.r.s															
fi.yoy.ny.pb															
fi.yoy.ny.s															
fd.nj.gn															
fi.nj.tr															
fi.yoy.nj.tr															
fi.yoy.nj.s															
fi.de.30															
fi.de.j															
fi.yoy.de.ib															
fi.yoy.de.j															
fd.md.pn															
fi.yoy.md.cb	1														
fi.yoy.md.s	0.44	1													
fd.prfc	0.1	-0.05	1												
fi.seamap	0.41	0.31	0.01	1											
fi.chesmap	0.29	0.78	0.74	0.43	1										
fi.chesfims	0.47	-0.14	0.08	0.05	0.81	1									
fi.vims.t	0.43	0.32	0.58	0.45	0.74	0.49	1								
fi.yoy.vims.tr	0.24	-0.18	-0.09	0.35	-0.17	-0.08	-0.13	1							
fi.va.ss	-0.22	-0.02	0.08	-0.1	-0.25	-0.17	-0.11	0.15	1						
fi.yoy.va.s	0.44	0.75	-0.24	0.45	0.12	-0.23	0.25	0.16	0.34	1					
fi.nc.gn	0.06	-0.38	-0.57	0.38	-0.11	0.1	-0.17	-0.47	0.02	0.13	1				
fi.sc.tr	-0.16	0.02	-0.44	0.16	0.04	-0.23	-0.56	-0.1	0.04	0.03	0.51	1			
fi.yoy.sc.el	-0.12	-0.54	-0.82	0.13	-0.68	-0.86	-0.64	0.21	0.11	0.25	0.46	0.53	1		
fi.ga.tr	0.08	0.02	-0.05	0.85	0.21	-0.18	0.38	0.38	-0.23	0.26	0.47	0.32	0.26	1	
fi.yoy.ga.tr	0.06	0.14	0.12	-0.46	-0.05	0.42	-0.12	0.01	0.22	0.2	-0.46	-0.2	0.02	-0.67	1

Table 5.3.7. P-values associated with the correlation coefficients for the pairwise comparisons of the fishery-dependent, fishery-independent, adult, and recruitment indices with the appropriate lags (correlation values are in Table 5.6). Values above the diagonal are corrected for multiple comparisons.

	fd.ma.pn	fi.yoy.ri.tr	fi.ct.tr	fi.yoy.ct.tr	fi.yoy.ct.t.s	fi.yoy.ct.r.s	fi.yoy.ny.pb	fi.yoy.ny.s	fd.nj.gn	fi.nj.tr	fi.yoy.nj.tr	fi.yoy.nj.s	fi.de.30	fi.de.j	fi.yoy.de.ib	fi.yoy.de.j	fd.md.pn
fd.ma.pn	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
fi.yoy.ri.tr	0.18	0	1	1	0.03	0.64	1	0.56	1	1	1	1	1	1	1	1	1
fi.ct.tr	0.99	0.12	0	1	1	1	1	1	1	0.06	1	1	1	1	1	1	1
fi.yoy.ct.tr	0.66	0.26	0.29	0	1	1	1	1	1	1	1	1	1	1	1	1	1
fi.yoy.ct.t.s	0.89	0	0.14	0.13	0	0.16	1	0.18	1	1	1	1	1	0.12	1	1	1
fi.yoy.ct.r.s	1	0	0.11	0.24	0	0	1	0.04	1	1	1	1	1	0.26	1	1	1
fi.yoy.ny.pb	0.3	0.83	0.16	0.18	0.58	0.7	0	1	1	1	1	1	1	1	1	1	1
fi.yoy.ny.s	0.46	0	0.22	0.1	0	0	0.28	0	1	1	1	1	1	1	1	1	1
fd.nj.gn	0.14	0.07	0.12	0.94	0.07	0.05	0.33	0.13	0	1	1	1	1	1	1	1	1
fi.nj.tr	0.54	0.63	0	0.2	0.29	0.03	0.26	0.55	0.11	0	1	1	1	1	1	1	1
fi.yoy.nj.tr	0.54	0.17	0.47	0.04	0.04	0.05	0.64	0	0.25	0.79	0	1	1	1	1	1	1
fi.yoy.nj.s	0.59	0.8	0.04	0.33	0.61	0.83	0.42	0.36	0.16	0.24	0.88	0	1	1	1	1	1
fi.de.30	0.2	0.54	0.64	0.06	0.07	0.01	0.53	0.16	0.72	0.25	0.03	0.85	0	1	1	1	1
fi.de.j	0.61	0.13	0.25	0.89	0	0	0.17	0.01	0.15	0.05	0.69	0.4	0.12	0	1	1	0.07
fi.yoy.de.ib	0.26	0.81	0.22	0.03	0.76	0.95	0.48	0.38	0.68	0.3	0.43	0.42	0.28	0.2	0	1	1
fi.yoy.de.j	0.23	0.18	0.36	0.56	0.93	0.63	0.75	0.38	0.04	0.99	0.42	0.16	0.2	0.84	1	0	1
fd.md.pn	0.55	0.96	0.04	0.97	0.01	0.01	0.72	0.37	0.13	0	0.46	0.52	0.01	0	0.18	0.67	0
fi.yoy.md.cb	0.4	0.97	0.33	0.02	0.66	0.92	0.94	0.98	0.55	0.06	0.07	0.68	0.33	0.11	0.01	0.18	0.37
fi.yoy.md.s	0.96	0.12	0.76	0.44	0.07	0.22	0.05	0.19	0.68	0.61	0.35	0.08	0.96	0.05	0.11	0.93	0.28
fd.prfc	0.98	0.58	0.12	0.85	0.07	0.01	0.17	0.25	0.46	0.01	0.78	0.32	0.01	0.02	0.85	0.54	0
fi.seamap	0.64	0.45	0.8	0.26	0.47	0.03	0.28	0.3	0.15	0.2	0.79	0.82	0.75	0.42	0.35	0.4	0.3
fi.chesmap	0.64	0.19	0.14	0.39	0.08	0	0.72	0.06	0.55	0.03	0.07	0.7	0.01	0.06	0.59	0.98	0.01
fi.chesfims	0.18	0.92	0.82	0.01	0.27	0.69	0.46	0.42	0.11	0.45	0.13	0.67	0.65	0	0.35	0.98	0.45
fi.vims.t	0.7	0.46	0.03	0.93	0.06	0	0.88	0.06	0.01	0	0.84	0.38	0.06	0	0.62	0.96	0
fi.yoy.vims.tr	0.65	0.78	0.93	0.33	0.15	0.6	0.09	0.22	0.83	0.81	0.38	0.86	0.48	0.69	0.21	0.11	0.67
fi.va.ss	0.41	0.91	0.34	0.25	0.58	0.78	0.82	0.8	0.97	0.41	0.75	0.53	0.4	0.5	0.21	0.42	0.53
fi.yoy.va.s	0.85	0.21	0.3	0.62	0.04	0.25	0.02	0.02	0.14	0.7	0.33	0.45	0.2	0.01	0.21	0.76	0.71
fi.nc.gn	0.49	0.13	0.2	0.69	0.12	0.85	0.69	0.33	0.52	0.45	0.53	0.64	0.47	0.06	0.79	0.62	0.41
fi.sc.tr	0.3	0.32	0.12	0.84	0.17	0.36	0.91	0.57	0.09	0.16	0.19	0.64	0.22	0.1	0.29	0.92	0.14
fi.yoy.sc.el	0.85	0.45	0.01	0.76	0.26	0.23	0.63	0.57	0.64	0.14	0.77	0.74	0.07	0.04	0.96	0.89	0
fi.ga.tr	0.78	0.85	0.69	0.17	0.55	0.32	0.34	0.75	0.48	0.28	0.89	0.26	0.77	0.91	0.57	0.68	0.88
fi.yoy.ga.tr	0.67	0.19	0.9	0.25	0.04	0.5	0.54	0.35	0.83	0.92	0.83	0.38	0.57	0.09	0.03	0.77	0.65

Table 5.3.7. (cont'd)

	fi.yoy.md.cb	fi.yoy.md.s	fd.prfc	fi.seamap	fi.chesmap	fi.chesfims	fi.vims.t	fi.yoy.vims.tr	fi.va.ss	fi.yoy.va.s	fi.nc.gn	fi.sc.tr	fi.yoy.sc.el	fi.ga.tr	fi.yoy.ga.tr
fd.ma.pn	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
fi.yoy.ri.tr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
fi.ct.tr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
fi.yoy.ct.tr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
fi.yoy.ct.t.s	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
fi.yoy.ct.r.s	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
fi.yoy.ny.pb	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
fi.yoy.ny.s	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
fd.nj.gn	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
fi.nj.tr	1	1	1	1	1	1	0.2	1	1	1	1	1	1	1	1
fi.yoy.nj.tr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
fi.yoy.nj.s	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
fi.de.30	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
fi.de.j	1	1	1	1	1	1	0.06	1	1	1	1	1	1	1	1
fi.yoy.de.ib	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
fi.yoy.de.j	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
fd.md.pn	1	1	0.35	1	1	1	0.08	1	1	1	1	1	1	1	1
fi.yoy.md.cb	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
fi.yoy.md.s	0.03	0	1	1	1	1	1	1	1	0	1	1	1	1	1
fd.prfc	0.64	0.83	0	1	1	1	1	1	1	1	1	1	0.49	1	1
fi.seamap	0.05	0.14	0.95	0	1	1	1	1	1	1	1	1	1	0.06	1
fi.chesmap	0.37	0	0.01	0.16	0	1	1	1	1	1	1	1	1	1	1
fi.chesfims	0.1	0.65	0.81	0.88	0.05	0	1	1	1	1	1	1	1	1	1
fi.vims.t	0.03	0.11	0	0.03	0.01	0.09	0	1	1	1	1	1	1	1	1
fi.yoy.vims.tr	0.24	0.39	0.68	0.1	0.59	0.8	0.51	0	1	1	1	1	1	1	1
fi.va.ss	0.41	0.95	0.77	0.71	0.44	0.64	0.67	0.59	0	1	1	1	1	1	1
fi.yoy.va.s	0.03	0	0.26	0.03	0.72	0.44	0.22	0.43	0.2	0	1	1	1	1	1
fi.nc.gn	0.86	0.25	0.09	0.24	0.74	0.87	0.61	0.15	0.95	0.7	0	1	1	1	1
fi.sc.tr	0.49	0.93	0.06	0.5	0.9	0.44	0.01	0.68	0.88	0.89	0.11	0	1	1	1
fi.yoy.sc.el	0.69	0.06	0	0.66	0.02	0.01	0.02	0.5	0.73	0.4	0.16	0.06	0	1	1
fi.ga.tr	0.78	0.95	0.86	0	0.54	0.68	0.18	0.18	0.49	0.38	0.14	0.26	0.45	0	1
fi.yoy.ga.tr	0.84	0.64	0.68	0.1	0.88	0.26	0.68	0.97	0.52	0.49	0.18	0.5	0.95	0.01	0

Table 5.3.8. Length cutoffs used to distinguish age 0 vs. age 1+ Atlantic menhaden. Based on inspection of spatial differences in length distribution of commercial samples throughout the year. Regions 1-3 are the more northerly regions, while region 4 is the most southern region. Regions are those specified in the commercial reduction fishery database.

Length Cutoffs for Age 0 vs. Age 1+ Atlantic menhaden		
Regions 1-3	Time of Year	Cutoff (≤FL mm)
	May	90
	June	110
	July	125
	Aug-April	150
Region 4	Time of Year	Cutoff (≤FL mm)
	April	108
	May	113
	June	119
	July	126
	Aug-March	135

Table 5.3.9. Values for each index used in the assessment and the associated CV values included in the stock assessment. Each index is scaled to its mean value.

Year	YOY index	CV	SAD index	CV	NAD index	CV
1959	0.70	0.96				
1960	0.35	0.98				
1961	0.33	1.02				
1962	1.60	0.92				
1963	0.93	0.98				
1964	0.21	1.01				
1965	0.48	0.94				
1966	0.63	1.00				
1967	0.79	1.01				
1968	0.56	0.82				
1969	0.61	0.80				
1970	0.41	0.89				
1971	1.59	0.77				
1972	2.03	0.73				
1973	1.48	0.93				
1974	2.10	0.86				
1975	2.79	0.85				
1976	3.15	0.86				
1977	2.71	0.86				
1978	1.59	0.88				
1979	2.36	0.86				
1980	1.70	0.67			0.76	0.74
1981	2.46	0.75			0.50	0.79
1982	2.05	0.70			2.37	0.76
1983	1.25	0.74			0.77	0.69
1984	0.94	0.76			0.39	0.85
1985	1.88	0.58			0.77	0.77
1986	1.05	0.63			4.78	0.64
1987	0.46	0.58			3.51	0.68
1988	0.87	0.52			1.86	0.38
1989	1.32	0.46			1.17	0.38
1990	1.59	0.45	2.73	0.49	0.56	0.35
1991	1.13	0.45	1.06	0.44	0.70	0.35
1992	0.70	0.45	0.53	0.51	0.69	0.33
1993	0.13	0.49	0.41	0.53	0.62	0.40
1994	0.52	0.45	0.63	0.57	0.30	0.39
1995	0.31	0.44	0.13	0.44	0.53	0.36
1996	0.24	0.44	0.81	0.38	0.23	0.40
1997	0.53	0.42	0.34	0.45	0.21	0.35
1998	0.50	0.44	0.69	0.50	0.14	0.36
1999	0.83	0.47	0.70	0.53	0.37	0.33

Year	YOY index	CV	SAD index	CV	NAD index	CV
2000	0.79	0.43	0.77	0.79	0.26	0.33
2001	0.37	0.42	0.62	0.52	0.30	0.39
2002	1.04	0.43	0.57	0.51	0.50	0.35
2003	0.50	0.42	0.70	0.40	0.22	0.31
2004	0.69	0.42	0.27	0.46	0.38	0.31
2005	0.73	0.40	0.77	0.39	0.77	0.30
2006	0.39	0.40	3.78	0.39	1.08	0.28
2007	0.56	0.41	0.28	0.39	1.14	0.27
2008	0.38	0.41	0.36	0.41	1.16	0.34
2009	0.32	0.41	2.49	0.41	1.28	0.30
2010	0.60	0.42	0.70	0.44	1.05	0.28
2011	0.28	0.40	3.00	0.34	1.67	0.31
2012	0.23	0.41	0.88	0.33	1.97	0.30
2013	0.23	0.43	0.78	0.35	0.98	0.29

Table 6.1.1. Number of individual length observations from NEFOP 1989-2103, by gear and quarter.

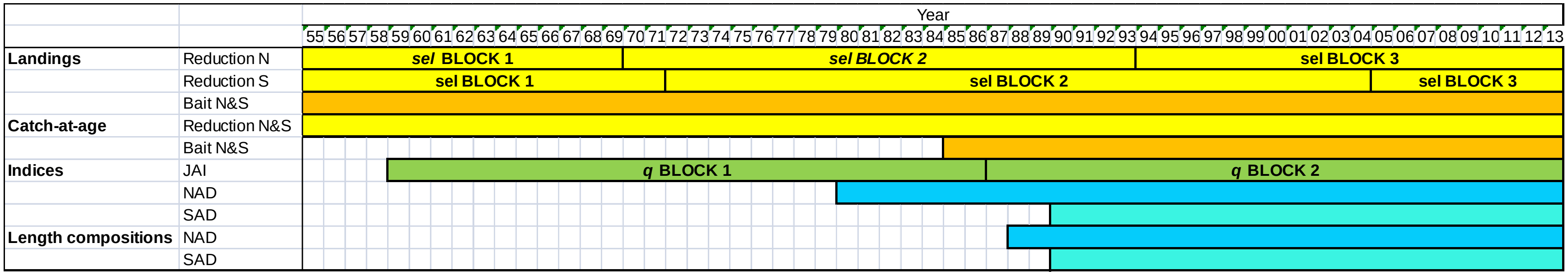
NORTH (Stat Area <625)

Gear	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec
Gillnet	1753	779	2107	83
Purse Seine		51		
Bottom Trawl	65	79	349	274
Midwater Trawl			18	8

SOUTH (Stat Area >= 625)

Gear	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec
Gillnet	6380	1199	6182	3606
Purse Seine	109	1330	828	76
Bottom Trawl	461			844
Midwater Trawl				

Table 6.1.2. Timeline of data sources and selectivity/catchability blocks applied. N=North, S=South, JAI=Juvenile Abundance Index, NAD = Northern ADult index, SAD = Southern ADult index.



		Year																																																								
		55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13
Landings	Reduction N	*sel* BLOCK 1	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	*sel BLOCK 2*	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	sel BLOCK 3	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
	Reduction S	sel BLOCK 1	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	sel BLOCK 2	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	sel BLOCK 3	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
	Bait N&S	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Catch-at-age	Reduction N&S	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
	Bait N&S																															🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Indices	JAI					*q* BLOCK 1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	*q* BLOCK 2	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	NAD																										🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	SAD																																				▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Length compositions	NAD																																		🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	SAD																																				▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

Table 7.2.1.1. Selectivity slope and A_{50} of the ascending and descending limbs with associated SE for the bait and reduction fisheries, and the NAD and SAD indices.

			Ascending Limb				Descending Limb			
Fishery/Index	**Region**	**Period**	**Slope**	**SE**	**A50**	**SE**	**Slope**	**SE**	**A50**	**SE**
Reduction	North	1955-1969	3.65	0.18	2.27	0.11	1.87	2.54	3.10	1.21
Reduction	North	1969-1993	5.52	1.04	2.03	0.11	1.74	1.28	2.46	0.93
Reduction	North	1994-2013	5.28	2.70	2.15	0.13	0.90	0.85	2.50	0.01
Reduction	South	1955-1971	3.97	0.29	1.13	0.14	2.46	2.56	1.67	0.60
Reduction	South	1972-2004	2.15	0.16	3.24	0.15	4.46	0.67	-1.0	0.005
Reduction	South	2005-2013	12.0	0.013	1.11	0.026	1.36	0.77	2.5	0.002
Bait	North	1955-2013	6.27	2.71	2.34	0.16	5.33	7.14	2.37	0.46
Bait	South	1955-2013	45.0	13.27	1.07	0.02	0.64	0.81	0.82	6.97
NAD	North		22.17	1322	1.12	74.1	NA	NA	NA	NA
SAD	South		35	0.04	0.16	0.003	5.11	1.58	0.99	0.46

Table 7.2.2.1. Fishing mortality rate at age estimates from 1955-2013.

Ages	0	1	2	3	4	5	6+
1955	0.006	0.215	1.121	2.561	2.397	1.662	0.583
1956	0.011	0.369	3.005	8.539	8.304	5.702	1.989
1957	0.008	0.294	2.494	7.136	6.944	4.727	1.646
1958	0.008	0.285	1.348	2.803	2.573	1.790	0.630
1959	0.008	0.267	1.768	4.488	4.291	2.975	1.044
1960	0.003	0.091	0.506	1.194	1.124	0.771	0.270
1961	0.006	0.196	0.640	0.832	0.658	0.448	0.159
1962	0.009	0.305	1.073	1.571	1.303	0.888	0.314
1963	0.009	0.315	1.158	1.722	1.437	0.959	0.338
1964	0.010	0.341	1.003	0.991	0.676	0.416	0.146
1965	0.011	0.389	1.176	1.145	0.779	0.495	0.177
1966	0.012	0.397	1.000	0.565	0.197	0.089	0.032
1967	0.007	0.245	0.656	0.460	0.231	0.133	0.048
1968	0.007	0.245	0.642	0.473	0.251	0.155	0.055
1969	0.006	0.213	0.547	0.325	0.127	0.068	0.025
1970	0.008	0.273	0.732	0.414	0.135	0.048	0.016
1971	0.007	0.232	0.625	0.400	0.155	0.054	0.014
1972	0.029	0.254	1.740	0.777	0.297	0.119	0.030
1973	0.017	0.148	1.177	0.807	0.448	0.180	0.044
1974	0.014	0.120	0.945	0.626	0.341	0.138	0.034
1975	0.012	0.109	0.816	0.448	0.215	0.089	0.025
1976	0.011	0.101	0.796	0.512	0.274	0.112	0.029
1977	0.011	0.096	0.679	0.322	0.134	0.055	0.016
1978	0.011	0.098	0.694	0.325	0.132	0.056	0.016
1979	0.013	0.111	0.766	0.341	0.130	0.053	0.014
1980	0.021	0.185	1.286	0.566	0.213	0.089	0.026
1981	0.023	0.200	1.408	0.653	0.263	0.109	0.031
1982	0.024	0.211	1.421	0.563	0.183	0.074	0.022
1983	0.027	0.236	1.581	0.624	0.201	0.081	0.023
1984	0.031	0.273	1.846	0.762	0.264	0.106	0.030
1985	0.013	0.116	1.167	1.198	0.808	0.307	0.072
1986	0.007	0.062	0.483	0.407	0.271	0.080	0.015
1987	0.009	0.083	0.617	0.379	0.203	0.073	0.017
1988	0.014	0.124	0.873	0.454	0.214	0.076	0.018
1989	0.020	0.172	1.299	0.775	0.399	0.156	0.040
1990	0.015	0.130	1.183	1.126	0.743	0.272	0.059
1991	0.016	0.143	1.177	1.015	0.659	0.221	0.045
1992	0.010	0.092	0.827	0.876	0.617	0.200	0.039
1993	0.013	0.116	0.849	0.572	0.336	0.104	0.020
1994	0.016	0.140	0.946	0.482	0.229	0.101	0.046
1995	0.028	0.245	1.795	1.250	0.728	0.385	0.192
1996	0.018	0.161	1.244	1.134	0.766	0.350	0.159

Ages	0	1	2	3	4	5	6+
1997	0.026	0.226	1.564	0.910	0.495	0.192	0.079
1998	0.034	0.305	2.075	1.050	0.513	0.182	0.070
1999	0.018	0.161	1.158	0.818	0.519	0.164	0.054
2000	0.009	0.080	0.684	0.762	0.552	0.250	0.113
2001	0.012	0.108	0.785	0.513	0.293	0.142	0.068
2002	0.011	0.094	0.681	0.398	0.213	0.099	0.047
2003	0.014	0.128	0.862	0.335	0.115	0.045	0.020
2004	0.010	0.086	0.632	0.395	0.222	0.103	0.048
2005	0.000	0.089	0.504	0.487	0.311	0.125	0.048
2006	0.000	0.052	0.370	0.532	0.385	0.192	0.089
2007	0.000	0.050	0.305	0.396	0.285	0.115	0.046
2008	0.000	0.037	0.240	0.319	0.232	0.094	0.038
2009	0.000	0.050	0.280	0.294	0.195	0.074	0.027
2010	0.000	0.067	0.372	0.423	0.290	0.110	0.040
2011	0.000	0.056	0.327	0.435	0.318	0.114	0.040
2012	0.000	0.040	0.238	0.351	0.268	0.087	0.027
2013	0.000	0.040	0.237	0.271	0.186	0.076	0.030

Table 7.2.3.1. Numbers at age in billions of fish estimated from the base run of the BAM model for 1955-2013.

Ages	0	1	2	3	4	5	6+
1955	26.356	4.394	2.754	0.563	0.000	0.000	0.000
1956	28.647	8.545	1.561	0.469	0.025	0.000	0.000
1957	13.399	9.247	2.602	0.040	0.000	0.000	0.000
1958	79.269	4.335	3.036	0.112	0.000	0.000	0.000
1959	12.136	25.647	1.435	0.412	0.004	0.000	0.000
1960	11.035	3.929	8.648	0.128	0.003	0.000	0.000
1961	10.974	3.591	1.580	2.721	0.022	0.001	0.000
1962	11.744	3.560	1.300	0.435	0.670	0.007	0.000
1963	9.198	3.797	1.156	0.232	0.051	0.108	0.002
1964	9.542	2.974	1.220	0.190	0.023	0.007	0.026
1965	8.791	3.082	0.931	0.234	0.040	0.007	0.017
1966	12.979	2.836	0.920	0.150	0.042	0.011	0.011
1967	7.657	4.185	0.840	0.177	0.048	0.021	0.013
1968	9.824	2.480	1.443	0.228	0.063	0.023	0.018
1969	13.030	3.182	0.855	0.396	0.080	0.029	0.023
1970	6.284	4.225	1.132	0.258	0.162	0.042	0.030
1971	16.899	2.034	1.416	0.284	0.097	0.084	0.043
1972	13.894	5.476	0.710	0.395	0.108	0.049	0.074
1973	15.032	4.402	1.870	0.065	0.103	0.048	0.071
1974	24.479	4.823	1.673	0.301	0.016	0.039	0.066
1975	37.953	7.879	1.885	0.339	0.091	0.007	0.060
1976	31.215	12.232	3.111	0.435	0.123	0.044	0.040
1977	30.940	10.069	4.868	0.733	0.147	0.055	0.048
1978	22.918	9.986	4.030	1.289	0.300	0.077	0.061
1979	31.398	7.395	3.988	1.051	0.527	0.156	0.081
1980	24.700	10.114	2.913	0.968	0.422	0.275	0.139
1981	27.024	7.890	3.701	0.421	0.311	0.203	0.237
1982	14.626	8.618	2.844	0.473	0.124	0.142	0.252
1983	28.181	4.658	3.072	0.359	0.152	0.061	0.233
1984	39.081	8.948	1.620	0.330	0.109	0.074	0.175
1985	32.804	12.357	3.000	0.134	0.087	0.050	0.146
1986	20.891	10.568	4.845	0.488	0.023	0.023	0.106
1987	14.315	6.769	4.375	1.561	0.184	0.010	0.077
1988	22.121	4.627	2.744	1.233	0.604	0.089	0.053
1989	17.760	7.116	1.800	0.598	0.443	0.290	0.082
1990	21.865	5.683	2.638	0.256	0.156	0.177	0.199
1991	18.050	7.030	2.197	0.422	0.047	0.044	0.198
1992	14.585	5.794	2.683	0.354	0.086	0.014	0.139
1993	8.245	4.710	2.328	0.613	0.083	0.028	0.090
1994	14.094	2.654	1.847	0.520	0.196	0.035	0.070

Ages	0	1	2	3	4	5	6+
1995	11.089	4.526	1.017	0.374	0.182	0.092	0.060
1996	9.203	3.519	1.561	0.088	0.061	0.052	0.069
1997	10.817	2.949	1.320	0.235	0.016	0.017	0.059
1998	11.959	3.440	1.036	0.144	0.053	0.006	0.042
1999	11.745	3.770	1.117	0.068	0.029	0.019	0.027
2000	9.732	3.764	1.414	0.183	0.017	0.010	0.026
2001	7.526	3.148	1.531	0.373	0.048	0.006	0.019
2002	14.137	2.426	1.245	0.364	0.126	0.021	0.014
2003	12.094	4.564	0.972	0.329	0.138	0.061	0.020
2004	13.390	3.890	1.769	0.214	0.133	0.073	0.047
2005	20.875	4.327	1.572	0.491	0.082	0.063	0.068
2006	14.757	6.811	1.744	0.496	0.171	0.036	0.074
2007	12.658	4.815	2.846	0.629	0.165	0.069	0.060
2008	15.006	4.130	2.018	1.095	0.239	0.074	0.073
2009	12.706	4.896	1.752	0.829	0.450	0.113	0.084
2010	27.144	4.146	2.051	0.692	0.349	0.220	0.114
2011	10.082	8.857	1.708	0.738	0.256	0.156	0.188
2012	7.970	3.290	3.689	0.643	0.270	0.111	0.196
2013	6.384	2.600	1.393	1.517	0.256	0.123	0.180

Table 7.2.3.2. Fecundity at age in billions of eggs during 1955-2013.

Ages	0	1	2	3	4	5	6+
1955	0	4040	73600	35069	20	0	0
1956	0	6379	37275	31952	2389	2	0
1957	0	5402	36641	2764	6	0	0
1958	0	4726	42756	5950	2	0	0
1959	0	7897	20332	20790	411	0	0
1960	0	9015	72504	6157	243	6	0
1961	0	3846	36632	108756	2018	70	3
1962	0	5919	26761	27109	55608	993	38
1963	0	7998	25101	14141	5653	14716	389
1964	0	7514	29123	10390	2423	1221	5263
1965	0	7190	24342	13676	3393	1042	3965
1966	0	4132	28354	9614	3902	1220	2144
1967	0	12654	19865	14482	4936	2545	1710
1968	0	5190	57723	17149	9390	3206	2782
1969	0	8916	21047	39489	12461	6952	4034
1970	0	20676	33099	19017	28798	11827	10382
1971	0	7681	74274	22550	14128	22733	20167
1972	0	7923	38810	51803	16805	13039	27518
1973	0	2570	34164	8090	25794	12955	31764
1974	0	3512	39723	17569	3301	16143	29383
1975	0	3348	29214	22119	10288	1884	36756
1976	0	3413	20953	23147	12212	8260	13218
1977	0	1752	22358	24819	14391	6971	13992
1978	0	1774	14244	33401	22393	11252	8724
1979	0	2135	17118	25115	30694	20082	16271
1980	0	1772	11045	27314	25501	26290	28423
1981	0	1444	9298	8912	21490	21522	32668
1982	0	2562	13029	7385	6286	17722	42771
1983	0	1298	16825	9069	6579	5295	47733
1984	0	2591	10408	9635	6066	5805	22739
1985	0	2275	12976	4704	5649	4414	18049
1986	0	1885	20792	12222	1713	2508	13281
1987	0	1936	15507	38077	10846	1261	12611
1988	0	834	13467	28646	33635	9158	9397
1989	0	2994	9252	15622	25830	26762	13306
1990	0	5206	28224	7502	8925	18192	26597
1991	0	4142	38963	18760	3045	4015	32503
1992	0	9507	33354	17991	7247	1515	17637
1993	0	2068	45211	28357	6855	3490	13541
1994	0	3874	20491	30209	16697	3873	11819
1995	0	1976	24225	19040	19195	11861	7905
1996	0	1014	34029	6036	6763	8738	12050

Ages	0	1	2	3	4	5	6+
1997	0	820	24151	17633	1940	3427	14145
1998	0	1477	10317	10399	7367	1063	14498
1999	0	8655	16270	3441	3962	3979	6750
2000	0	4139	36677	10153	1782	2194	7175
2001	0	2301	54903	25502	4977	1029	5634
2002	0	5651	38296	35095	14980	3367	3698
2003	0	4907	25956	24921	22896	10849	4238
2004	0	4274	35273	11792	14797	17138	11589
2005	0	1242	28594	28462	6117	8523	19992
2006	0	5090	22211	26936	16568	3102	11028
2007	0	6166	56617	32848	15336	9325	5695
2008	0	6901	45047	55267	22779	9784	12441
2009	0	8259	40717	43708	32544	15530	14541
2010	0	7730	33166	36121	26519	19100	20357
2011	0	18370	39400	34103	18576	14328	17956
2012	0	6161	80231	32307	21548	9581	19934
2013	0	4870	27938	74244	17824	14489	17130

Table 7.2.3.3. Biomass of Atlantic menhaden by age from 1959 to 2013.

Year	0	1	2	3	4	5	6+	Total
1955	735.3	274.6	568.7	188.7	0.1	0.0	0.0	1767
1956	610.2	496.5	306.4	166.0	11.1	0.0	0.0	1590
1957	470.3	491.0	407.5	14.3	0.0	0.0	0.0	1383
1958	1490.3	284.8	475.5	33.9	0.0	0.0	0.0	2284
1959	543.7	1125.9	226.1	120.6	1.9	0.0	0.0	2018
1960	282.5	327.7	1119.0	36.3	1.1	0.0	0.0	1767
1961	373.1	230.5	306.0	692.6	9.5	0.3	0.0	1612
1962	466.2	268.0	238.8	145.9	271.7	4.0	0.1	1395
1963	392.8	312.1	216.7	76.4	25.2	61.5	1.4	1086
1964	388.4	256.6	239.4	58.3	11.1	4.7	19.0	977
1965	305.1	262.3	190.8	75.2	16.5	4.2	13.5	868
1966	512.7	203.6	203.2	51.0	18.4	5.4	7.9	1002
1967	336.1	385.9	163.4	70.9	22.6	11.0	7.2	997
1968	484.3	202.1	367.6	86.4	38.1	13.2	11.2	1203
1969	621.5	288.0	170.3	182.5	49.5	23.6	15.3	1351
1970	201.7	457.1	244.3	96.3	109.1	37.5	30.3	1176
1971	633.7	201.3	423.9	112.3	57.7	73.3	50.9	1553
1972	164.0	389.9	217.9	219.1	66.7	42.4	77.7	1178
1973	347.2	233.8	326.6	34.8	85.8	41.7	82.4	1152
1974	570.4	270.6	326.6	96.6	12.0	43.4	76.4	1396
1975	645.2	364.0	306.2	117.0	45.5	6.1	82.2	1566
1976	483.8	459.9	374.9	131.8	56.4	30.6	39.3	1577
1977	488.8	340.3	514.1	170.2	66.9	29.9	43.7	1654
1978	474.4	349.5	391.7	262.0	113.1	45.9	35.9	1672
1979	568.3	293.6	410.0	206.5	168.9	85.5	59.0	1792
1980	390.3	345.9	289.6	204.8	138.1	122.9	102.4	1594
1981	537.8	289.6	317.1	78.2	111.3	97.7	135.9	1568
1982	213.5	358.5	299.5	77.4	36.4	76.1	164.8	1226
1983	569.3	175.1	344.7	72.2	40.6	25.6	171.6	1399
1984	664.4	357.0	192.4	71.1	33.9	29.0	96.4	1444
1985	551.1	457.2	311.1	31.8	29.9	21.2	77.7	1480
1986	367.7	372.0	498.1	97.4	8.6	11.2	57.0	1412
1987	209.0	265.3	426.6	308.3	59.5	5.5	49.3	1323
1988	378.3	165.6	297.7	239.3	188.3	42.0	35.6	1347
1989	435.1	324.5	196.5	122.5	142.0	126.3	52.1	1399
1990	507.3	354.0	373.7	55.4	49.2	83.3	111.9	1535
1991	694.9	378.2	379.1	114.2	16.1	19.0	126.7	1728
1992	316.5	428.8	403.5	104.2	35.3	6.9	75.3	1370
1993	262.2	228.4	417.3	169.9	33.6	15.0	54.7	1181
1994	174.8	191.1	265.2	166.3	81.0	17.3	45.5	941
1995	94.3	217.7	199.1	110.3	87.3	50.5	33.5	793
1996	109.5	139.3	293.7	31.3	30.1	33.8	46.0	684

Year	0	1	2	3	4	5	6+	Total
1997	168.7	110.3	230.8	88.9	8.4	12.3	47.8	667
1998	502.3	161.3	143.5	53.4	30.7	4.0	42.2	937
1999	212.6	314.4	177.3	19.9	16.4	14.2	22.5	777
2000	96.3	250.3	287.8	56.9	8.1	7.7	22.8	730
2001	258.1	177.5	365.9	132.4	22.8	3.9	17.5	978
2002	369.0	206.0	274.6	163.7	65.3	13.3	12.0	1104
2003	362.8	294.4	200.6	125.4	89.0	41.0	15.1	1128
2004	137.9	258.3	320.1	66.2	65.8	58.6	38.9	946
2005	336.1	170.1	273.3	156.7	30.9	35.8	62.3	1065
2006	366.0	395.7	262.9	151.4	77.1	15.0	44.7	1313
2007	365.8	335.1	513.8	187.6	72.2	39.0	26.6	1540
2008	657.3	313.0	382.5	320.5	106.6	41.2	47.8	1869
2009	395.2	375.5	340.1	249.3	166.9	64.7	55.6	1647
2010	1004.3	323.4	341.1	206.3	133.4	92.3	77.0	2178
2011	373.0	713.8	329.2	204.4	95.2	67.6	83.9	1867
2012	294.9	257.9	692.4	187.4	107.1	46.3	91.6	1678
2013	236.2	203.9	253.4	436.8	92.1	63.3	80.1	1366

Table 7.3.1. Results of the runs test for SDNRs near 1, 2, 3, and 4 for each index. A No indicates that the residuals are not random, while a Yes indicates that the residuals are random in nature. The ultimate goal is to attain a Yes for randomized residuals.

Run	NAD	SAD	JAI
SDNR=1	No	Yes	No
SDNR=2	Yes	Yes	No
SDNR=3	Yes	Yes	No
SDNR=4	Yes	Yes	No

Table 7.3.2. Sum of squared residuals for the index fits under different levels of weightings to attain SDNRs ~1, 2, 3, and 4.

Run	NAD	SAD	JAI
SDNR=1	26.77	20.87	14.41
SDNR=2	18.99	15.99	12.23
SDNR=3	14.36	15.24	11.58
SDNR=4	14.47	15.79	10.32

Table 7.4.1.1. Table of likelihood components for the base run and all sensitivity runs.

Run	total	unwgt	cRn L	cRs L	cBn L	cBs L	SAD lenc	NAD lenc	cRn agec	cRs agec	cBn agec	cBs agec	SAD	NAD	JAI	priors	SRfit
Base run	-3737	-3737	0.05	0.48	0.02	0.02	-1186.5	-1130.6	-577.6	-523.9	-266.5	-270.1	50.6	68.4	98.9	3.2	-6.5
Am-022	-3389	-3390	0.20	3.07	0.07	0.11	-1186.4	-1113.8	-569.2	-481.6	-251.3	-268.0	116.1	140.0	220.3	3.2	-4.3
Am-022a	-3910	-3908	0.06	0.07	0.00	0.01	-1186.7	-1136.8	-575.8	-511.7	-276.2	-278.5	15.4	22.8	18.8	3.2	-8.0
Am-022c	-2927	-2939	1.06	13.24	0.33	0.56	-1181.9	-1112.6	-560.3	-462.6	-240.8	-271.1	212.3	298.5	364.5	8.5	-0.1
Am-023	-3869	-3875	0.03	0.08	0.00	0.00	-1185.9	-1123.3	-580.0	-538.1	-274.1	-274.4	43.6	57.2		12.0	-8.0
Am-024	-2623	-2623	0.08	0.74	0.03	0.03		-1143.9	-574.5	-529.4	-263.5	-271.6		65.3	93.4	1.2	-4.1
Am-025	-2724	-2730	0.02	0.05	0.00	0.00	-1186.9		-579.4	-521.8	-273.1	-277.5	55.4		52.8	12.7	-7.4
Am-026	-1610	-1610	0.02	0.05	0.00	0.00			-579.3	-524.6	-273.6	-278.7			45.8	5.0	-6.3
Am-027	-3735	-3739	0.05	0.45	0.01	0.02	-1186.3	-1129.0	-577.7	-527.3	-266.4	-270.8	50.3	68.9	99.2	7.7	-6.6
Am-028	-3653	-3654	0.08	0.72	0.02	0.03	-1186.6	-1129.4	-555.8	-507.0	-228.1	-265.6	47.6	64.6	105.0	3.2	-6.0
Am-029	-3707	-3709	0.08	0.66	0.03	0.03	-1186.8	-1131.5	-572.3	-512.8	-251.8	-268.8	49.8	63.1	101.6	3.2	-5.4
Am-030	4088	4074	0.18	1.22	0.06	0.08	-144.4	755.3	1446.2	1658.5	94.7	74.2	37.4	92.2	58.3	7.2	4.5
Am-040	-3695	-3700	0.08	0.45	0.02	0.02	-1185.5	-1131.1	-566.5	-500.0	-265.7	-271.4	51.0	71.2	97.8	4.0	-4.5
Am-041	-3692	-3693	0.12	1.05	0.05	0.05	-1181.1	-1140.3	-571.9	-506.0	-248.0	-270.7	58.6	67.2	97.8	1.8	-4.0
Am-042	-3241	-3263	0.05	0.84	0.04	0.03	-1185.2	-1138.5	-327.3	-287.4	-265.4	-271.1	51.8	69.6	89.9	10.6	1.7
Am-043	-3113	-3118	0.02	0.41	0.01	0.01	-1184.7	-1134.1	-267.5	-232.4	-237.5	-240.0	51.1	57.2	69.3	10.0	-7.6
Am-044	-3751	-3754	0.04	0.12	0.01	0.01	-1186.2	-1125.1	-579.2	-536.0	-271.6	-271.5	45.9	59.9	60.2	4.9	-4.4
Am-045	-3718	-3721	0.04	0.58	0.02	0.02	-1186.4	-1126.7	-575.2	-522.1	-266.5	-270.7	51.4	67.7	106.3	7.5	-6.0
Am-046	-3713	-3721	0.09	0.97	0.03	0.03	-1185.4	-1127.1	-576.7	-527.6	-262.9	-268.7	54.6	72.2	99.4	10.8	-6.0
Am-047	-3737	-3747	0.03	0.16	0.01	0.01	-1184.0	-1138.0	-575.7	-526.9	-265.9	-272.9	48.0	69.4	98.4	13.5	-5.1
Am-048	-3736	-3734	0.10	0.58	0.04	0.03	-1231.3	-1101.5	-578.3	-522.0	-264.7	-270.0	51.6	77.3	104.3	5.7	-12.8
Am-049	-3748	-3757	0.04	0.34	0.01	0.01	-1180.6	-1140.1	-578.0	-529.3	-268.1	-272.9	50.9	68.0	93.0	12.5	-6.5
Am-050	-2991	-2995	0.05	0.30	0.01	0.01	-1184.2	-1137.2	-327.5	-262.4	-149.6	-143.4	48.6	65.6	95.1	6.4	-6.1
Am-053	-3726	-3736	0.06	0.49	0.02	0.02	-1186.3	-1130.7	-576.9	-522.7	-266.6	-270.1	50.8	67.9	98.5	12.6	-6.2
Am-054	-3725	-3737	0.07	0.43	0.01	0.02	-1185.9	-1127.8	-576.7	-525.8	-266.7	-270.9	50.1	68.5	97.5	13.7	-6.1
Am-055	-3712	-3717	0.07	0.45	0.01	0.01	-1186.3	-1127.0	-563.8	-519.0	-267.3	-271.0	50.0	69.2	97.9	3.4	-3.2

Table 7.4.1.2. Standard deviation of the normalized residuals for the base run and each sensitivity run.

Run	SAD lenc	NAD lenc	cRn agec	cRs agec	cBn agec	cBs agec	SAD	NAD	JAI
Base run	1.16	1.16	1.08	1.25	1.22	1.19	2.1	2.04	1.91
Am-022	1.15	1.3	1.1	1.51	1.4	1.31	3.18	2.91	2.86
Am-022a	1.14	0.96	1.07	1.27	1.01	0.99	1.16	1.18	0.83
Am-022c	1.12	1.37	1.27	1.59	1.61	1.33	4.29	4.25	3.67
Am-023	1.16	1.15	1.06	1.19	1.09	1.14	1.95	1.86	
Am-024		1.44	1.09	1.2	1.32	1.22		1.99	1.86
Am-025	1.09		1.04	1.25	0.98	1.08	2.19		1.4
Am-026			1.04	1.22	0.97	1.03			1.3
Am-027	1.17	1.16	1.08	1.24	1.22	1.22	2.09	2.04	1.92
Am-028	1.16	1.16	251.96	1.08	307.69	1.27	2.03	1.98	1.97
Am-029	1.15	1.16	0.78	1.23	1.48	1.18	2.08	1.96	1.94
Am-030	5.36	7.47	88.87	47.81	8.04	7.84	1.8	2.36	1.47
Am-040	1.19	1.15	1.21	1.27	1.25	1.22	2.1	2.08	1.9
Am-041	1.26	1.27	1.21	1.17	1.67	1.36	2.26	2.02	1.9
Am-042	1.18	1.15	0.68	1.24	1.24	1.18	2.12	2.12	2.41
Am-043	1.19	1.11	0.51	1.24	1.29	1.32	2.11	2.14	2.35
Am-044	1.17	1.17	1.07	1.17	1.16	1.17	2	1.9	1.9
Am-045	1.16	1.18	1.07	1.32	1.21	1.21	2.11	2.03	1.98
Am-046	1.17	1.16	1.11	1.21	1.34	1.22	2.18	2.09	1.92
Am-047	1.21	1.14	1.07	1.28	1.17	1.18	2.04	2.05	1.91
Am-048	0.96	1.39	1.06	1.3	1.24	1.25	2.12	2.16	1.97
Am-049	1.22	1.15	1.07	1.24	1.18	1.14	2.1	2.03	1.86
Am-050	1.23	1.16	0.97	1.23	1.07	1.28	2.05	1.99	1.88
Am-053	1.14	1.17	1.08	1.25	1.22	1.23	2.1	2.03	1.91
Am-054	1.16	1.17	1.06	1.25	1.21	1.21	2.09	2.04	1.9
Am-055	1.17	1.17	0.99	1.25	1.17	1.19	2.08	2.05	1.9

Table 7.4.1.3. Estimated $\boldsymbol{R_0}$ and index catchabilities from each of the sensitivity runs.

Run	R_0	q NAD	q SAD	q_1 JAI	q_2 JAI
Base run	15.5	0.43	0.21	0.09	0.05
Am-022	15.32	0.51	0.23	0.09	0.06
Am-022a	14.86	0.5	0.21	0.1	0.05
Am-022c	14.55	0.72	0.23	0.09	0.06
Am-023	18.43	0.25	0.16		
Am-024	13.56	2.15		0.1	0.06
Am-025	23.7		0.11	0.07	0.03
Am-026	22.3			0.07	0.03
Am-027	15.76	0.4	0.21	0.09	0.05
Am-028	14.64	0.51	0.23	0.09	0.06
Am-029	14.43	0.54	0.23	0.1	0.06
Am-030	20.97	0.49	0.04	0.07	0.03
Am-040	15.2	0.43	0.21	0.09	0.05
Am-041	13.2	3.27	0.26	0.1	0.06
Am-042	12.81	1.11	0.25	0.05	0.06
Am-043	13	0.48	0.21	0.05	
Am-044	16.42	0.31	0.18	0.05	
Am-045	16.98	0.42	0.22	0.06	
Am-046	7.24	0.51	0.33	0.18	0.11
Am-047	78.84	0.73	0.09	0.02	0.01
Am-048	14.11	0.45	0.22	0.11	0.05
Am-049	17.15	0.67	0.18	0.08	0.05
Am-050	17.73	0.44	0.19	0.08	0.05
Am-053	16.41	0.44	0.21	0.09	0.05
Am-054	20.82	0.38	0.2	0.08	0.05
Am-055	28.54	0.38	0.21	0.07	0.05

7.4.2.1. Table of likelihood components for the base run and retrospective analyses.

Run	total	unwgt	cRn L	cRs L	cBn L	cBs L	SAD lenc	NAD lenc	cRn agec	cRs agec	cBn agec	cBs agec	SAD	NAD	JAI	priors	SRfit
Base run	-3737	-3737	0.05	0.48	0.02	0.02	-1186.5	-1130.6	-577.6	-523.9	-266.5	-270.1	50.6	68.4	98.9	3.2	-6.5
End year 2012	-3623	-3622	0.05	0.45	0.01	0.02	-1140.6	-1085.1	-567.5	-518.4	-258.3	-267.5	48.1	67.5	98.8	3.2	-6.2
End year 2011	-3484	-3490	0.05	0.42	0.01	0.02	-1089.0	-1042.5	-555.8	-506.7	-249.2	-255.8	48.2	67.2	92.8	10.5	-6.9
End year 2010	-3381	-3385	0.05	0.42	0.01	0.02	-1046.9	-998.8	-545.6	-495.2	-240.7	-247.6	42.9	62.0	84.1	8.4	-7.1
End year 2009	-3257	-3263	0.05	0.42	0.01	0.02	-1001.1	-955.9	-535.0	-485.3	-233.5	-238.2	45.6	60.8	79.6	9.2	-6.3

7.4.2.2. Standard deviation of the normalized residuals for the base run and each retrospective run.

Run	SAD lenc	NAD lenc	cRn agec	cRs agec	cBn agec	cBs agec	SAD	NAD	JAI
Base run	1.16	1.16	1.08	1.25	1.22	1.19	2.1	2.04	1.91
Retrospective 2012	1.16	1.17	1.08	1.24	1.22	1.09	2.09	2.05	1.93
Retrospective 2011	1.16	1.2	1.09	1.25	1.21	1.09	2.14	2.08	1.89
Retrospective 2010	1.12	1.2	1.09	1.27	1.2	1.02	2.07	2.03	1.82
Retrospective 2009	1.09	1.02	1.11	1.27	1.16	1.03	2.19	2.05	1.78

7.4.2.3. Estimated R_0 and index catchabilities from the retrospective analysis.

Run	R_0	q NAD	q SAD	q_1 JAI	q_2 JAI
Base run	15.5	0.43	0.21	0.09	0.05
Retrospective 2012	15.95	0.4	0.2	0.09	0.05
Retrospective 2011	16.3	0.37	0.19	0.09	0.05
Retrospective 2010	16.38	0.36	0.18	0.09	0.05
Retrospective 2009	16.29	0.36	0.18	0.09	0.05

Table 8.2.1. Current and TC recommended fishing mortality and fecundity benchmarks (targets and thresholds) along with terminal year values from the base run of the BAM. Fecundity (FEC) is in billions of eggs.

Current Reference Points	Benchmark	Current value
$F_{15\%\ (threshold)}$	3.41	0.27 (age-3; full ***F***)
$F_{30\%\ (target)}$	1.07	0.27 (age-3; full ***F***)
$FEC_{15\%\ (threshold)}$	45,889	156,495
$FEC_{30\%\ (target)}$	92,444	156,495
Recommended Reference Points	Benchmark	Current value
$F_{20\%\ (threshold)}$	2.01	0.24 (age-2)
$F_{36\%\ (target)}$	0.82	0.24 (age-2)
$FEC_{20\%}$	61,401	156,495
$FEC_{36\%}$	111,077	156,495

Table 8.3.2.1. ***Table A***: Benchmarks calculated for the base run and each sensitivity run along with the 2013 values relative to the benchmark values. Values with a – indicate an extreme, unrealistic scenario. The fishing mortality rate for age-2 was used for these calculations. ***Table B (next page):*** For reference, the same benchmarks were calculated using the fishing mortality rate for age-3 fish. When comparing the upper and lower tables, note that fully selected age changes over time.

Table A: Benchmarks age-2 fishing mortality rate.

Run	$F_{15\%}$	$F_{30\%}$	$FEC_{15\%}$	$FEC_{30\%}$	$F_{2013}/F_{15\%}$	$F_{2013}/F_{30\%}$	$FEC_{2013}/FEC_{15\%}$	$FEC_{2013}/FEC_{30\%}$
Base run	3.41	1.07	45889	92444	0.07	0.22	3.41	1.69
Am-022	3.34	1.05	45378	91399	0.08	0.25	3.1	1.54
Am-022a	4.13	1.2	43992	88600	0.05	0.18	3.09	1.54
Am-022c	3.6	1.11	43099	86804	0.07	0.23	2.72	1.35
Am-023	2.61	0.99	54566	109928	0.06	0.16	6.34	3.15
Am-024	3.55	1.09	40168	80921	0.13	0.41	1.95	0.97
Am-025	2.38	0.94	70171	141366	0.06	0.15	4.4	2.19
Am-026	2.45	0.95	66031	133012	0.09	0.23	3.27	1.62
Am-027	3.63	1.08	50699	102139	0.08	0.26	3.53	1.75
Am-028	3.63	1.19	43361	87352	0.08	0.24	3.12	1.55
Am-029	3.63	1.13	42735	86064	0.08	0.26	3.04	1.51
Am-030	6.71	1.34	62095	125081	0.01	0.04	9.11	4.52
Am-040	2.36	0.9	45022	90678	0.13	0.33	3.72	1.85
Am-041	4.91	1.32	39083	78728	0.07	0.27	1.88	0.93
Am-042	3.81	1.09	37931	76416	0.1	0.36	2.43	1.21
Am-043	2.77	0.94	38499	77541	0.1	0.3	4.23	2.1
Am-044	2.63	0.98	48627	97936	0.08	0.21	5.55	2.76
Am-045	2.91	0.96	50290	101310	0.1	0.31	2.99	1.49
Am-046	1.2	0.62	70233	141487	0.28	0.55	2.14	1.06
Am-047	7	6.39	69443	71864	0.04	0.04	2.36	2.28
Am-048	3.67	1.08	41793	84175	0.06	0.22	3.35	1.66
Am-049	1.69	0.82	56110	113027	0.19	0.38	3.12	1.55
Am-050	3.5	1.12	48800	98301	0.06	0.19	3.49	1.73
Am-053	3.41	1.08	42755	93351	0.07	0.21	3.59	1.66
Am-054	2.71	0.94	28181	98036	0.1	0.3	6.1	1.75
Am-055	3.35	1.07	0	69349	0.07	0.21		2.43

Table B: Benchmarks using age-3 fishing mortality rate.

Run	$F_{15\%}$	$F_{30\%}$	$FEC_{15\%}$	$FEC_{30\%}$	$F_{2013}/F_{15\%}$	$F_{2013}/F_{30\%}$	$FEC_{2013}/FEC_{15\%}$	$FEC_{2013}/FEC_{30\%}$
Base run	3.41	1.07	45889	92444	0.08	0.25	3.41	1.69
Am-022	3.34	1.05	45378	91399	0.09	0.28	3.1	1.54
Am-022a	4.13	1.2	43992	88600	0.07	0.23	3.09	1.54
Am-022c	3.6	1.11	43099	86804	0.09	0.3	2.72	1.35
Am-023	2.61	0.99	54566	109928	0.04	0.1	6.34	3.15
Am-024	3.55	1.09	40168	80921	0.16	0.51	1.95	0.97
Am-025	2.38	0.94	70171	141366	0.06	0.16	4.4	2.19
Am-026	2.45	0.95	66031	133012	0.09	0.24	3.27	1.62
Am-027	3.63	1.08	50699	102139	0.07	0.22	3.53	1.75
Am-028	3.63	1.19	43361	87352	0.09	0.27	3.12	1.55
Am-029	3.63	1.13	42735	86064	0.09	0.29	3.04	1.51
Am-030	6.71	1.34	62095	125081	0.01	0.05	9.11	4.52
Am-040	2.36	0.9	45022	90678	0.1	0.25	3.72	1.85
Am-041	4.91	1.32	39083	78728	0.12	0.43	1.88	0.93
Am-042	3.81	1.09	37931	76416	0.11	0.4	2.43	1.21
Am-043	2.77	0.94	38499	77541	0.09	0.26	4.23	2.1
Am-044	2.63	0.98	48627	97936	0.05	0.14	5.55	2.76
Am-045	2.91	0.96	50290	101310	0.09	0.28	2.99	1.49
Am-046	1.2	0.62	70233	141487	0.23	0.46	2.14	1.06
Am-047	7	6.39	69443	71864	0.03	0.04	2.36	2.28
Am-048	3.67	1.08	41793	84175	0.08	0.26	3.35	1.66
Am-049	1.69	0.82	56110	113027	0.12	0.26	3.12	1.55
Am-050	3.5	1.12	48800	98301	0.07	0.21	3.49	1.73
Am-053	3.41	1.08	42755	93351	0.08	0.25	3.59	1.65
Am-054	2.71	0.94	28181	98036	0.09	0.25	6.10	1.75
Am-055	3.35	1.07	-	69348	0.08	0.24	-	2.42

Table 8.3.2.2. Benchmarks calculated for the base run and each retrospective run.

Run	$F_{15\%}$	$F_{30\%}$	$FEC_{15\%}$	$FEC_{30\%}$
Base run	3.41	1.07	45889	92444
Retrospective 2012	3.06	0.97	47236	95152
Retrospective 2011	2.65	0.93	48270	97249
Retrospective 2010	3.05	0.99	48490	97655
Retrospective 2009	3.8	1.1	48224	97132

2014 Atlantic Menhaden Benchmark Stock Assessment Figures

Figure 3.3.1. Uncorrected and corrected values of ***L***$_\infty$ and ***K*** estimated for cohort-based, annual von Bertalanffy curves.

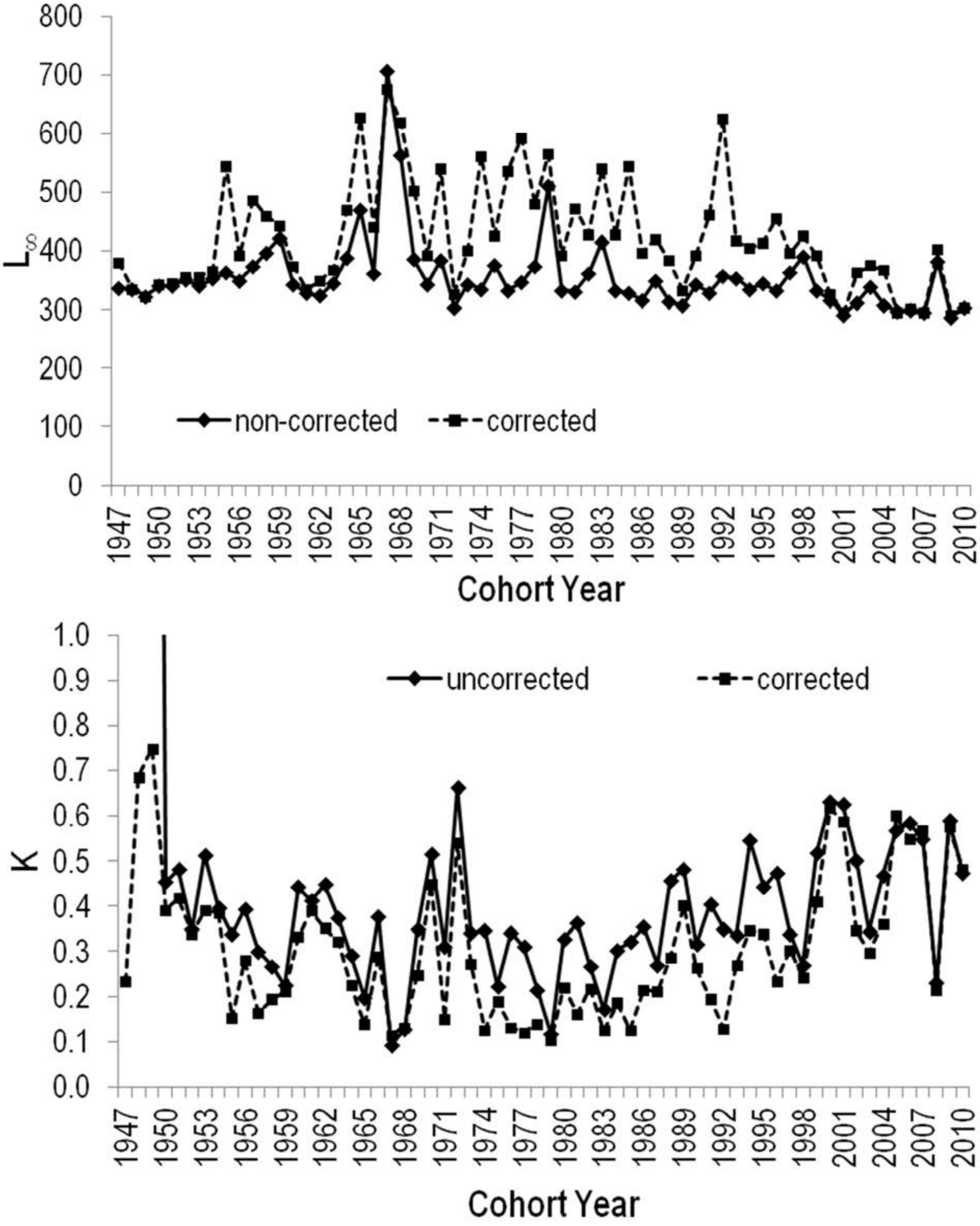


Figure 3.6.1. Annual calculated values of ***M*** from age-constant ***M*** approaches and average ***M*** across ages 1-10 (constant for ages 6+) of MSVPA-X.

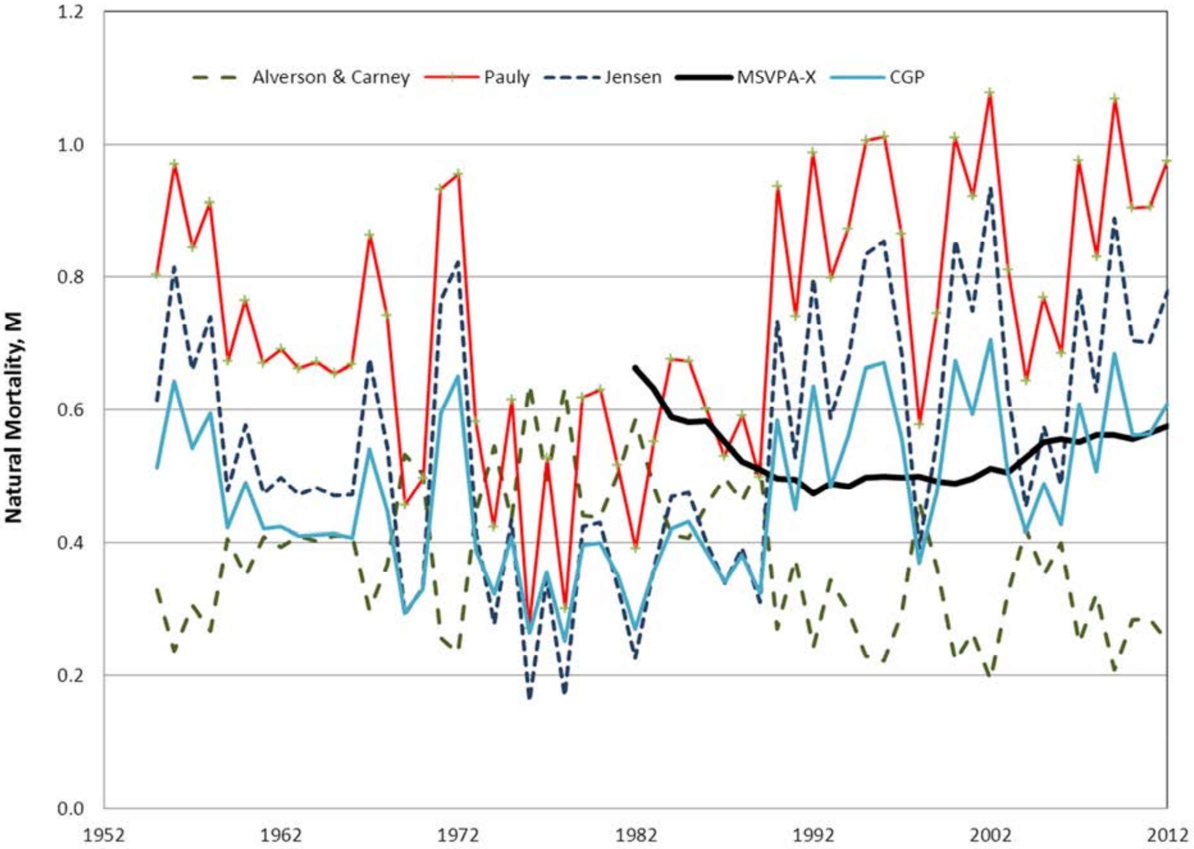


Figure 3.6.2. Age-varying estimates of ***M*** averaged across all available years for three age-varying methods based on weight at age (B&D=Boudreau & Dickie, P&W=Peterson & Wroblewski, L=Lorenzen, and CGP=Charnov) and MSVPA-X.

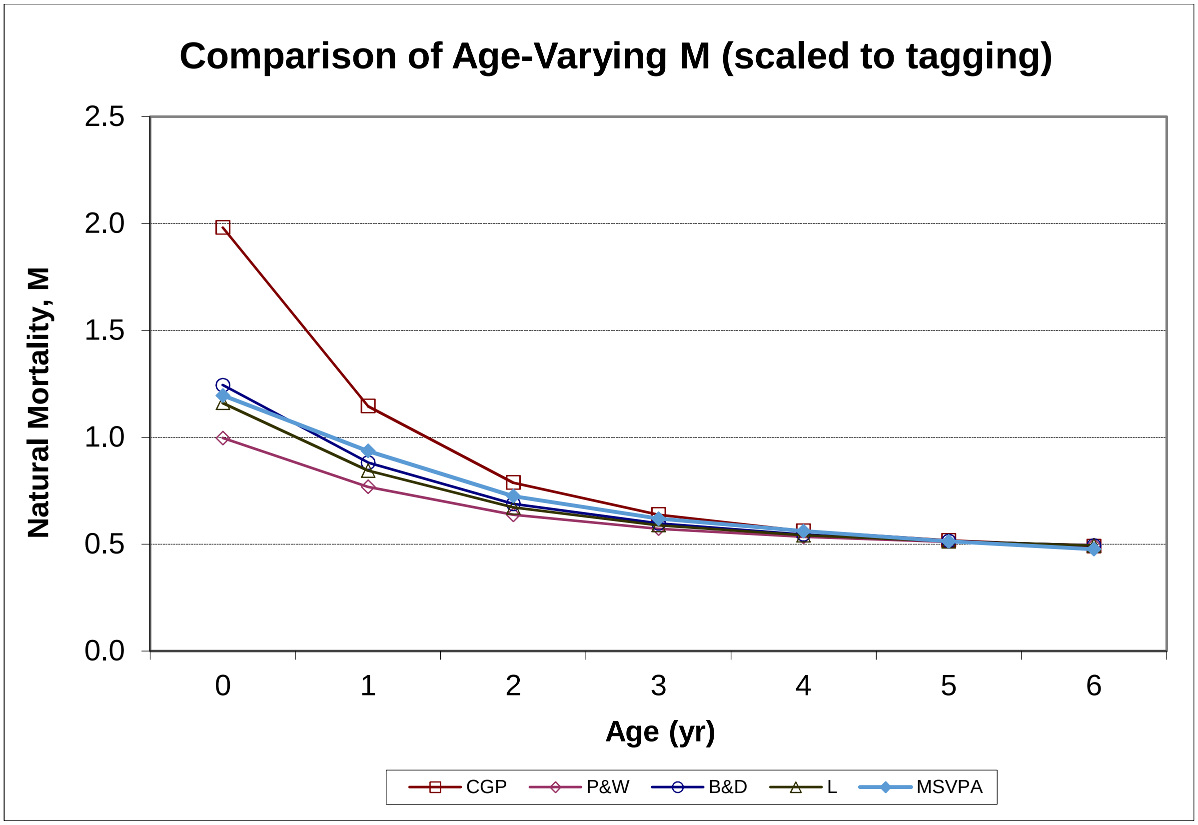


Figure 3.6.3. Different potential scalings for MSVPA-X age-varying ***M***.

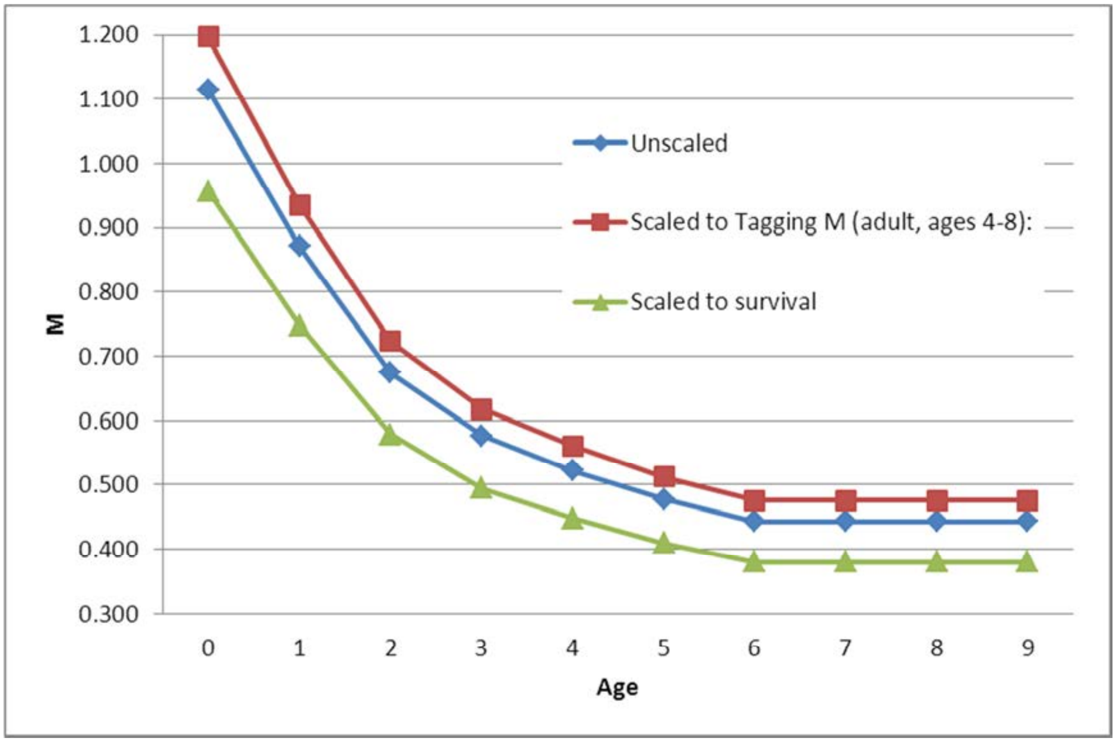


Figure 3.6.4. Comparison of several age-varying methods for estimating ***M*** scaled to average ***M*** over ages.

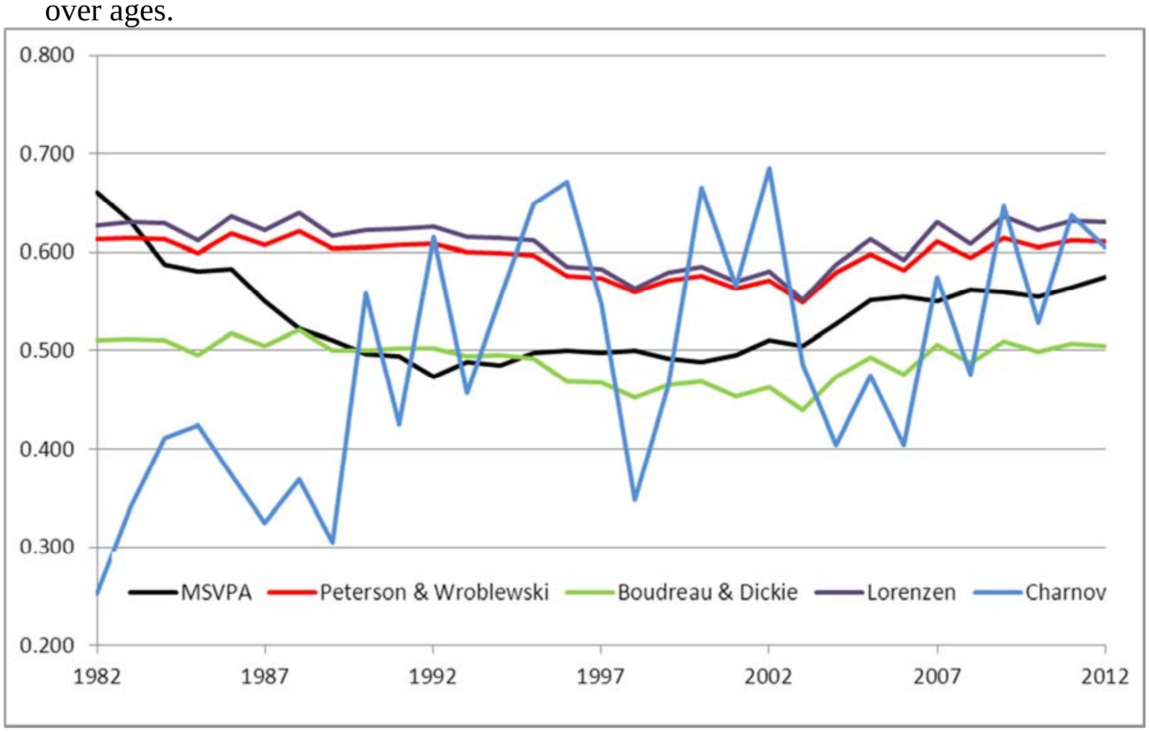


Figure 4.1.1. Landings (in thousands of metric tons) and nominal fishing effort (in vessel-weeks) for the reduction purse-seine fishery, 1940-2013.

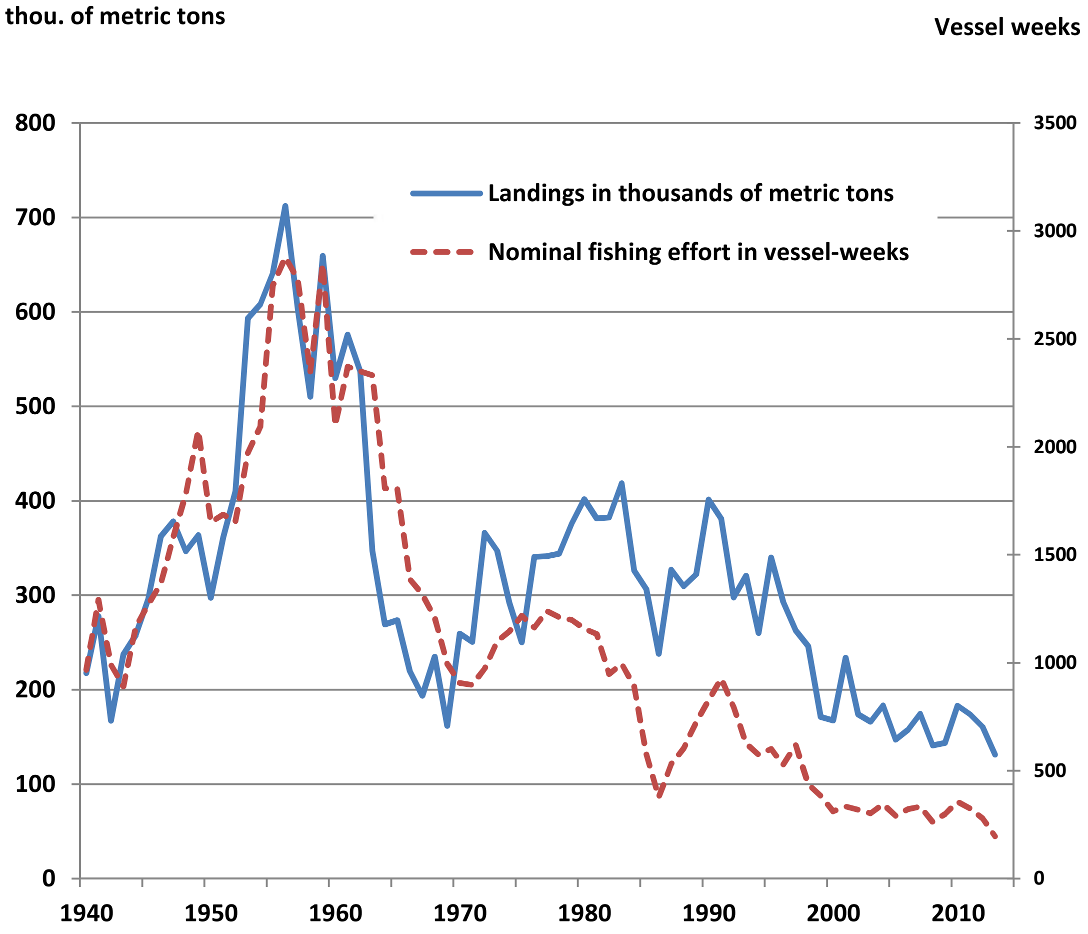
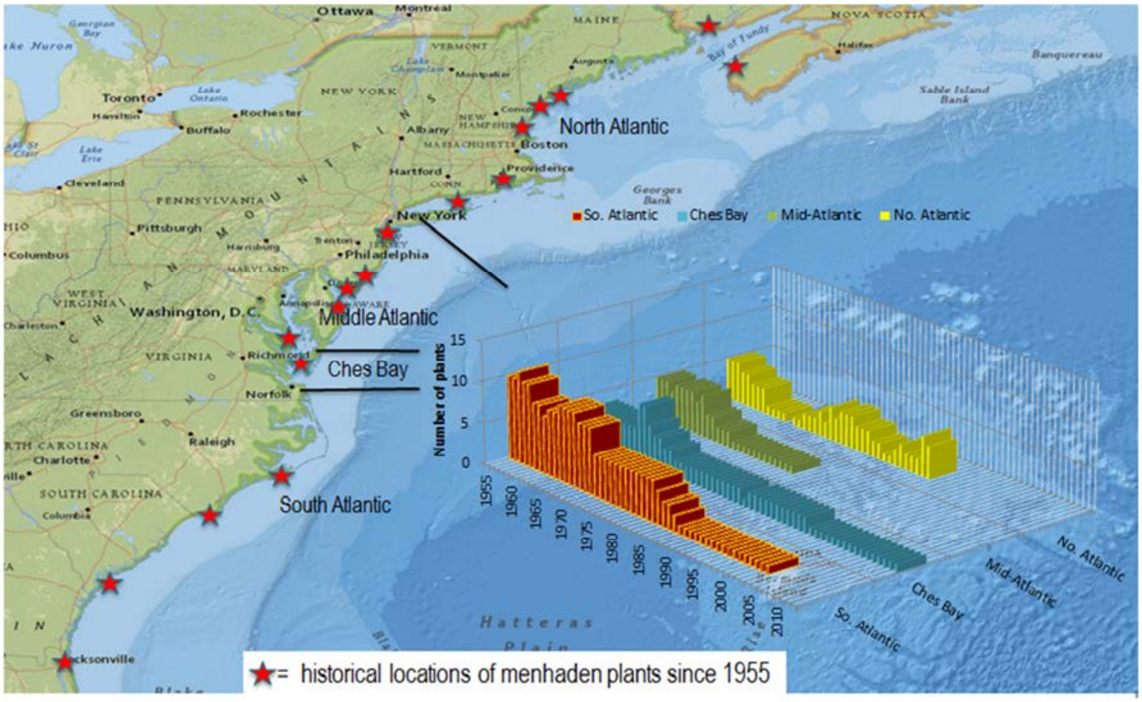


Figure 4.1.2: Top) NMFS statistical reporting areas for the Atlantic menhaden fishery, historical locations of menhaden plants, and number of plants by area, 1955-2013 [note that line between Middle Atlantic and Chesapeake Bay areas defines north versus south regions for the BAM fleets as areas model]; Bottom) stacked chart of number of menhaden plants by area and year, 1955-2013.



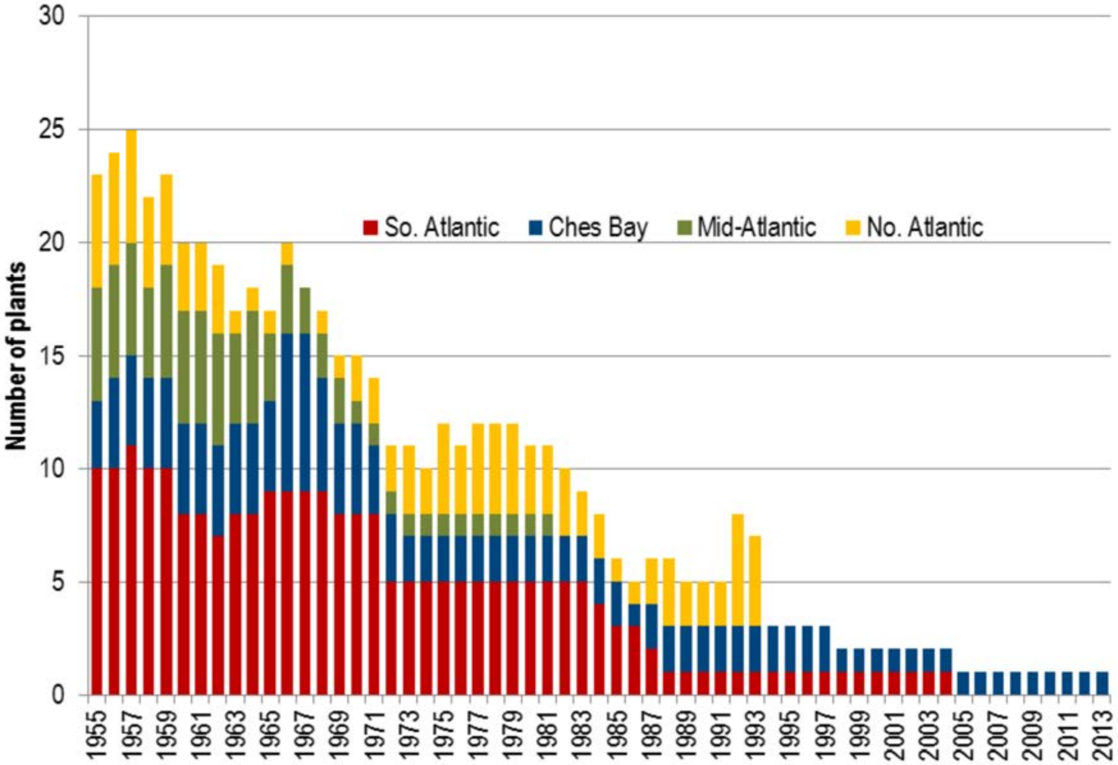


Figure 4.1.3.4.1. Locations of all purse-seine sets by Omega Protein vessels (red) and last sets of trips that were sampled for age and size composition of the catch (= port samples; green) during 2011; data are from CDFR data base.

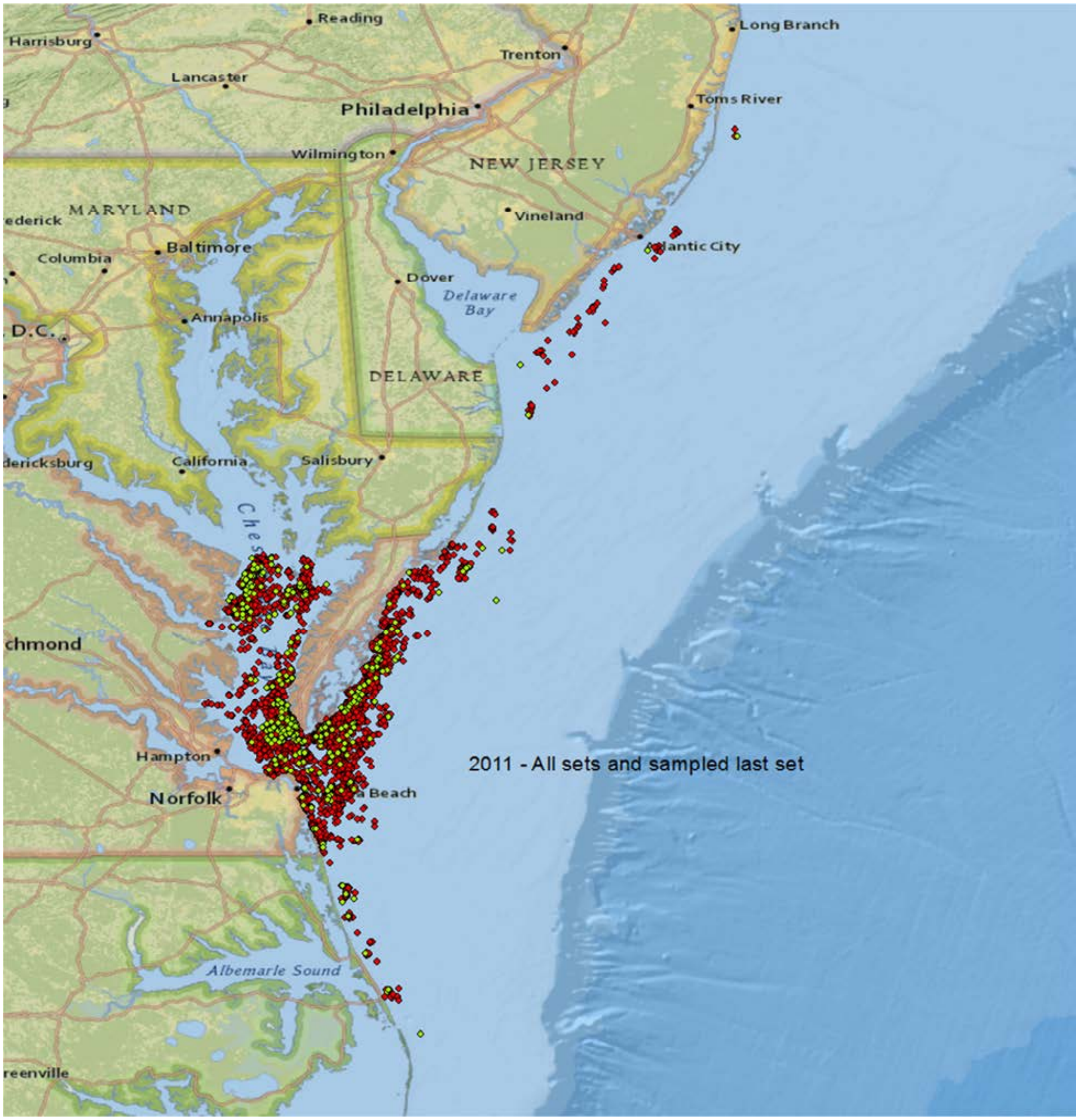


Figure 4.1.3.4.2. Locations of all purse-seine sets by Omega Protein vessels (red) and last sets of trips that were sampled for age and size composition of the catch (= port samples; green) during 2012; data are from CDFR data base.

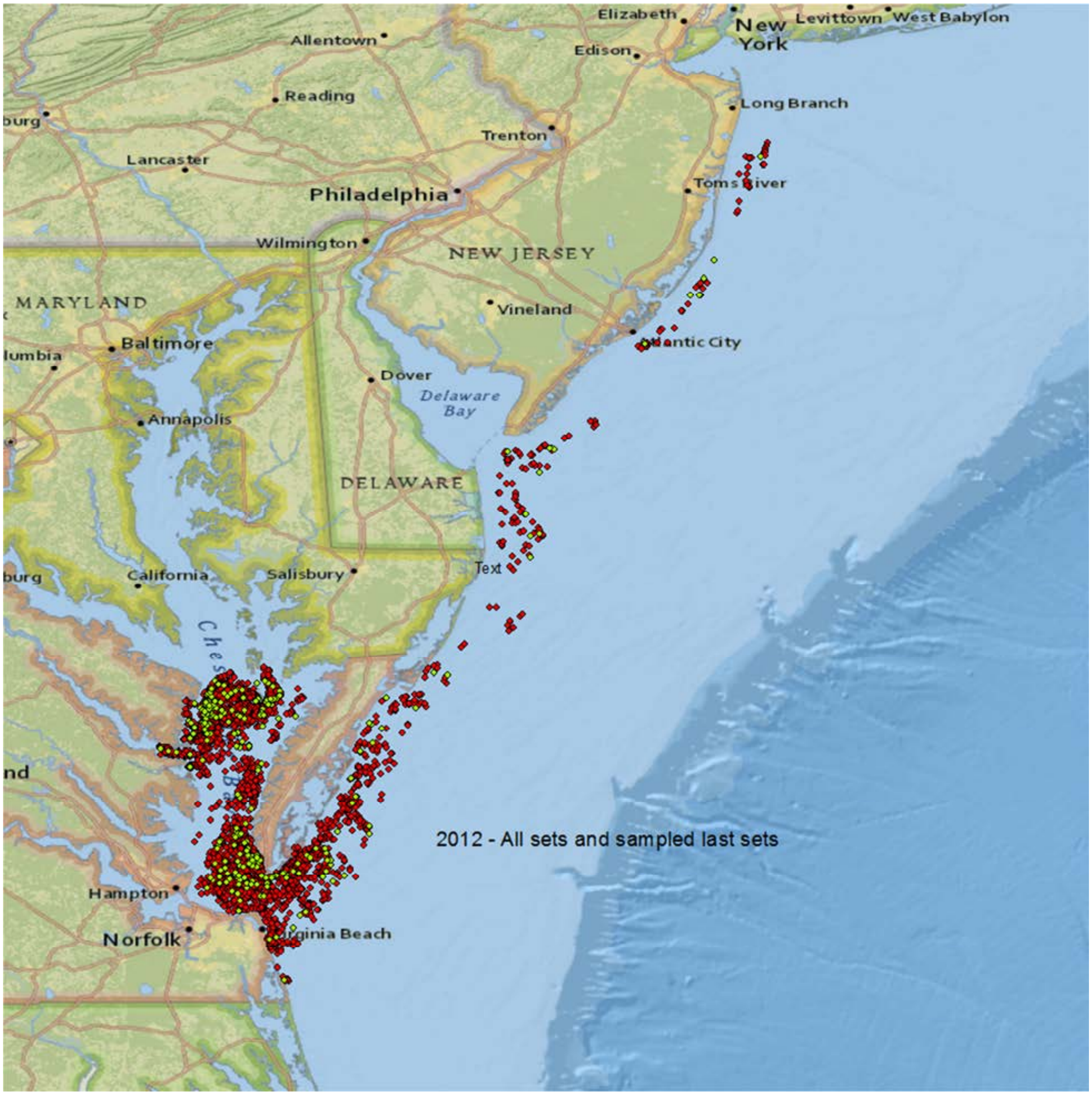


Figure 4.1.3.4.3. Locations of all purse-seine sets by Omega Protein vessels (red) and last sets of trips that were sampled for age and size composition of the catch (= port samples; green) during 2013; data are from CDFR data base.

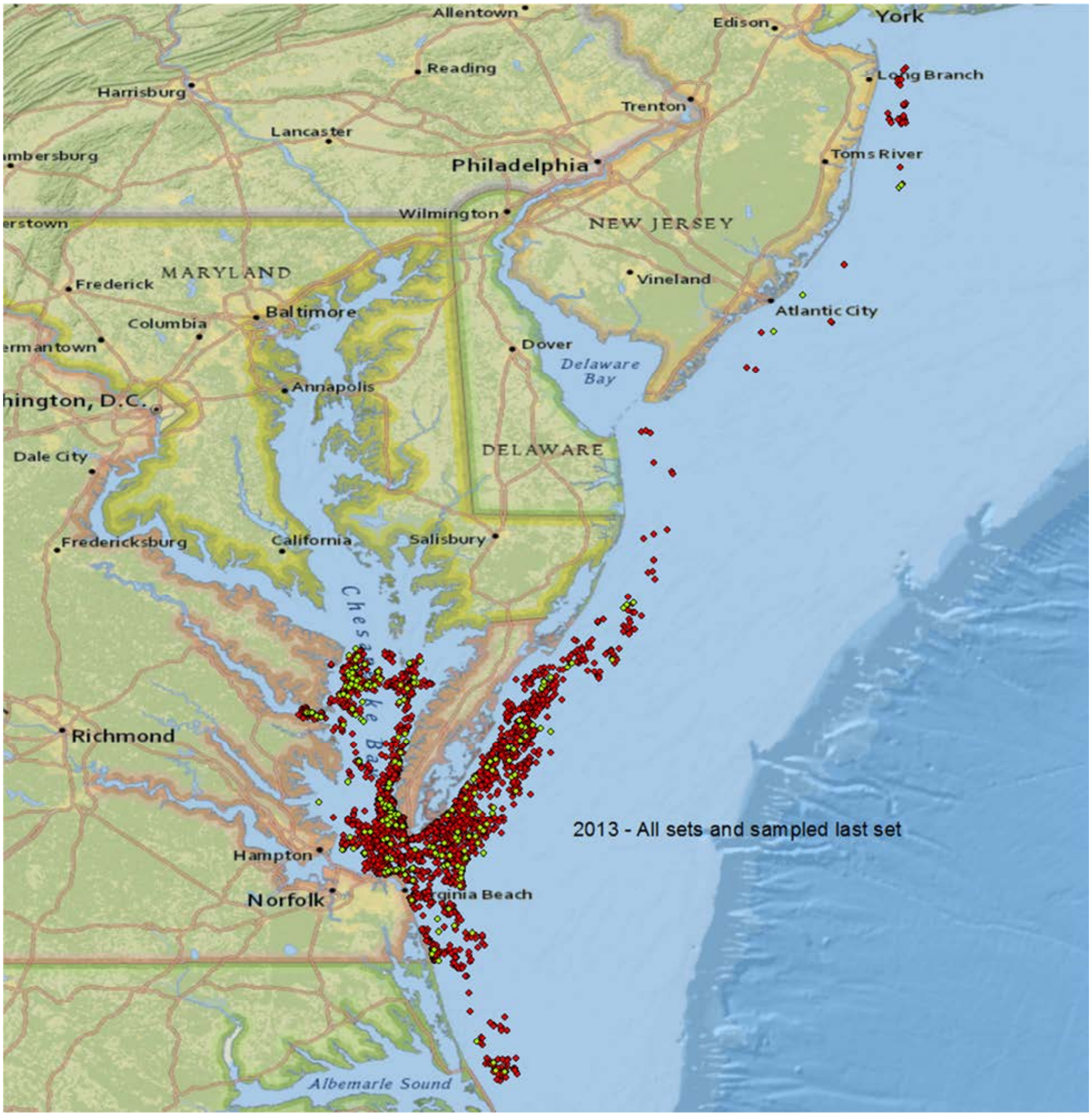


Figure 4.1.3.4.4. Scatterplot of mean fork length (mm) of Atlantic menhaden in the port samples: reduction fishery on left with smaller plant number being farther north; bait fishery on right with larger plant number being farther north.

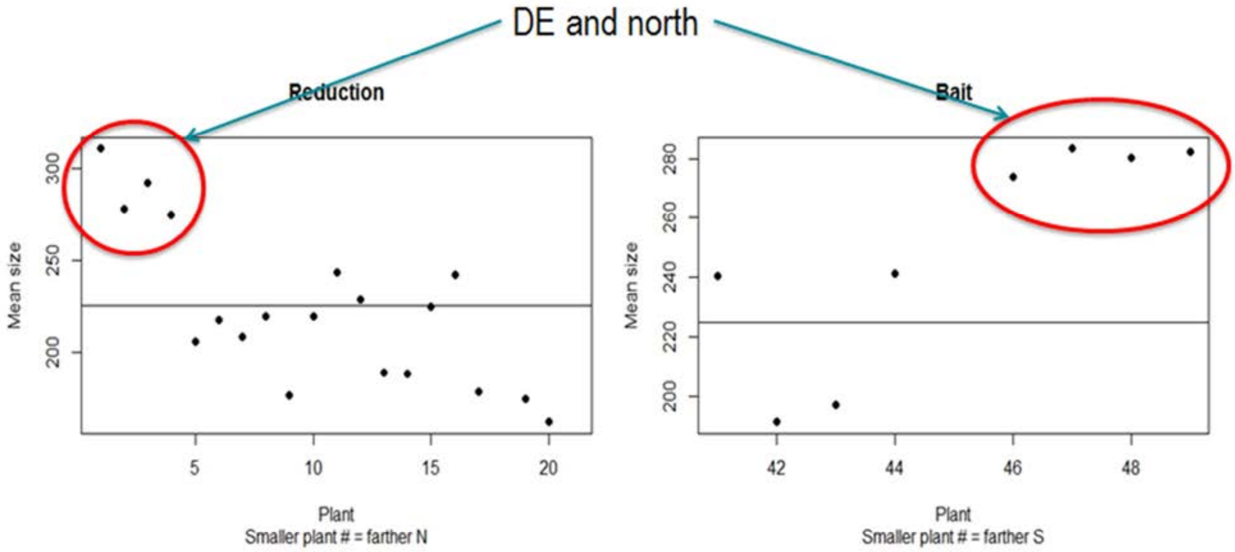


Figure 4.1.4.1. Scatterplot, trend line, and regression of Atlantic menhaden landings (in thousands of metric tons) by purse-seine for reduction on nominal fishing effort (in vessel-weeks), 1940-2013.

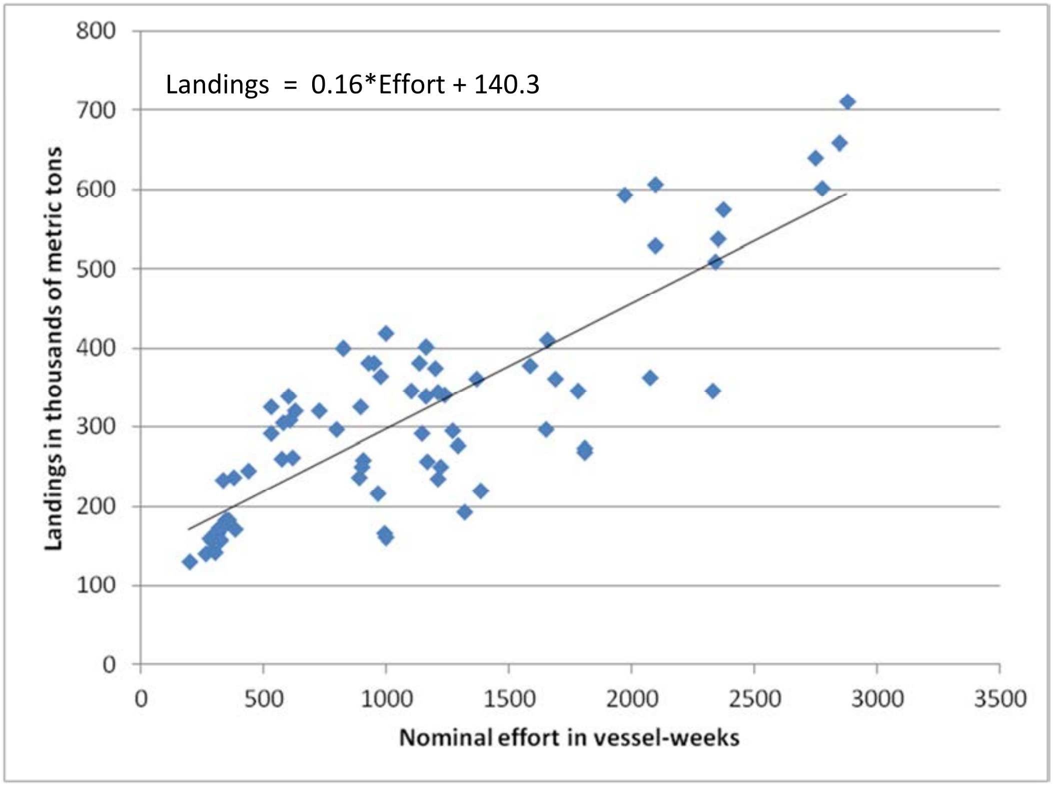


Figure 4.2.2.1. Atlantic menhaden bait landings (in thousands of metric tons) from 1985 to 2013.

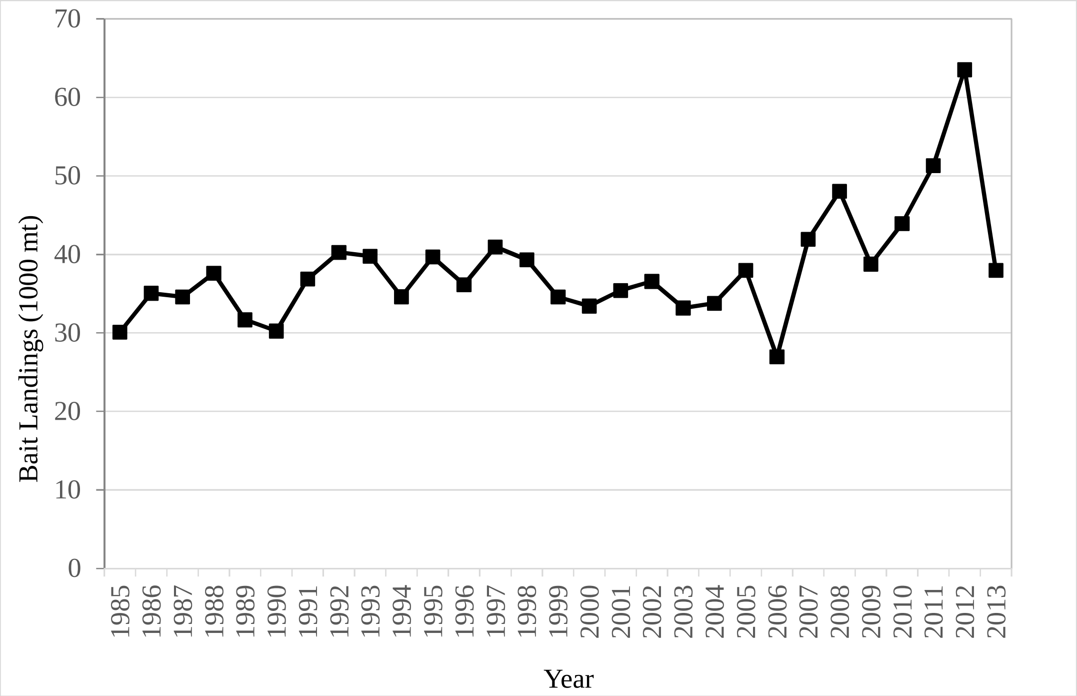


Figure 4.3.2.1. Recreational harvest estimates of Atlantic menhaden for two assessment regions along the Atlantic coast of U.S.

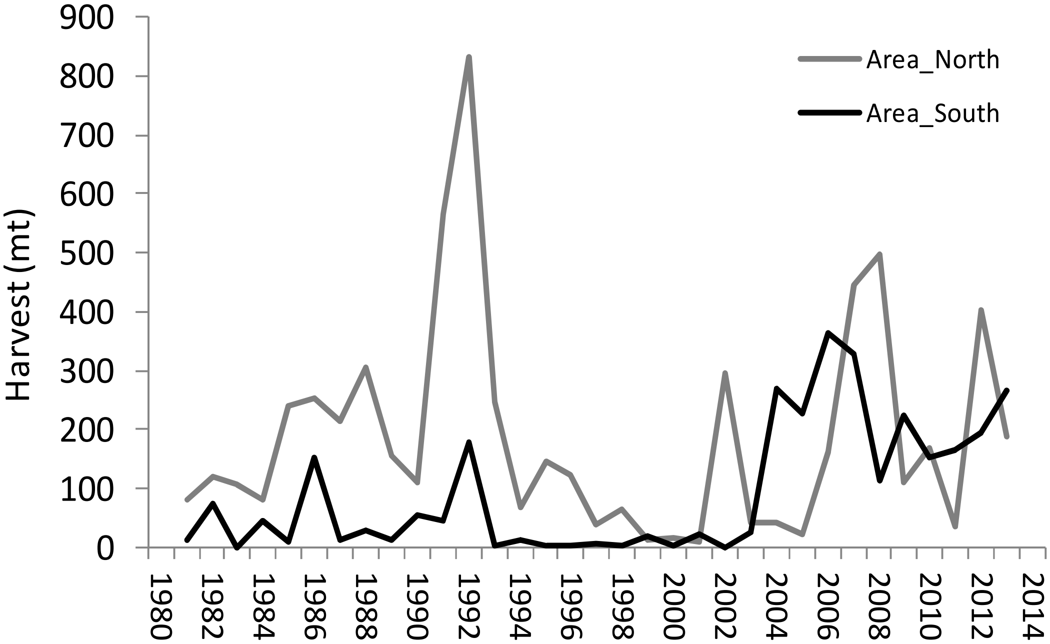


Figure 5.1.1. Map of fishery areas from which fishery-dependent source data were collected.

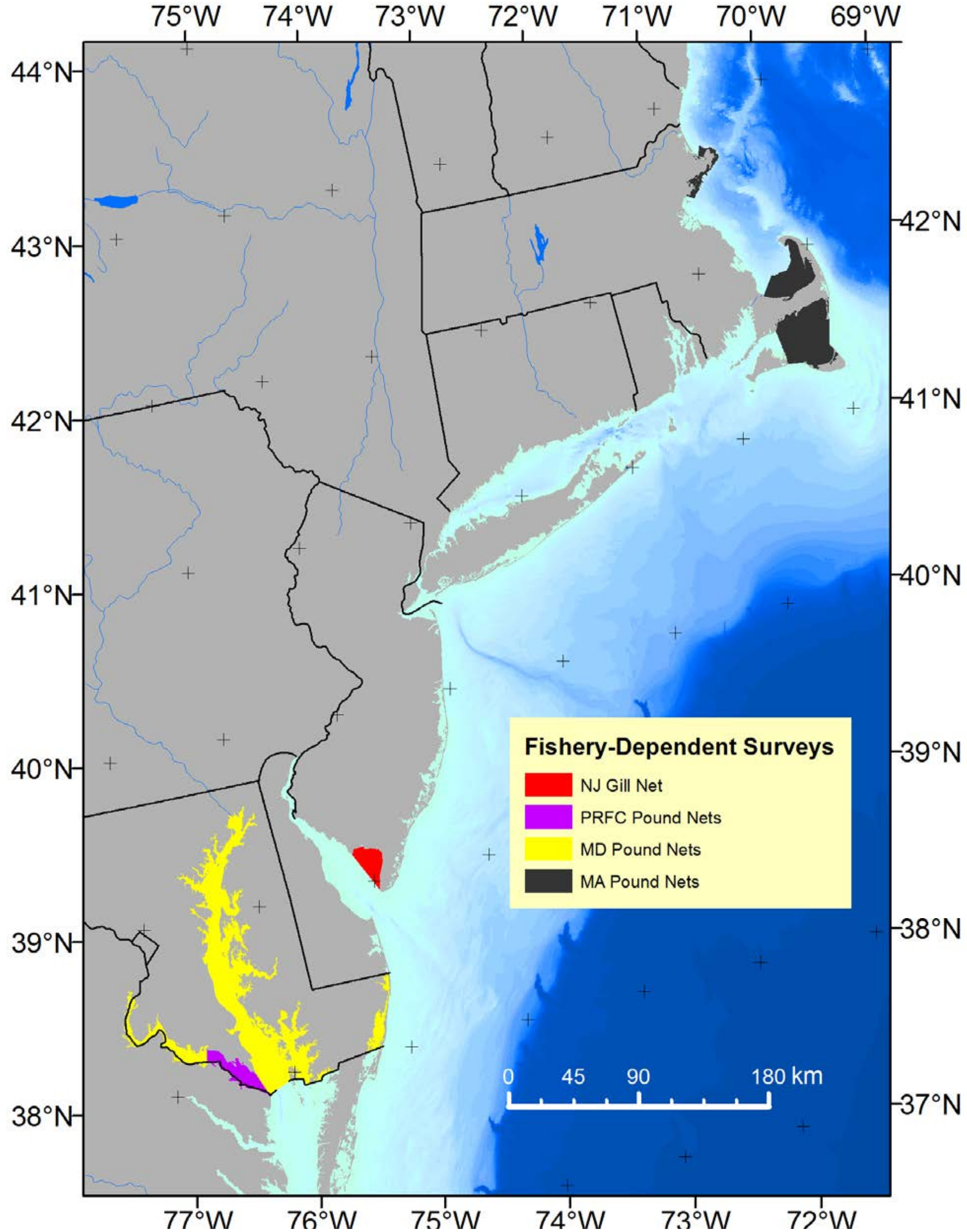


Figure 5.2.1. Map of all fishery independent indices considered for use in the assessment (survey areas highlighted in red).

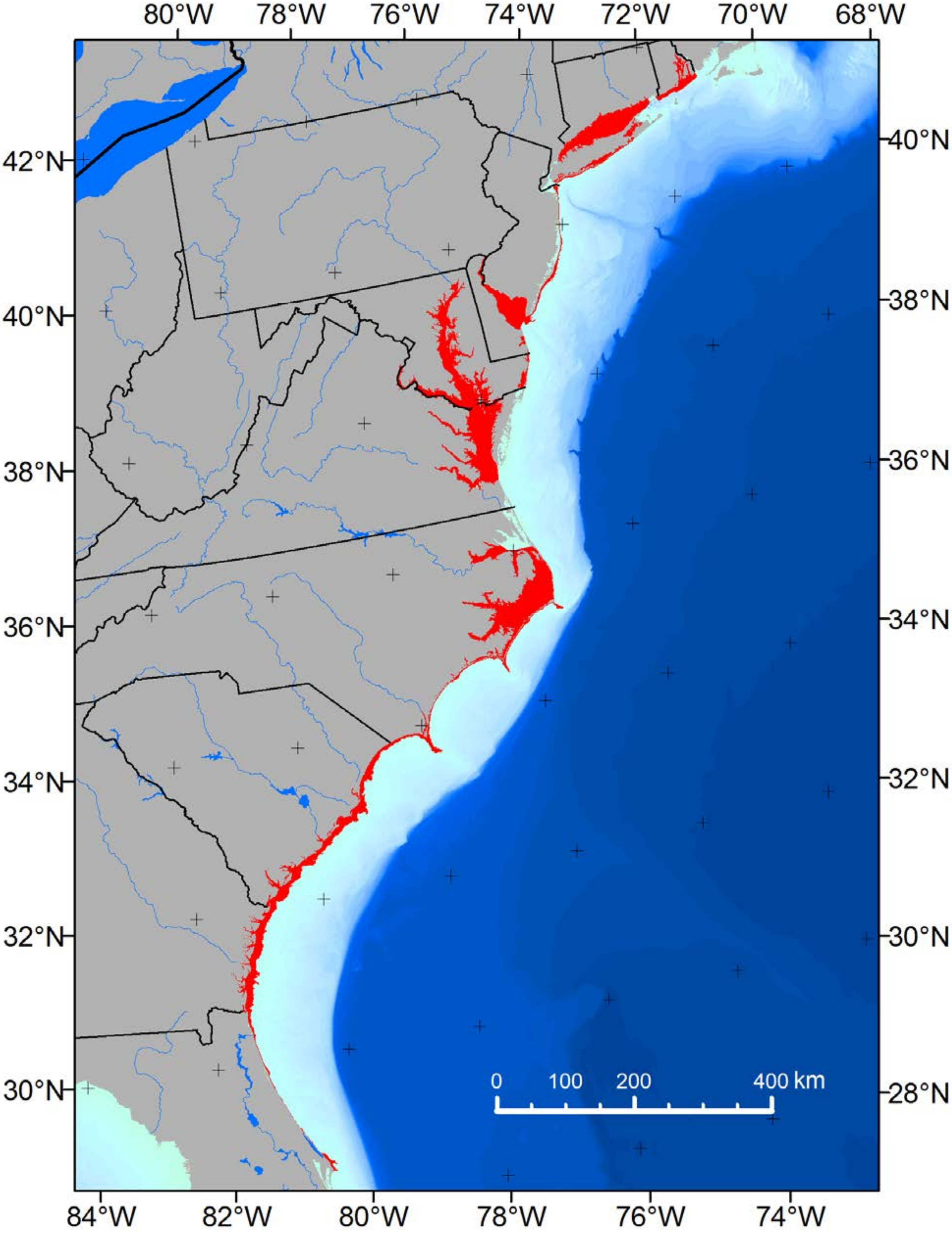


Figure 5.3.1. The four scaled fishery-dependent indices used in the correlation analysis, which includes the Potomac River Fishery Commission pound nets (PRFC), Maryland pound nets (MD pn), Massachusetts pound nets (MA pn), and New Jersey gill nets (NJ gn).

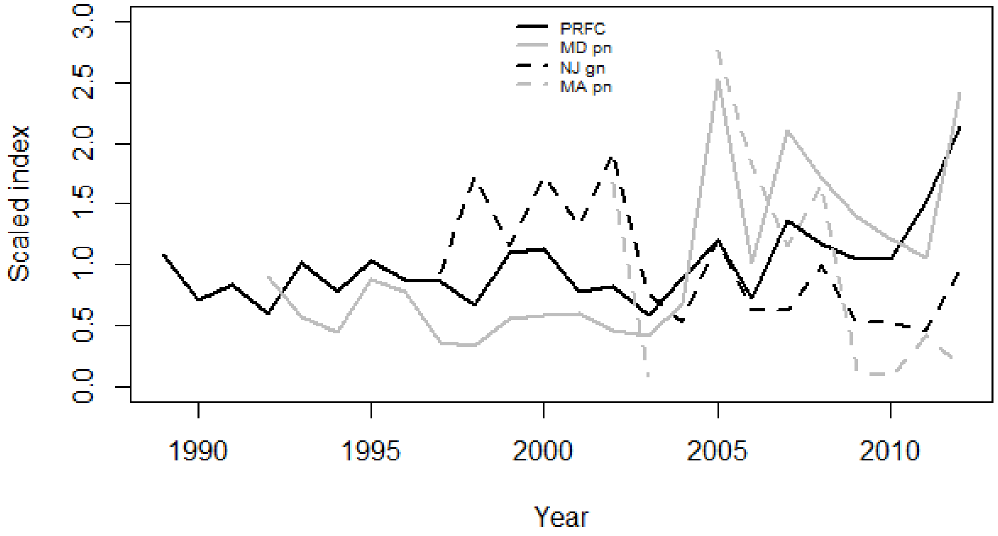


Figure 5.3.2. A significant correlation in the catch rates of adult menhaden was found between the Potomac River Fishery Commission pound net index (PRFC) and the Maryland pound net index (MD pn). The correlation was 0.71 ($p < 0.01$).

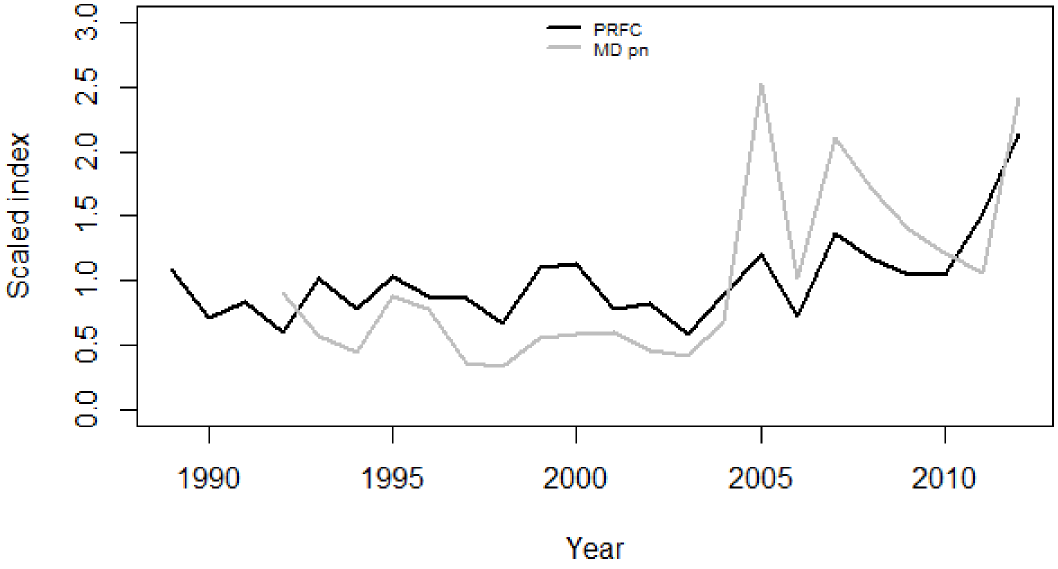


Figure 5.3.3. A significant correlation in YOY abundance was found between the Delaware inland bays trawl survey and the Maryland seine survey. The correlation was 0.66 (p = 0.02).

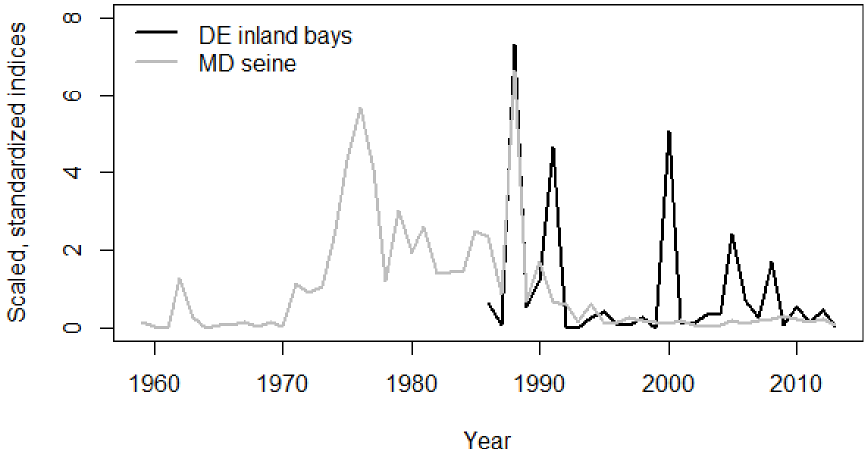


Figure 5.3.4. Significant correlations were found between the Rhode Island trawl survey and the New Jersey trawl survey (correlation = 0.80; p <0.01) and New York seine survey (correlation = 0.83 ; p < 0.01). In addition, there is a correlation of 0.63 with an uncorrected p < 0.01 for the comparison between the New Jersey trawl survey and the New York seine survey.

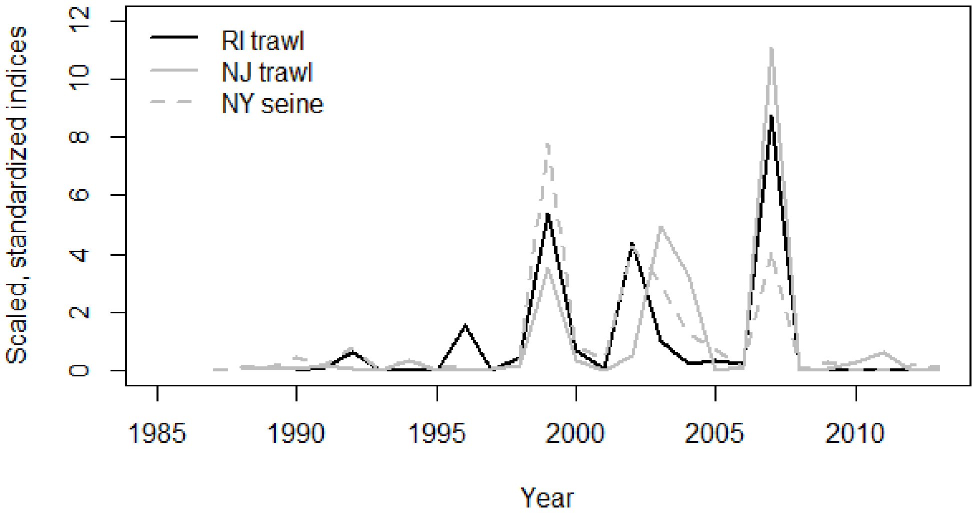


Figure 5.3.5. A significant correlation was found between the Maryland Chesapeake Bay survey and the Virginia seine survey. The correlation was 0.73 (p < 0.01).

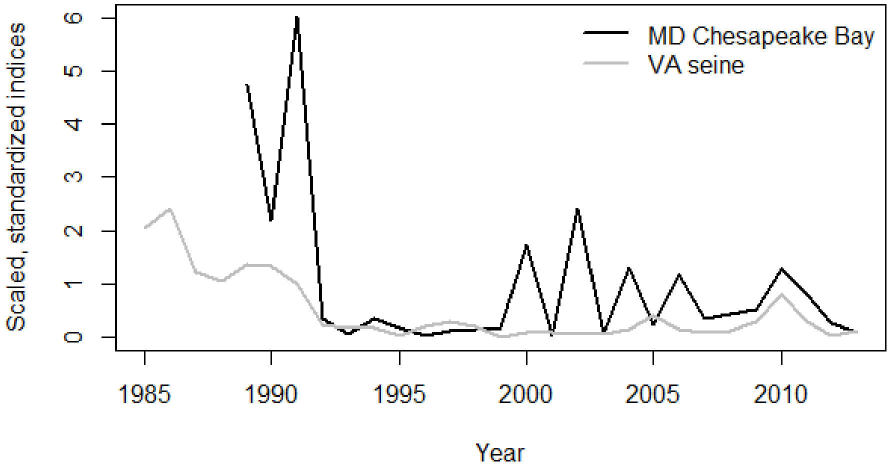


Figure 5.3.6. Significant correlations were found between the Delaware inland bay trawl survey and the Maryland Chesapeake Bay survey (correlation = 0.54; uncorrected p=0.01) and Georgia trawl survey (correlation = 0.60; uncorrected p=0.02).

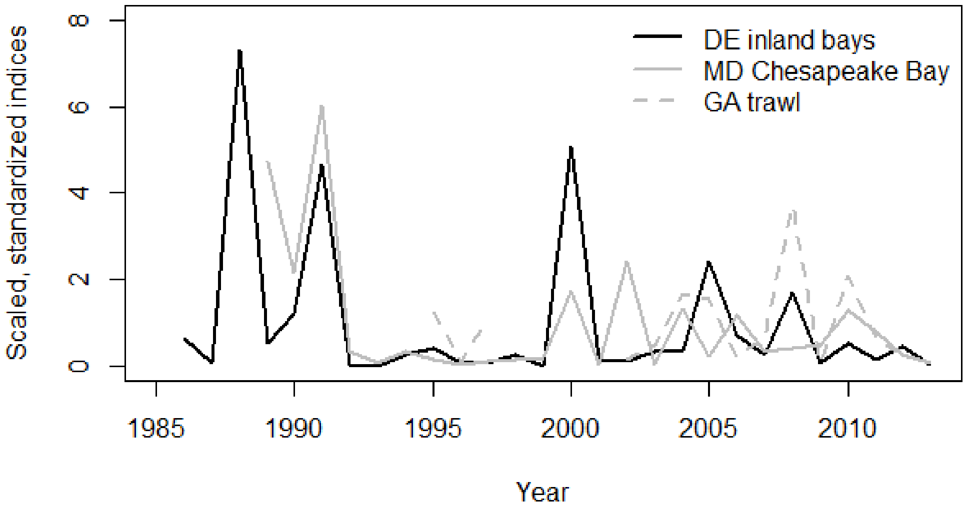


Figure 5.3.7. Significant correlations were found between the Maryland Chesapeake Bay trawl survey and the Connecticut trawl survey (correlation = 0.55; uncorrected p=0.02), Connecticut Thames River seine survey (correlation = 0.55; uncorrected p=0.03), and Maryland seine survey (correlation = 0.45; uncorrected p=0.02).

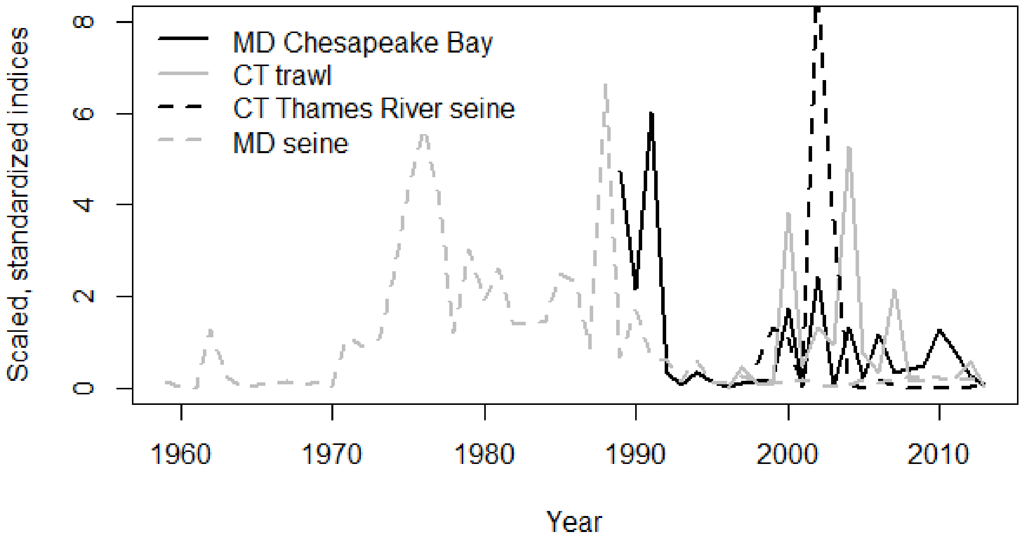


Figure 5.3.8. Significant correlations were found between the Connecticut Thames River seine survey and the Connecticut River seine survey (correlation = 0.74; uncorrected p<0.01); Connecticut River seine survey and New York seine survey (correlation = 0.40; uncorrected p=0.04); and New York seine survey and New Jersey seine survey (correlation = 0.48; uncorrected p=0.01).

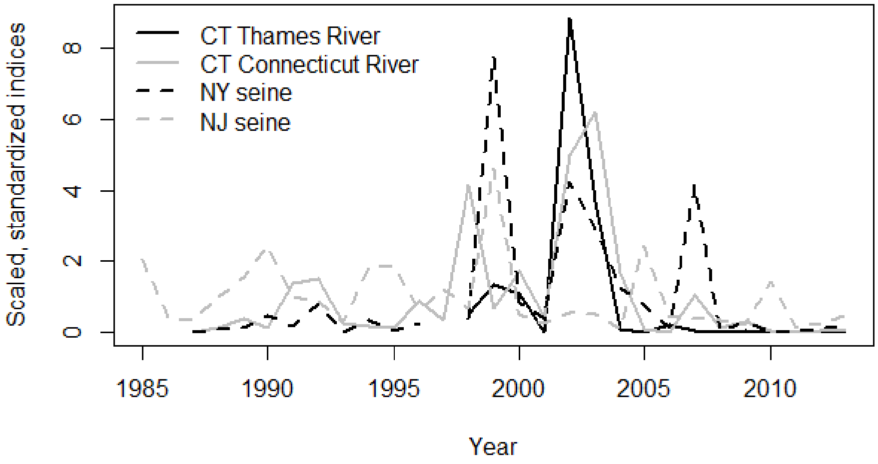


Figure 5.3.9. Significant correlations were found between the Connecticut Thames River seine survey and the Delaware 16ft trawl survey (correlation = 0.76; uncorrected p<0.01), while a correlation was also found between the Delaware 16ft trawl survey and the New York Peconic Bay trawl survey (correlation = 0.63; uncorrected p=0.01).

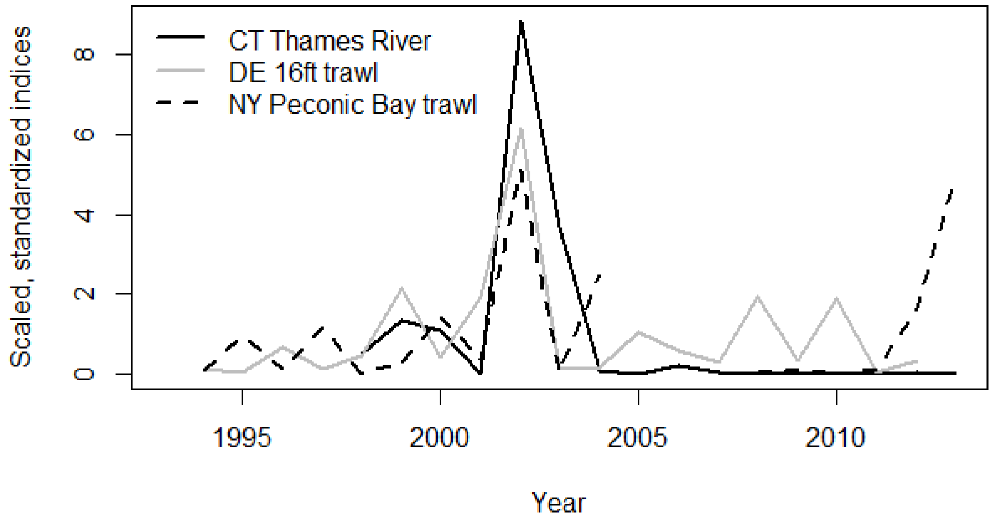


Figure 5.3.10. Significant correlations were found between the Connecticut River seine survey and the South Carolina electrofishing survey (correlation = 0.70; uncorrected p=0.01).

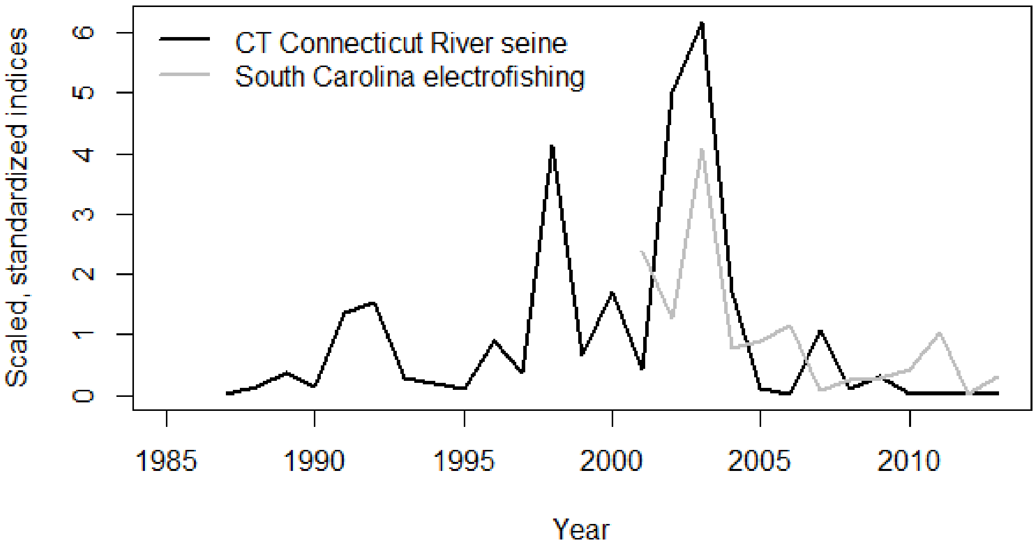


Figure 5.3.11. Significant correlations were found between the VIMS trawl survey and the Delaware 30ft trawl survey (correlation = 0.41; uncorrected p=0.05), SEAMAP (correlation = 0.57; uncorrected p<0.01), and CHESFIMS (correlation = 0.80; uncorrected p<0.01). In addition, a correlation of 0.68 was found between the Delaware 30ft trawl survey and CHESMAP (uncorrected p=0.01).

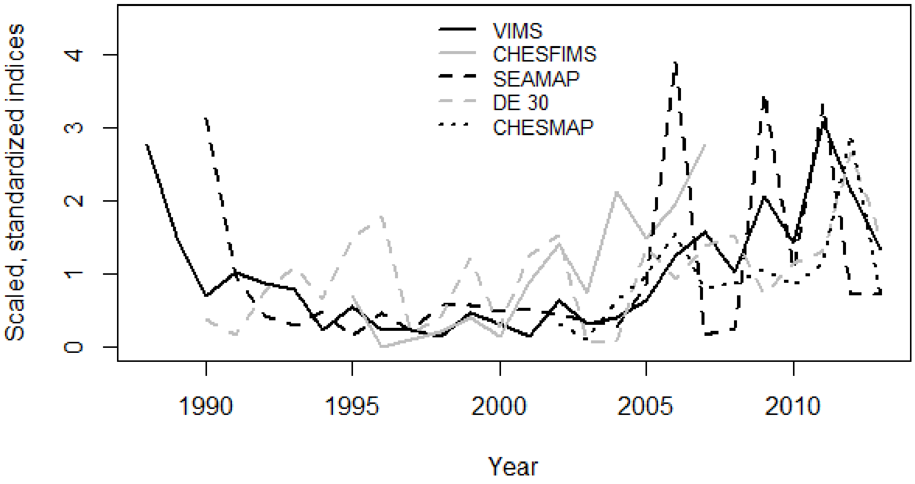


Figure 5.3.12. Significant correlations were found between the Connecticut Long Island Sound Trawl survey and the VIMS trawl survey (correlation = 0.58; uncorrected p = 0.01), the Delaware 30ft trawl survey (correlation = 0.63; uncorrected p < 0.01), CHESMAP (correlation = 0.71; uncorrected p = 0.01), and CHESFIMS (correlation = 0.70; uncorrected p=0.01).

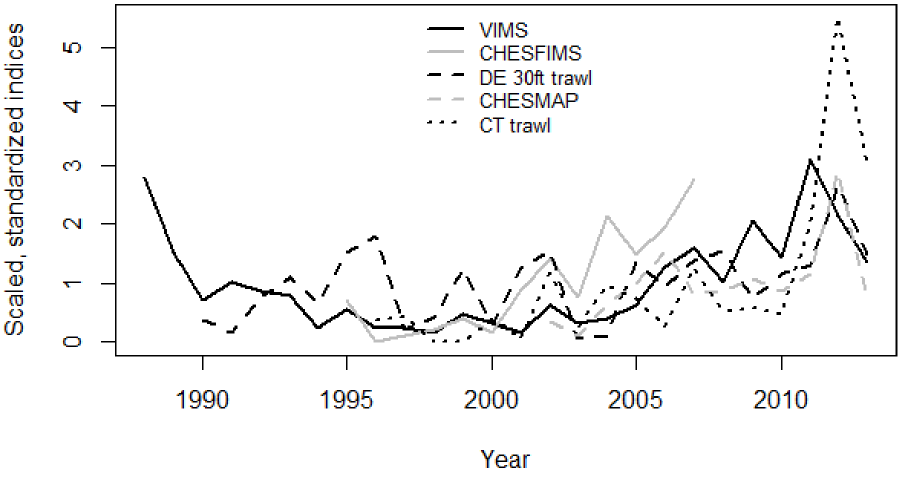


Figure 5.3.13. Significant correlations were found between the Georgia trawl survey and SEAMAP (correlation = 0.90; uncorrected p < 0.01), the North Carolina gill net survey (correlation = 0.73; uncorrected p = 0.01), and the South Carolina trammel net survey (correlation = 0.64; uncorrected p = 0.01). In addition, the North Carolina gill net survey and the South Carolina trammel net survey were correlated at 0.79 (uncorrected p < 0.01).

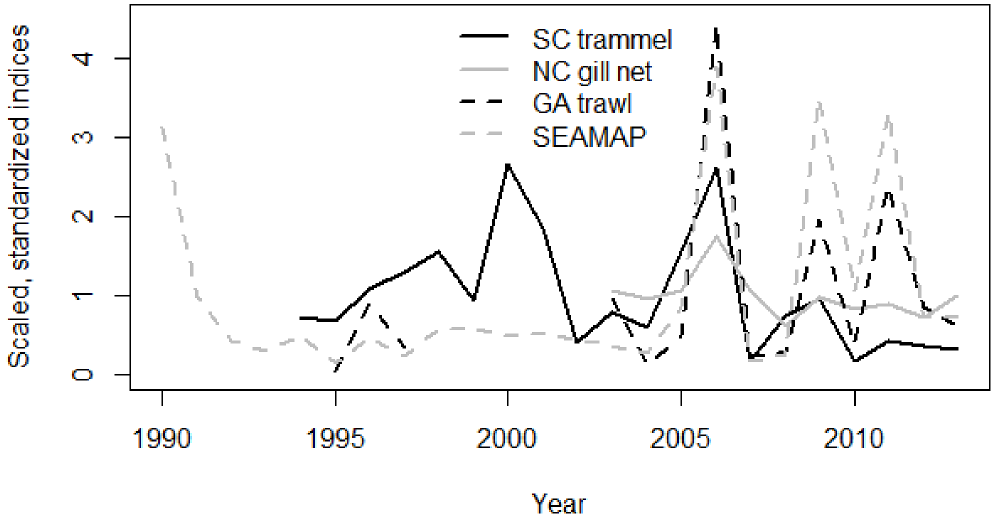


Figure 5.3.14. Significant correlations were found between the New Jersey trawl survey and SEAMAP (correlation = 0.43; uncorrected p = 0.04) and the VIMS trawl survey (correlation = 0.61; uncorrected p < 0.01).

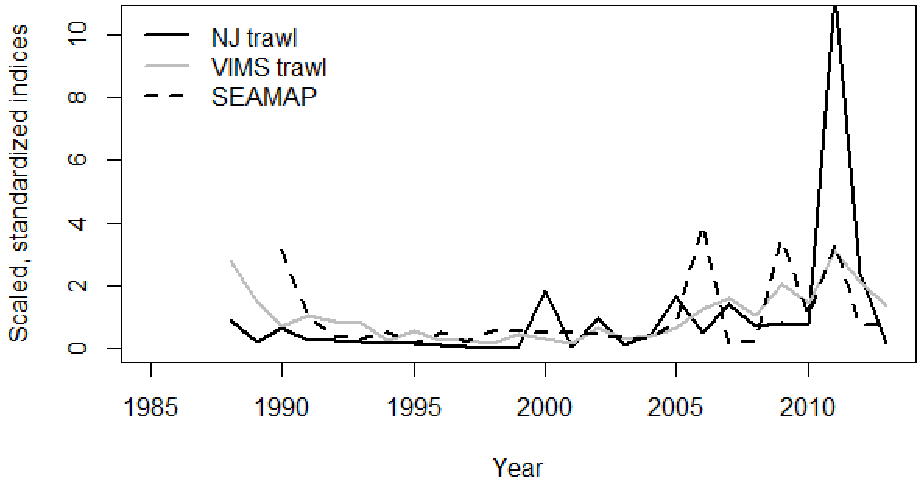


Figure 5.3.15. A significant correlation was found between the Delaware 16 ft trawl survey and CHESFIMS (correlation = 0.75; uncorrected p < 0.01).

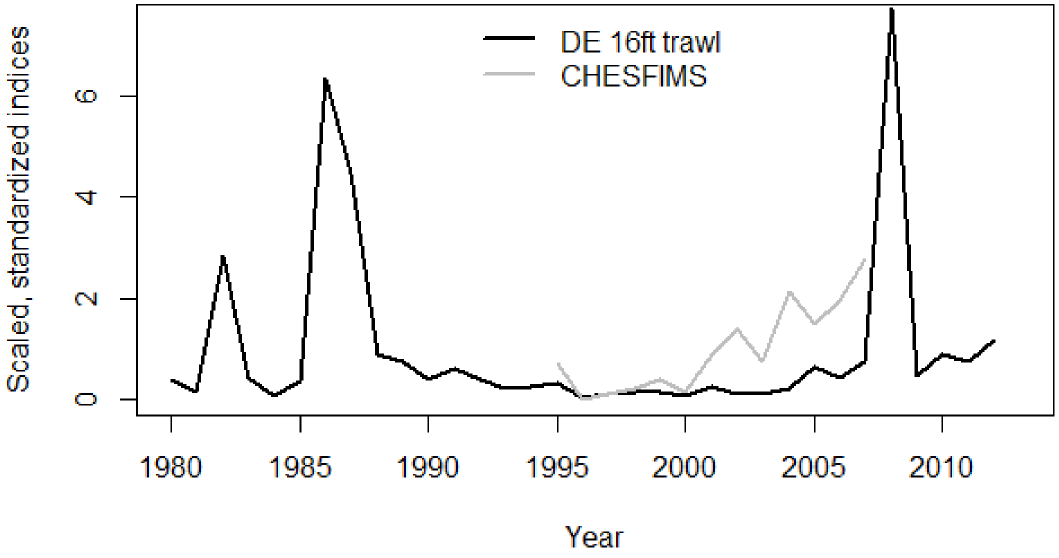


Figure 5.3.16. The observed recruitment or YOY index over time for Atlantic menhaden.

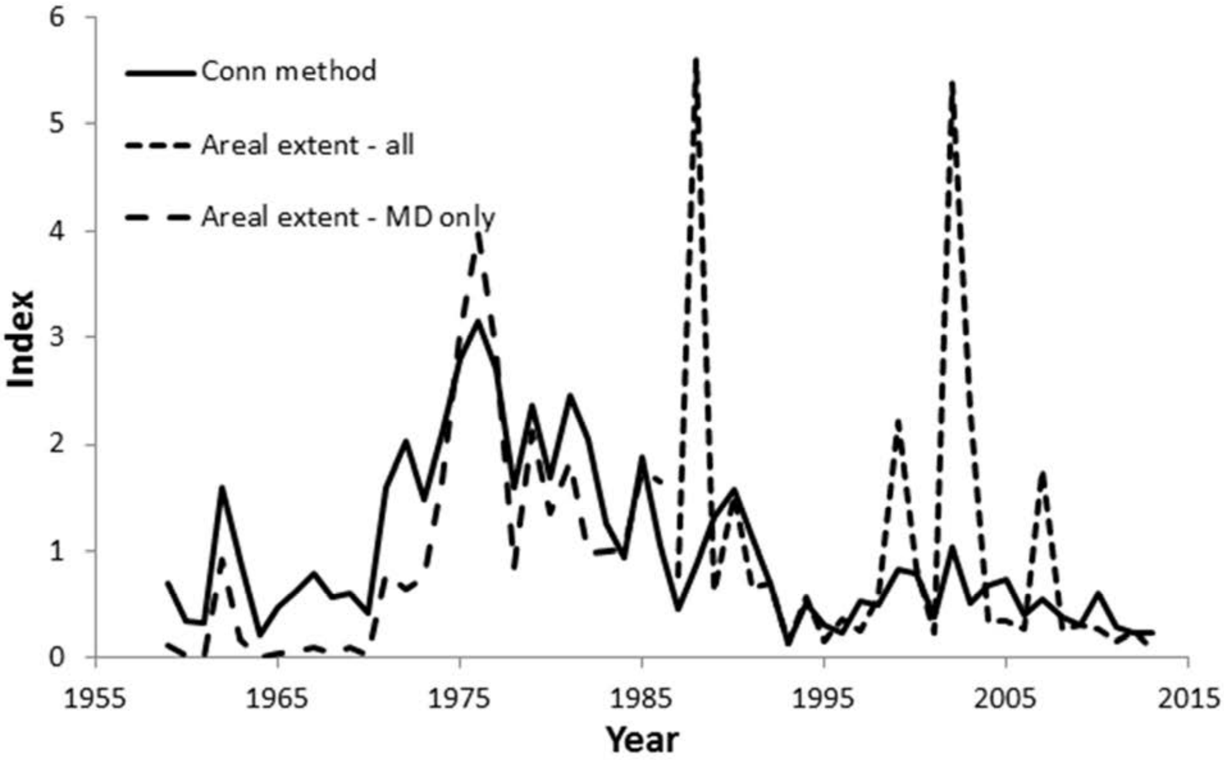


Figure 5.3.17. PCA on the length compositions of the nine different trawl gears.

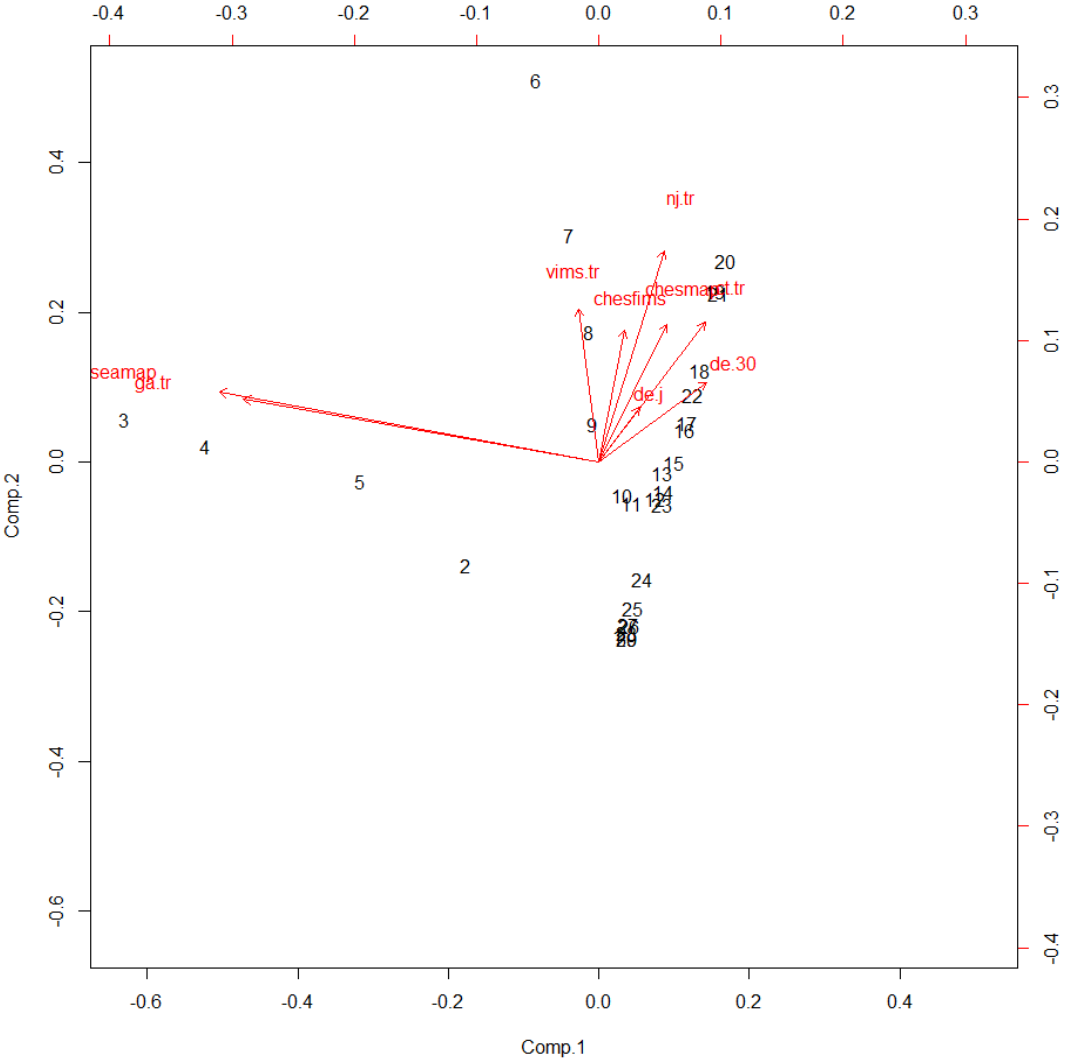


Figure 5.3.18. The observed Northern Adult Index (NAD) and Southern Adult Index (SAD) of abundance for use in the base run of the Atlantic menhaden stock assessment.

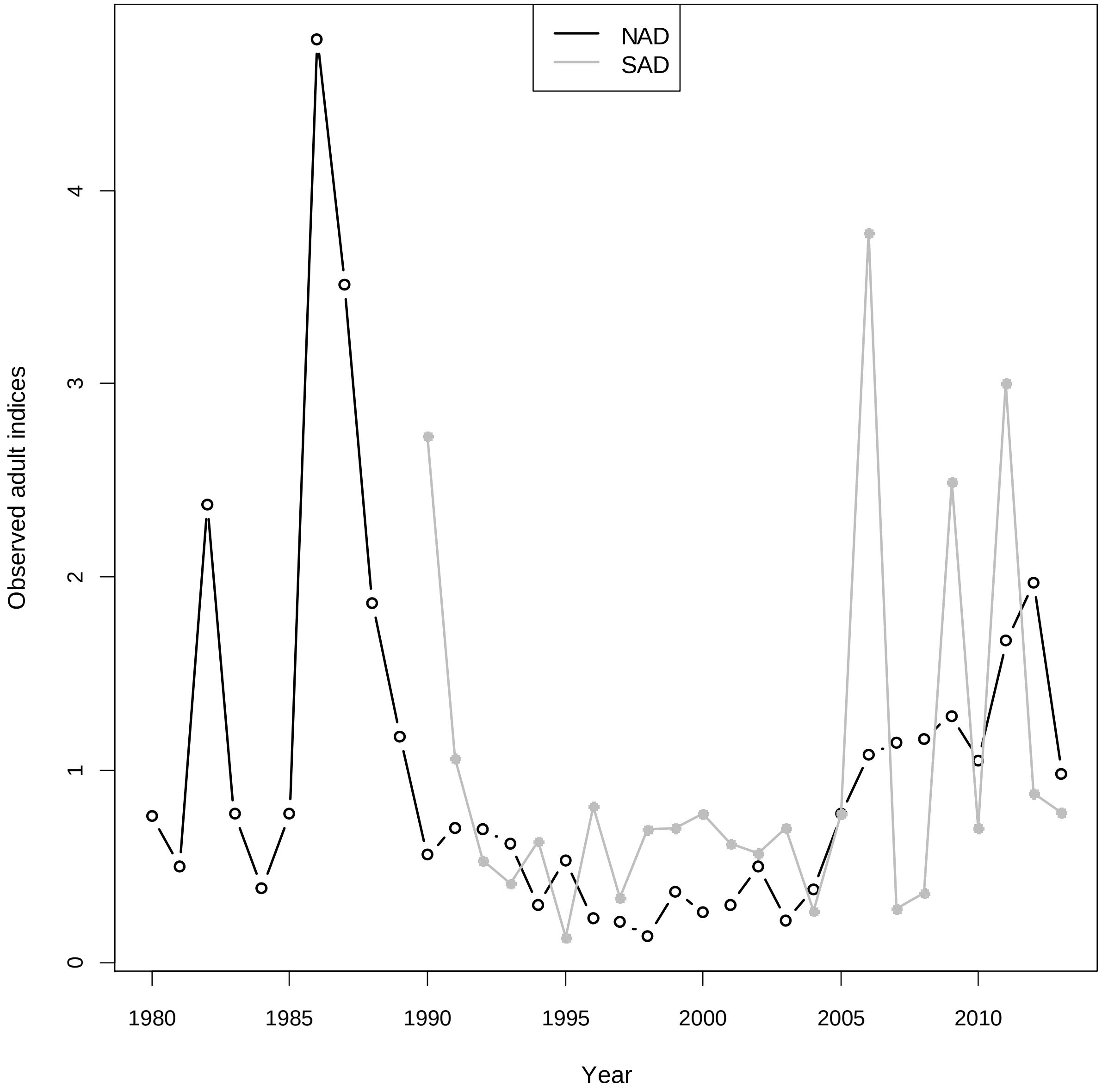
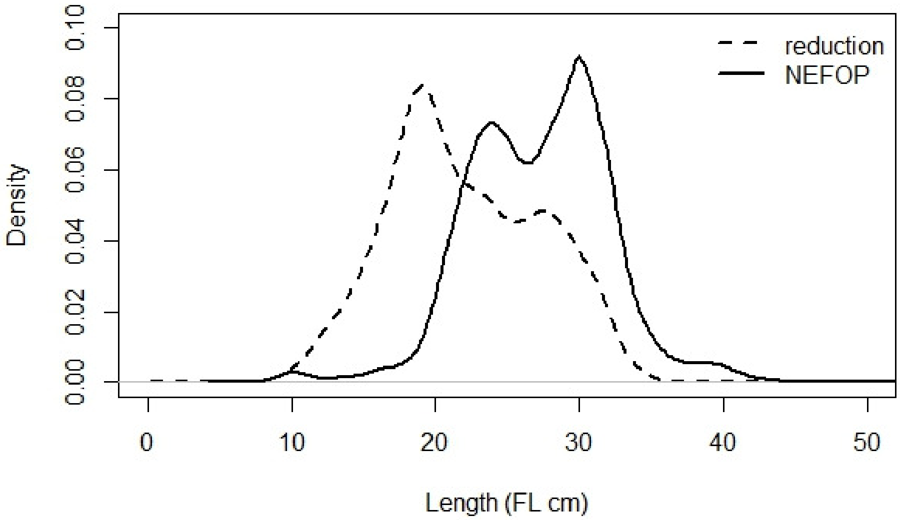


Figure 6.1.1. Comparison of length data from the commercial reduction fishery to the Northeast Fishery Observer Program (NEFOP) for all years of data available (above) and for years of overlapping data only (bottom).



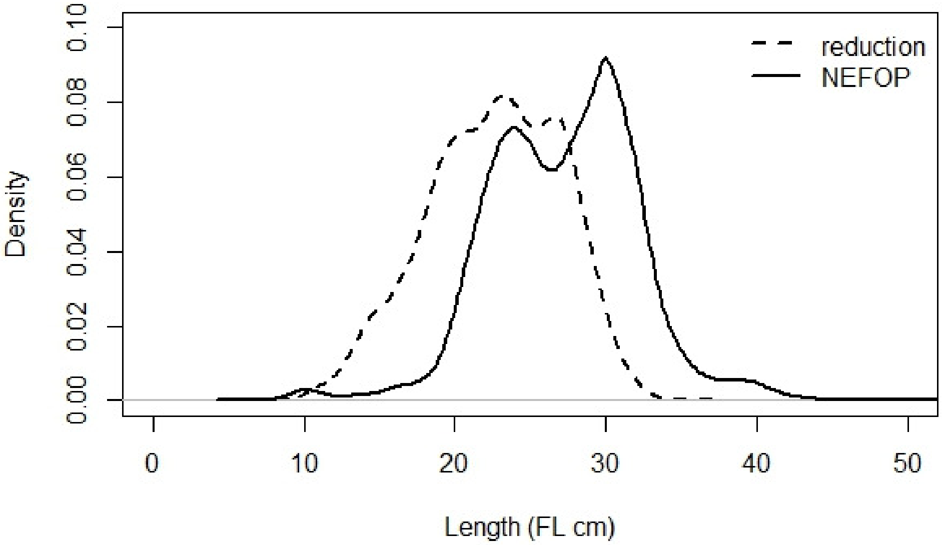
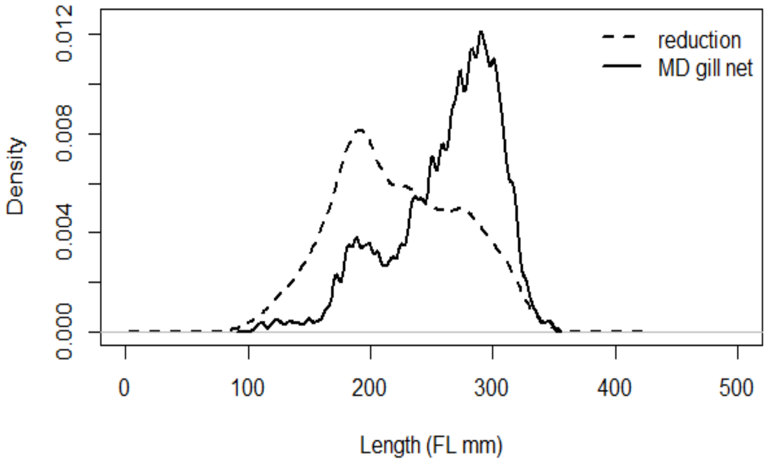


Figure 6.1.2. Comparison of length data from the commercial reduction fishery to the Maryland gill net survey for all years of data available (above) and for years of overlapping data only (bottom).



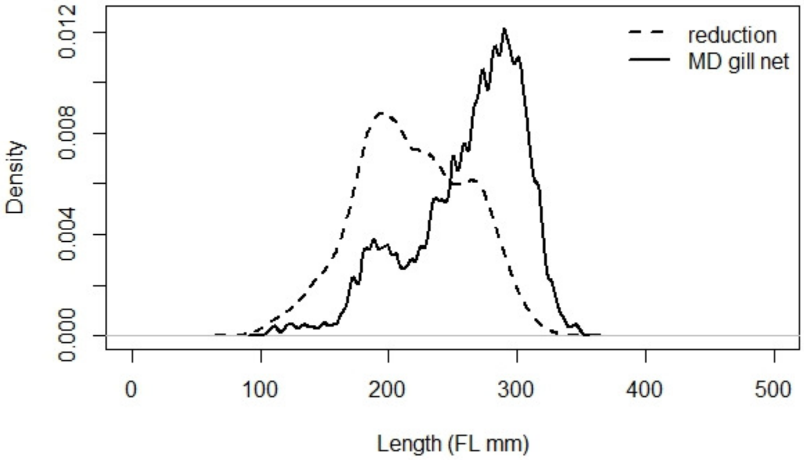
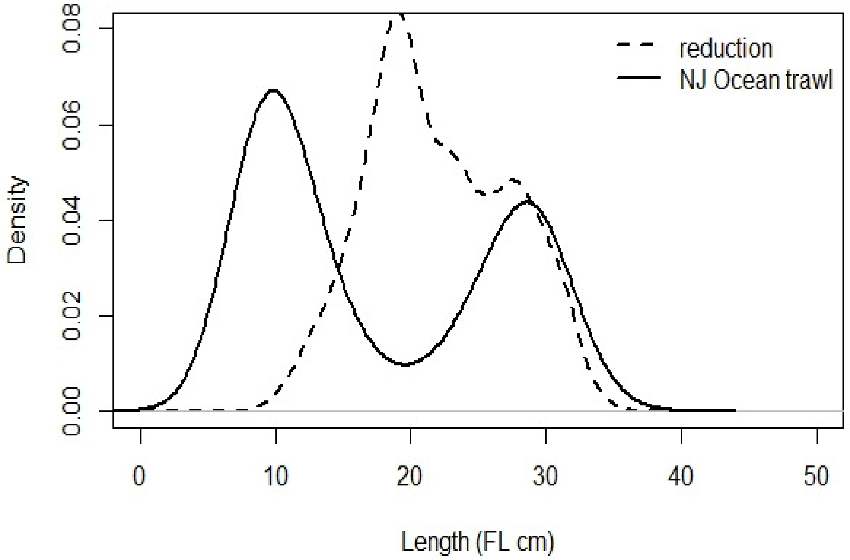


Figure 6.1.3. Comparison of length data from the commercial reduction fishery to the New Jersey ocean trawl survey for all years of data available (above) and for years of overlapping data only (bottom).



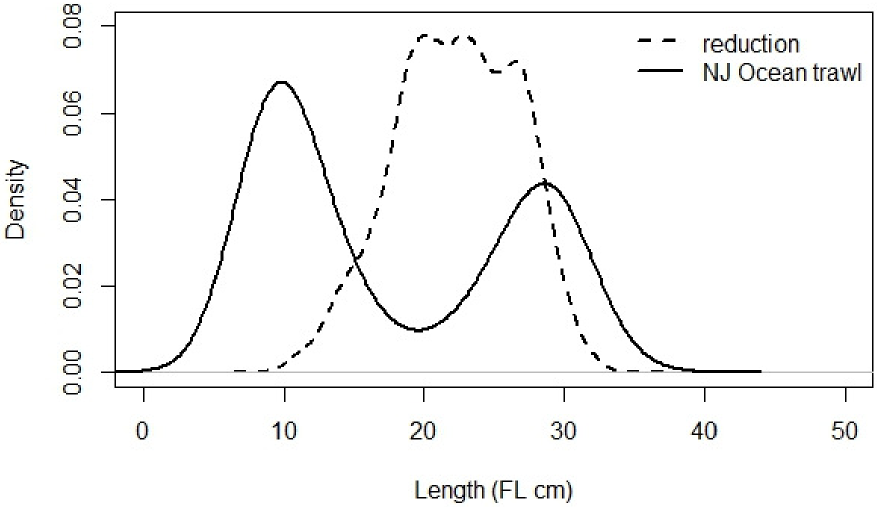
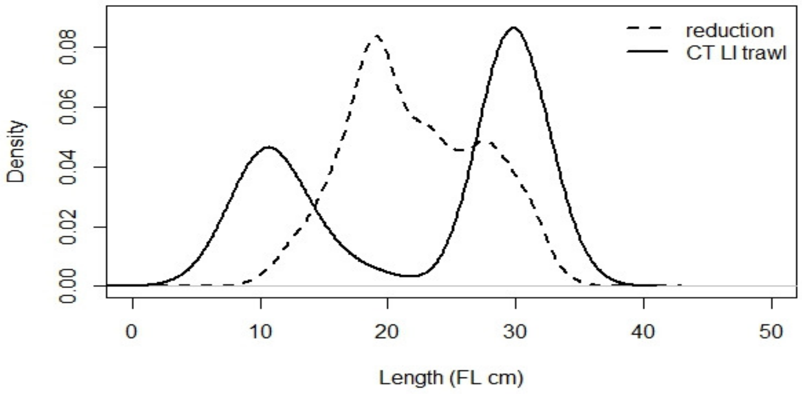


Figure 6.1.4. Comparison of length data from the commercial reduction fishery to the Connecticut Long Island Sound Trawl survey for all years of data available (above) and for years of overlapping data only (bottom).



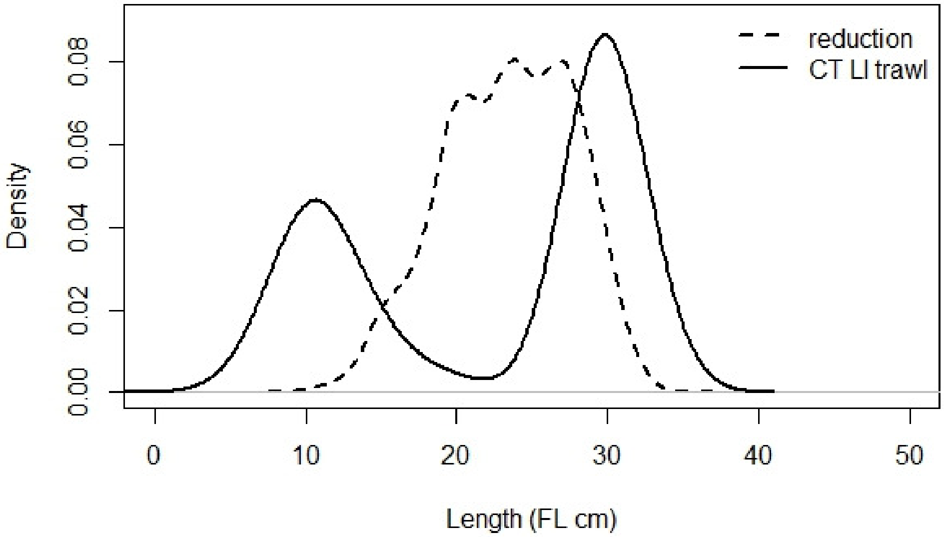


Figure 6.1.5. Menhaden length frequency distributions from the NEFOP, the commercial reduction fishery and the composite fishery-independent survey index (NAD) for the northern region.

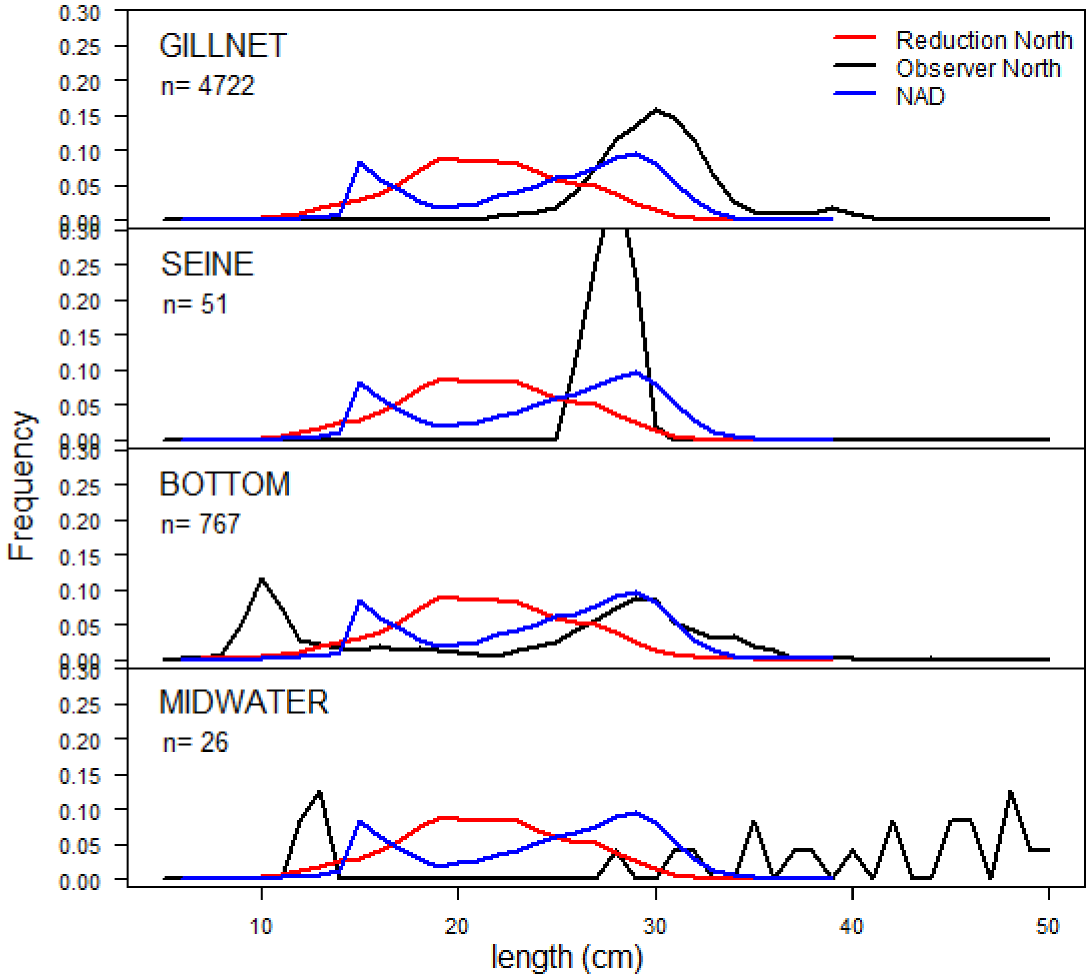


Figure 6.1.6. Menhaden length frequency distributions from the NEFOP, the commercial reduction fishery and the composite fishery-independent survey index (SAD) for the southern region.

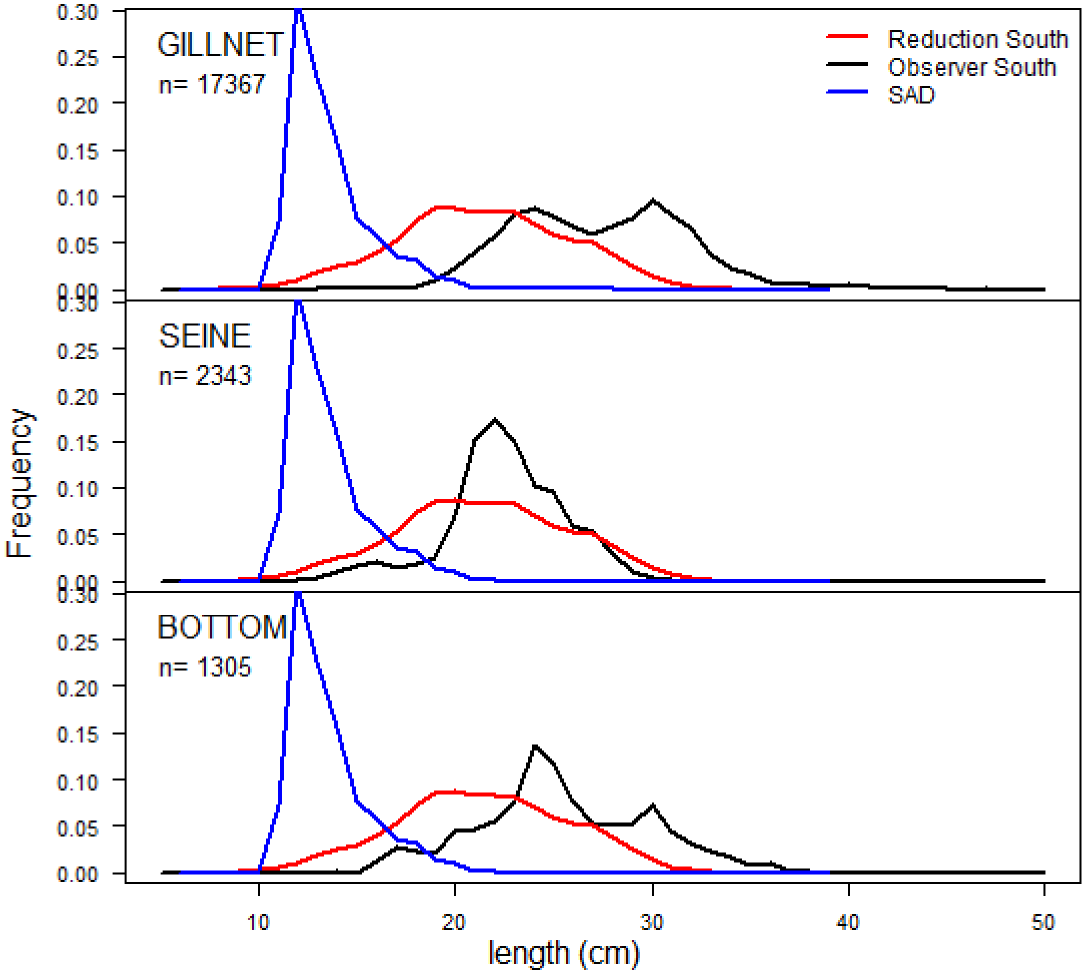


Figure 6.1.7. Length (mm FL) versus age based on the commercial reduction fishery sampling for the time period 1955 to 2013.

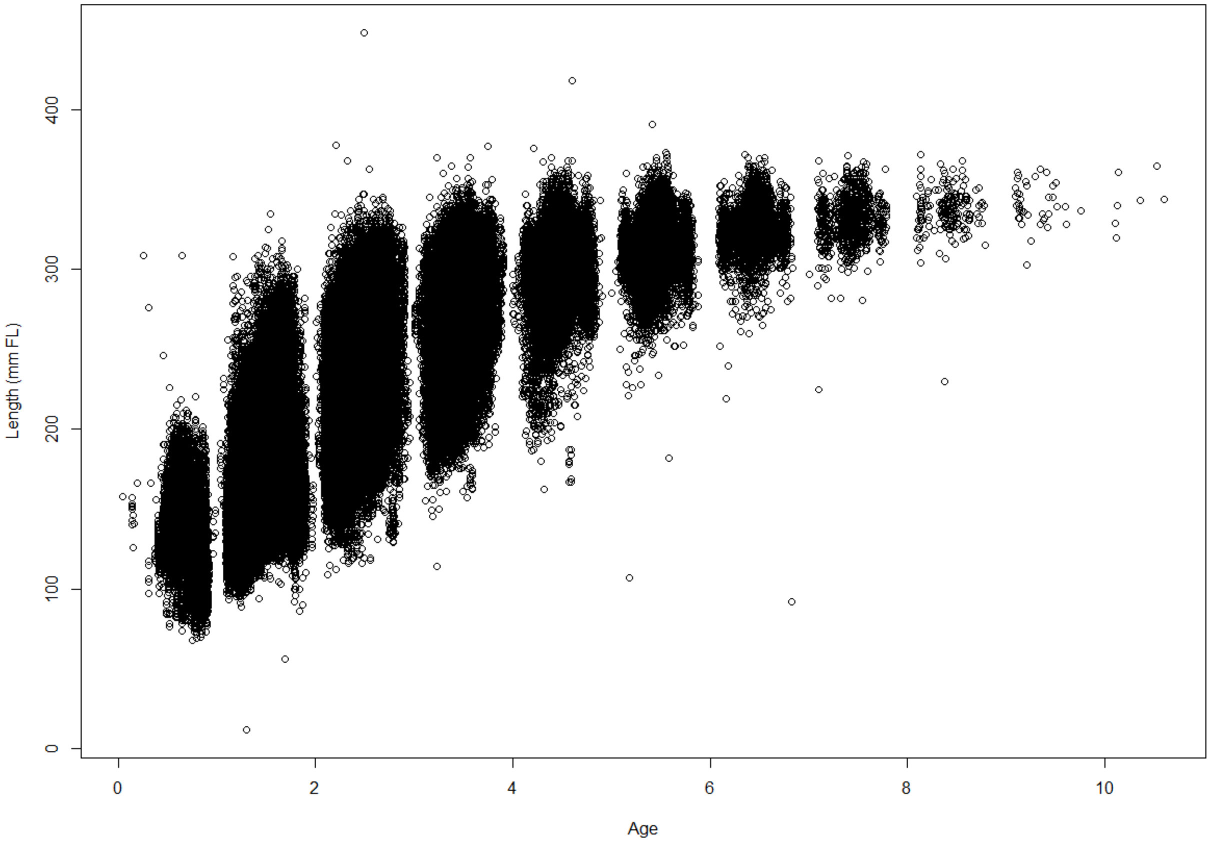


Figure 7.1.1. Observed and predicted removals of Atlantic menhaden from 1955-2013 from north of Virginia Eastern Shore by the commercial reduction fishery.

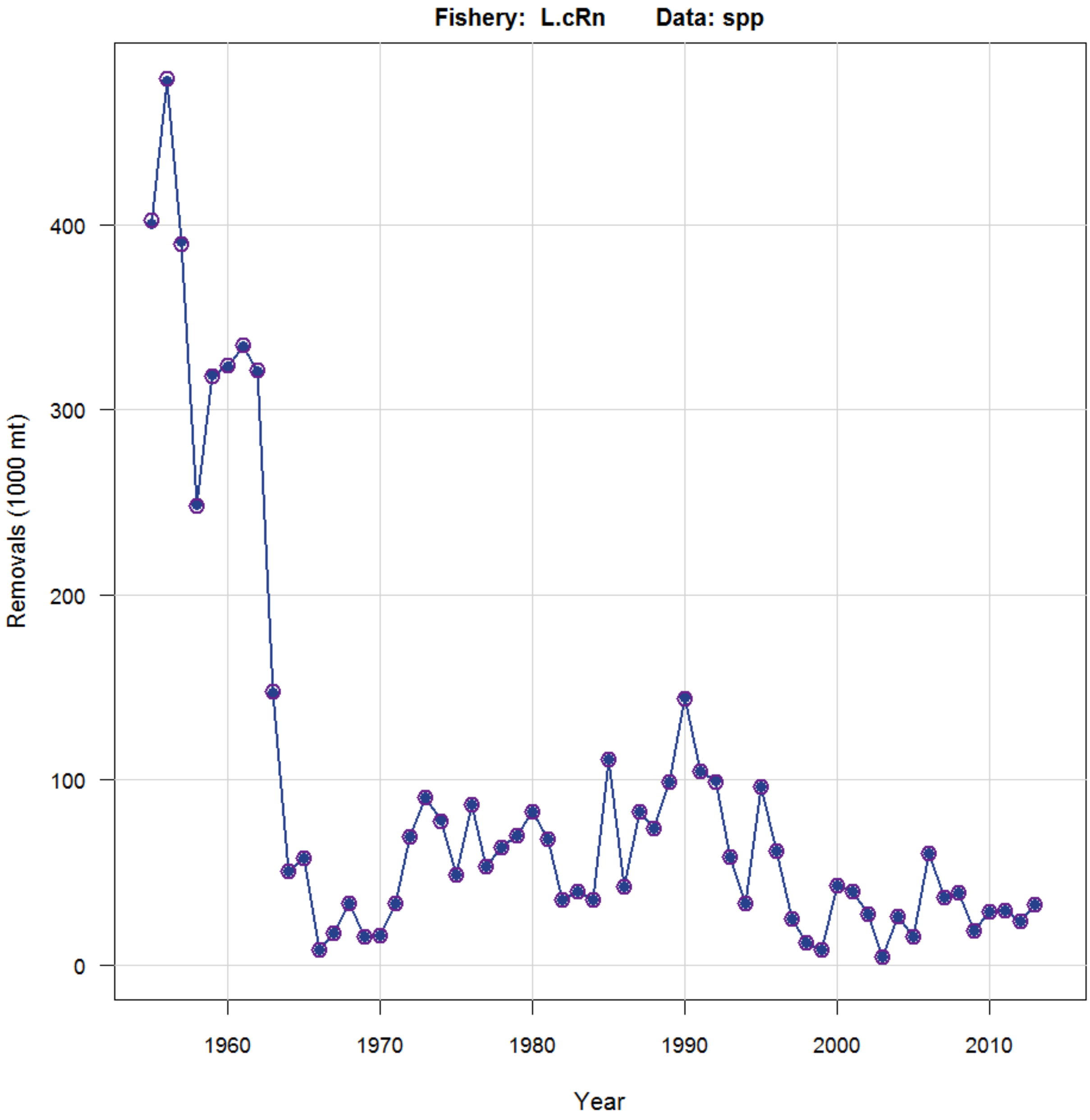


Figure 7.1.2. Observed and predicted removals of Atlantic menhaden from 1955-2013 from Virginia Eastern Shore and south by the commercial reduction fishery.

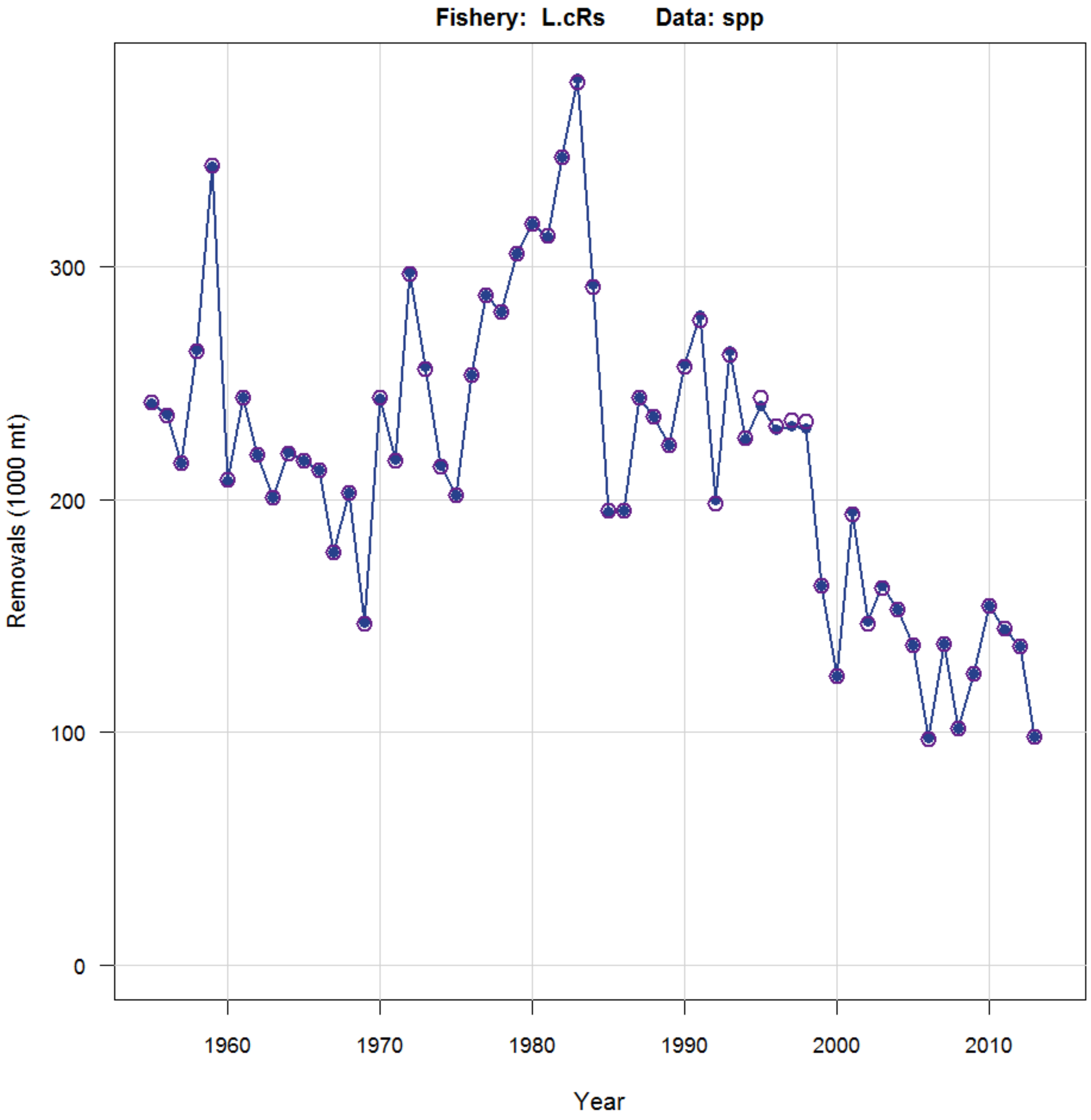


Figure 7.1.3. Observed and predicted removals of Atlantic menhaden from 1955-2013 from north of Virginia Eastern Shore by the commercial bait fishery.

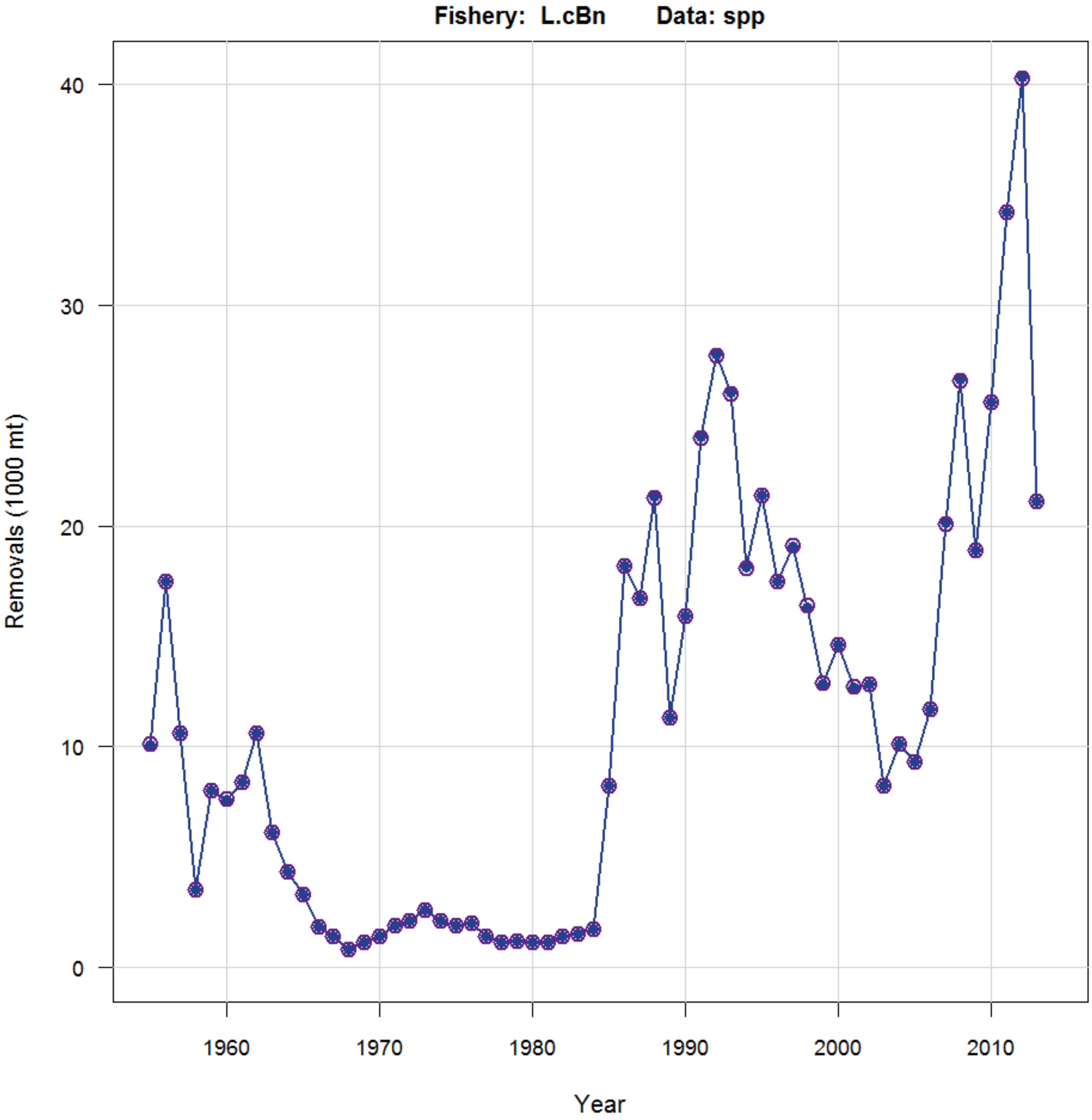


Figure 7.1.4. Observed and predicted removals of Atlantic menhaden from 1955-2013 from Virginia Eastern Shore and south by the commercial bait fishery.

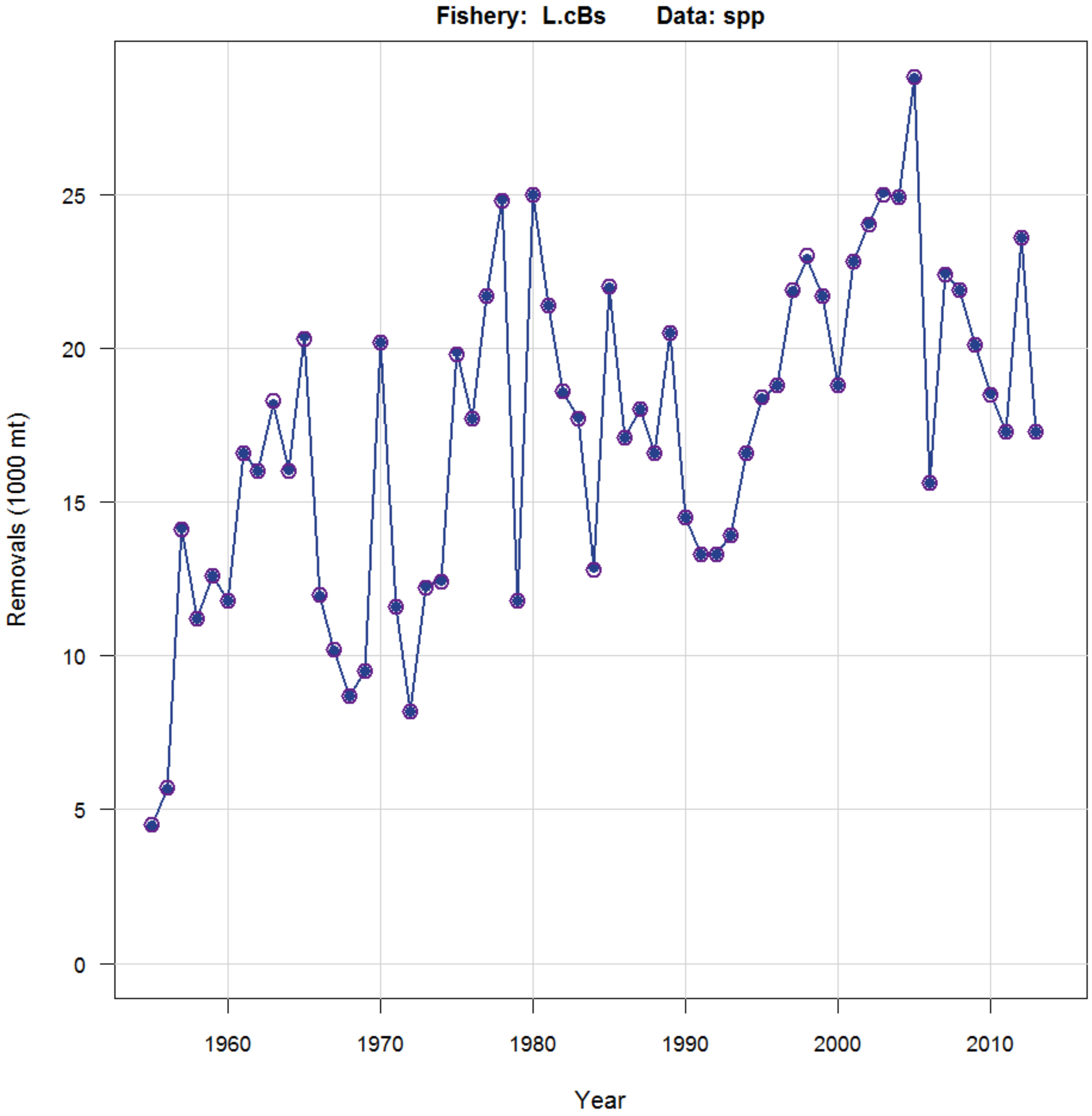


Figure 7.1.5. Annual observed and predicted catch-at-age of Atlantic menhaden from 1955-2013 from north of Virginia Eastern Shore by the commercial reduction fishery.

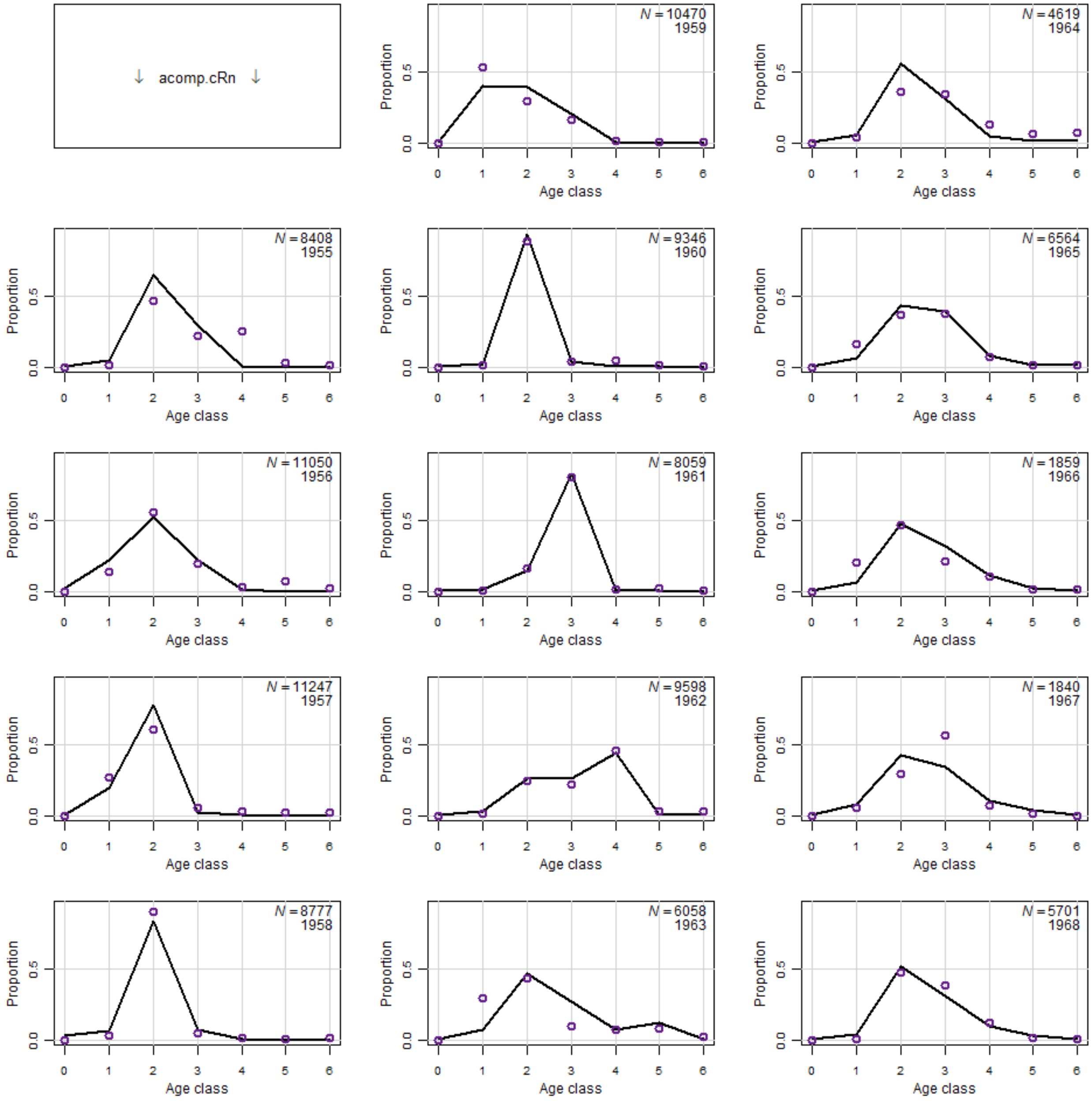


Figure 7.1.5. Continued.

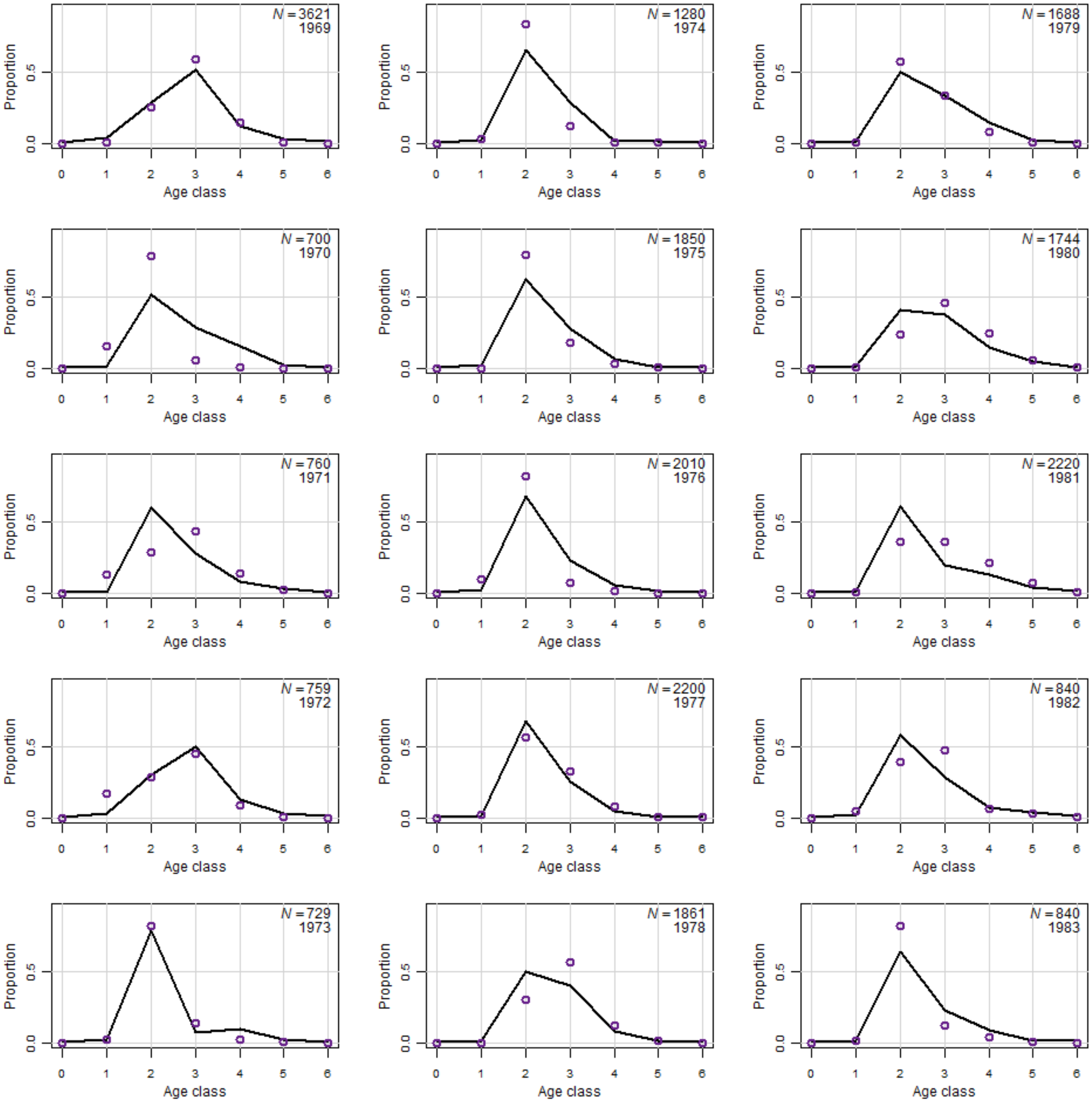


Figure 7.1.5. Continued.

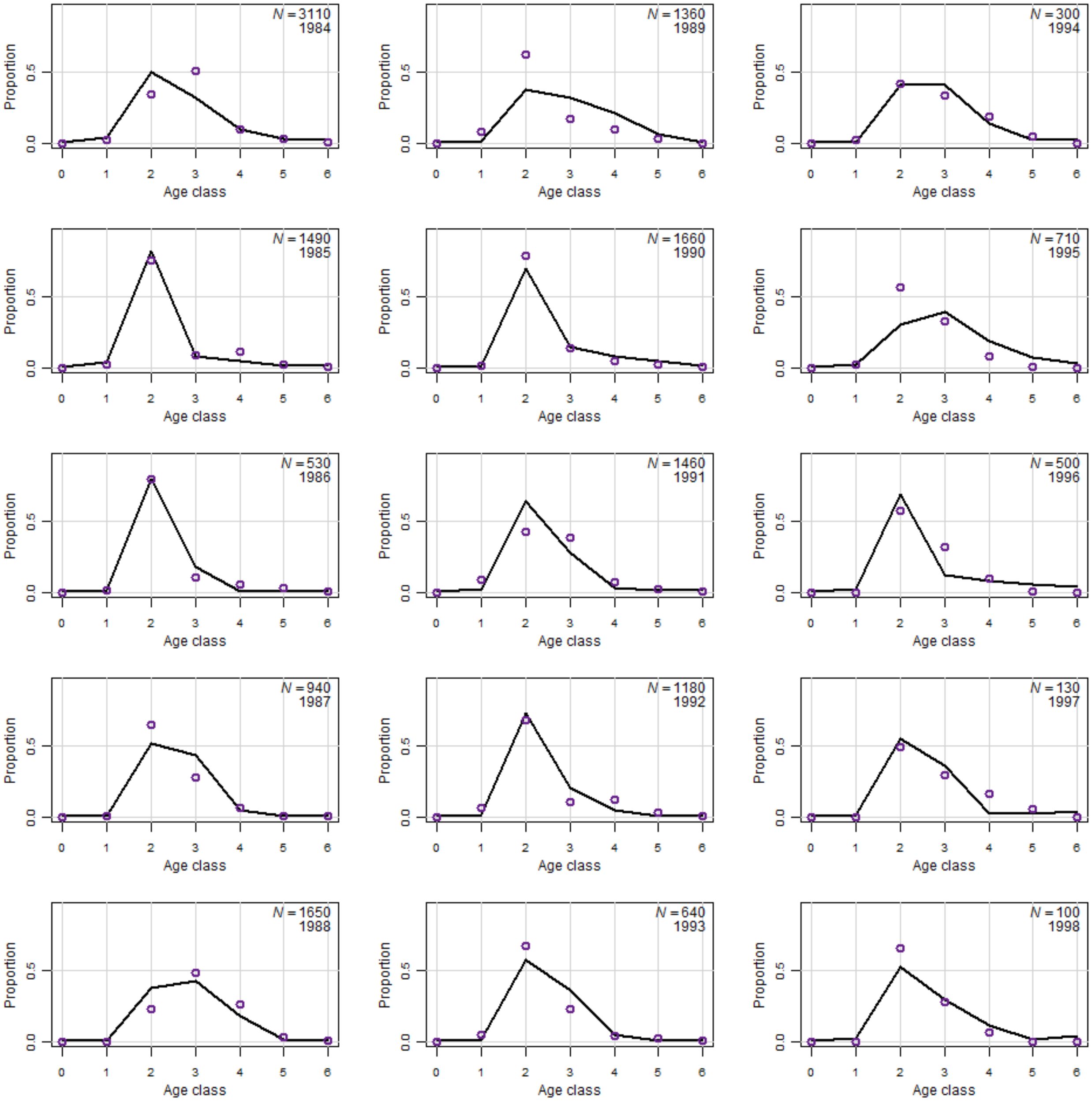


Figure 7.1.5. Continued.

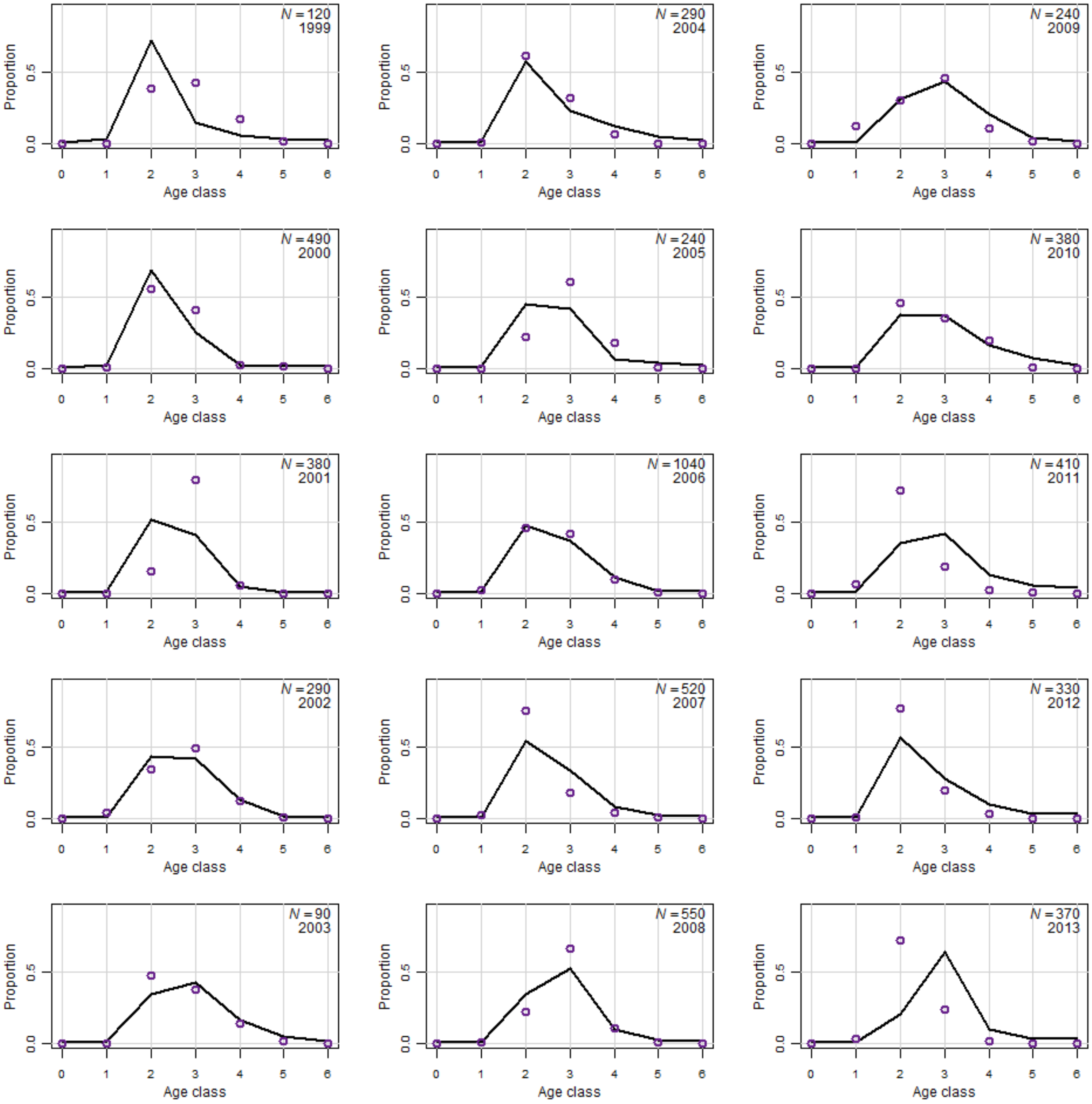


Figure 7.1.6. Annual observed and predicted catch-at-age of Atlantic menhaden from 1955-2013 from Virginia Eastern Shore and south by the commercial reduction fishery.

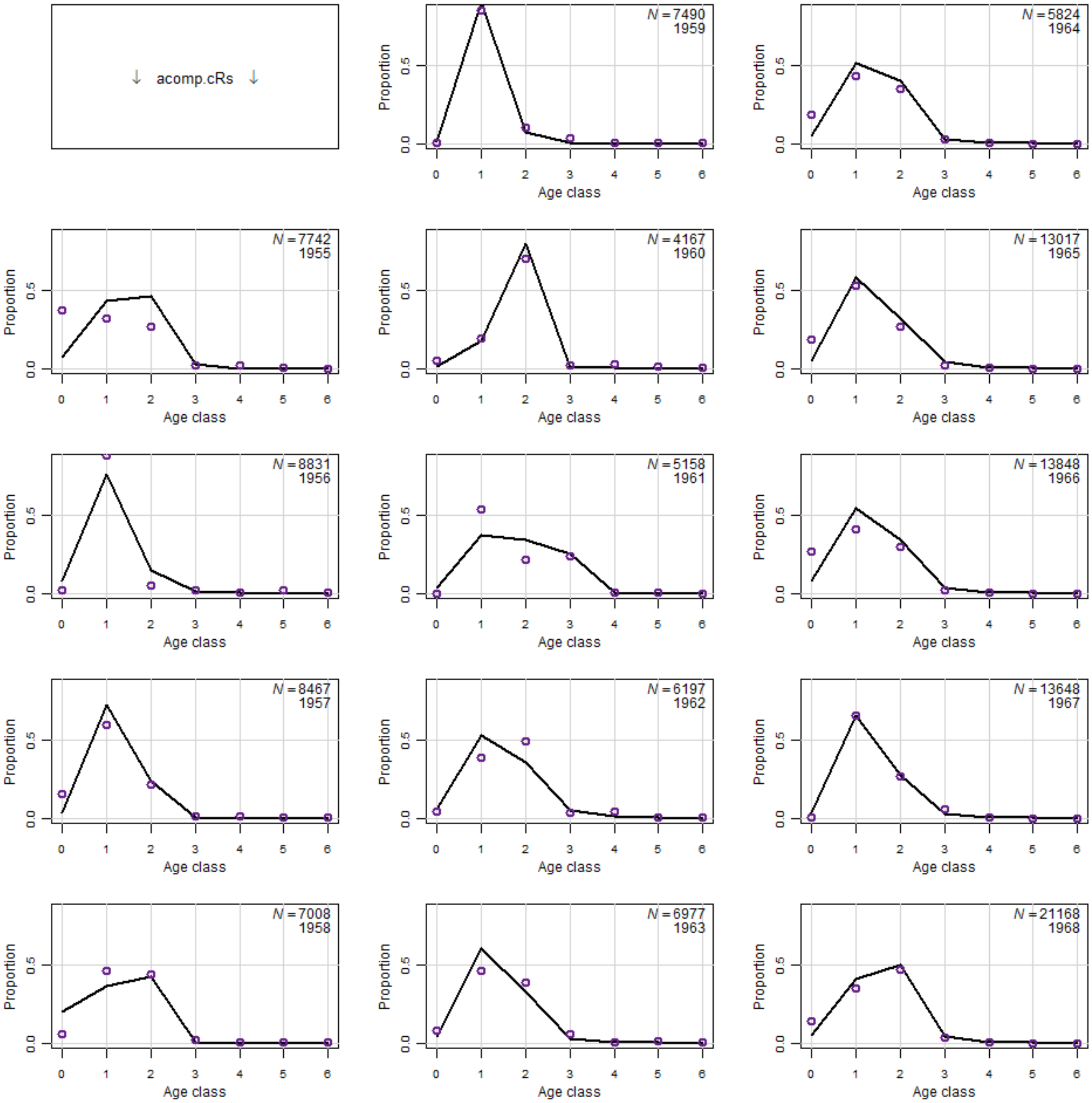


Figure 7.1.6. continued.

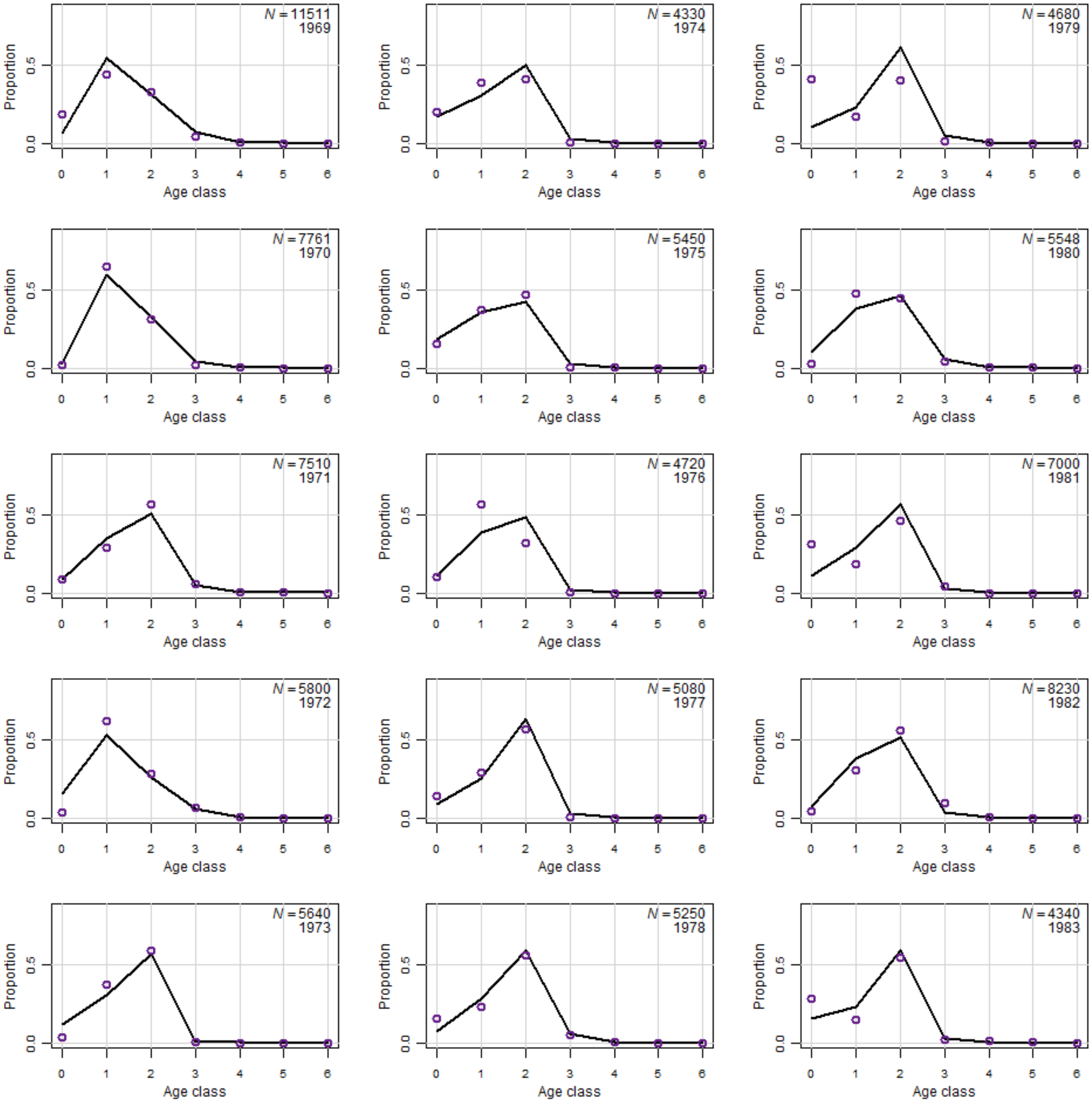


Figure 7.1.6. Continued.

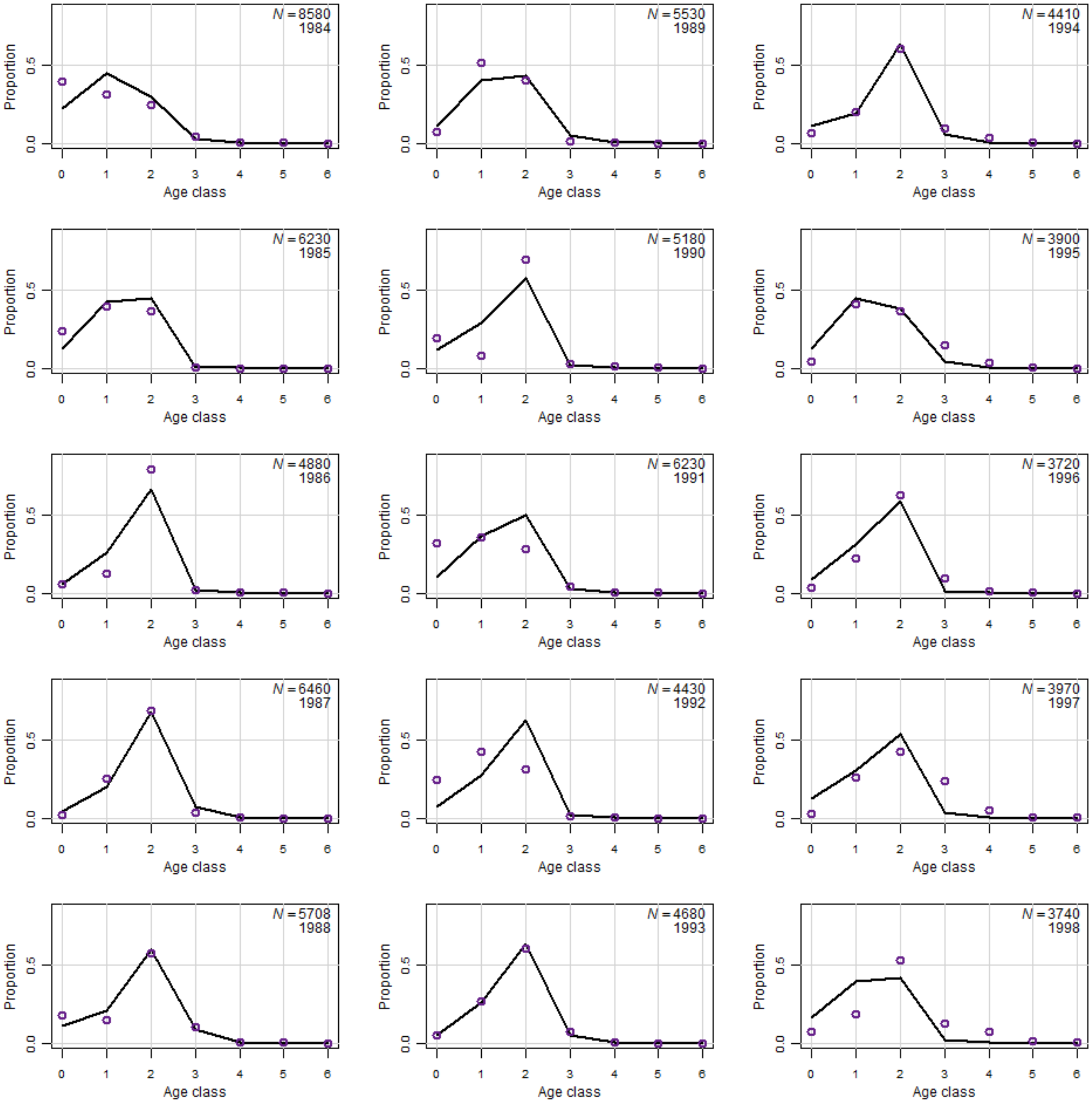


Figure 7.1.6. Continued.

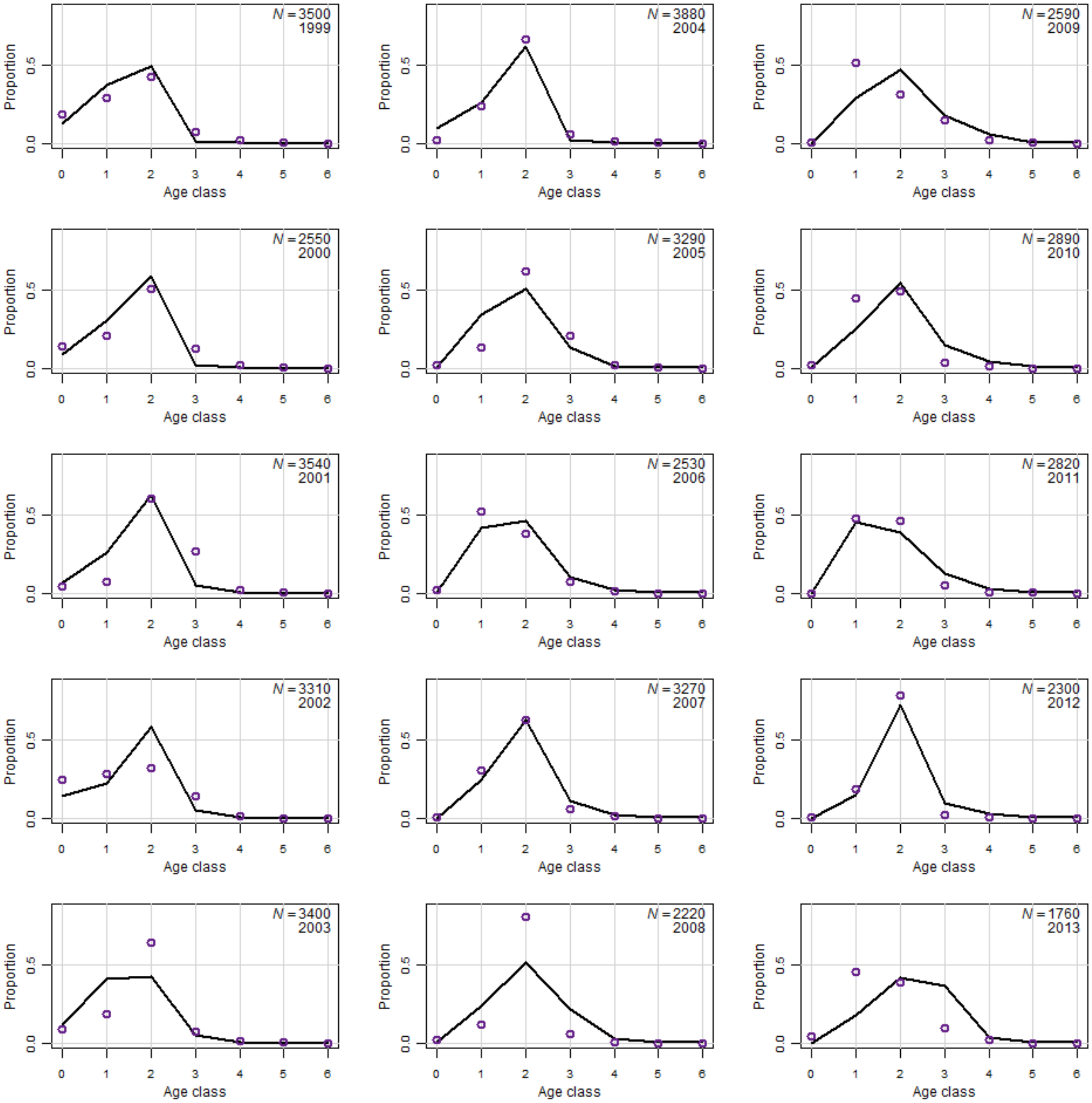


Figure 7.1.7. Annual observed and predicted catch-at-age of Atlantic menhaden from 1985-2013 from north of Virginia Eastern Shore by the commercial bait fishery.

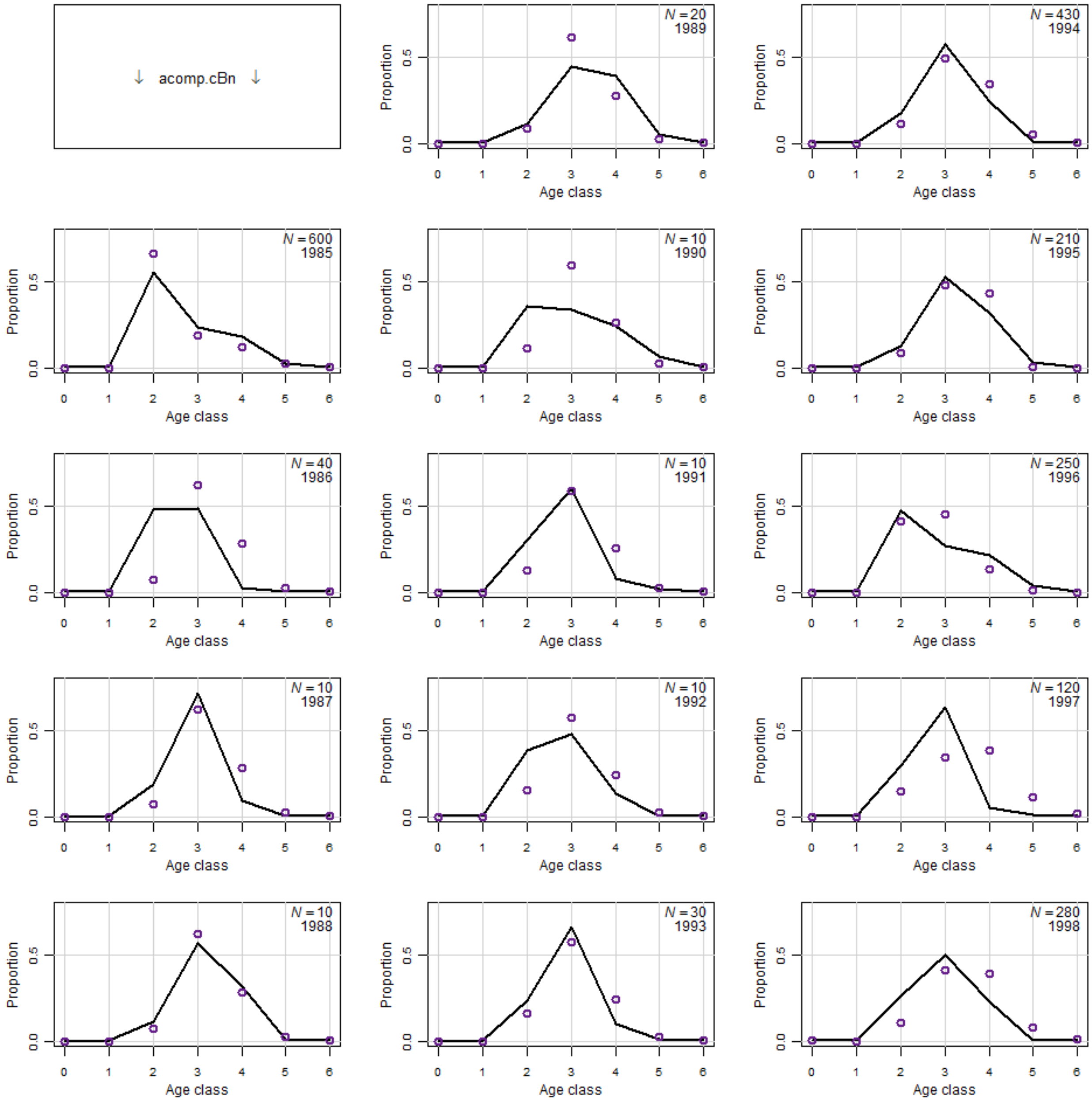


Figure 7.1.7. Continued.

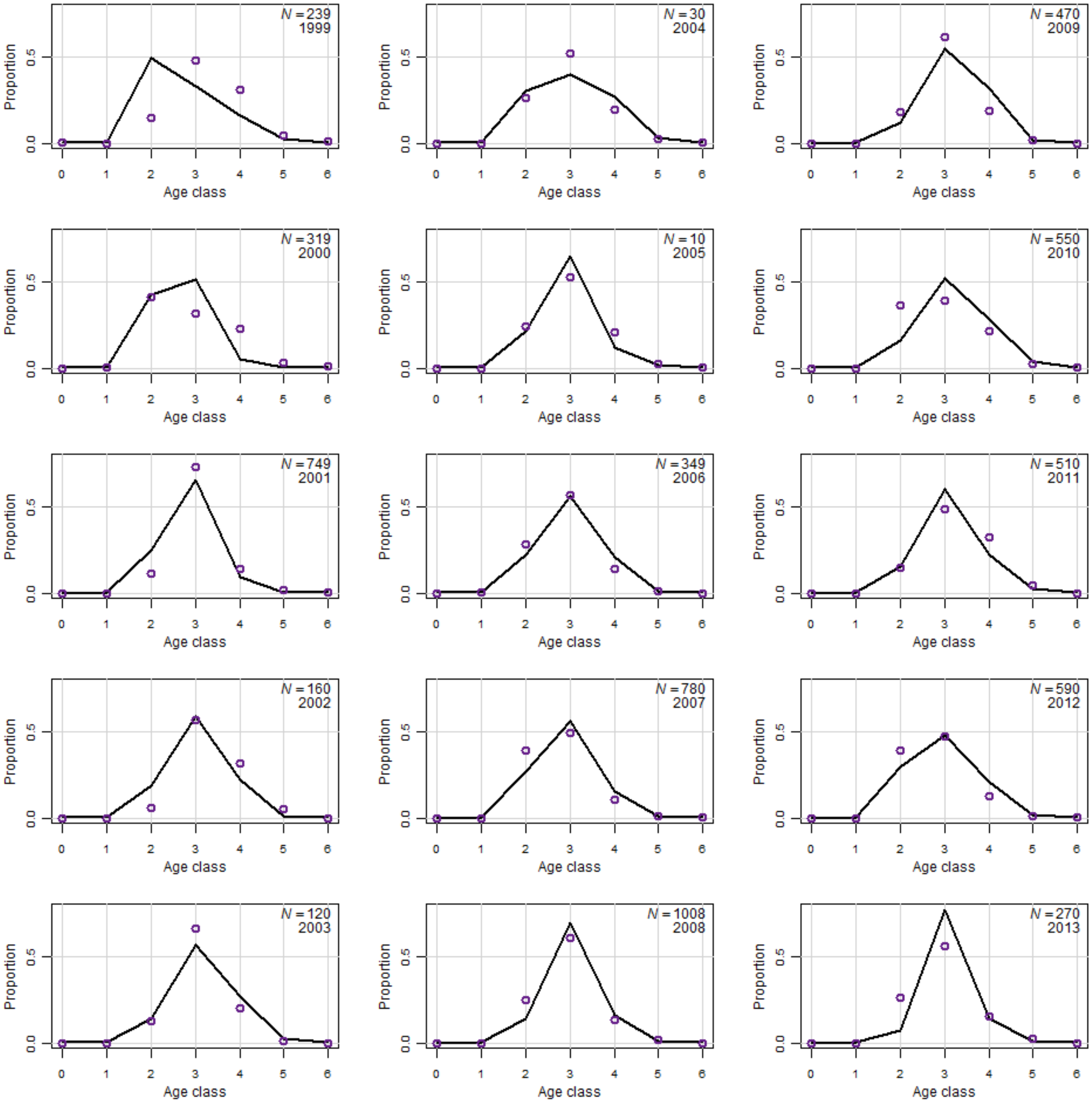


Figure 7.1.8. Annual observed and predicted catch-at-age of Atlantic menhaden from 1985-2013 from Virginia Eastern Shore and south by the commercial bait fishery.

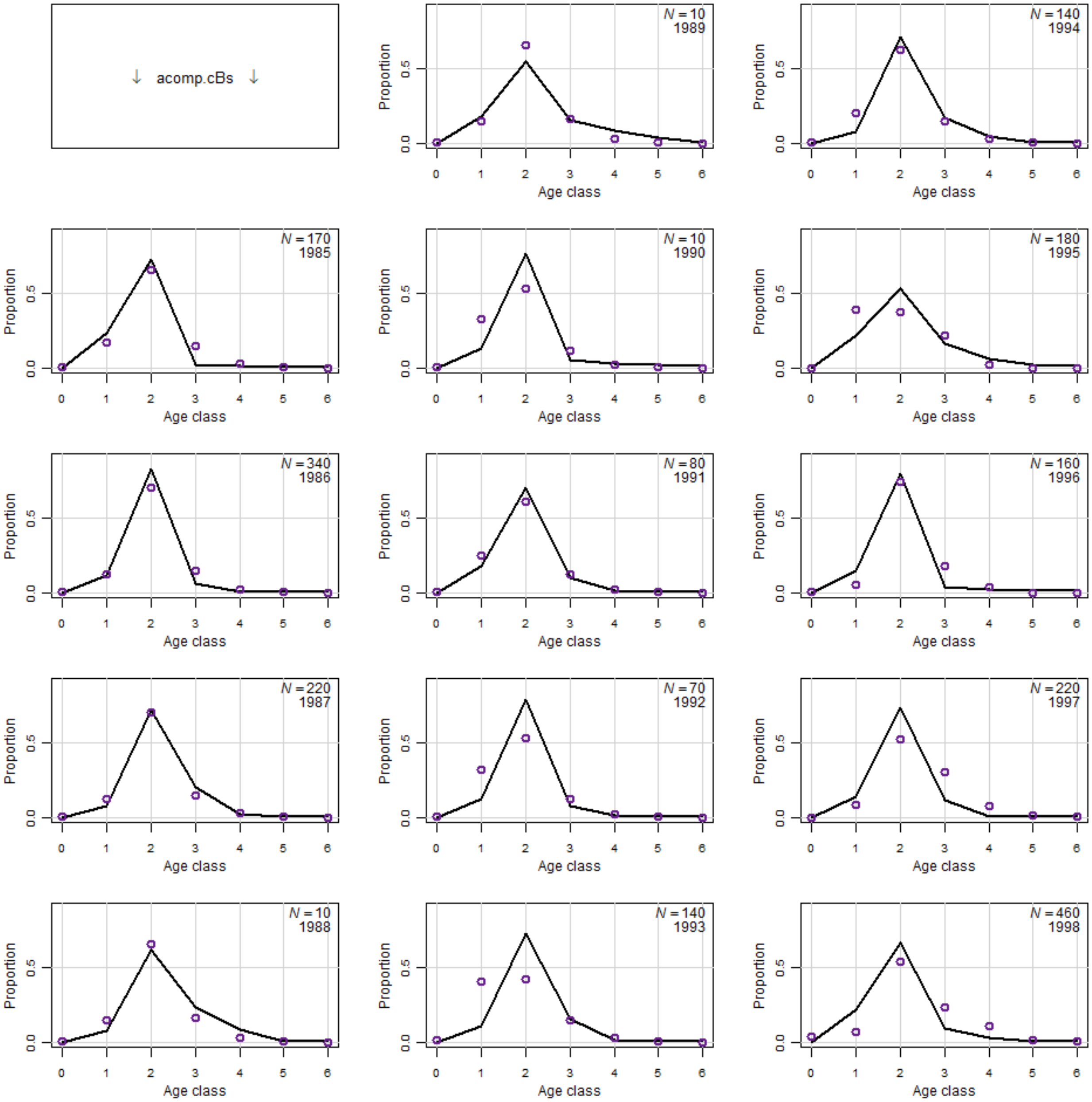


Figure 7.1.8. Continued.

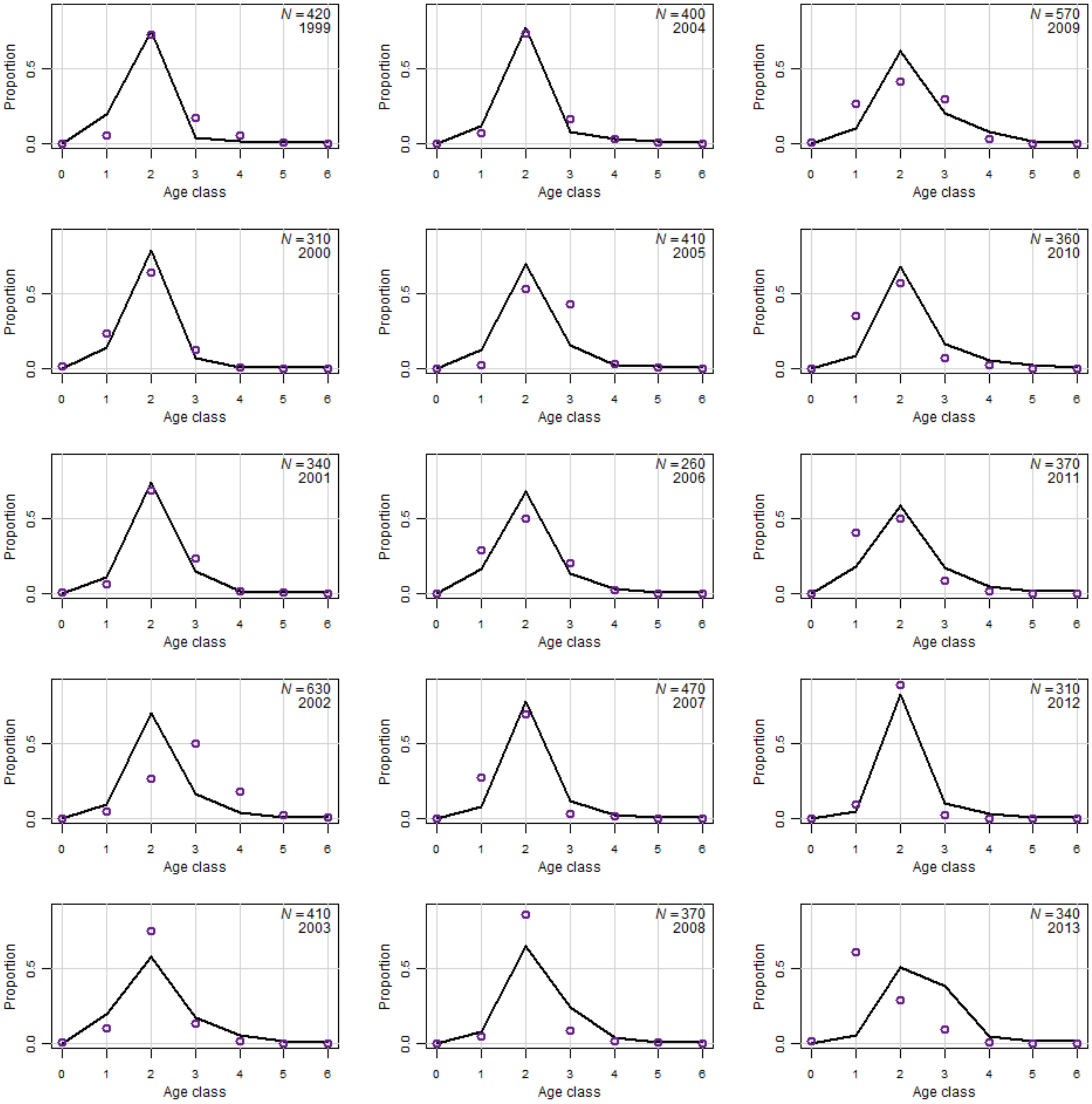
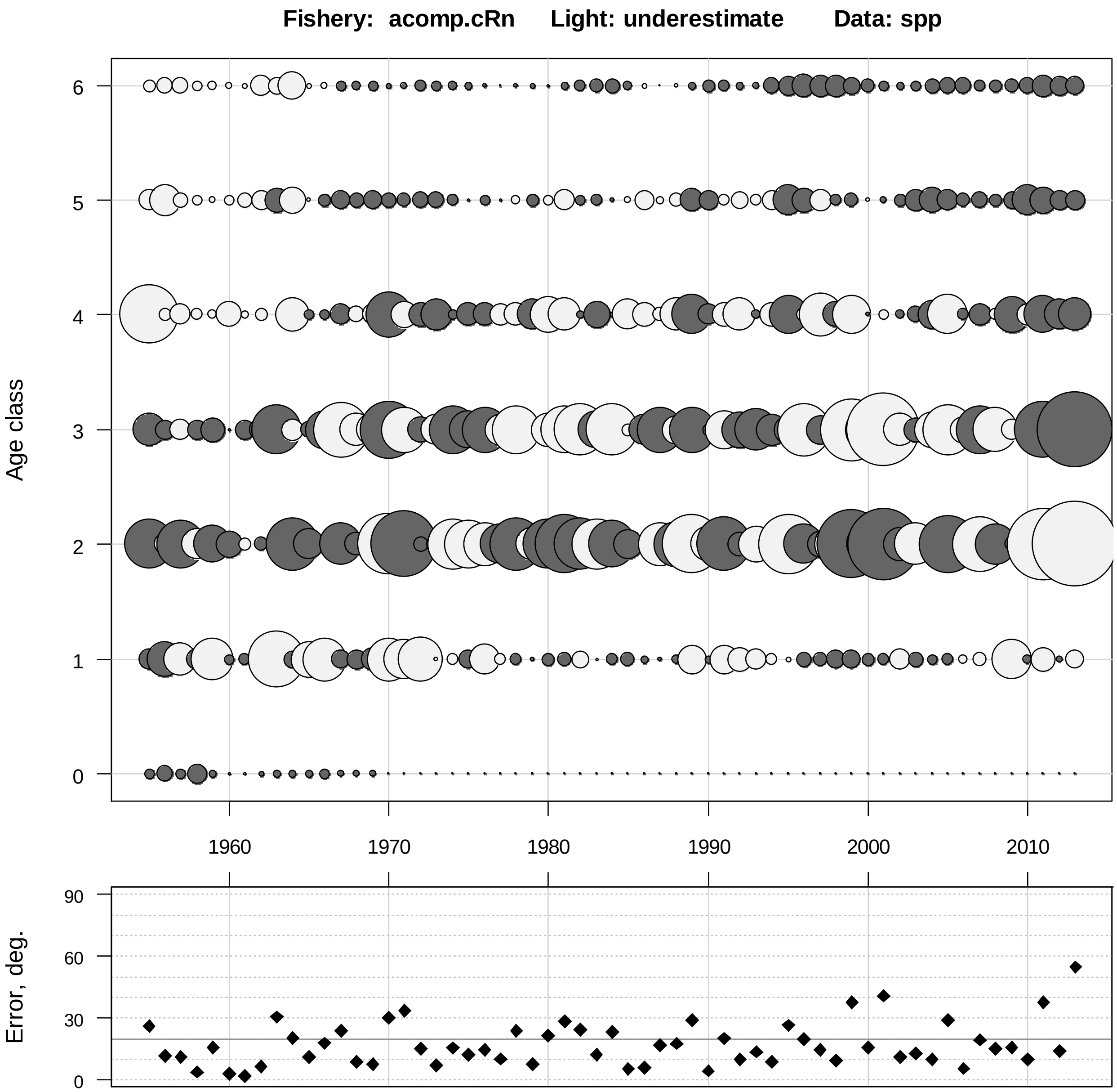


Figure 7.1.9. Relative (upper panel) and absolute (lower panel) bubble plots of the residuals of the predicted catch-at-age for Atlantic menhaden from 1955-2013 from north of Virginia Eastern Shore by the commercial reduction fishery. The error degrees in the upper panel represents a composite fit by year across ages, while in the lower plot contains correlations between years.



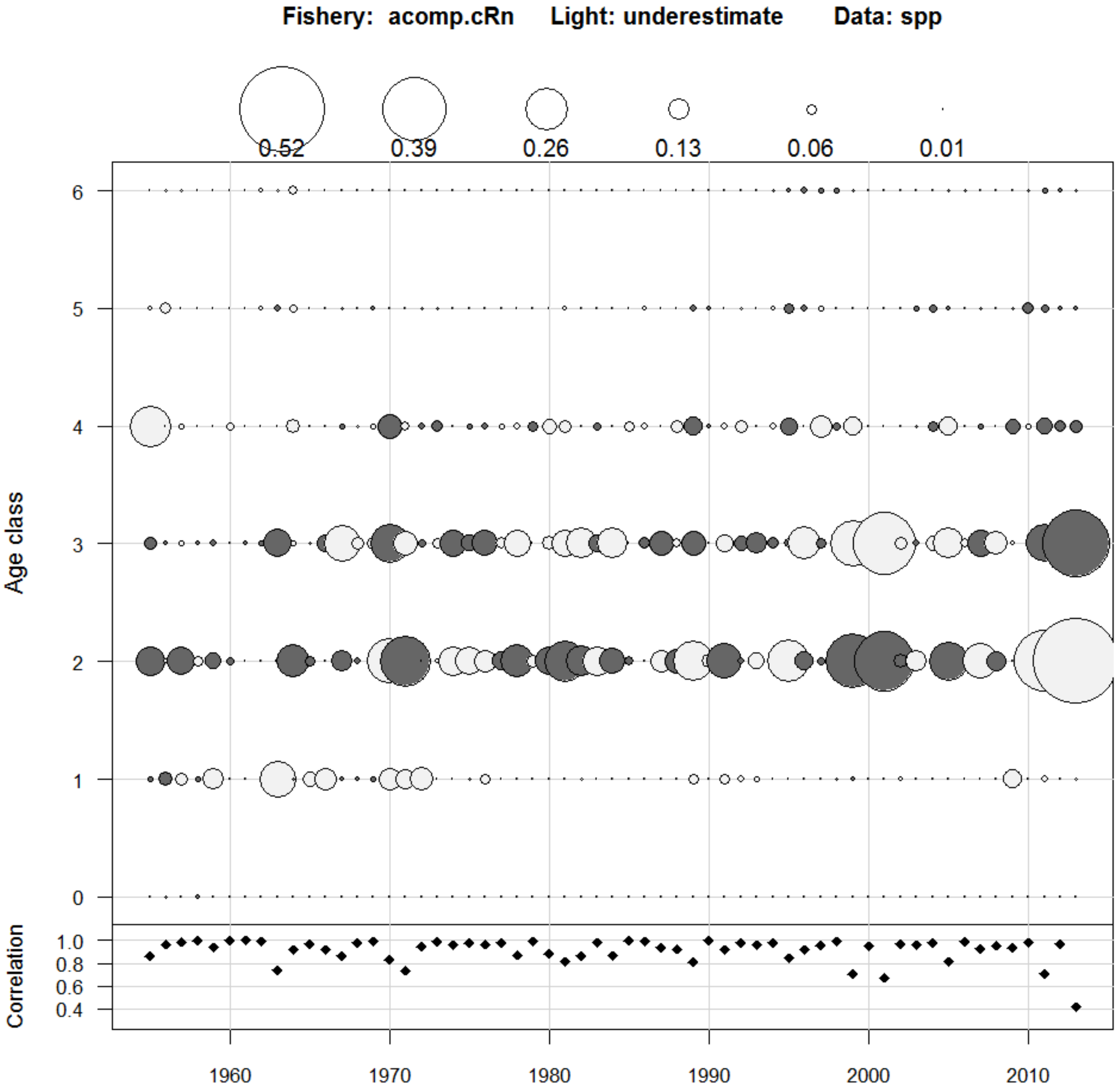
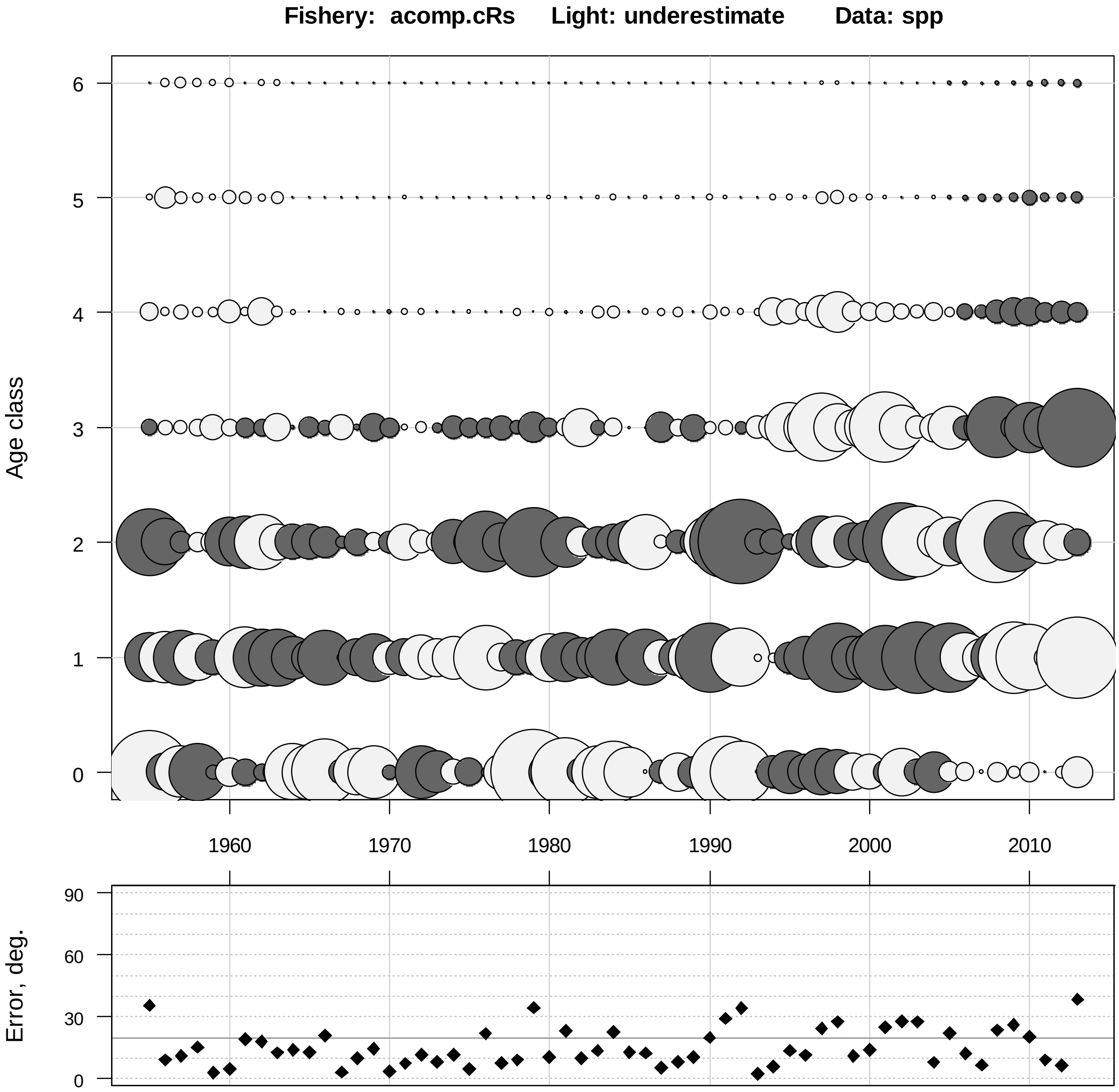

Fishery: acomp.cRn Light: underestimate Data: spp
0.52
0.39
0.26
0.13
0.06
0.01
Age class
0
1
2
3
4
5
6
Correlation
1.0
0.8
0.6
0.4
1960
1970
1980
1990
2000
2010

Figure 7.1.10. Relative (upper panel) and absolute (lower panel) bubble plots of the residuals of the predicted catch-at-age for Atlantic menhaden from 1955-2013 from Virginia Eastern Shore and south by the commercial reduction fishery. The error degrees in the upper panel represents a composite fit by year across ages, while in the lower plot contains correlations between years.



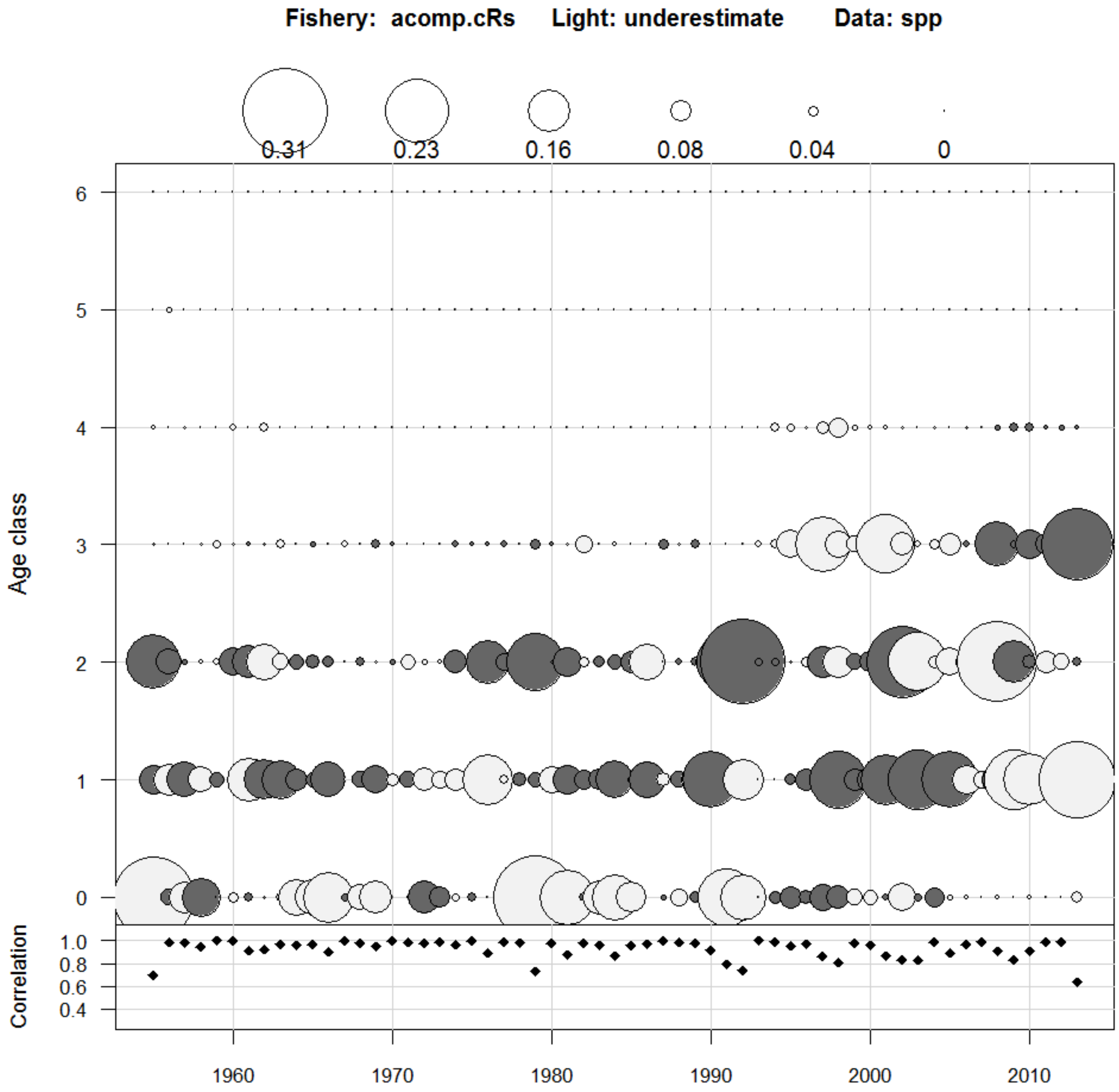
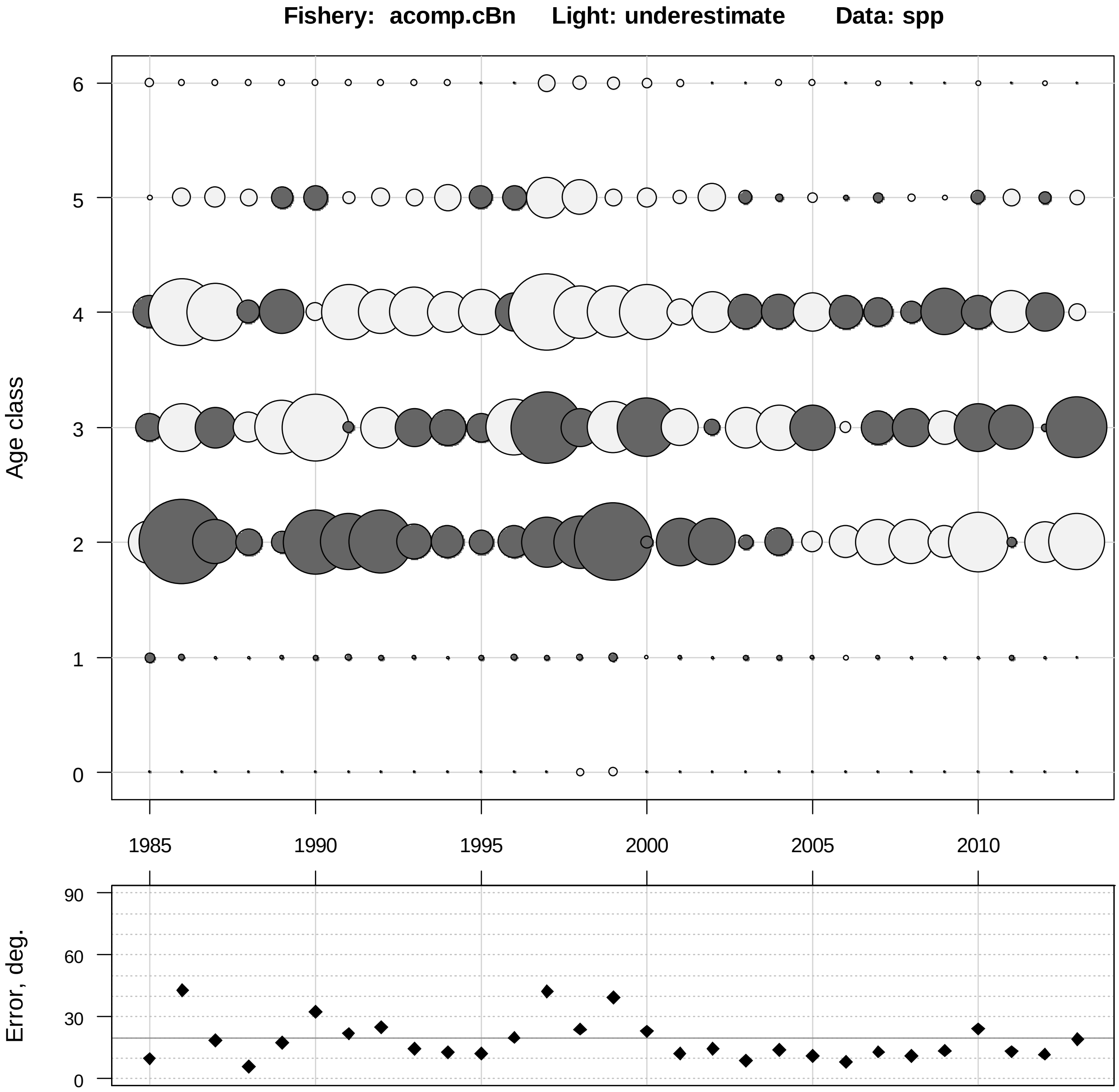

Fishery: acomp.cRs Light: underestimate Data: spp
0.31
0.23
0.16
0.08
0.04
0
Age class
6
5
4
3
2
1
0
Correlation
1.0
0.8
0.6
0.4
1960
1970
1980
1990
2000
2010

Figure 7.1.11. Relative (upper panel) and absolute (lower panel) bubble plots of the residuals of the predicted catch-at-age for Atlantic menhaden from 1985-2013 from north of Virginia Eastern Shore by the commercial bait fishery. The error degrees in the upper panel represents a composite fit by year across ages, while in the lower plot contains correlations between years.



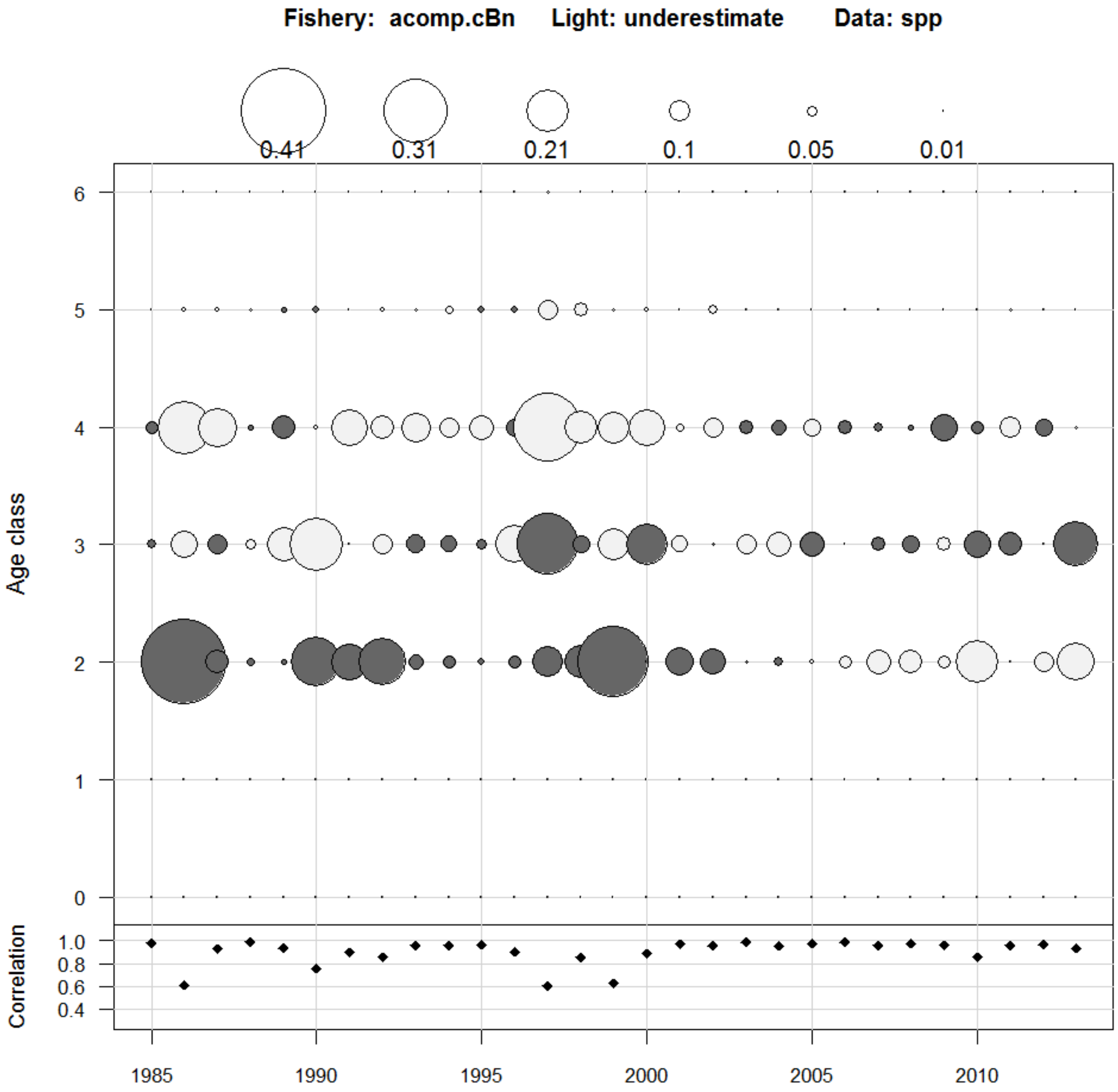
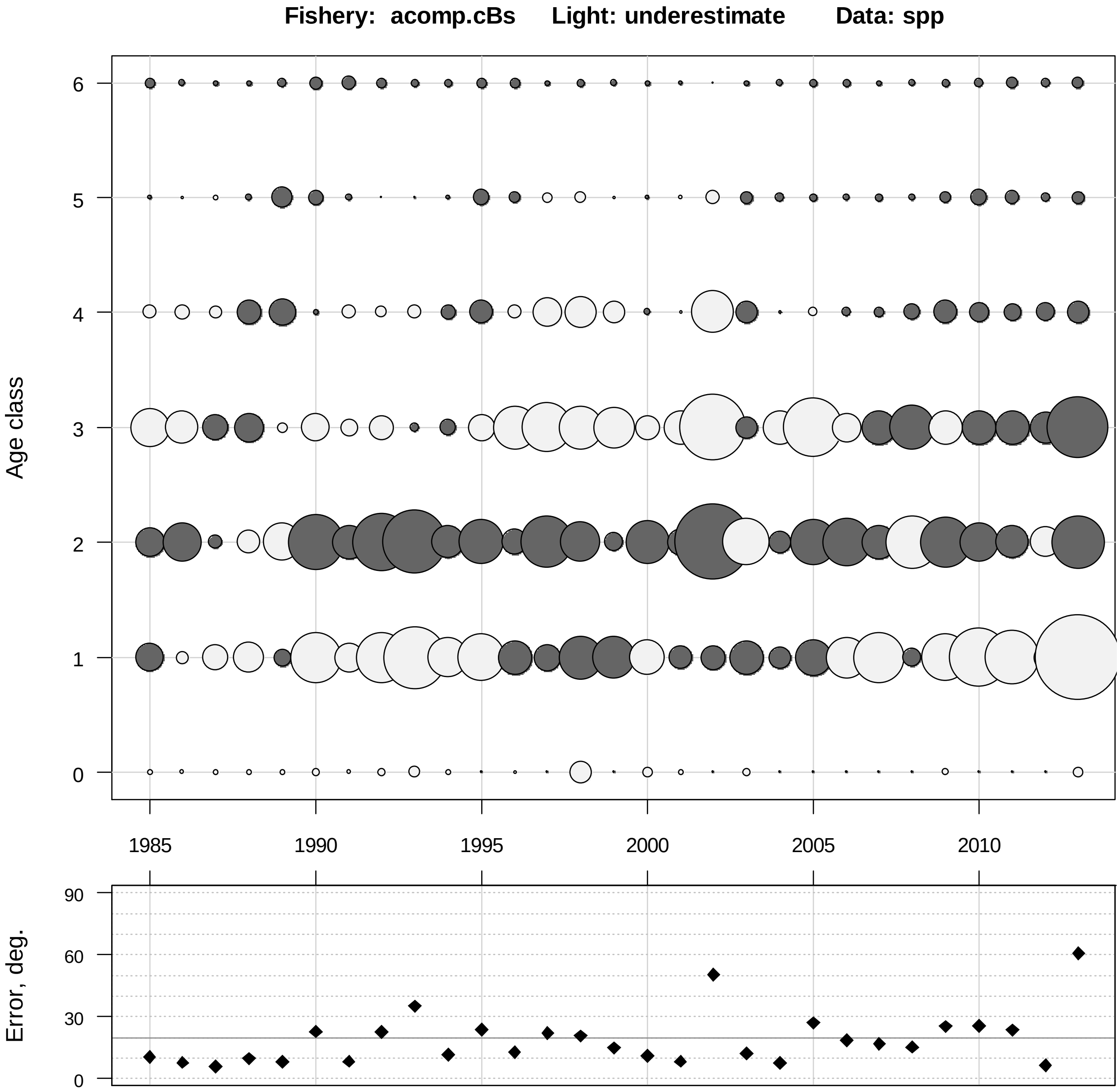

Fishery: acomp.cBn
Light: underestimate
Data: spp
0.41
0.31
0.21
0.1
0.05
0.01
Age class
6
5
4
3
2
1
0
Correlation
1.0
0.8
0.6
0.4
1985
1990
1995
2000
2005
2010

Figure 7.1.12. Relative (upper panel) and absolute (lower panel) bubble plots of the residuals of the predicted catch-at-age for Atlantic menhaden from 1985-2013 from Virginia Eastern Shore and south by the commercial bait fishery. The error degrees in the upper panel represents a composite fit by year across ages, while in the lower plot contains correlations between years.



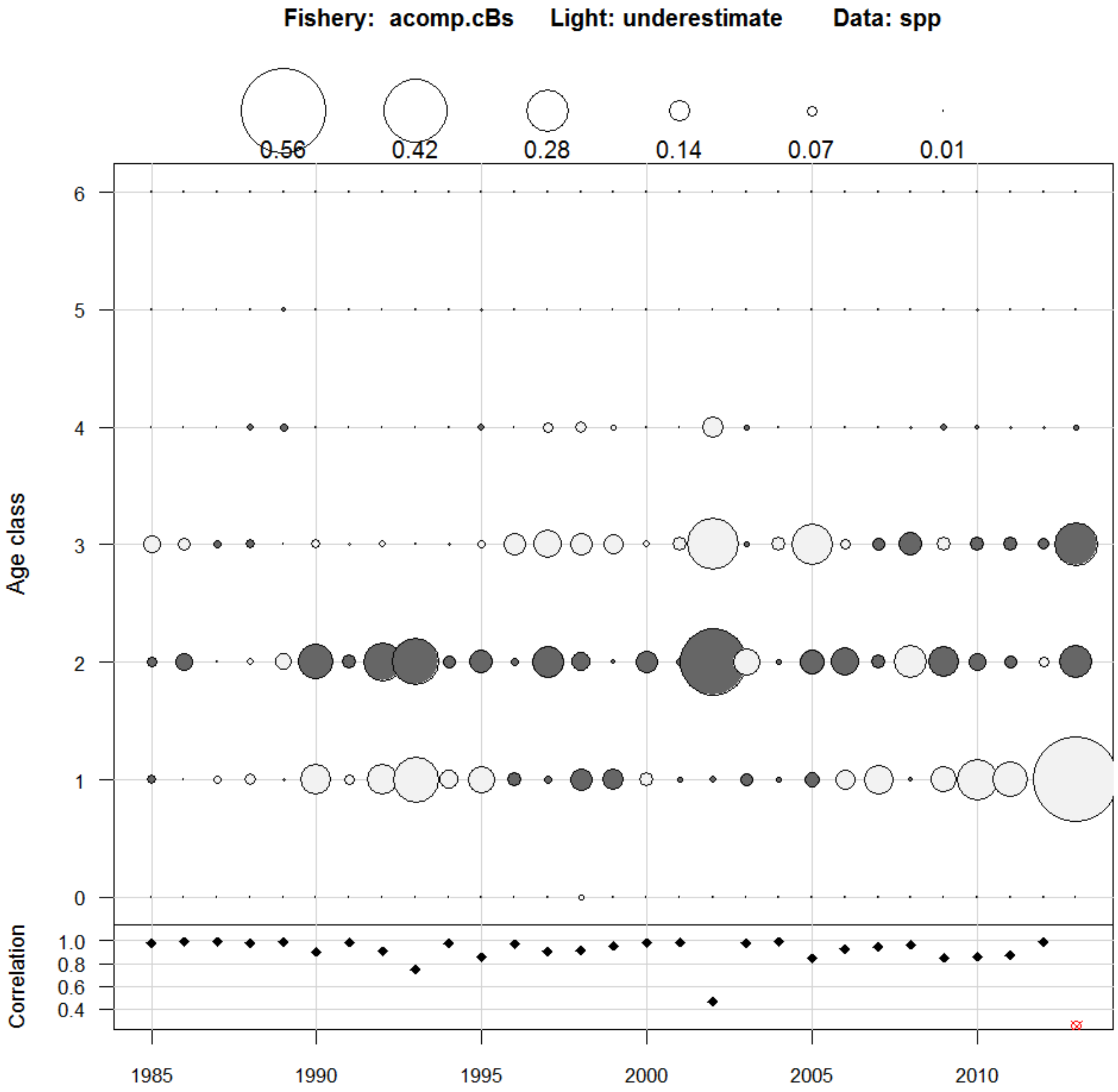

Fishery: acomp.cBs
Light: underestimate
Data: spp
0.56
0.42
0.28
0.14
0.07
0.01
Age class
0
1
2
3
4
5
6
Correlation
1.0
0.8
0.6
0.4
1985
1990
1995
2000
2005
2010

Figure 7.1.13. The observed and predicted recruitment index for 1959-2013 comprised of a series of state surveys.

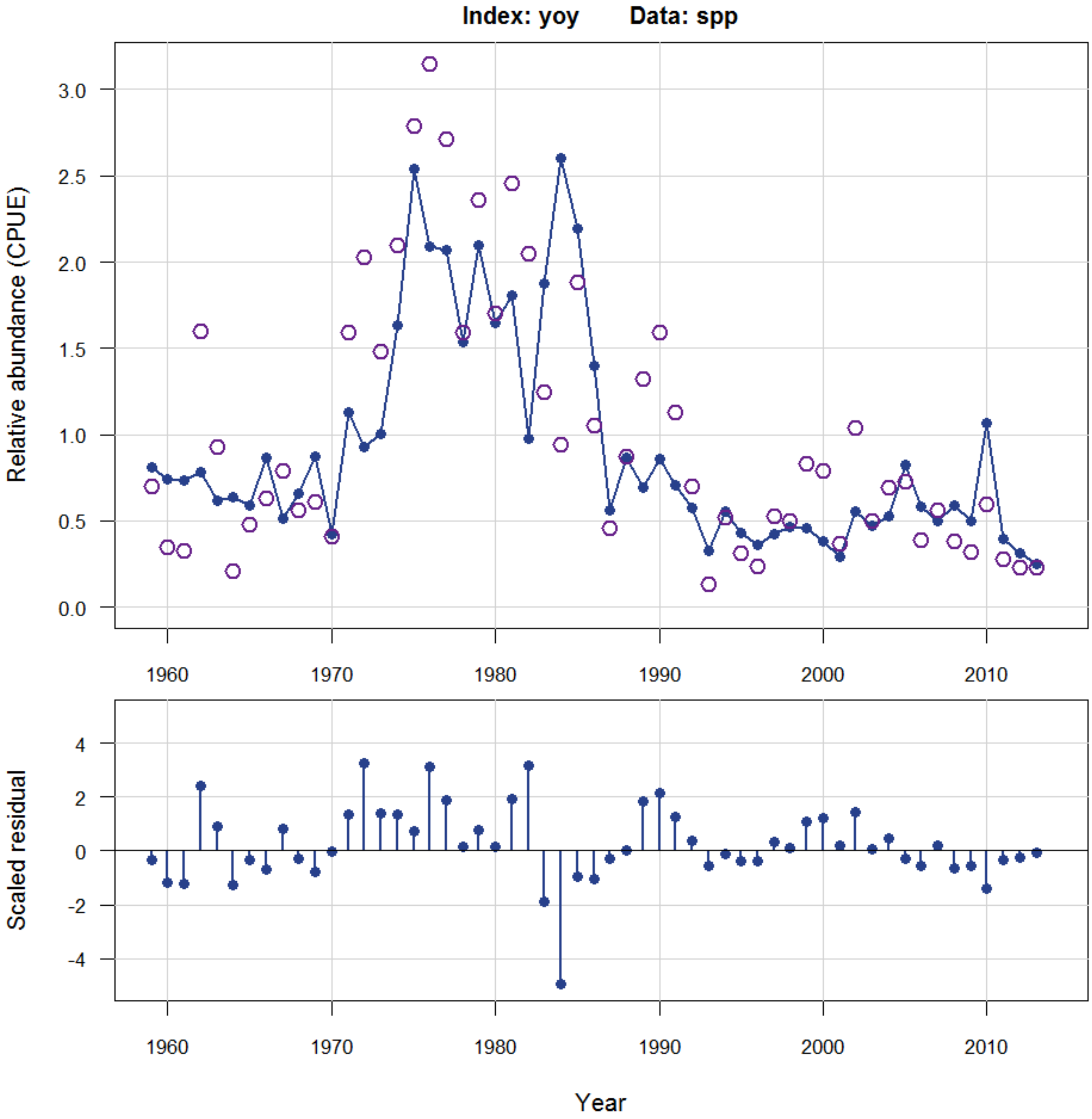


Figure 7.1.14. The observed and predicted NAD index for 1980-2013 comprised of a series of state trawl surveys in the northern region**.**

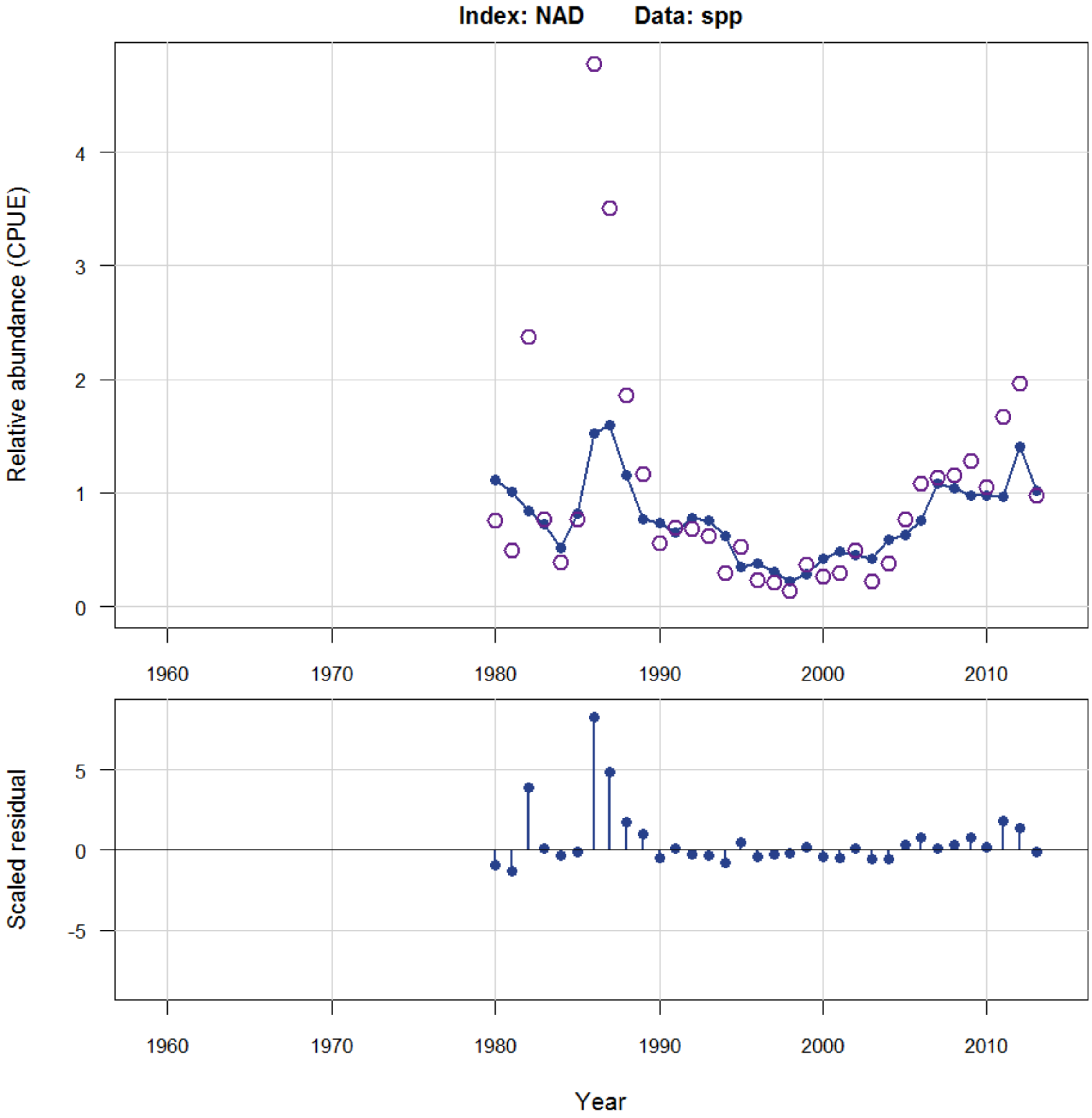


Figure 7.1.15. The observed and predicted SAD index for 1990-2013 comprised of two state trawl surveys in the southern region.

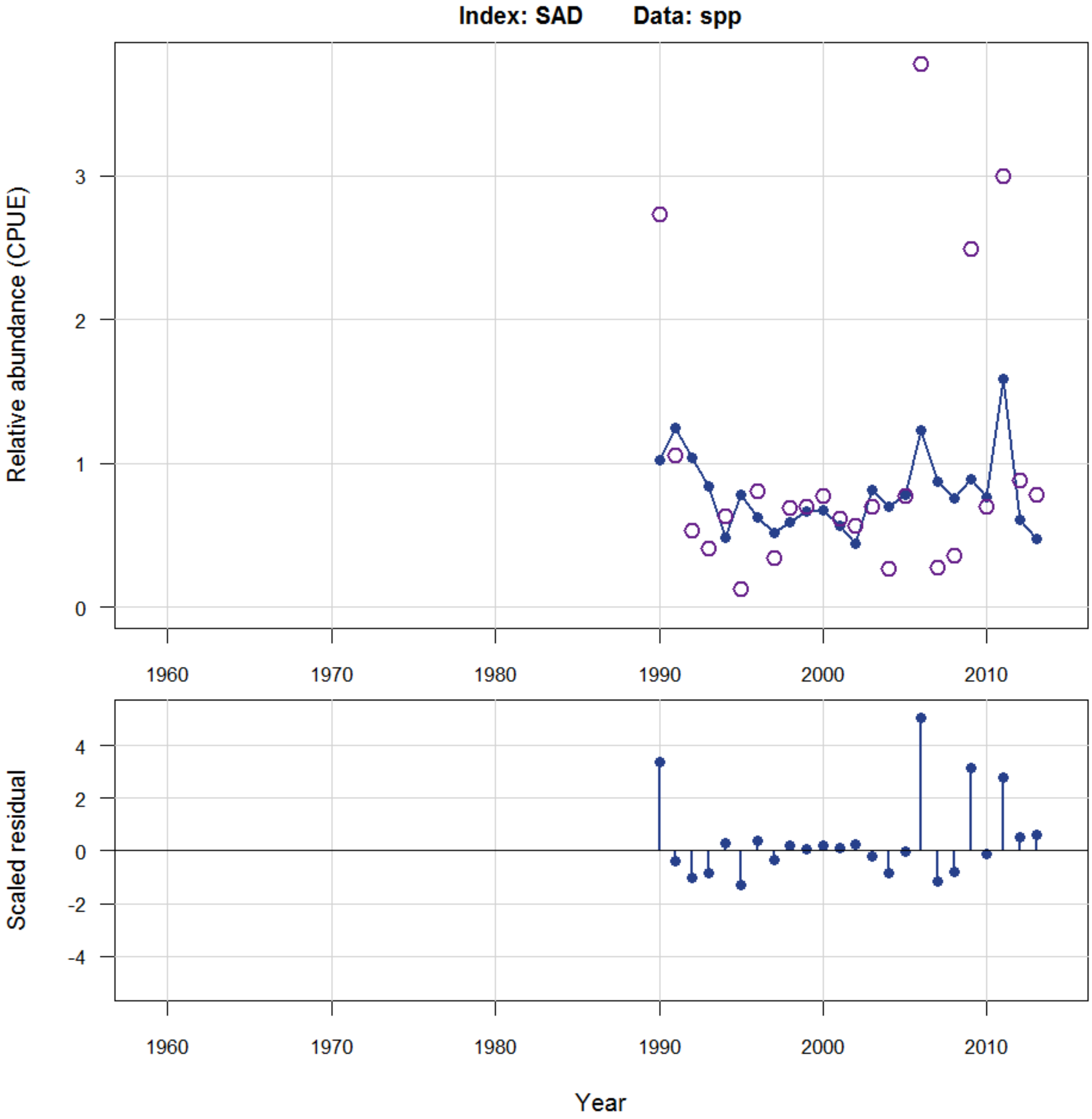


Figure 7.1.16. Annual observed and predicted length measurements of Atlantic menhaden from 1986-2013 for the NAD index.

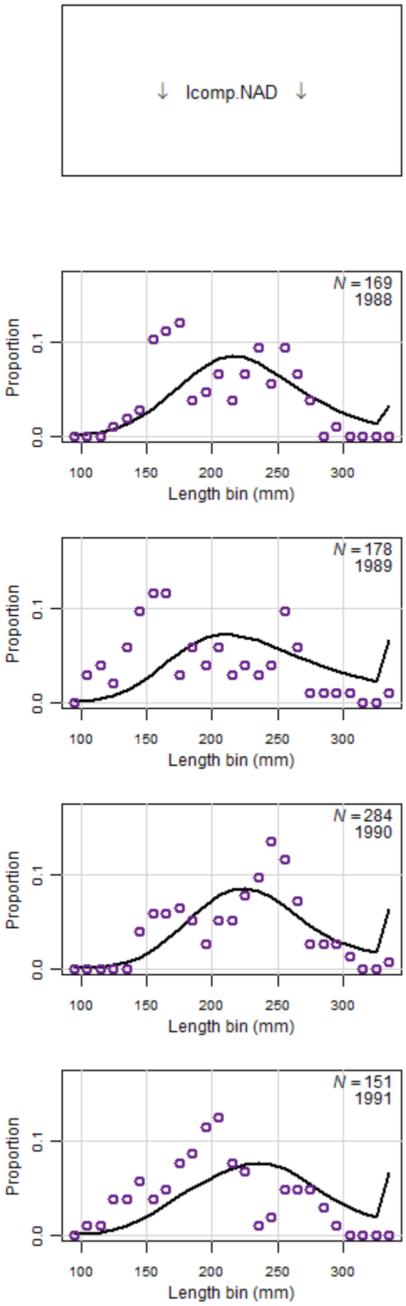


Figure 7.1.16. Continued.

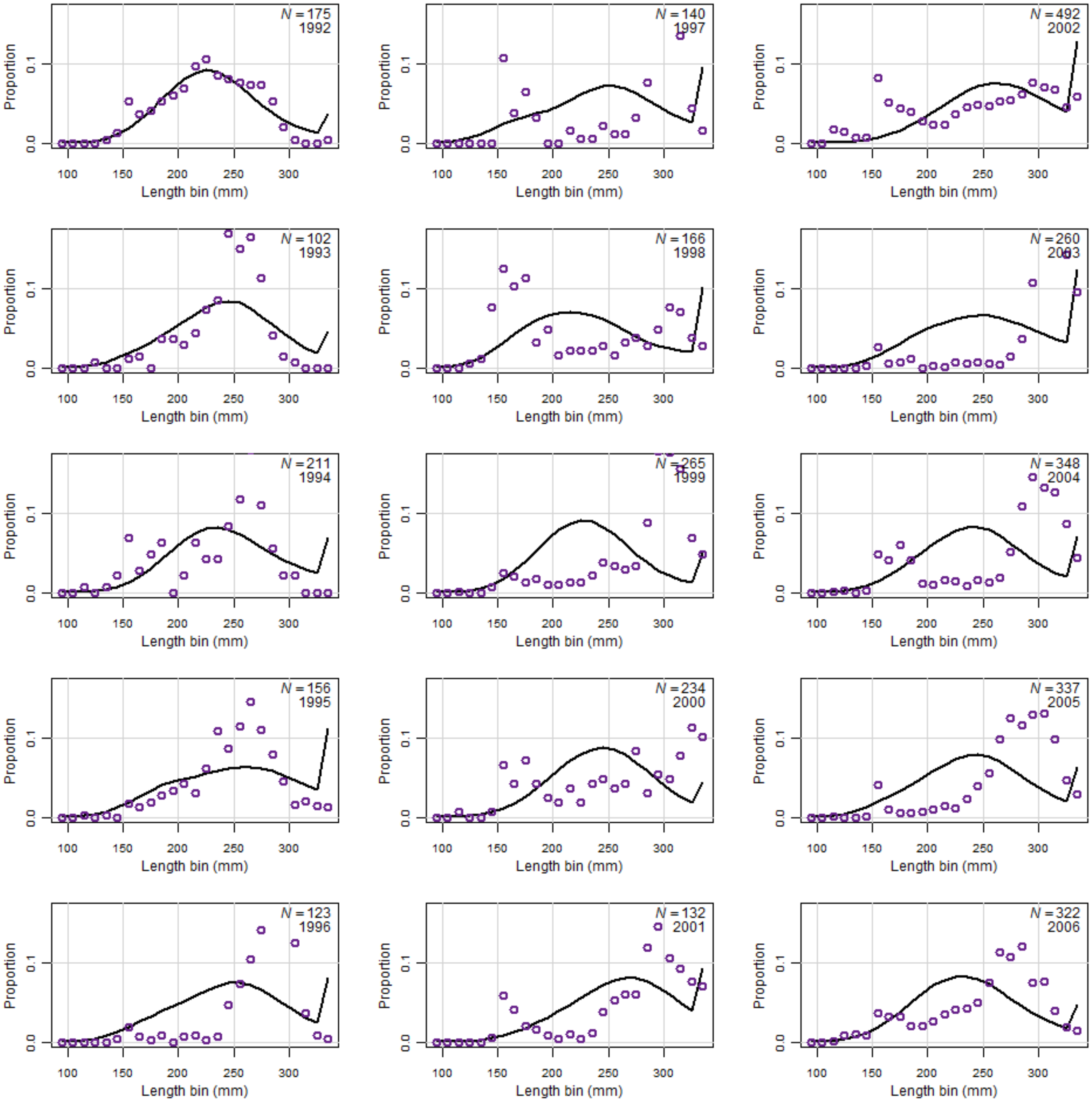


Figure 7.1.16. Continued.

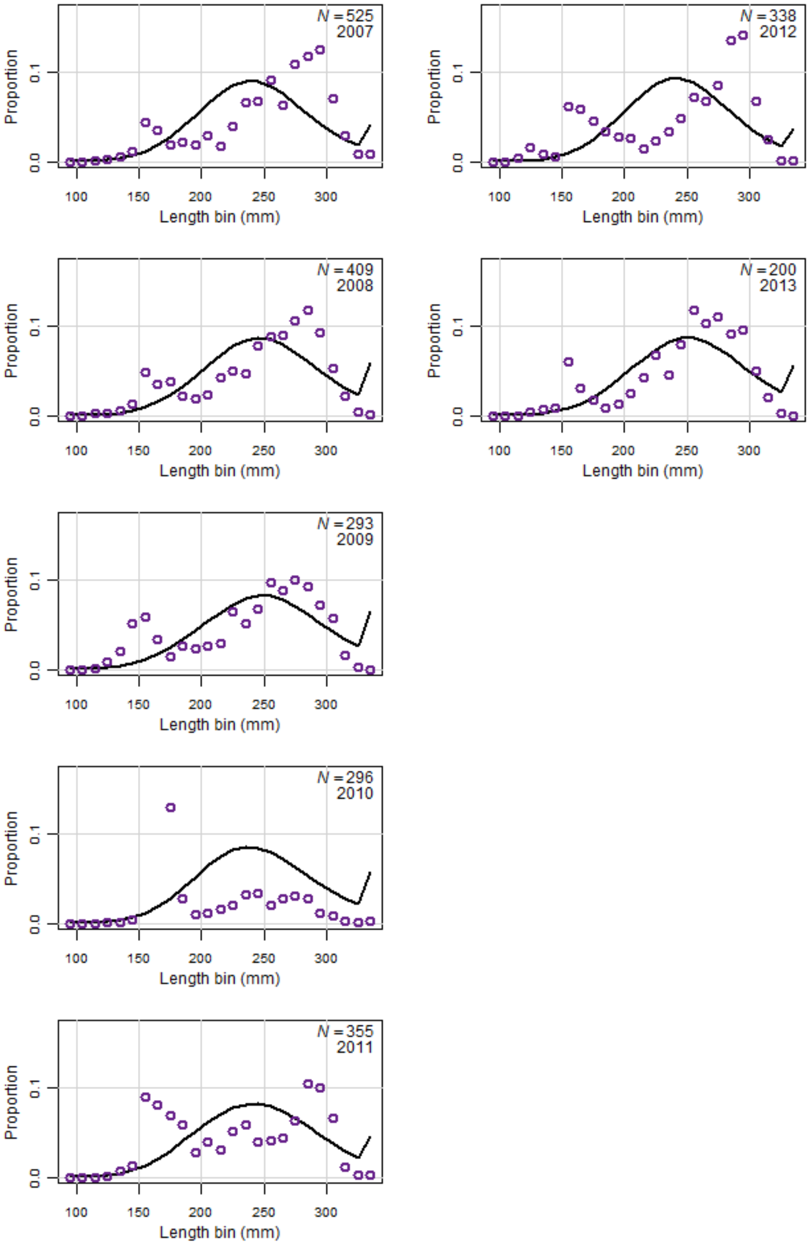


Figure 7.1.17. Annual observed and predicted length measurements of Atlantic menhaden from 1990-2013 for the SAD index.

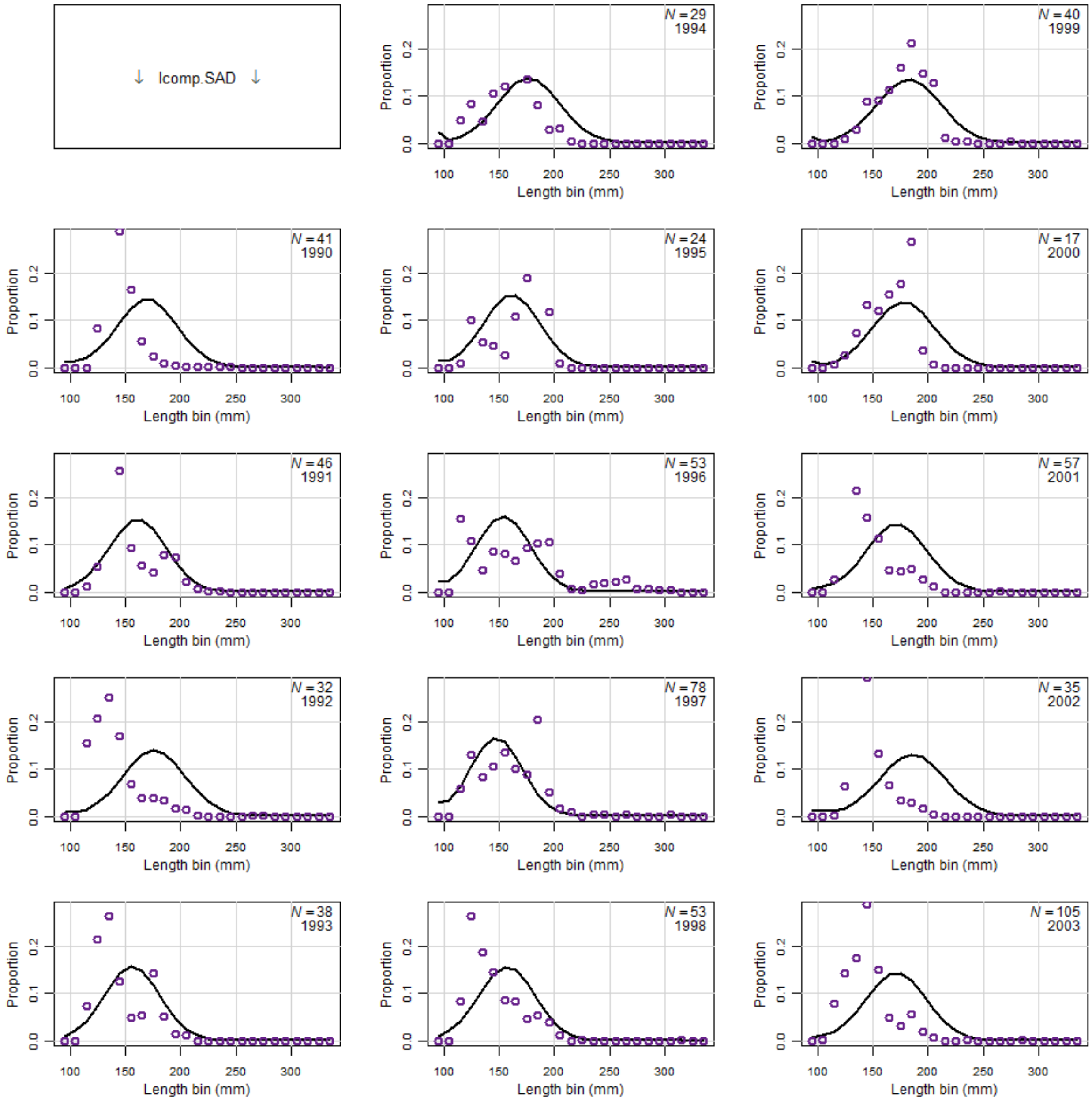


Figure 7.1.17. Continued.

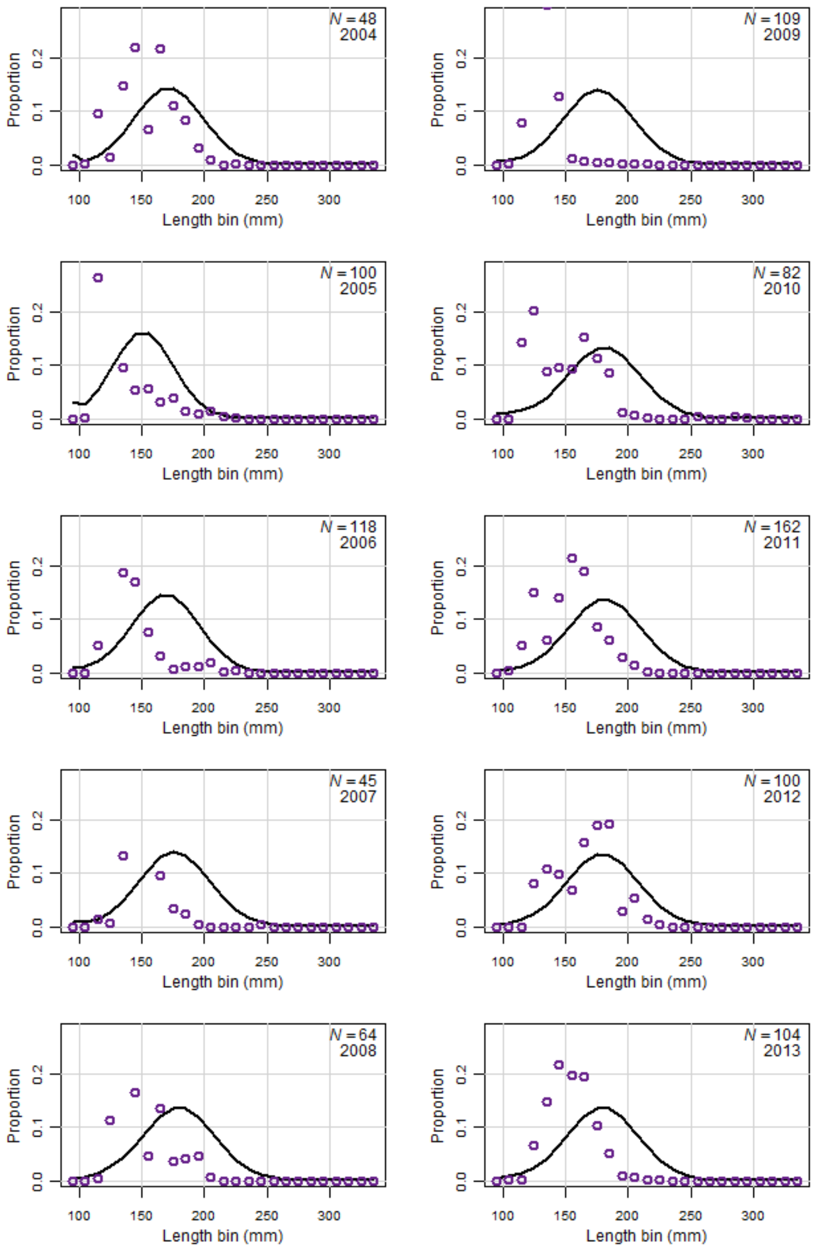
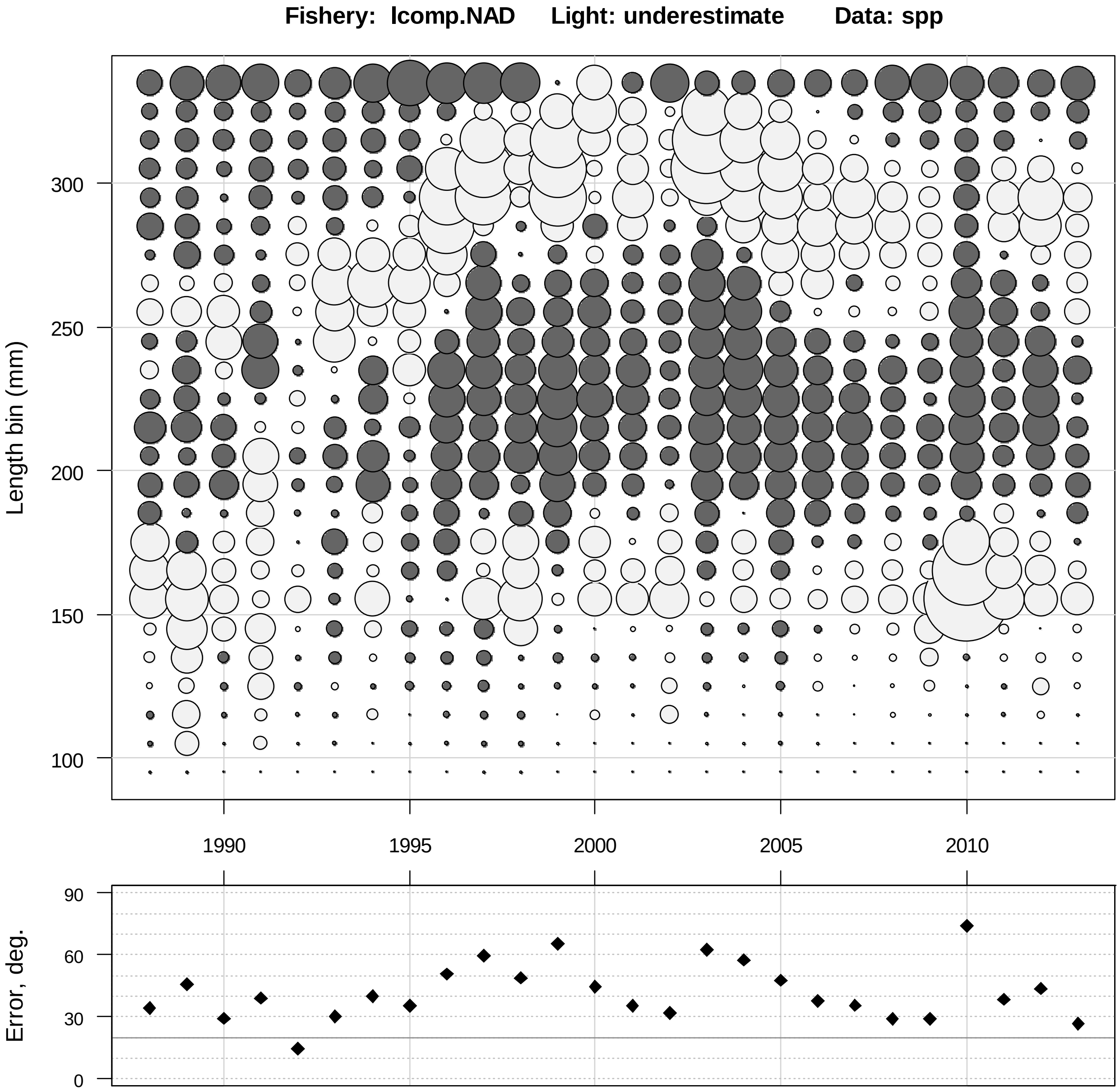


Figure 7.1.18. Relative (upper panel) and absolute (lower panel) bubble plots of the residuals of the predicted lengths for Atlantic menhaden from 1986-2013 from the NAD. The error degrees in the upper panel represents a composite fit by year across lengths, while in the lower plot contains correlations between years.



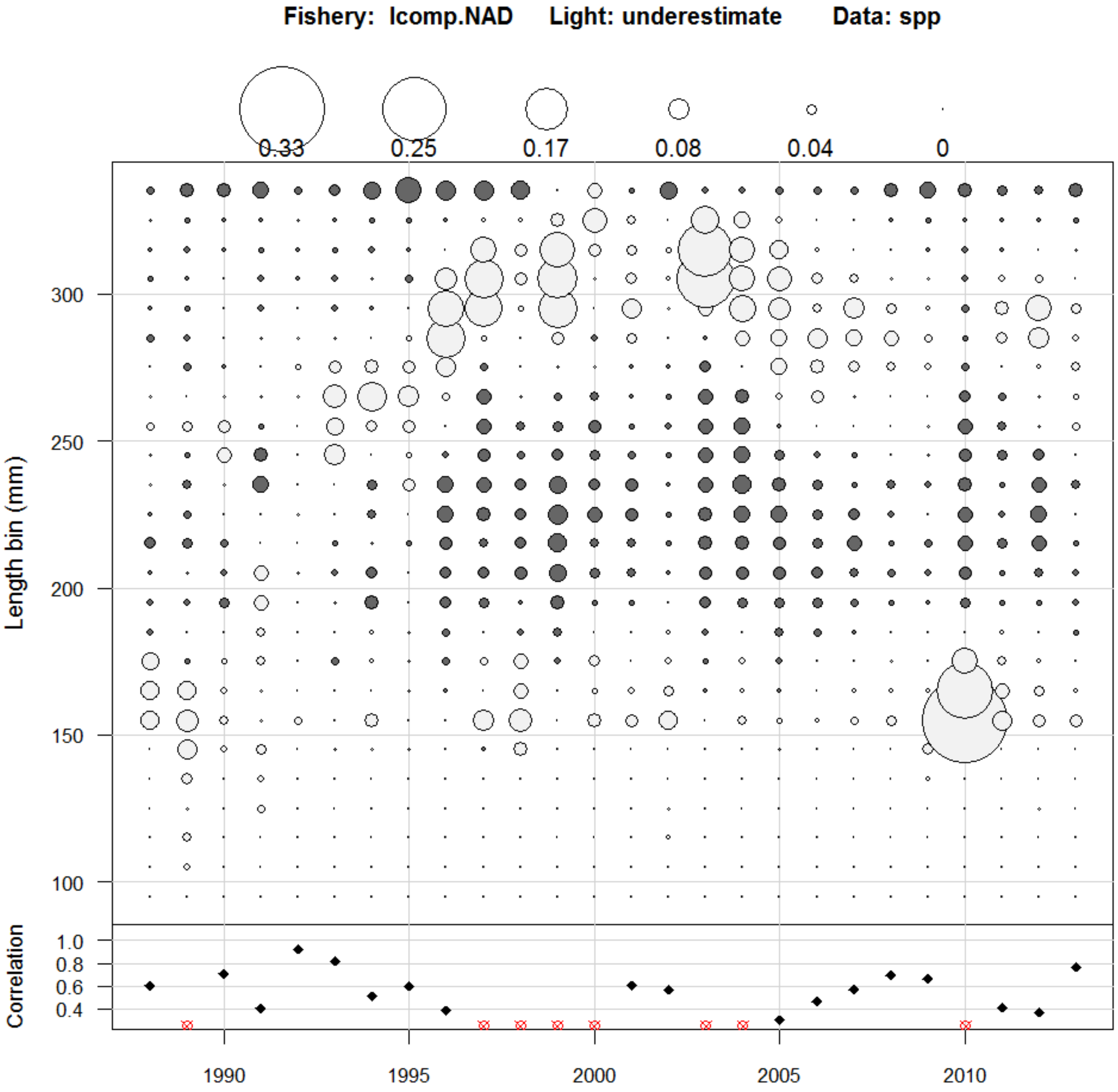
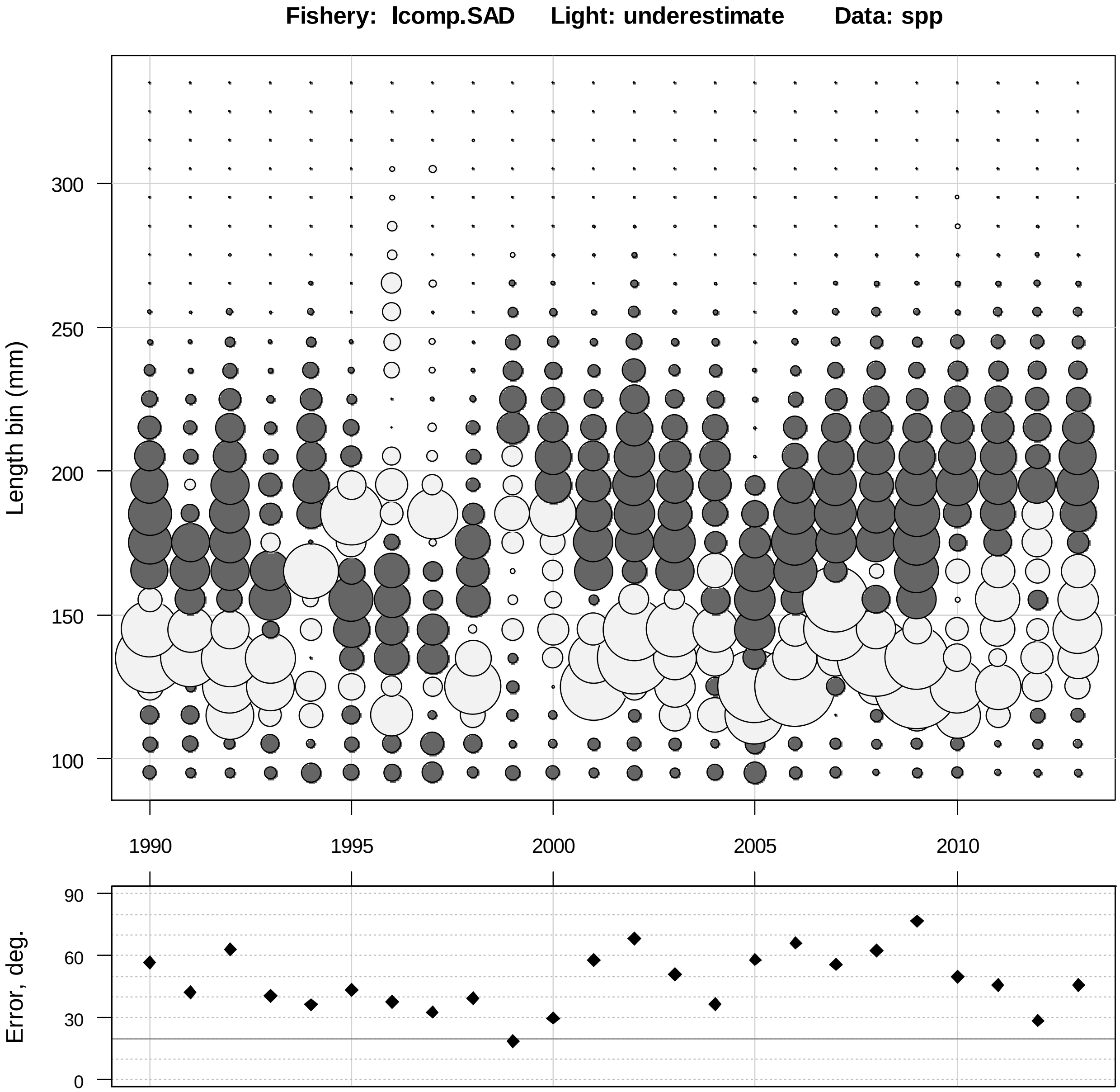

Fishery: lcomp.NAD Light: underestimate Data: spp
0.33
0.25
0.17
0.08
0.04
0
Length bin (mm)
300
250
200
150
100
Correlation
1.0
0.8
0.6
0.4
1990
1995
2000
2005
2010

Figure 7.1.19. Relative (upper panel) and absolute (lower panel) bubble plots of the residuals of the predicted lengths for Atlantic menhaden from 1990-2013 from the SAD. The error degrees in the upper panel represents a composite fit by year across lengths, while in the lower plot contains correlations between years.



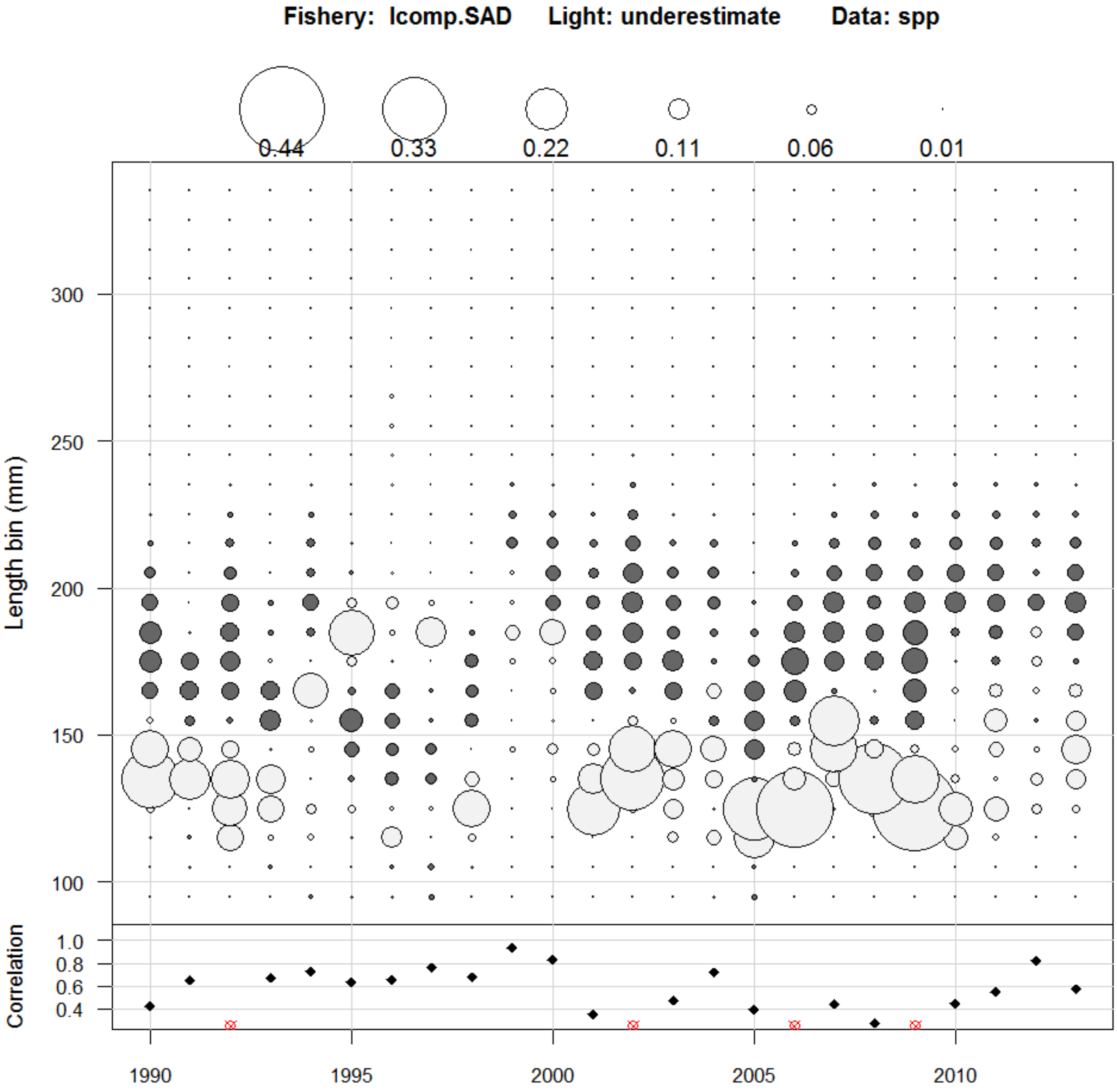

Fishery: lcomp.SAD Light: underestimate Data: spp
0.44
0.33
0.22
0.11
0.06
0.01
Length bin (mm)
300
250
200
150
100
Correlation
1.0
0.8
0.6
0.4
1990
1995
2000
2005
2010

Figure 7.2.1.1. Selectivity for the northern commercial reduction fleet for 1955-1969.

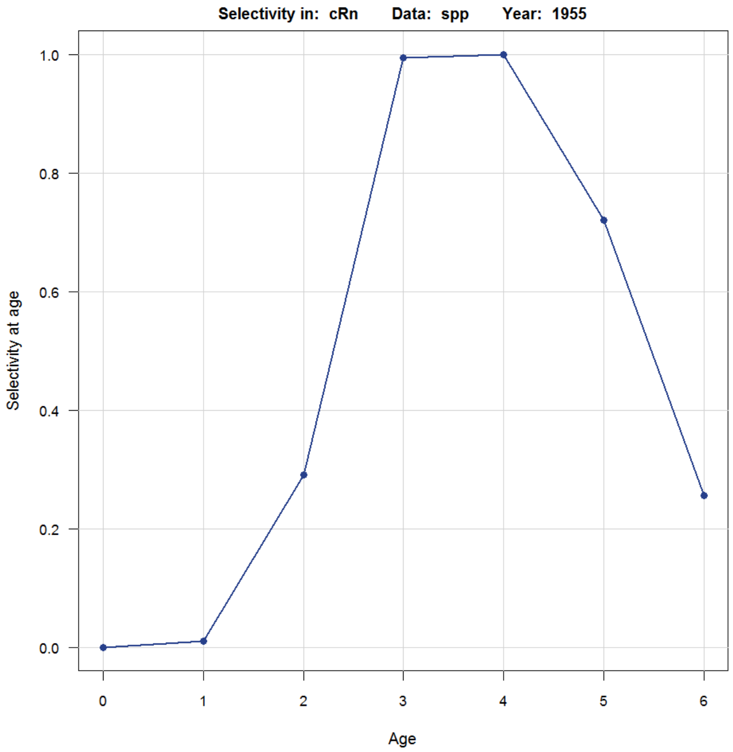


Figure 7.2.1.2. Selectivity for the northern commercial reduction fleet for 1970-1993.

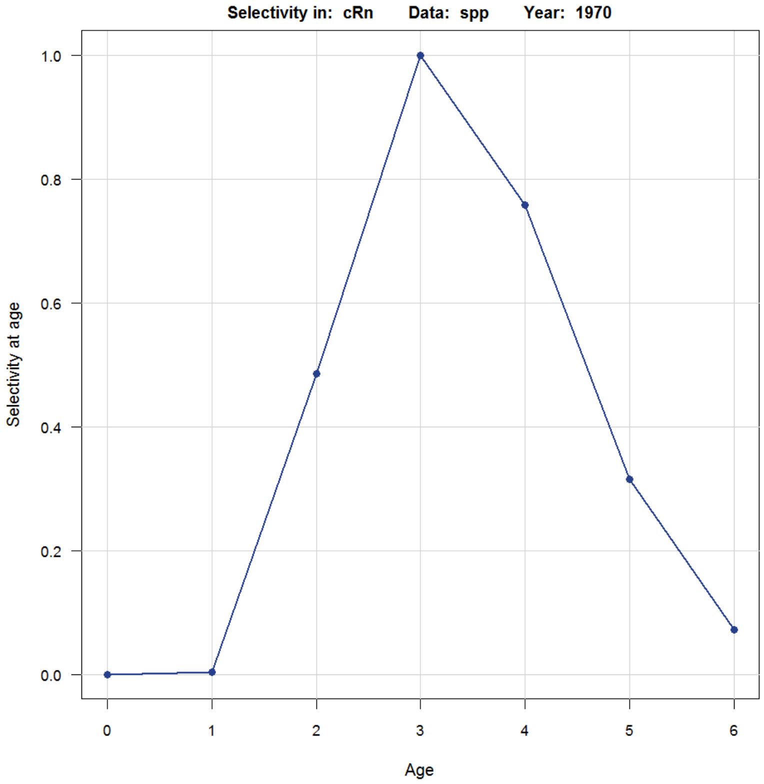


Figure 7.2.1.3. Selectivity for the northern commercial reduction fleet for 1994-2013.

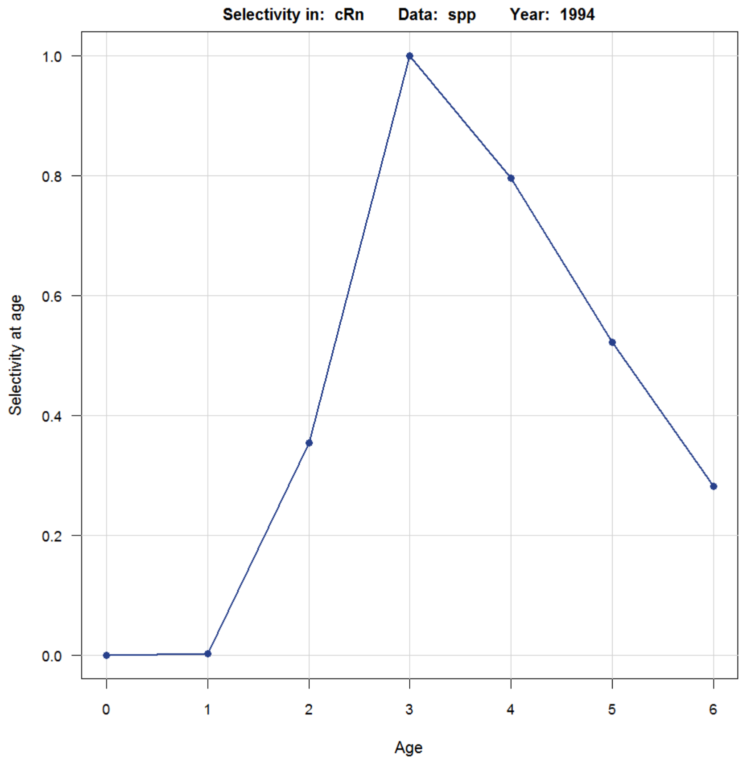


Figure 7.2.1.4. Selectivity for the southern commercial reduction fleet for 1955-1971.

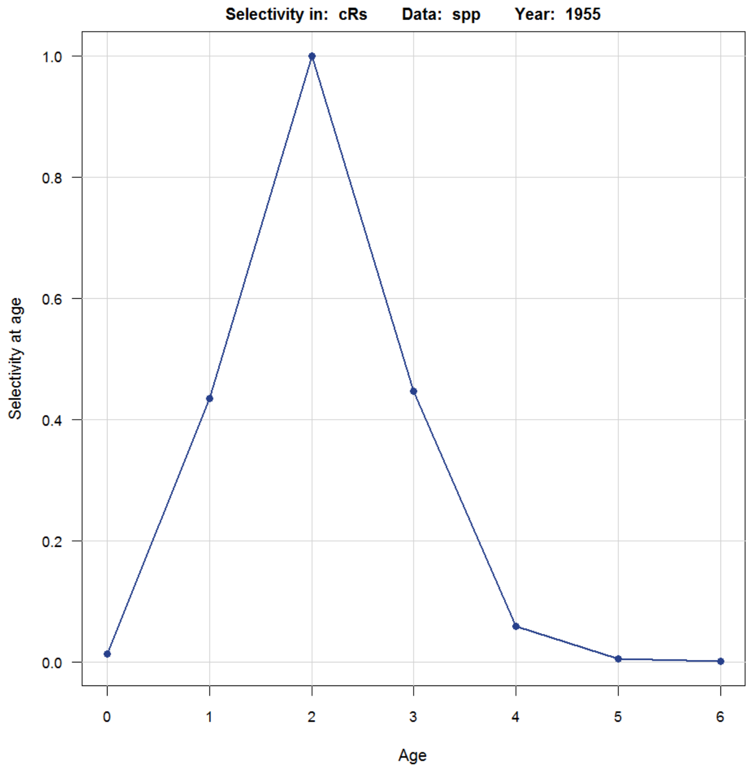


Figure 7.2.1.5. Selectivity for the southern commercial reduction fleet for 1972-2004.

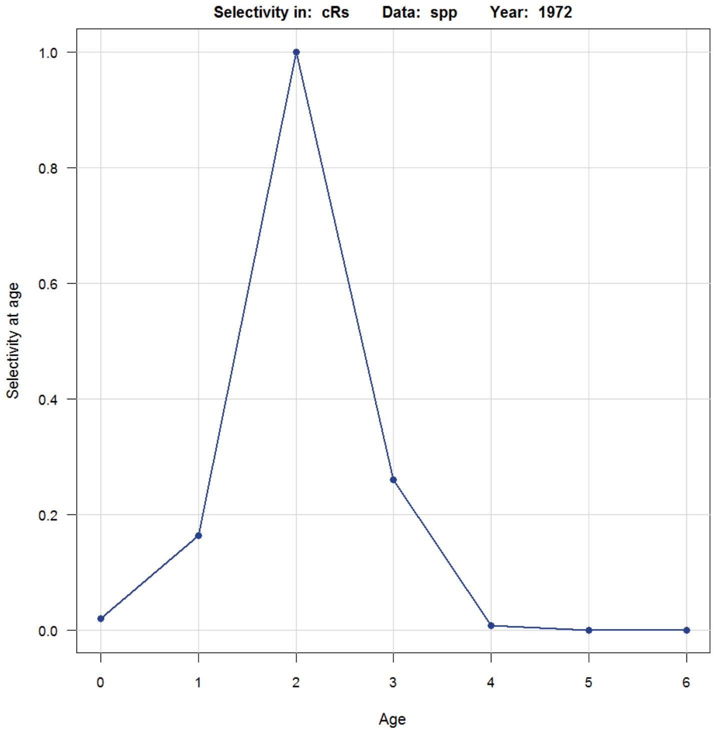


Figure 7.2.1.6. Selectivity for the southern commercial reduction fleet for 2005-2013.

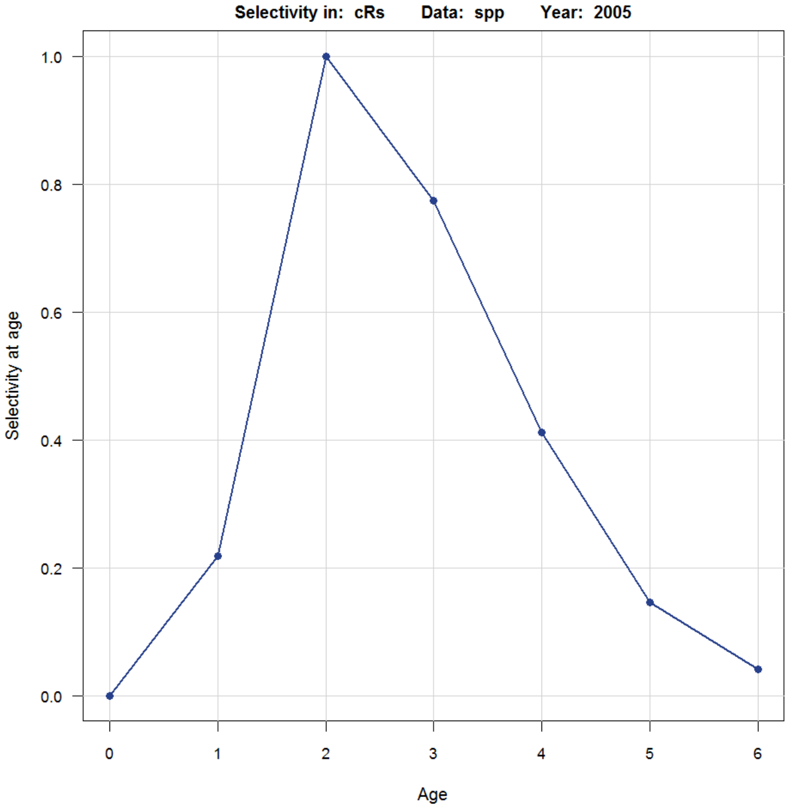


Figure 7.2.1.7. Selectivity for the northern commercial bait fleet for 1955-2013**.**

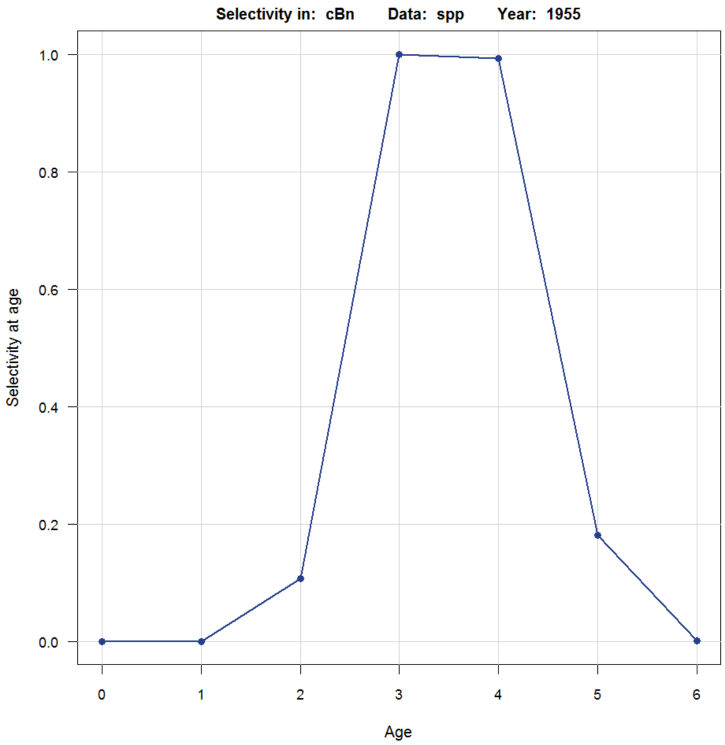


Figure 7.2.1.8. Selectivity for the southern commercial bait fleet for 1955-2013.

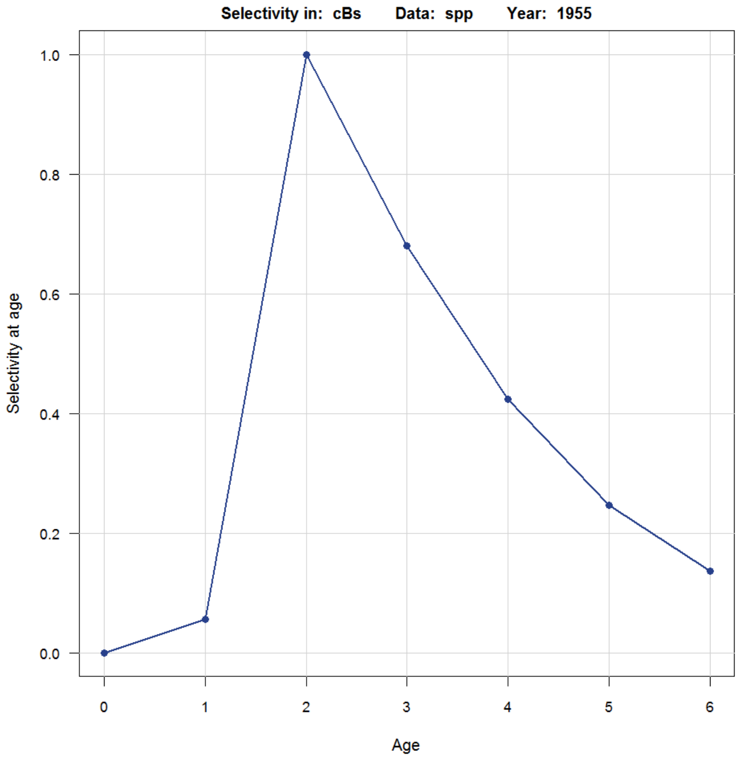


Figure 7.2.1.9. Selectivity for the NAD index for 1980-2013.

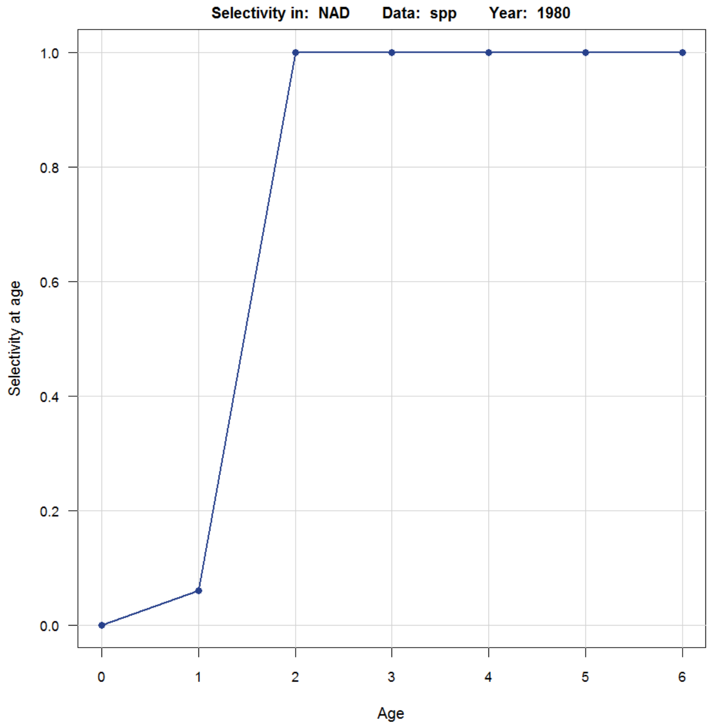


Figure 7.2.1.10. Selectivity for the SAD index for 1990-2013.

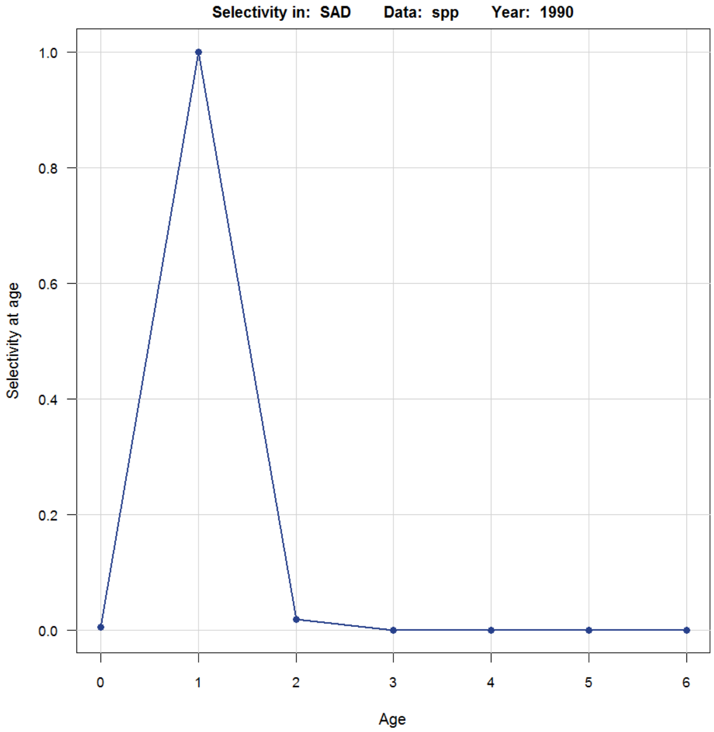


Figure 7.2.2.1. Fishing mortality rate for the northern commercial reduction fishery from 1955-2013.

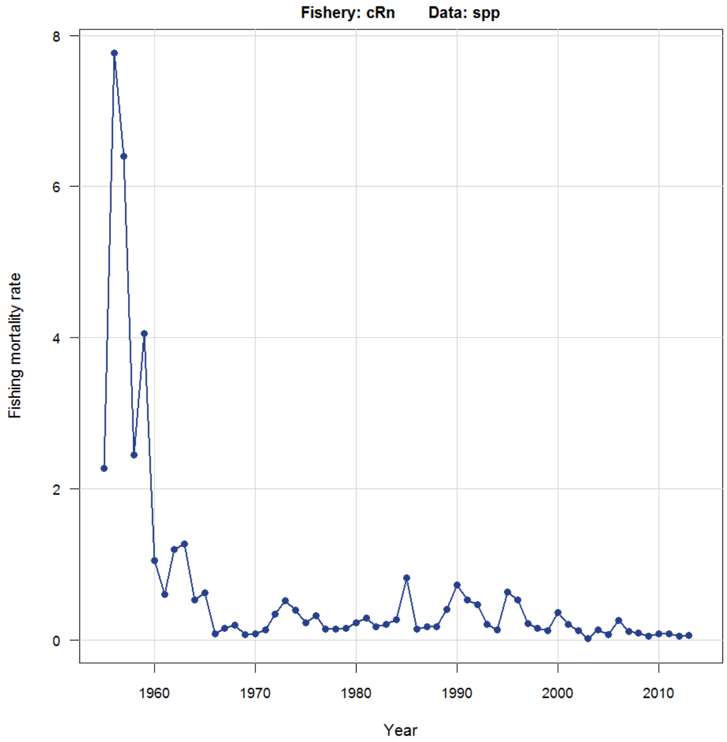


Figure 7.2.2.2. Fishing mortality rate for the southern commercial reduction fishery from 1955-2013.

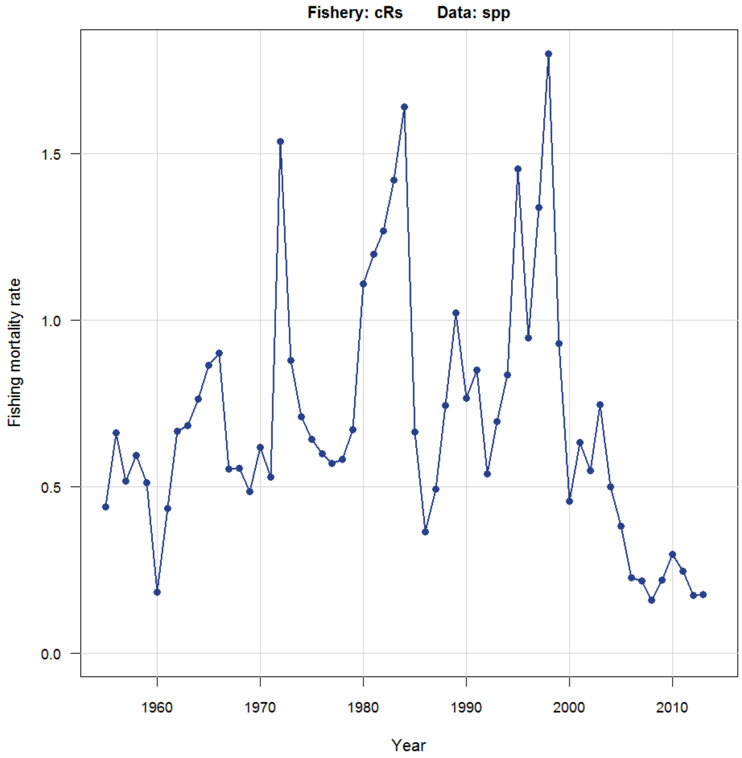


Figure 7.2.2.3. Fishing mortality rate for the northern commercial bait fishery from 1955-2013.

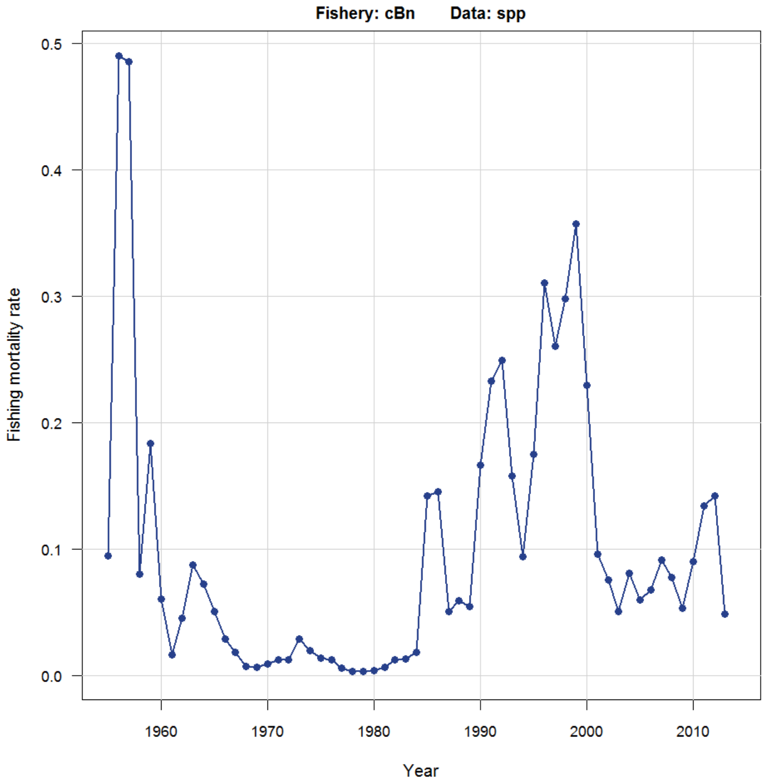


Figure 7.2.2.4. Fishing mortality rate for the southern commercial bait fishery from 1955-2013.

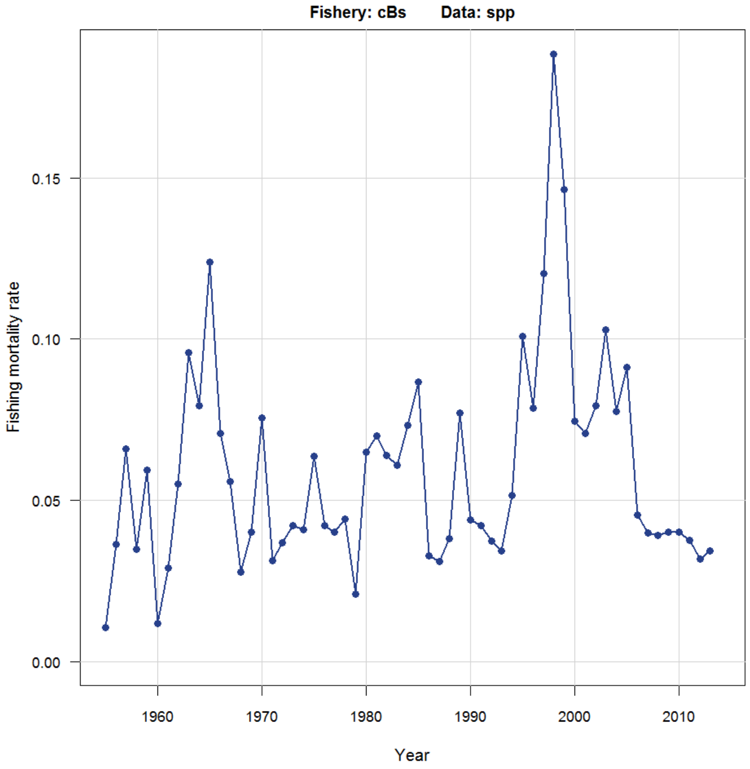
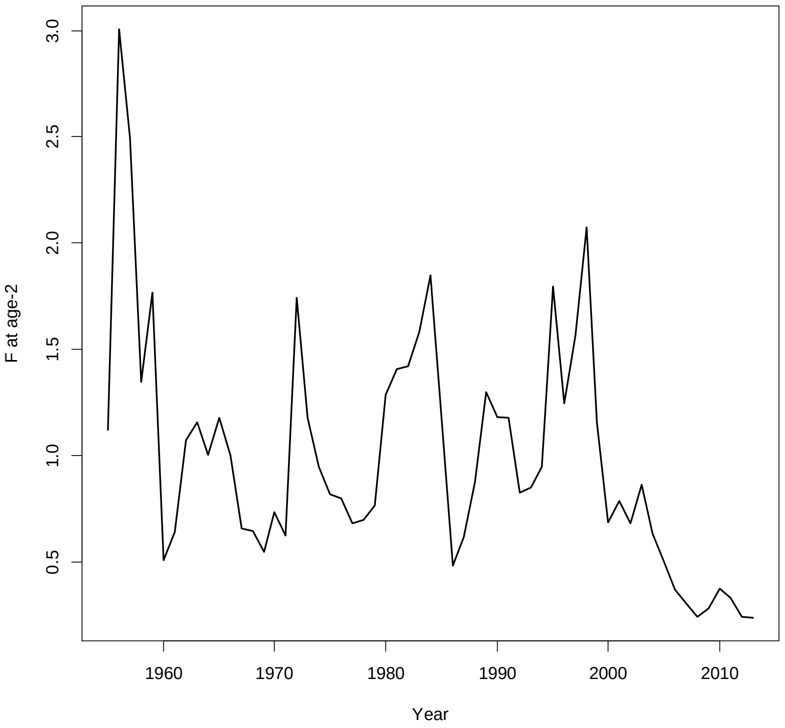


Figure 7.2.2.5. Full F at age 2 (upper panel) and at age 3 (lower panel) over the time course of the fishery from 1955-2013.



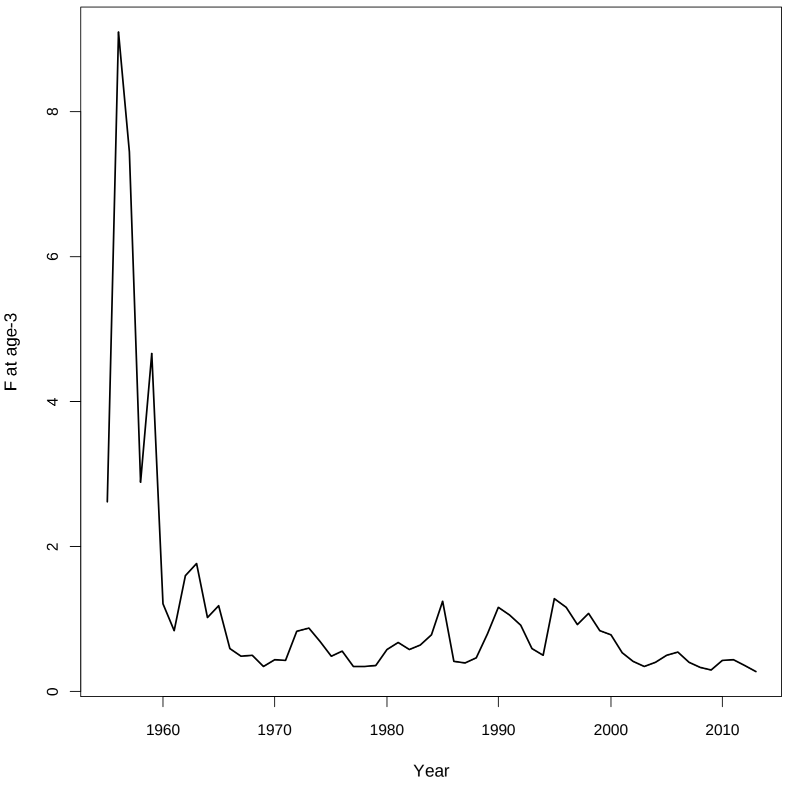


Figure 7.2.3.1. Numbers at age (upper panel) and proportion of numbers at age (lower panel) estimated from the base run of the BAM for ages 0-6+ during the time period 1955-2013.

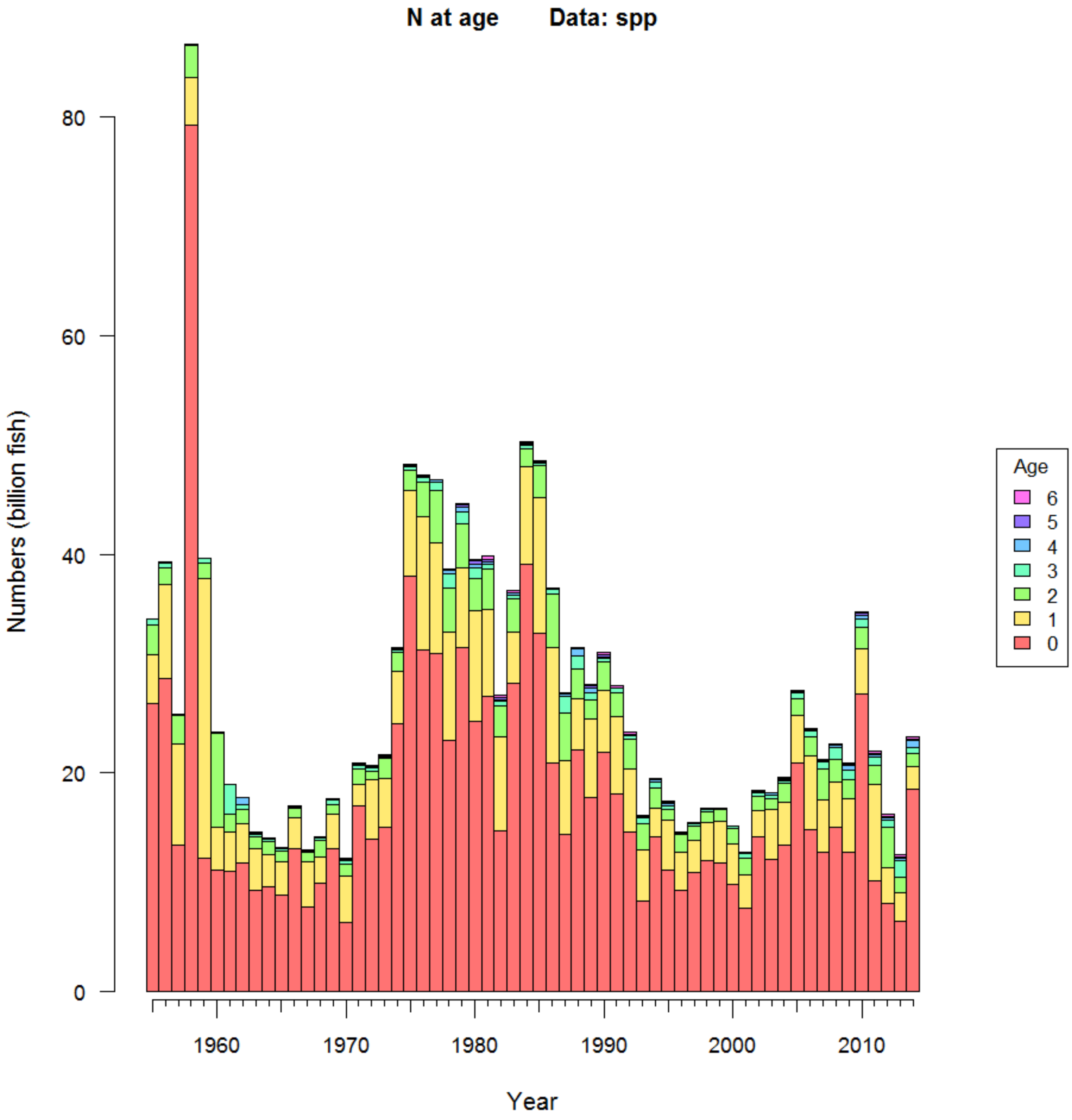


Figure 7.2.3.1. Continued.

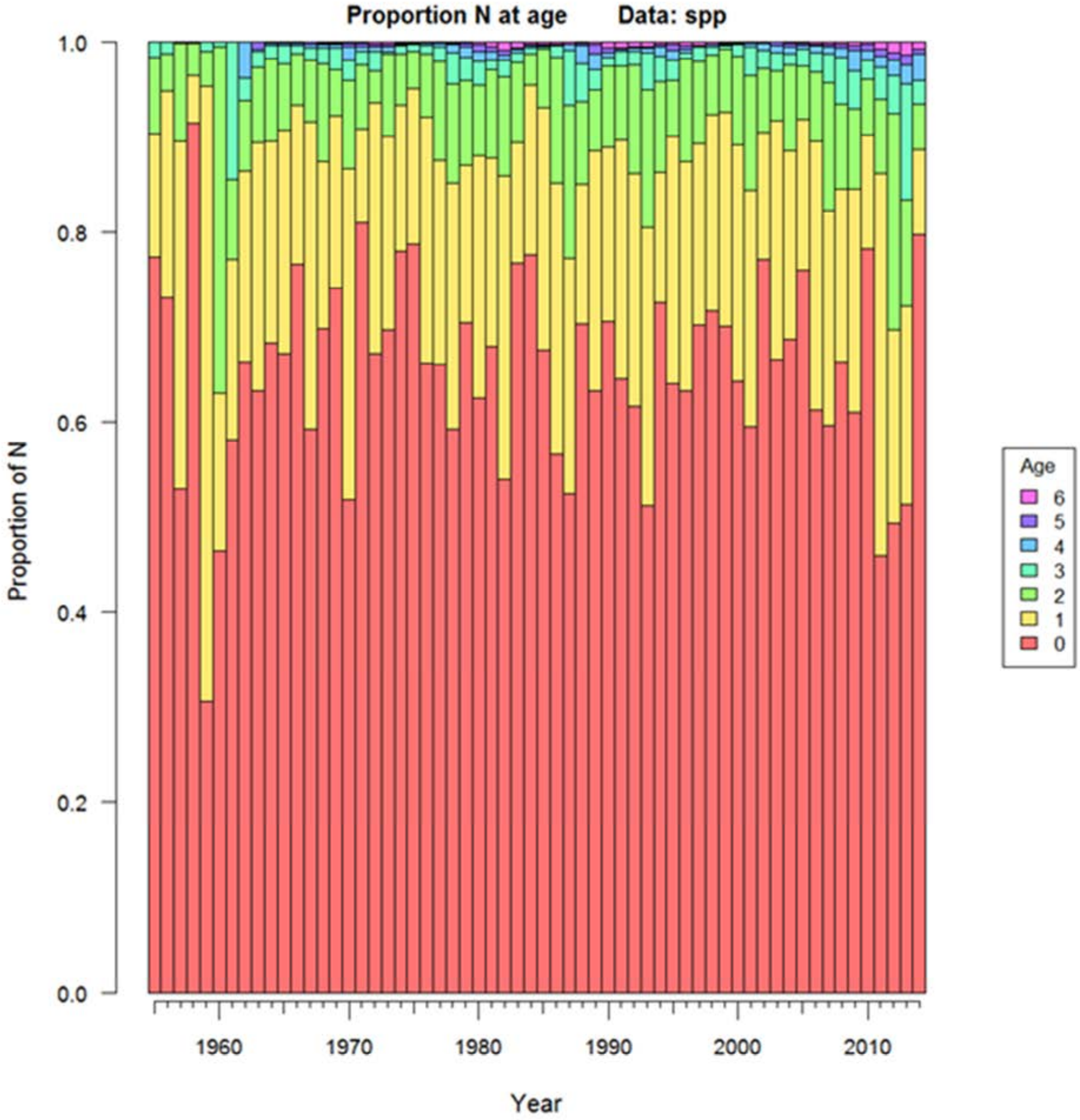


Figure 7.2.3.2. Fecundity in billions of eggs over time, 1955-2014, with the last year being a projection based on 2013 mortality.

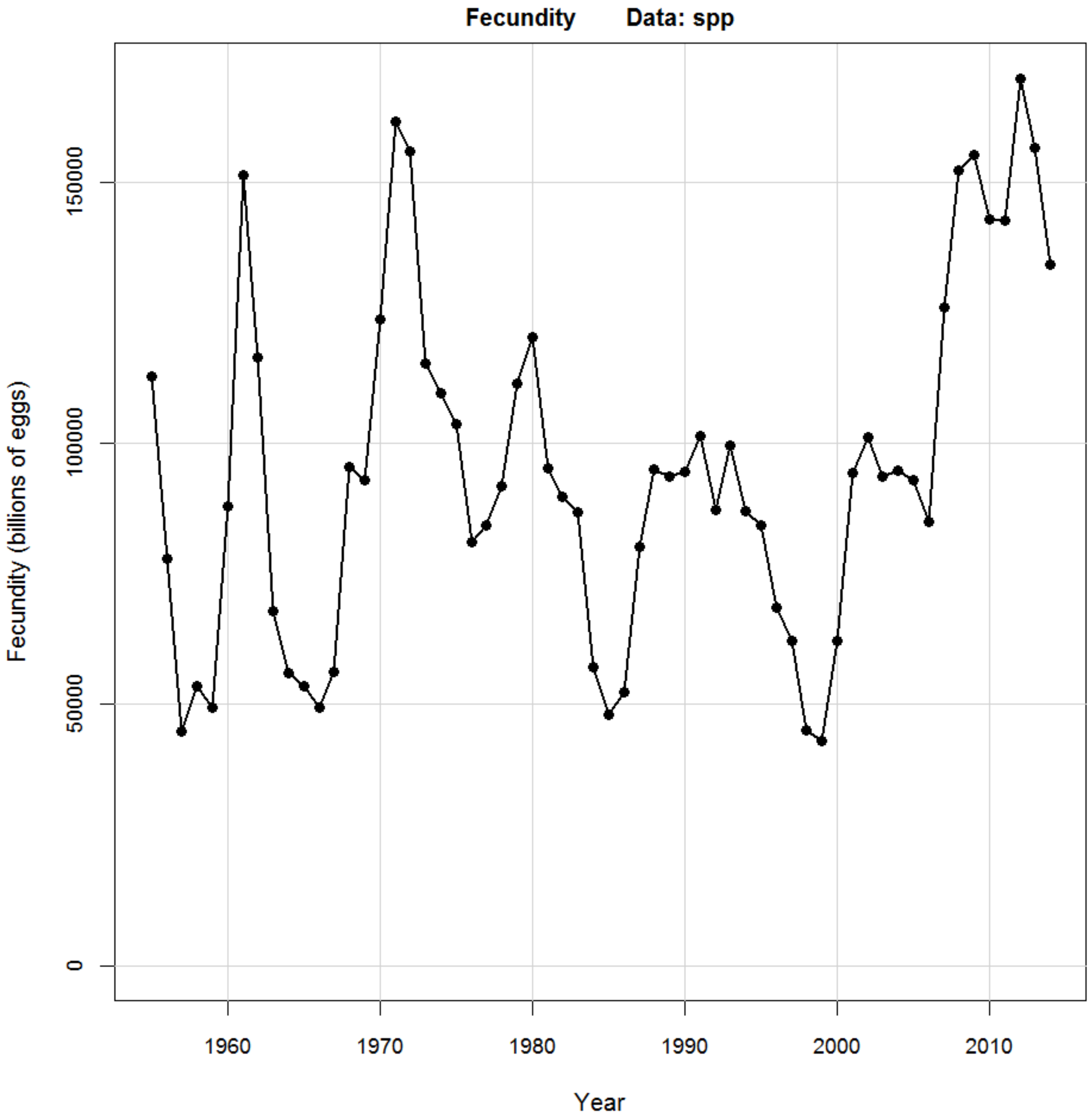


Figure 7.2.3.3. Biomass (upper panel) and biomass at age (lower panel) over time as predicted from the base run of the BAM for Atlantic menhaden.

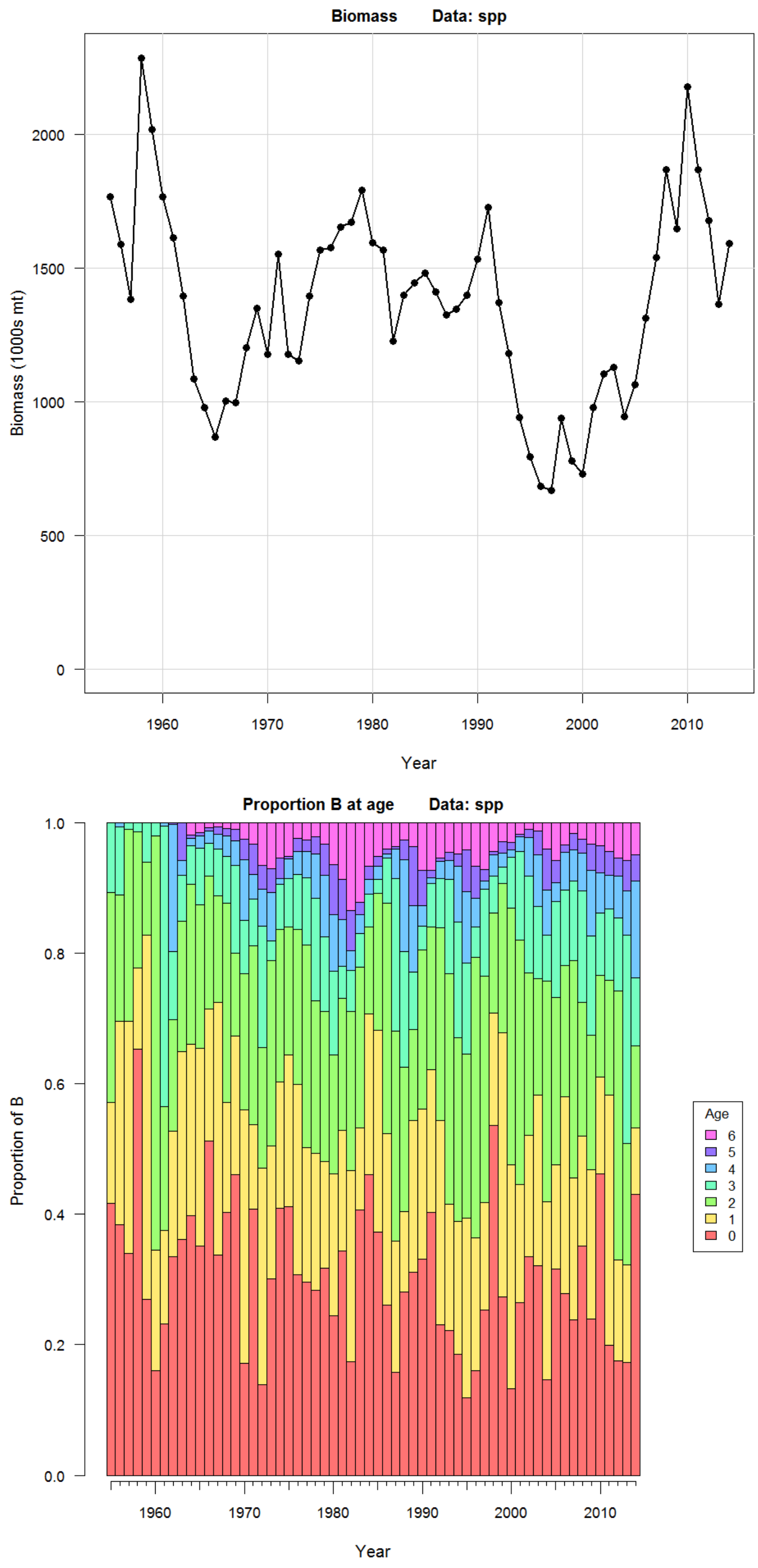


Figure 7.2.3.4. Biomass (1000s mt) and abundance over time for Atlantic menhaden from 1959-2013.

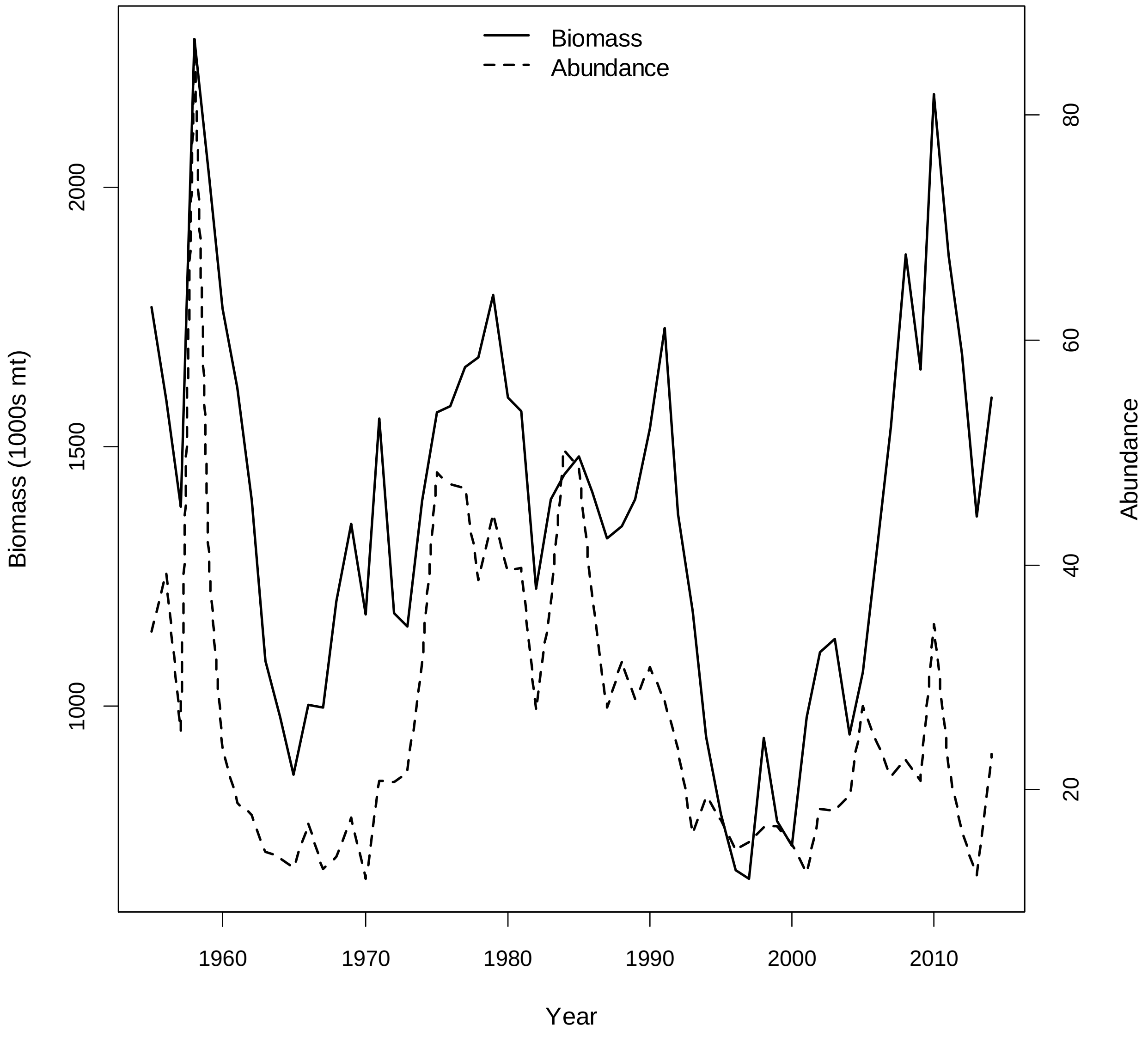


Figure 7.2.3.5. Number of recruits in billions of fish predicted from the base run of BAM for 1955-2013.

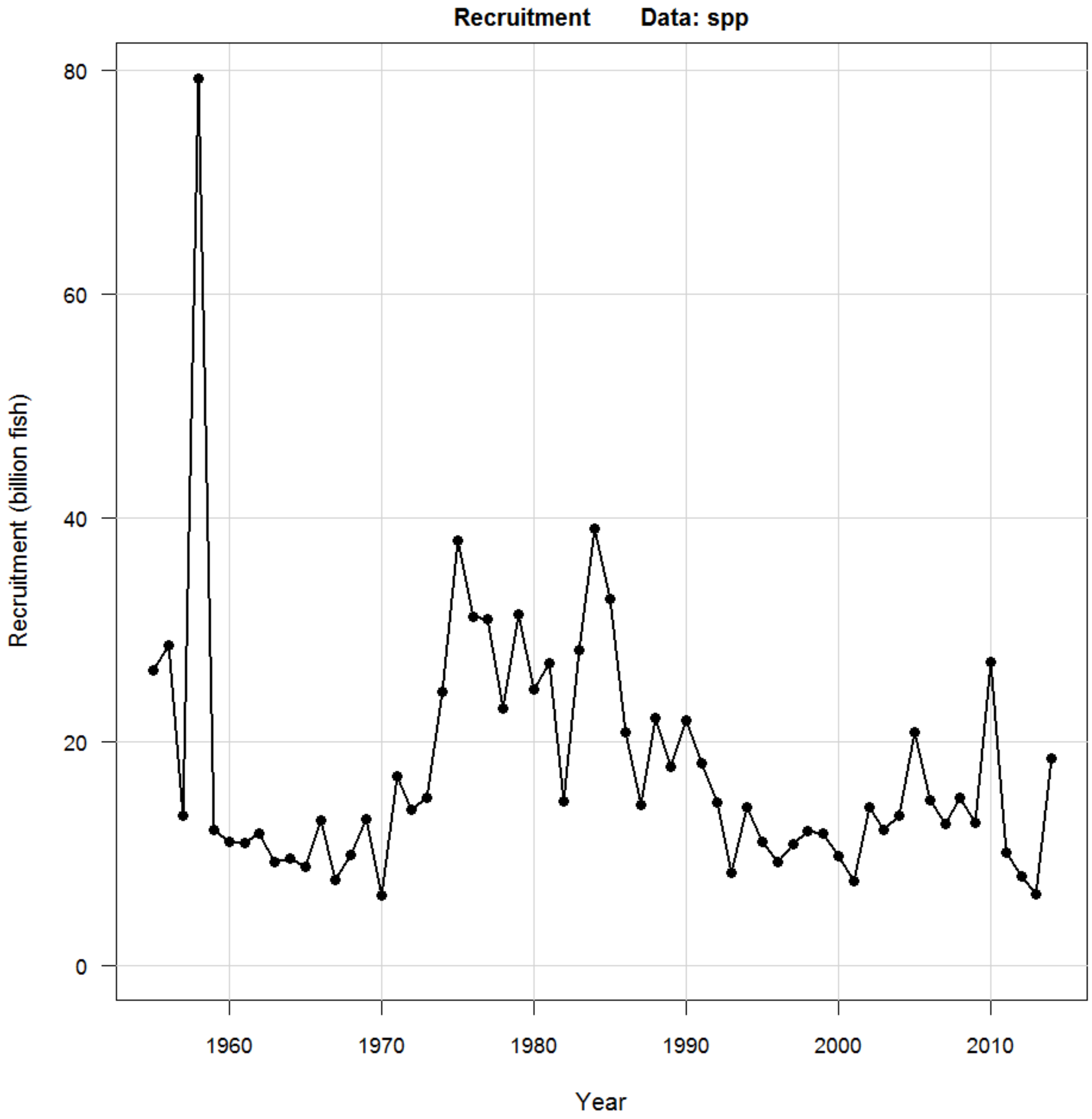


Figure 7.2.3.6. Deviations in log recruitment from 1955-2013 with a loess smoother.

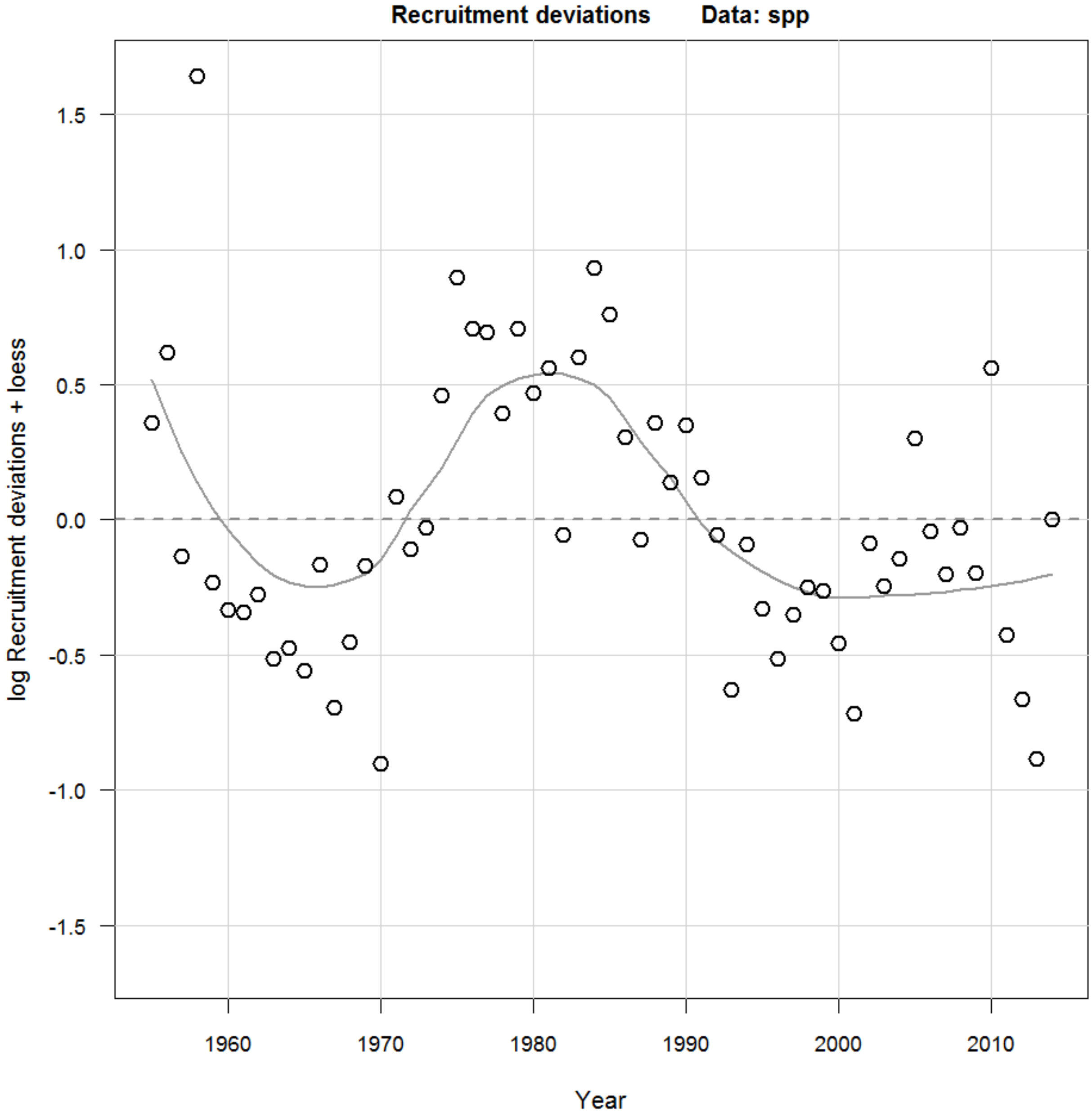
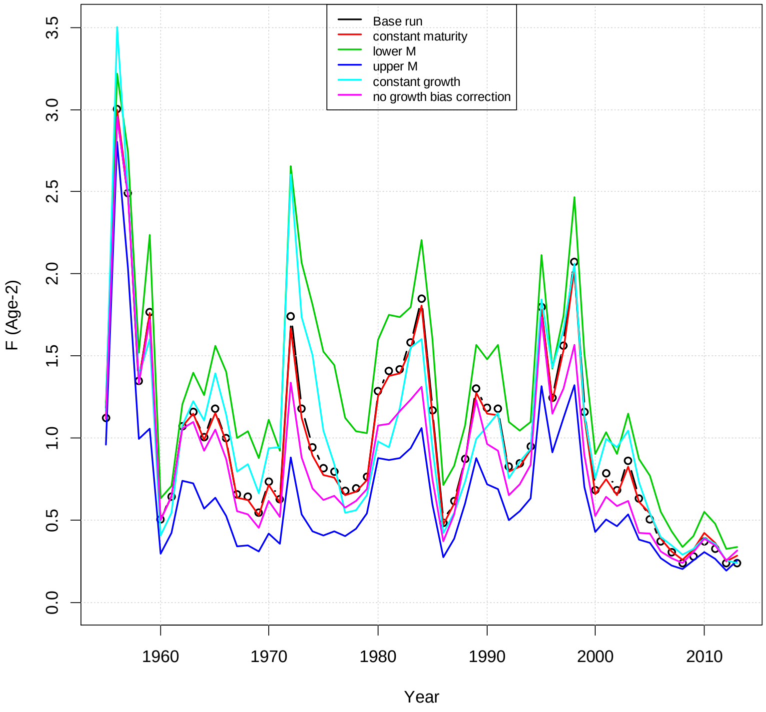


Figure 7.4.1.1. Full F at age-2 (upper) and age-3 (lower) for sensitivity runs considering differences in growth and life history parameters in the assessment model.



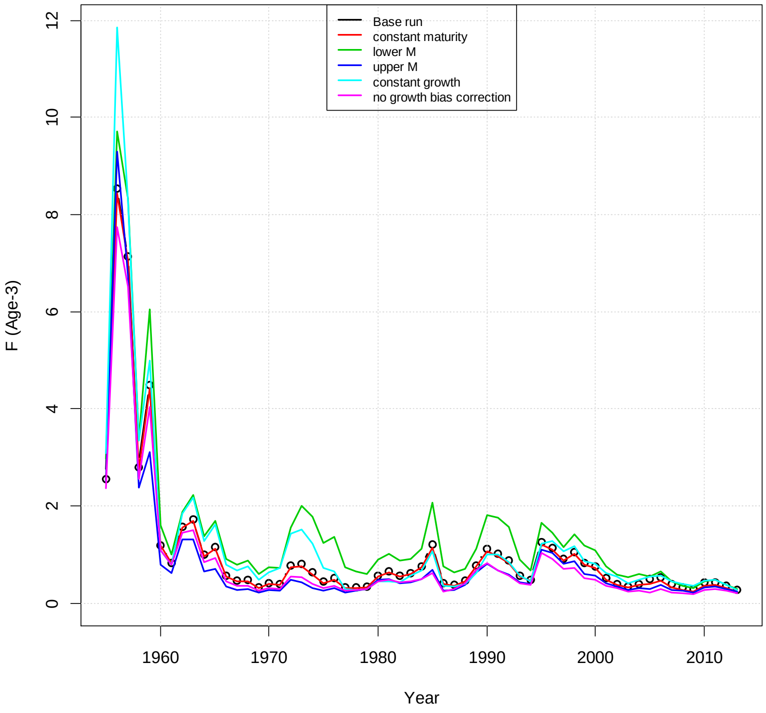
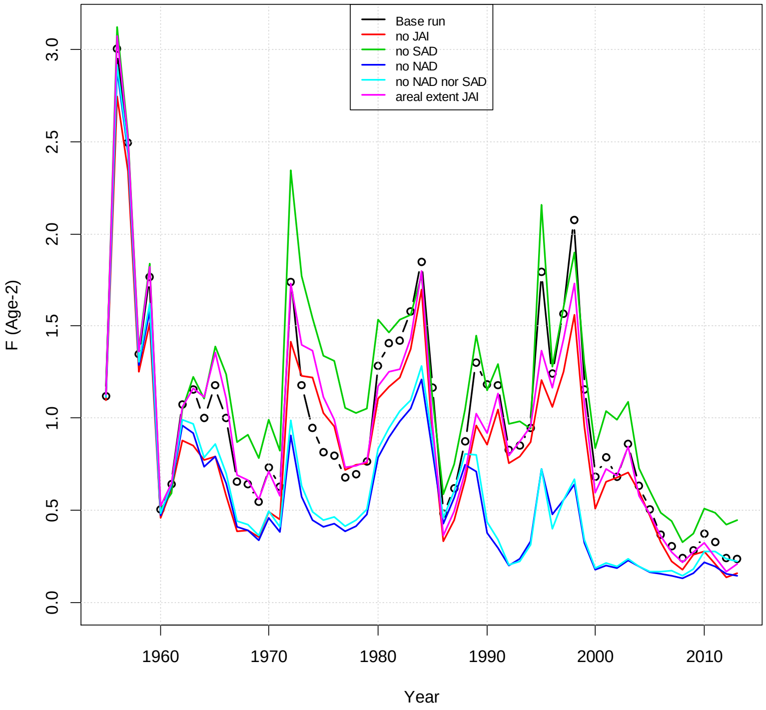


Figure 7.4.1.2. Full F at age-2 (upper) and age-3 (lower) for sensitivity runs considering differences in indices in the assessment model.



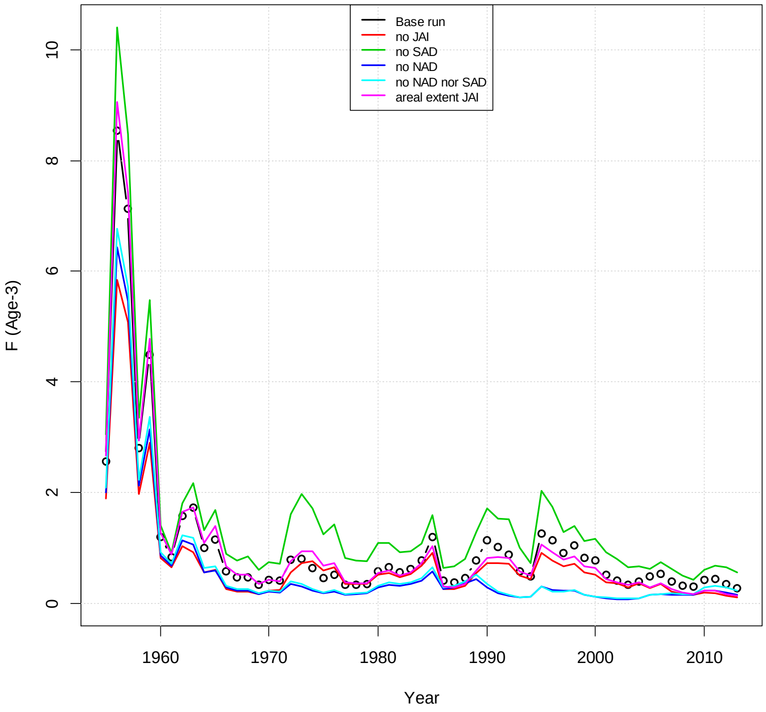
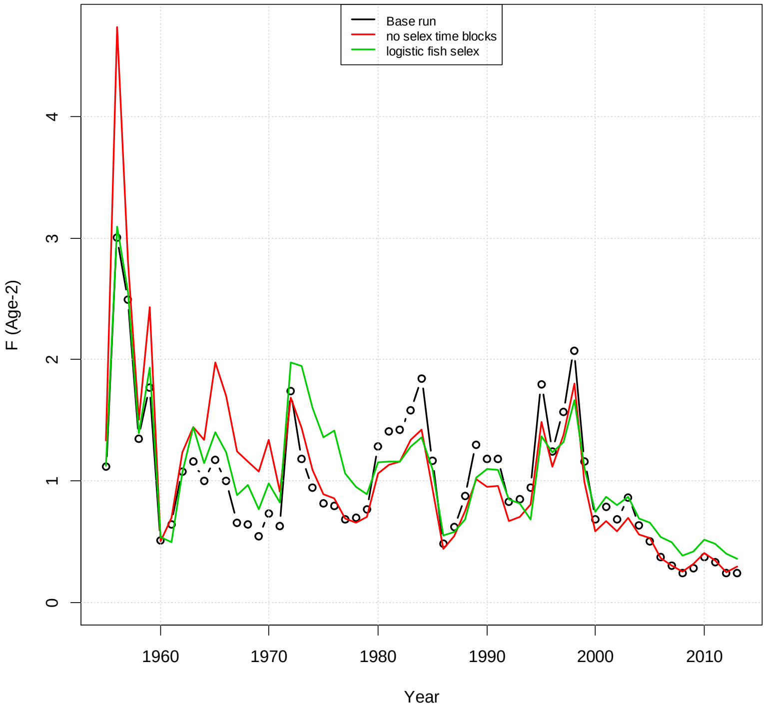


Figure 7.4.1.3. Full F at age-2 (upper) and age-3 (lower) for sensitivity runs considering differences in fishery selectivity in the assessment model.



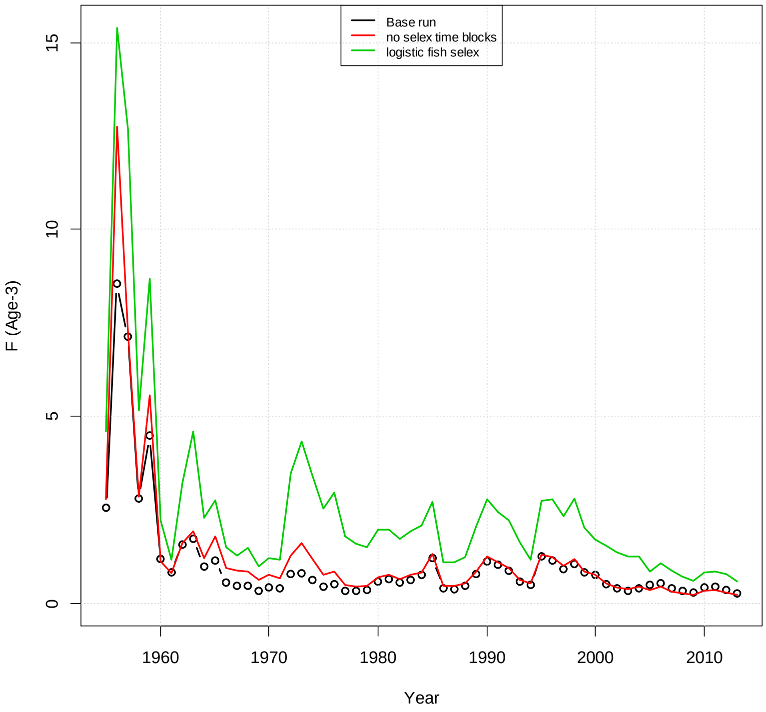
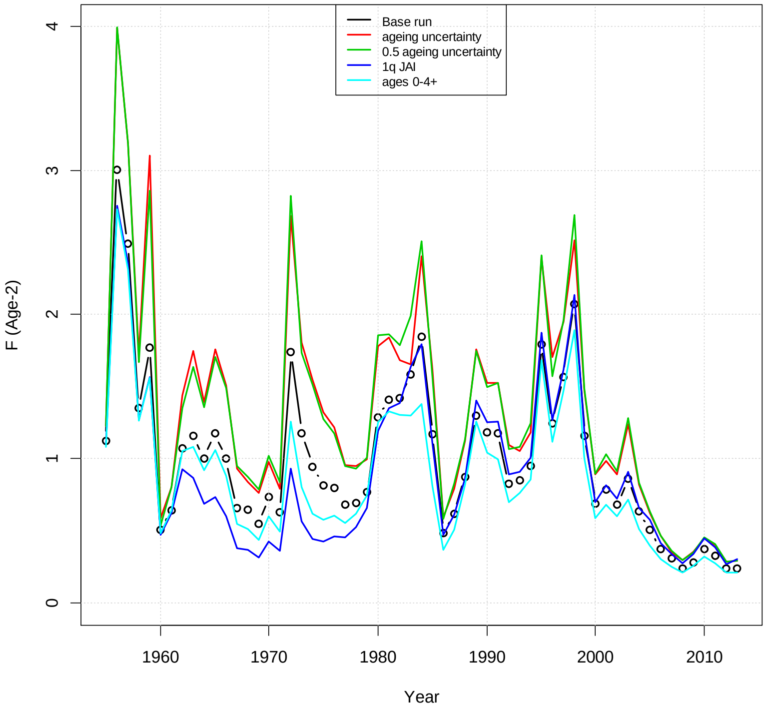


Figure 7.4.1.4. Full F at age-2 (upper) and age-3 (lower) for sensitivity runs considering differences in ageing uncertainty, catchability for the JAI index, and ages modeled in the assessment model.



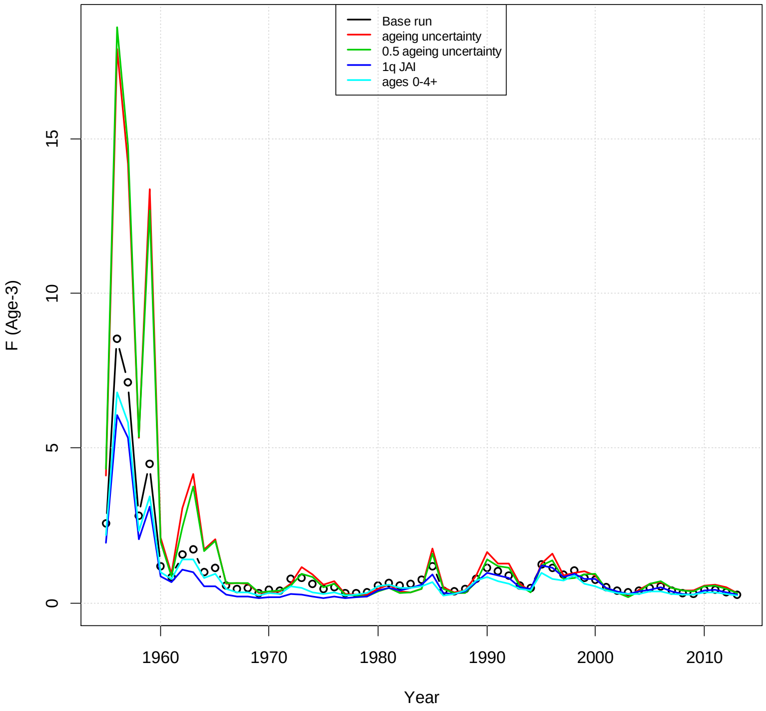
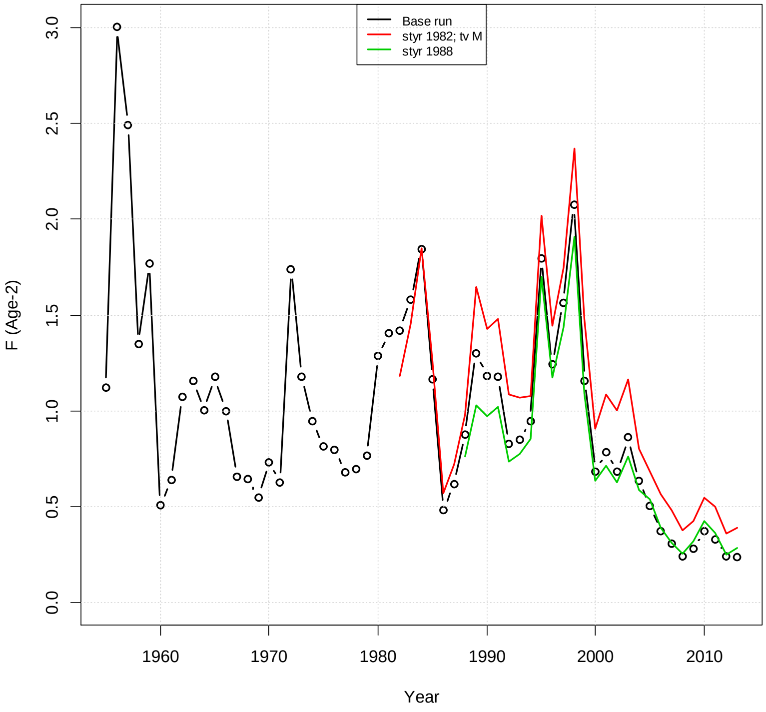


Figure 7.4.1.5. Full F at age-2 (upper) and age-3 (lower) for sensitivity runs considering differences in start year of the assessment model.



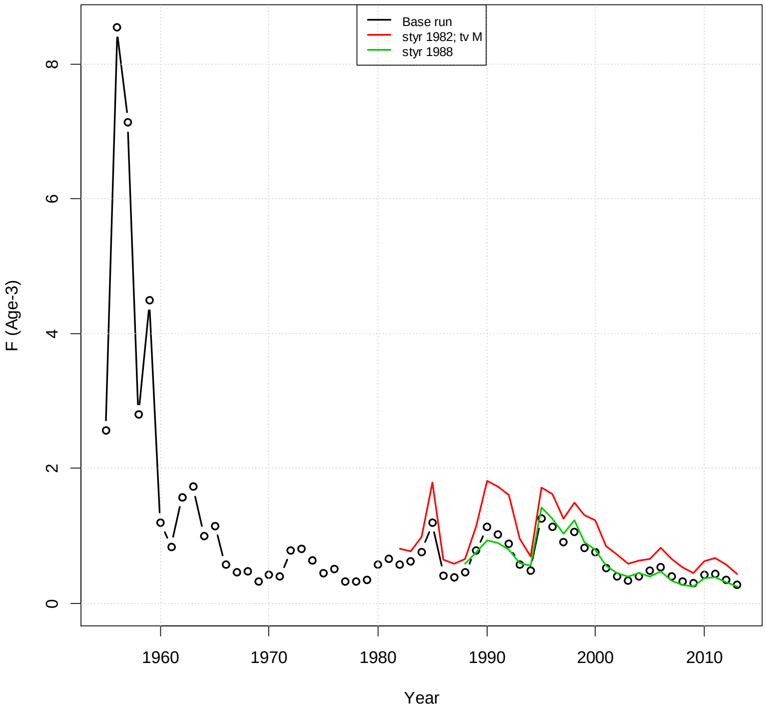
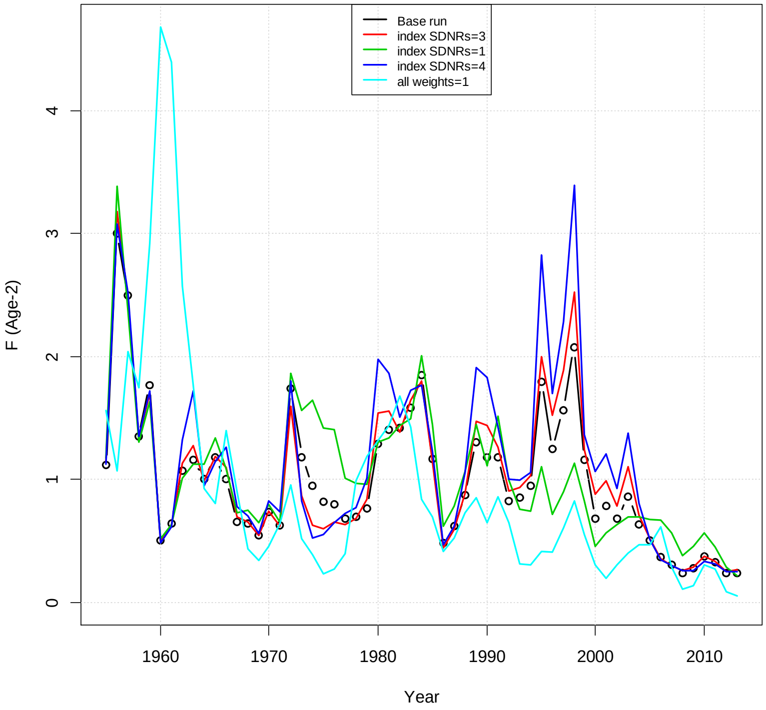


Figure 7.4.1.6. Full F at age-2 (upper) and age-3 (lower) for sensitivity runs considering differences in weighting of the likelihood components for the assessment model.



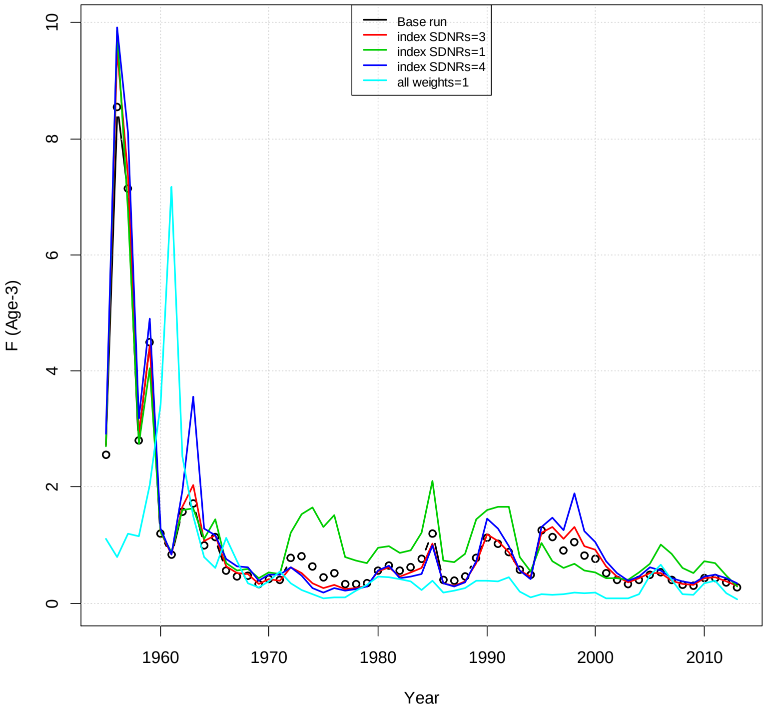
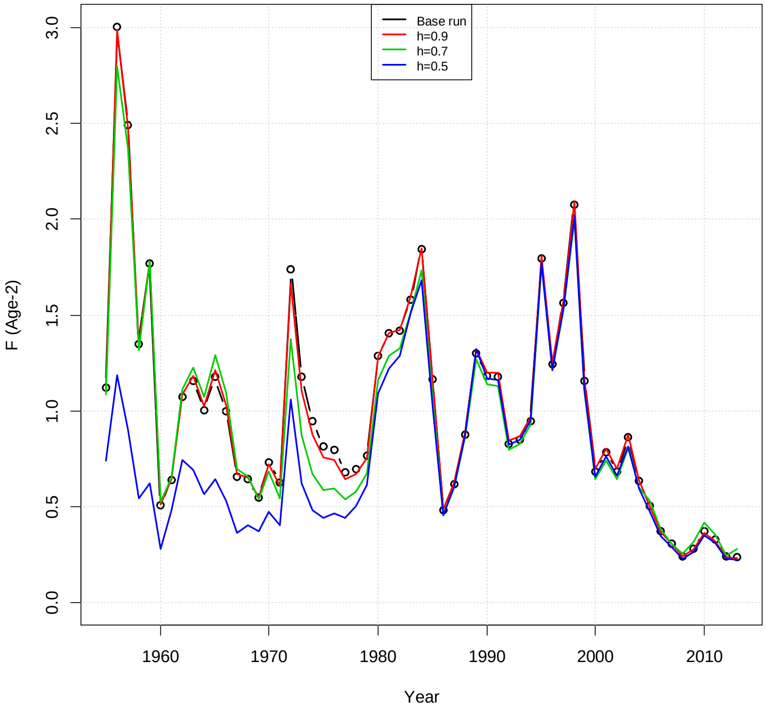


Figure 7.4.1.7. Full F at age-2 (upper) and age-3 (lower) for sensitivity runs considering differences in steepness.



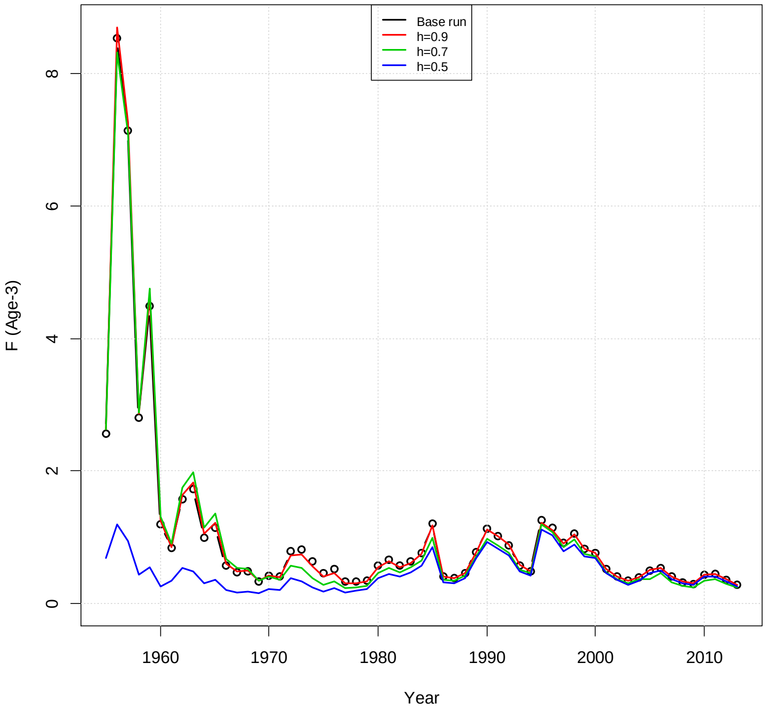


Figure 7.4.1.8. Age-1+ biomass in 1000s mt for sensitivity runs considering differences in growth and life history parameters in the assessment model.

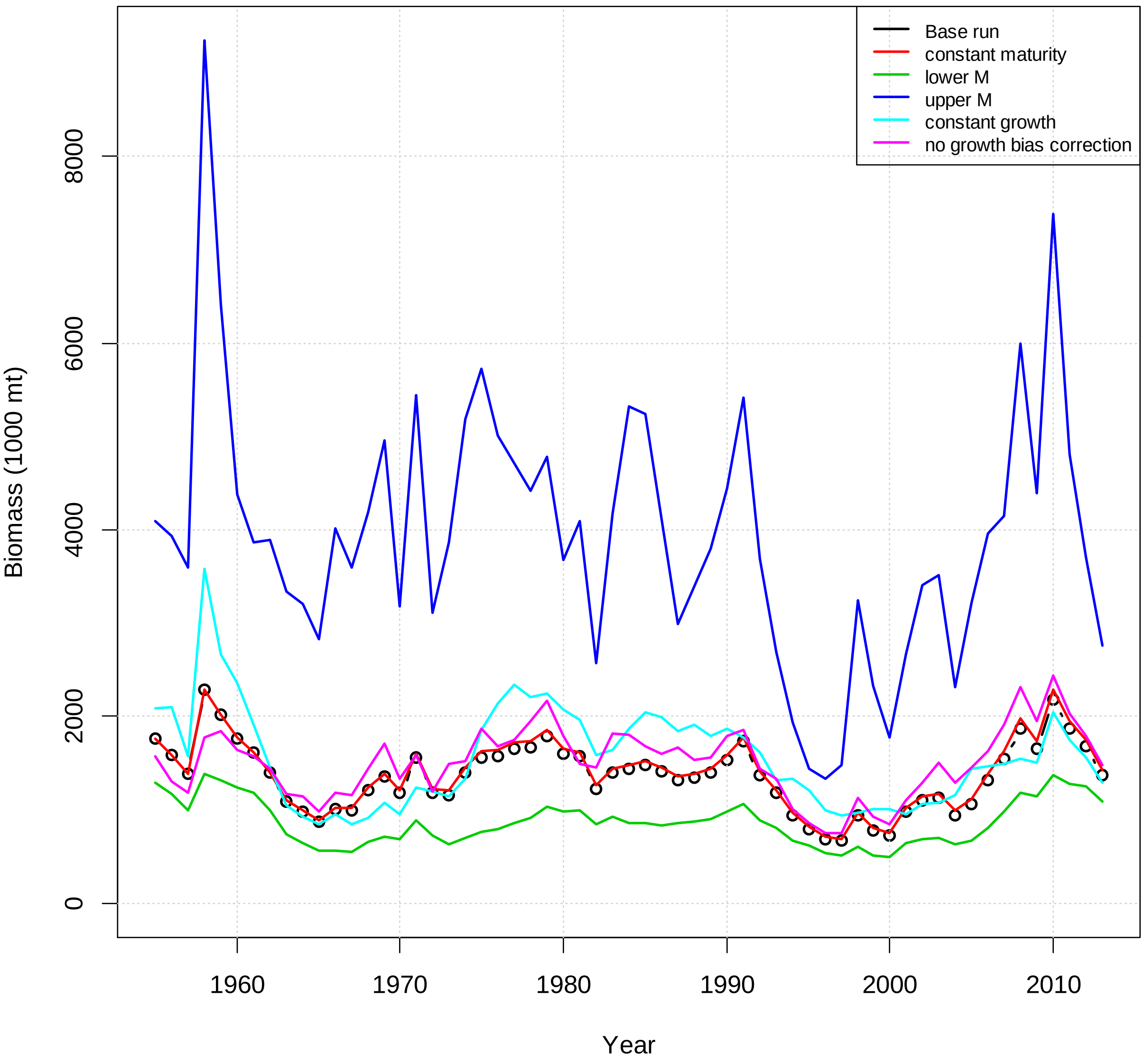


Figure 7.4.1.9. Age-1+ biomass in 1000s mt for sensitivity runs considering differences in indices in the assessment model.

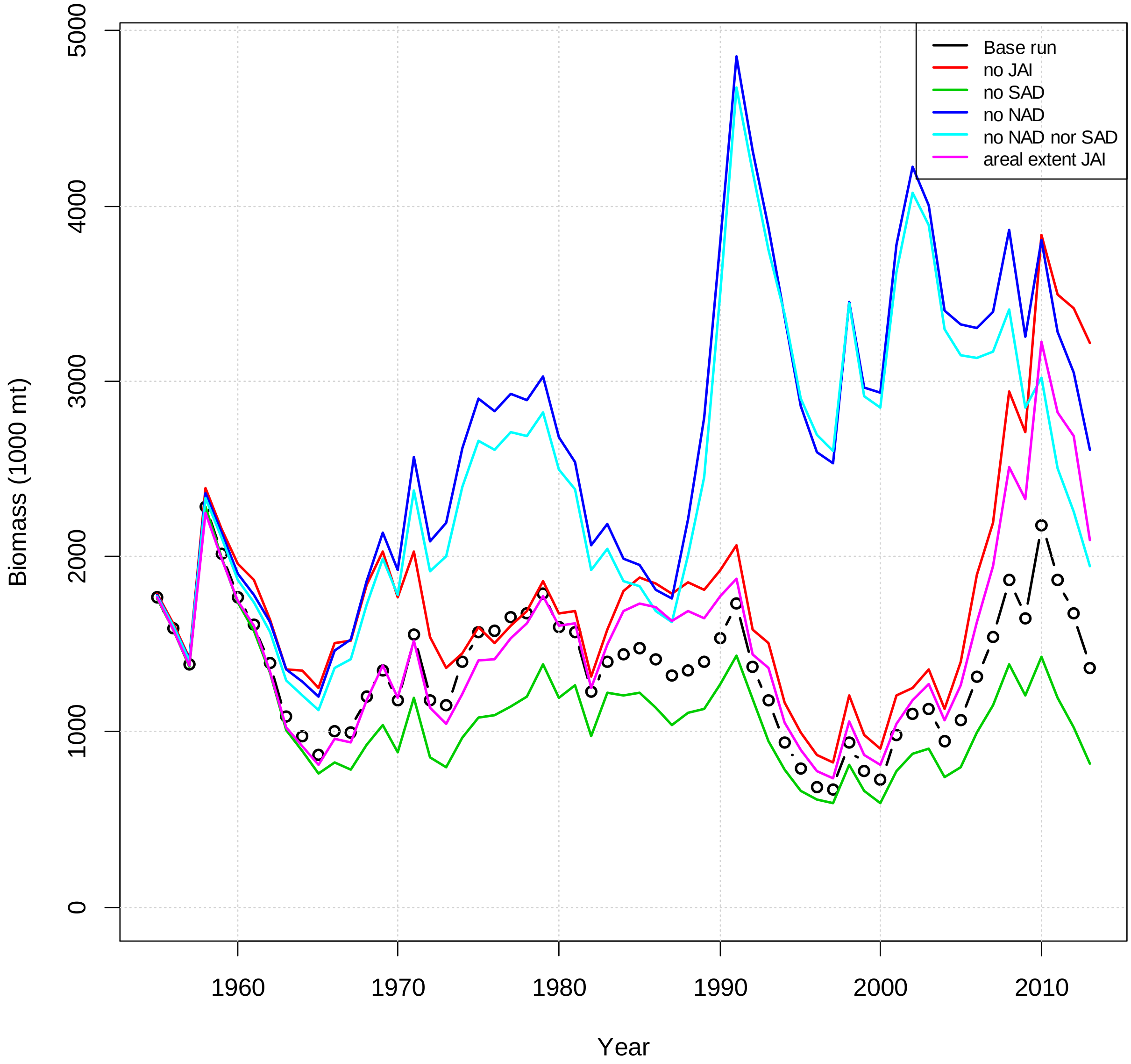


Figure 7.4.1.10. Age-1+ biomass in 1000s mt for sensitivity runs considering differences in fishery selectivity in the assessment model.

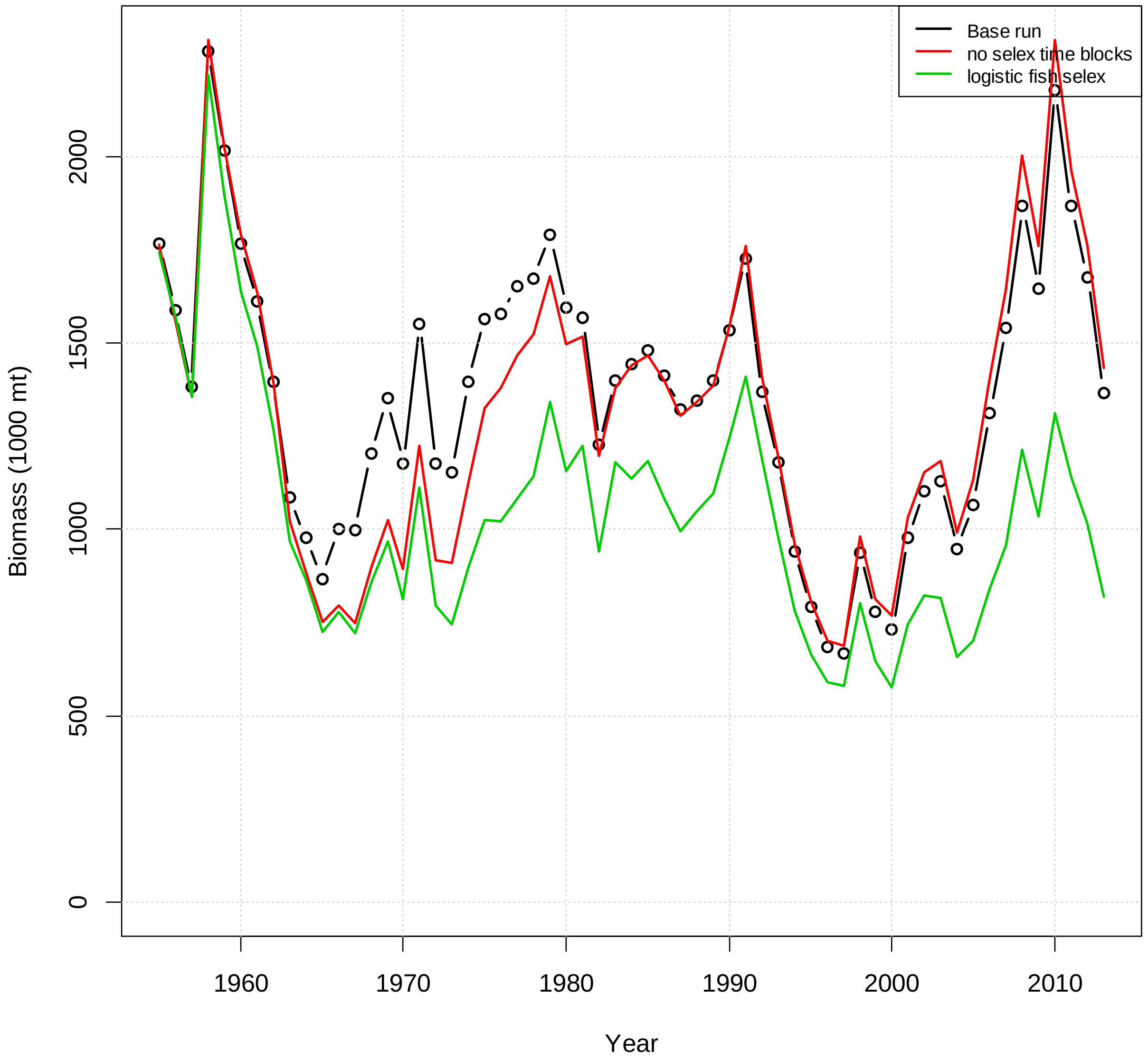


Figure 7.4.1.11. Age-1+ biomass in 1000s mt for sensitivity runs considering differences in ageing uncertainty, catchability for the JAI index, and ages modeled in the assessment model.

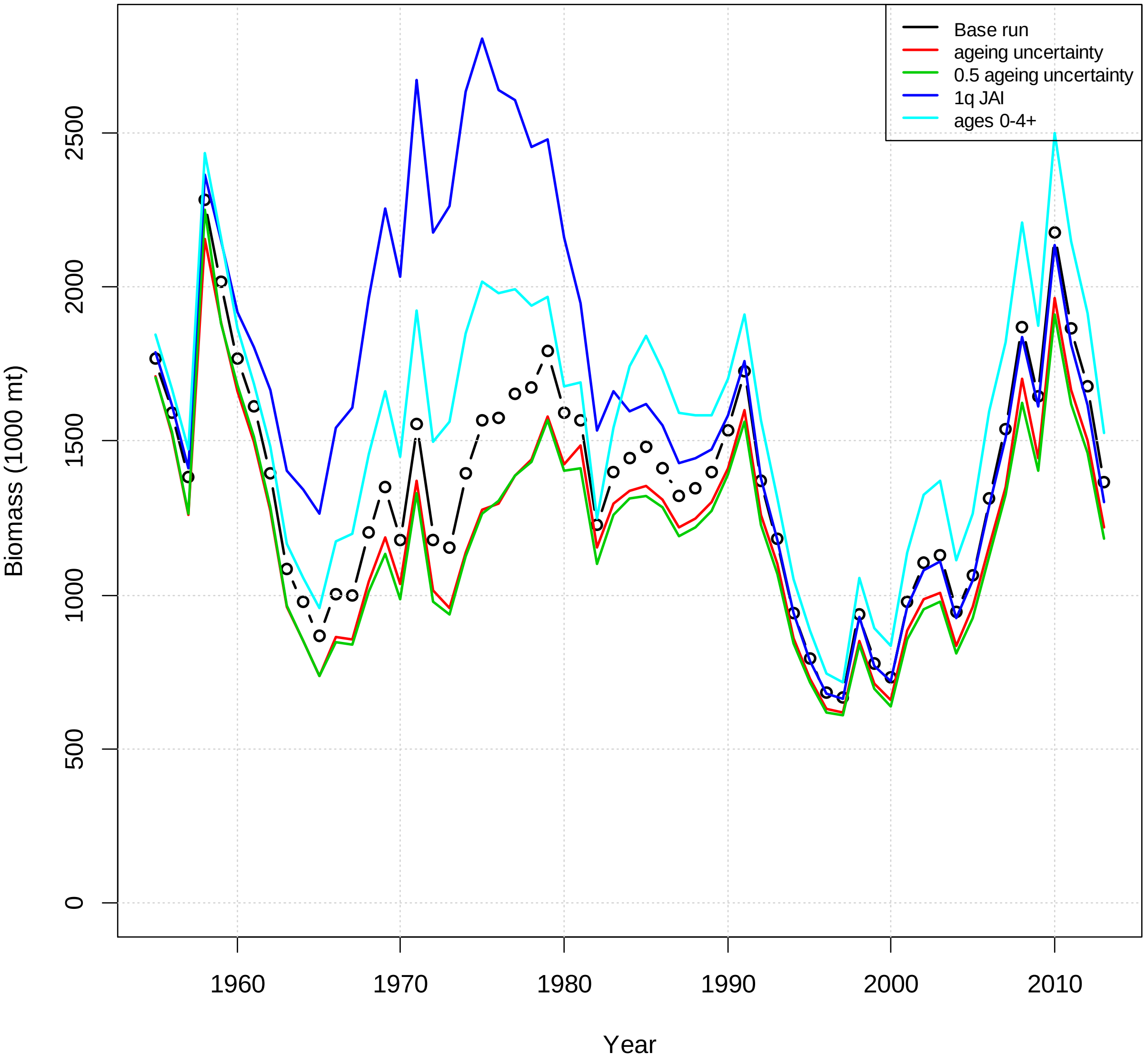


Figure 7.4.1.12. Age-1+ biomass in 1000s mt for sensitivity runs considering differences in start year of the assessment model.

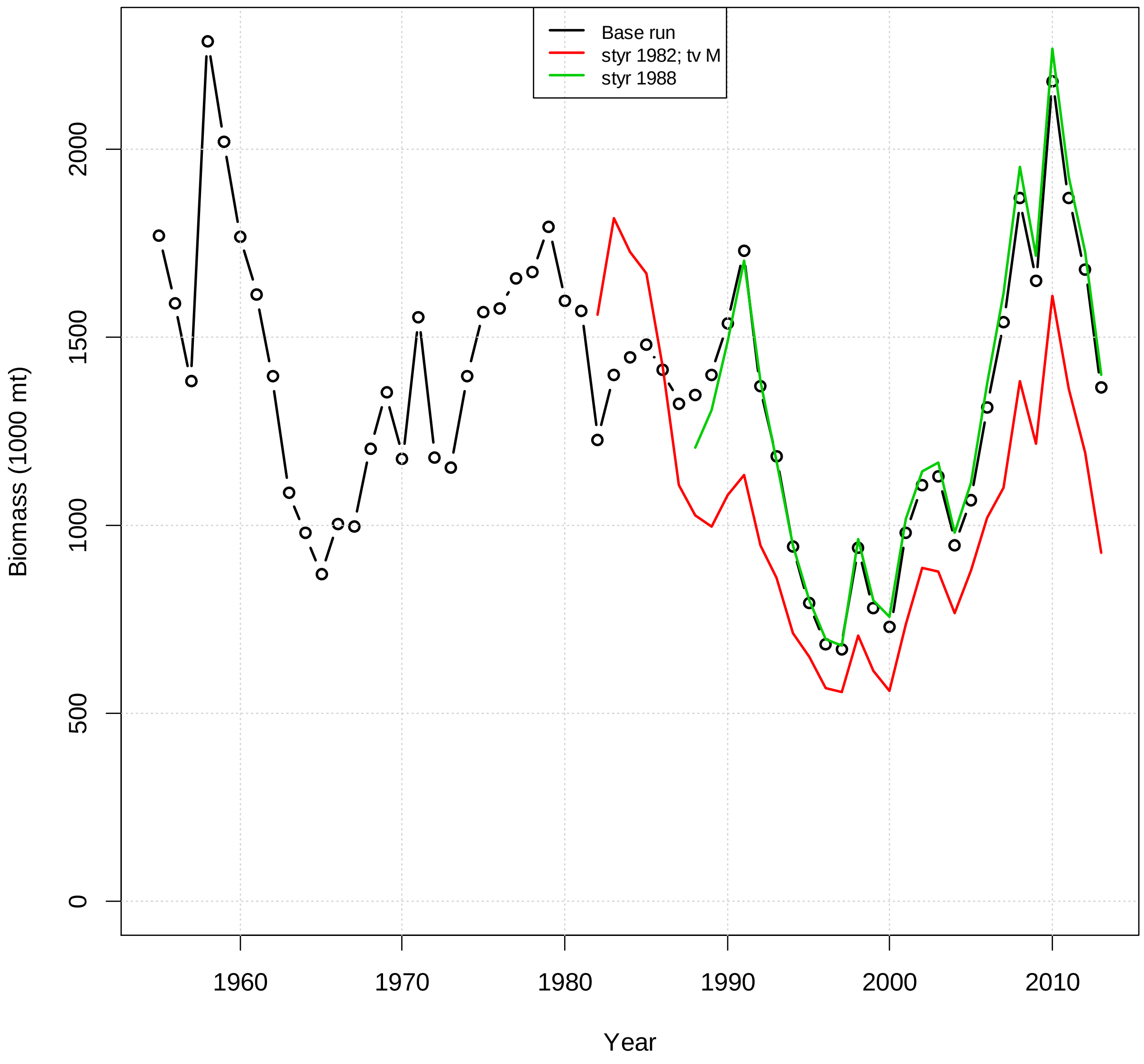


Figure 7.4.1.13. Age-1+ biomass in 1000s mt for sensitivity runs considering differences in weighting of the likelihood components for the assessment model.

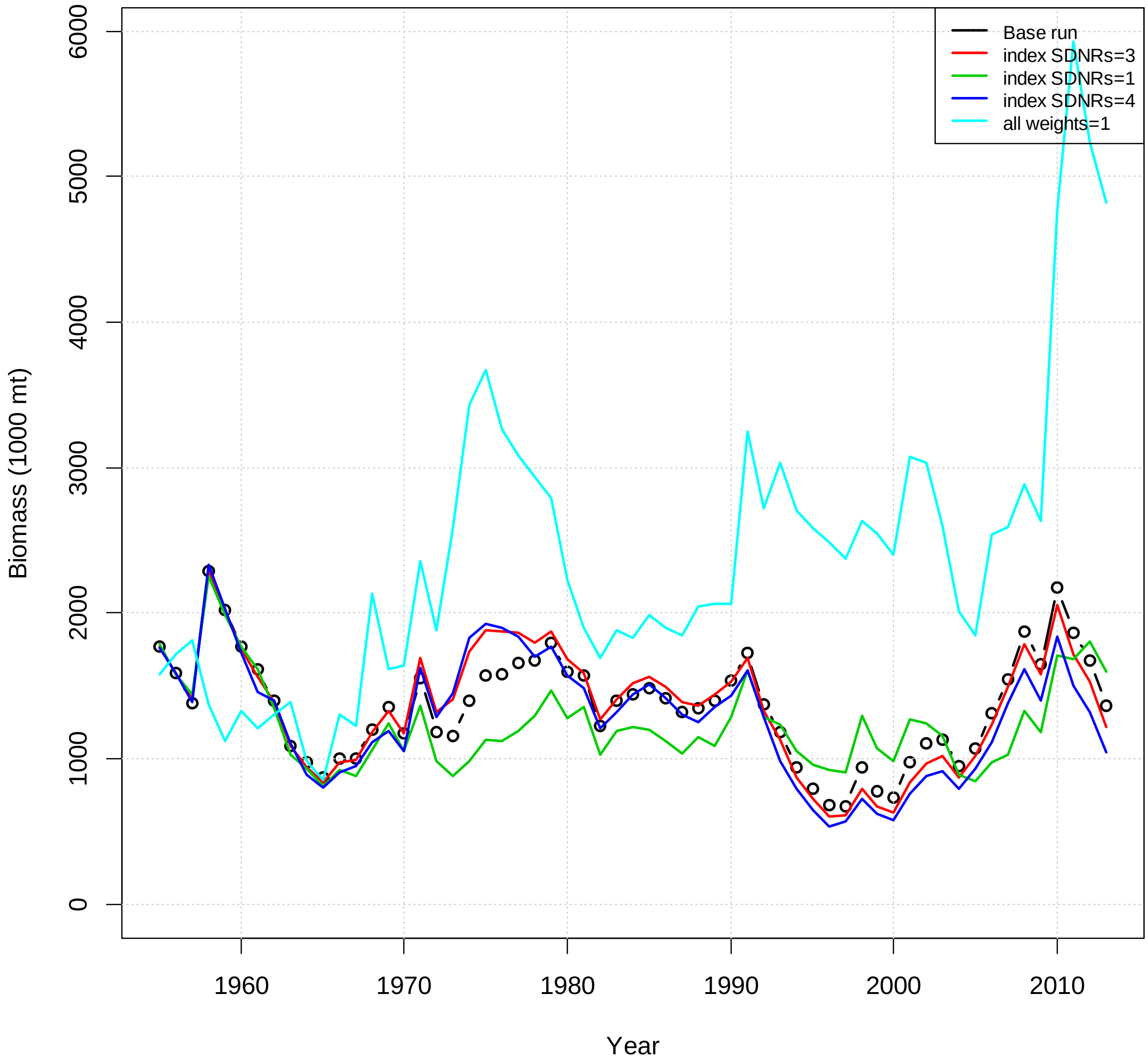


Figure 7.4.1.14. Age-1+ biomass in 1000s mt for sensitivity runs considering differences in steepness.

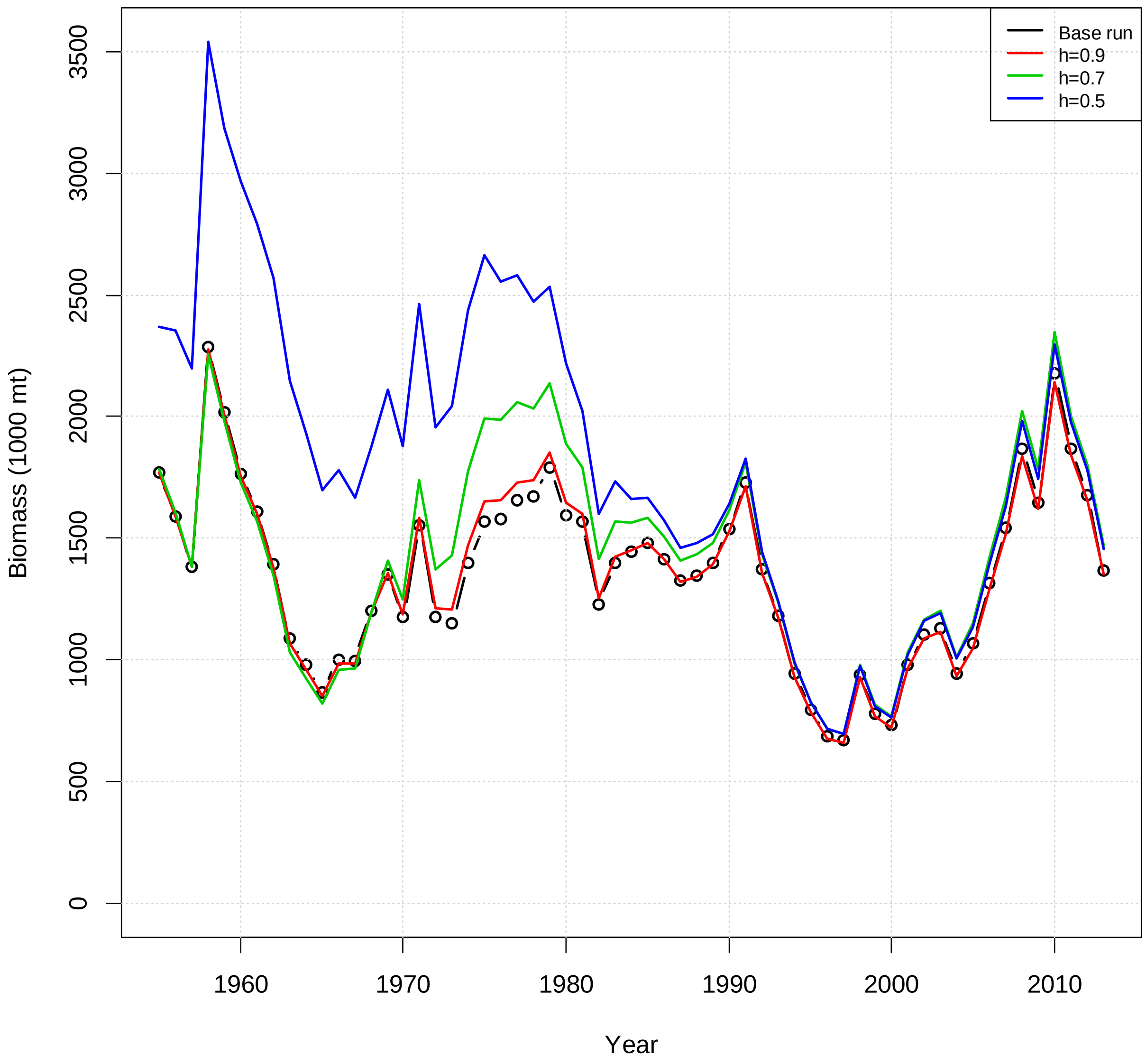


Figure 7.4.1.15. Recruitment over time for sensitivity runs considering differences in growth and life history parameters in the assessment model.

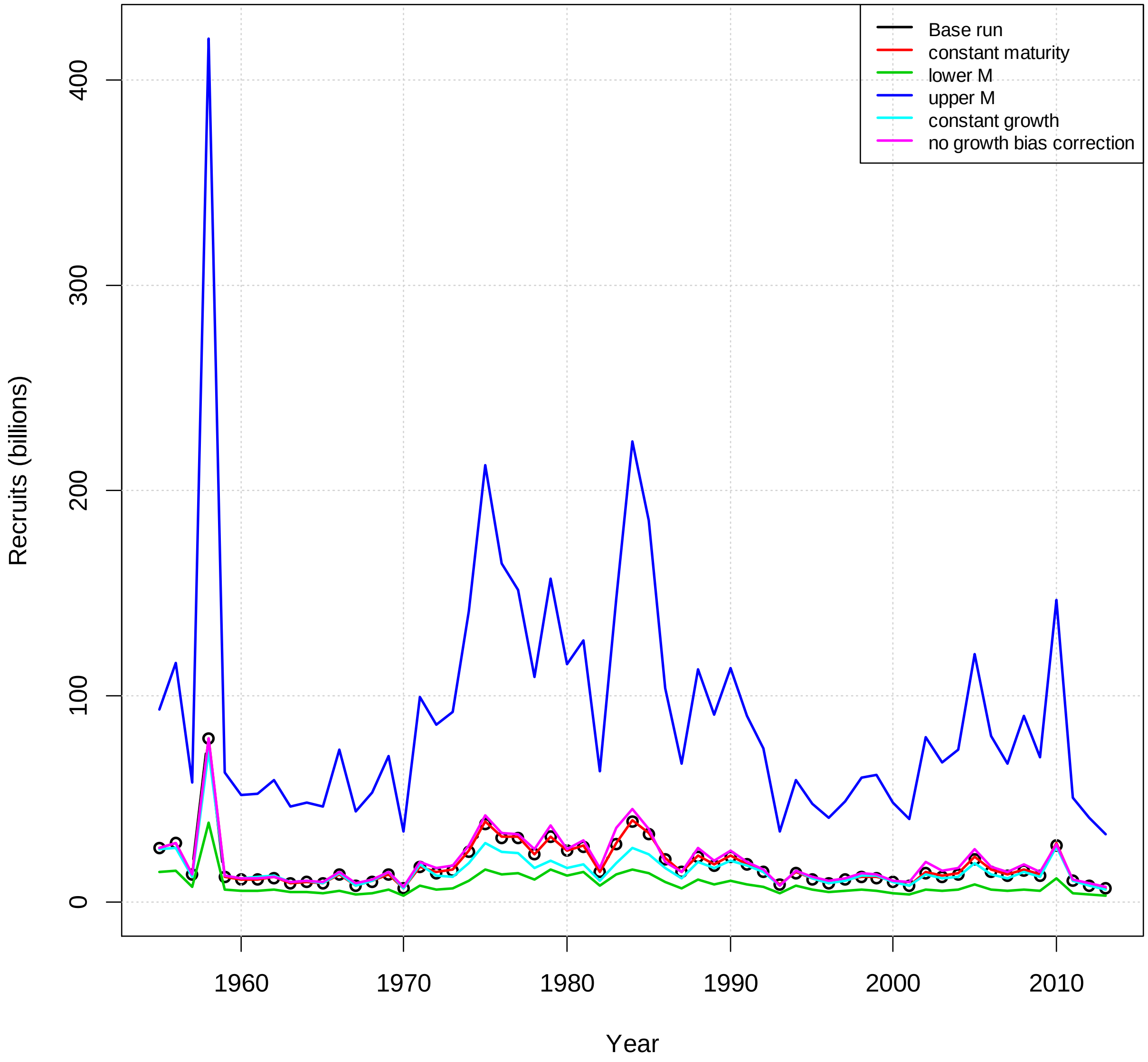


Figure 7.4.1.16. Recruitment over time for sensitivity runs considering differences in indices in the assessment model.

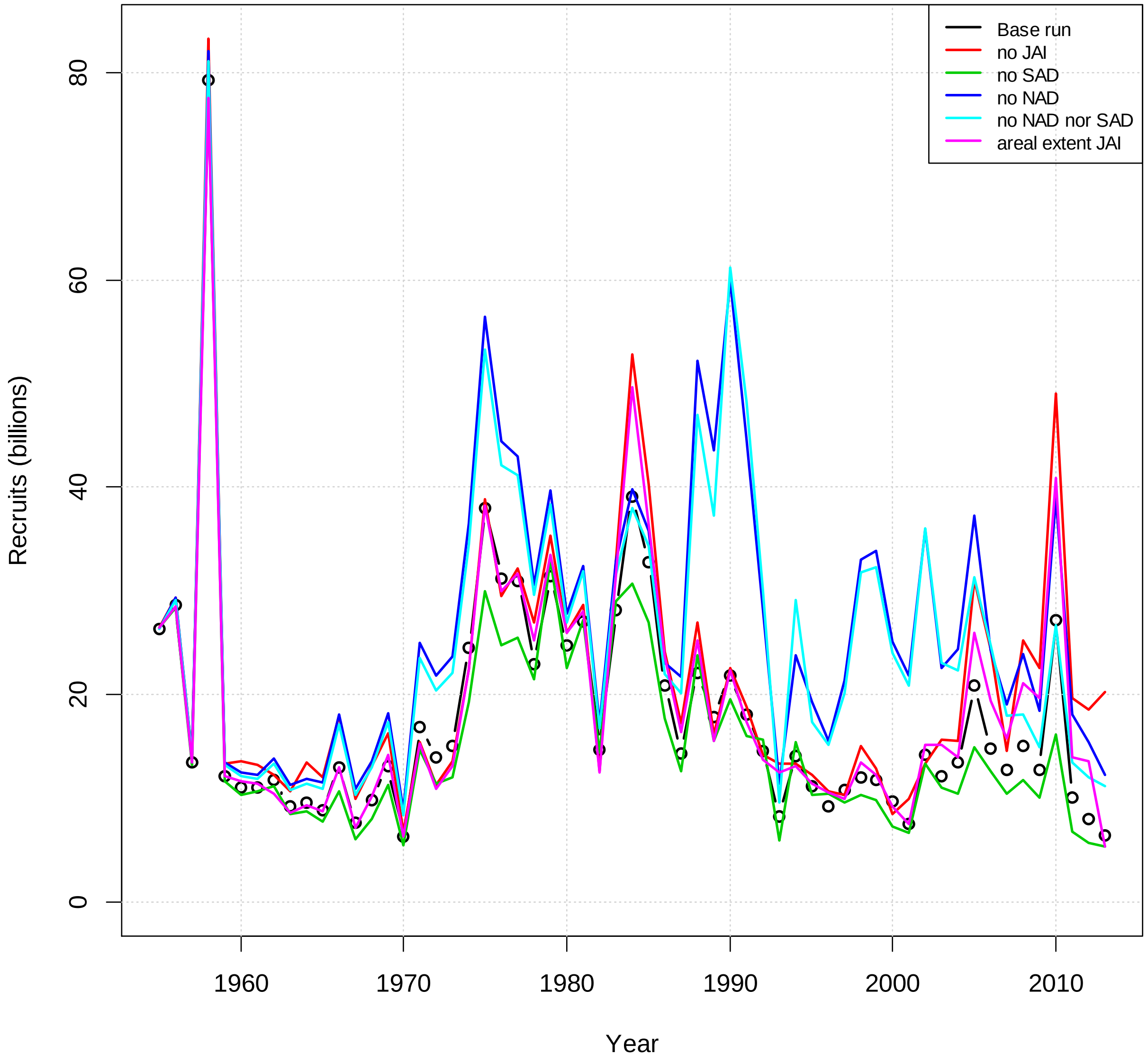


Figure 7.4.1.17. Recruitment over time for sensitivity runs considering differences in fishery selectivity in the assessment model.

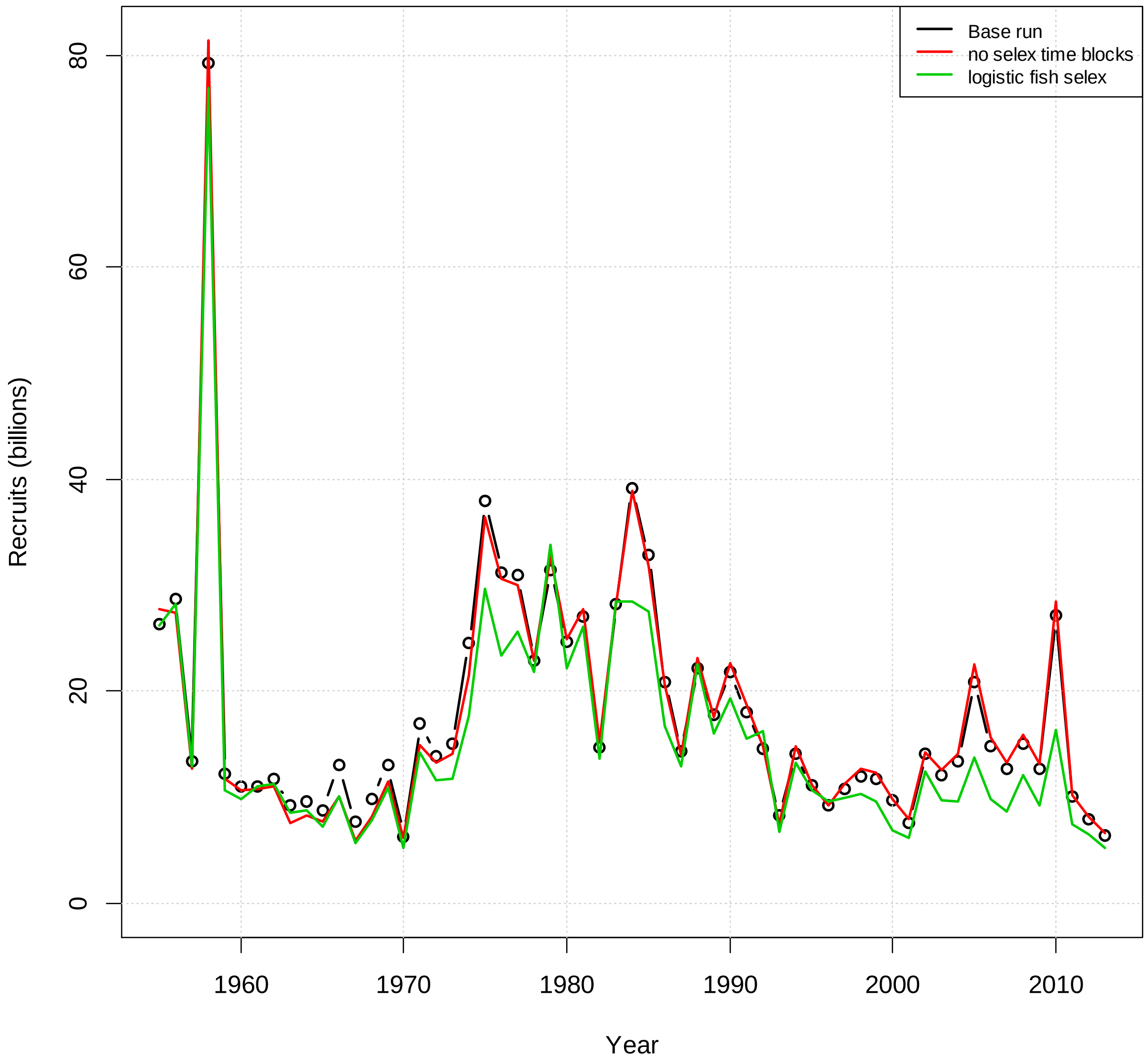


Figure 7.4.1.18. Recruitment over time for sensitivity runs considering differences in ageing uncertainty, catchability for the JAI index, and ages modeled in the assessment model.

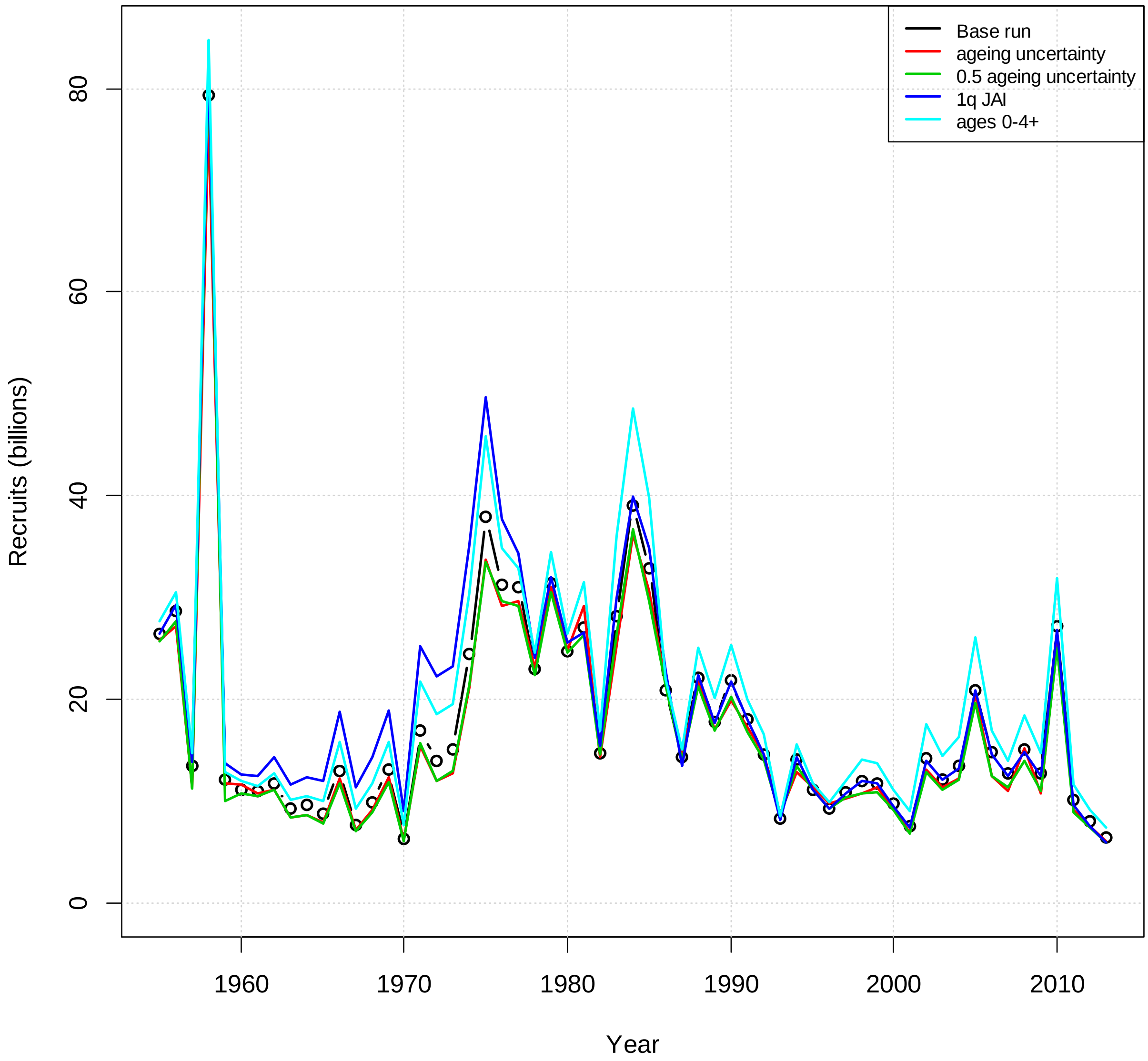


Figure 7.4.1.19. Recruitment over time for sensitivity runs considering differences in start year of the assessment model.

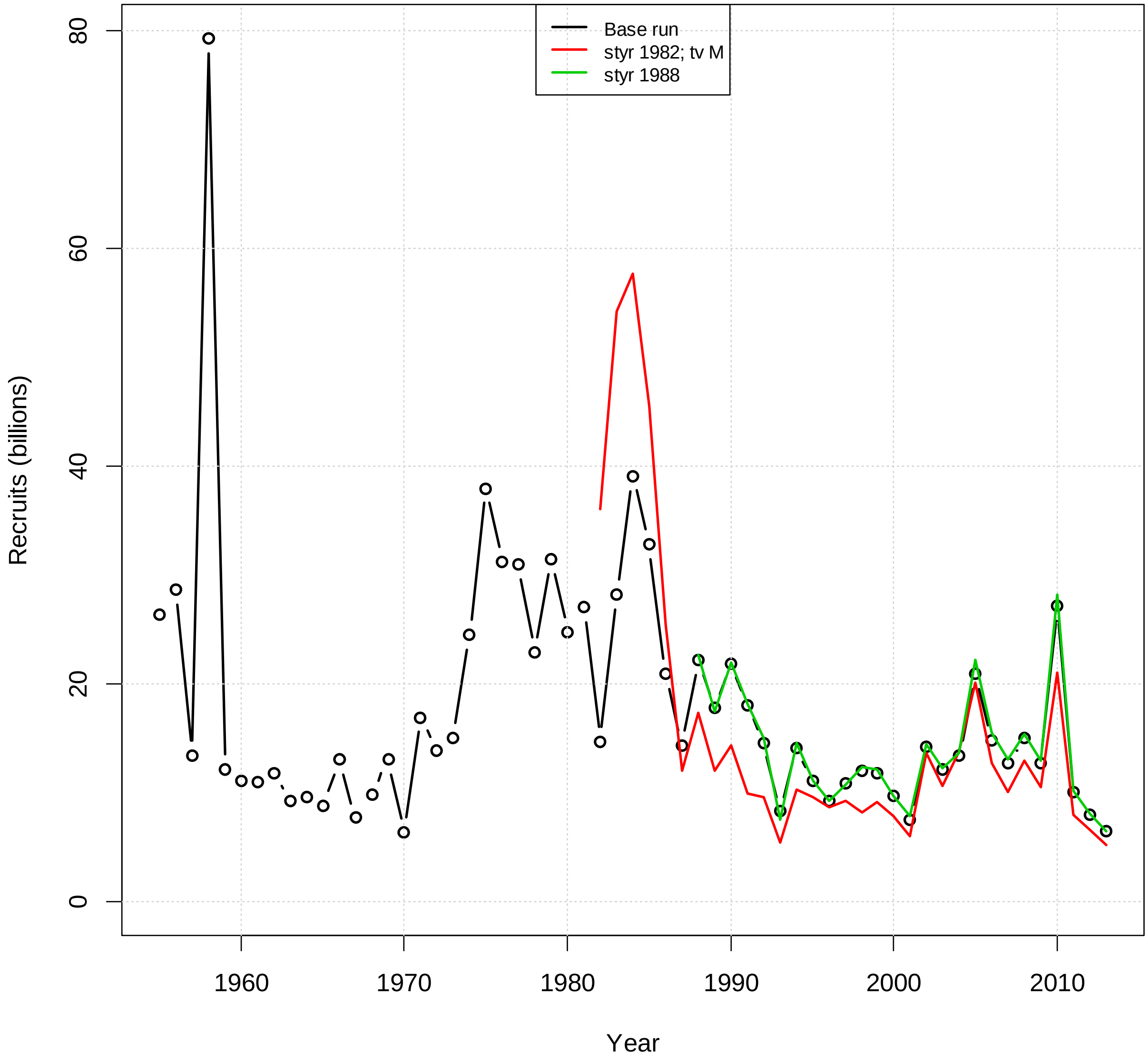


Figure 7.4.1.20. Recruitment over time for sensitivity runs considering differences in weighting of the likelihood components for the assessment model.

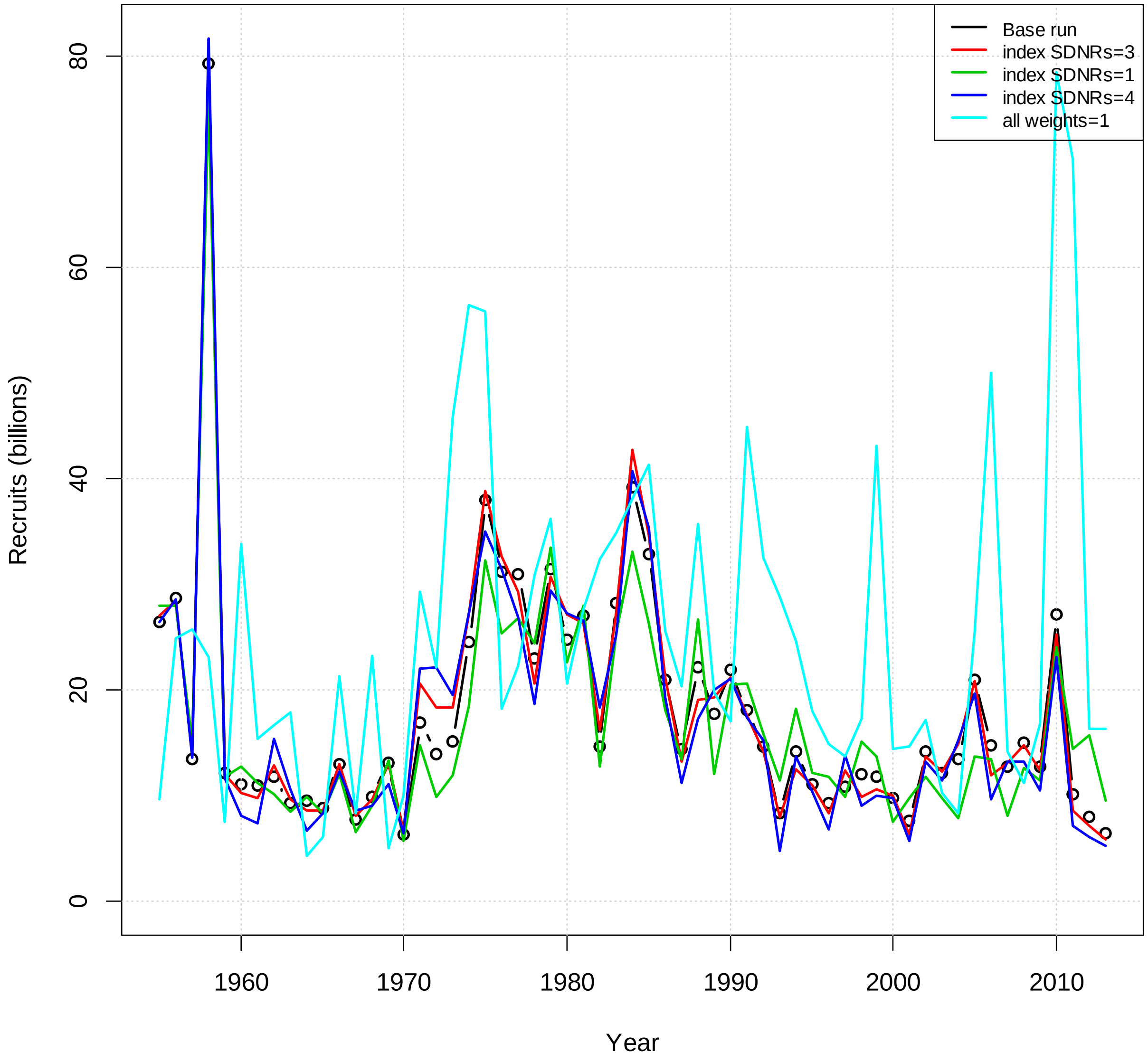


Figure 7.4.1.21. Recruitment over time for sensitivity runs considering differences in steepness.

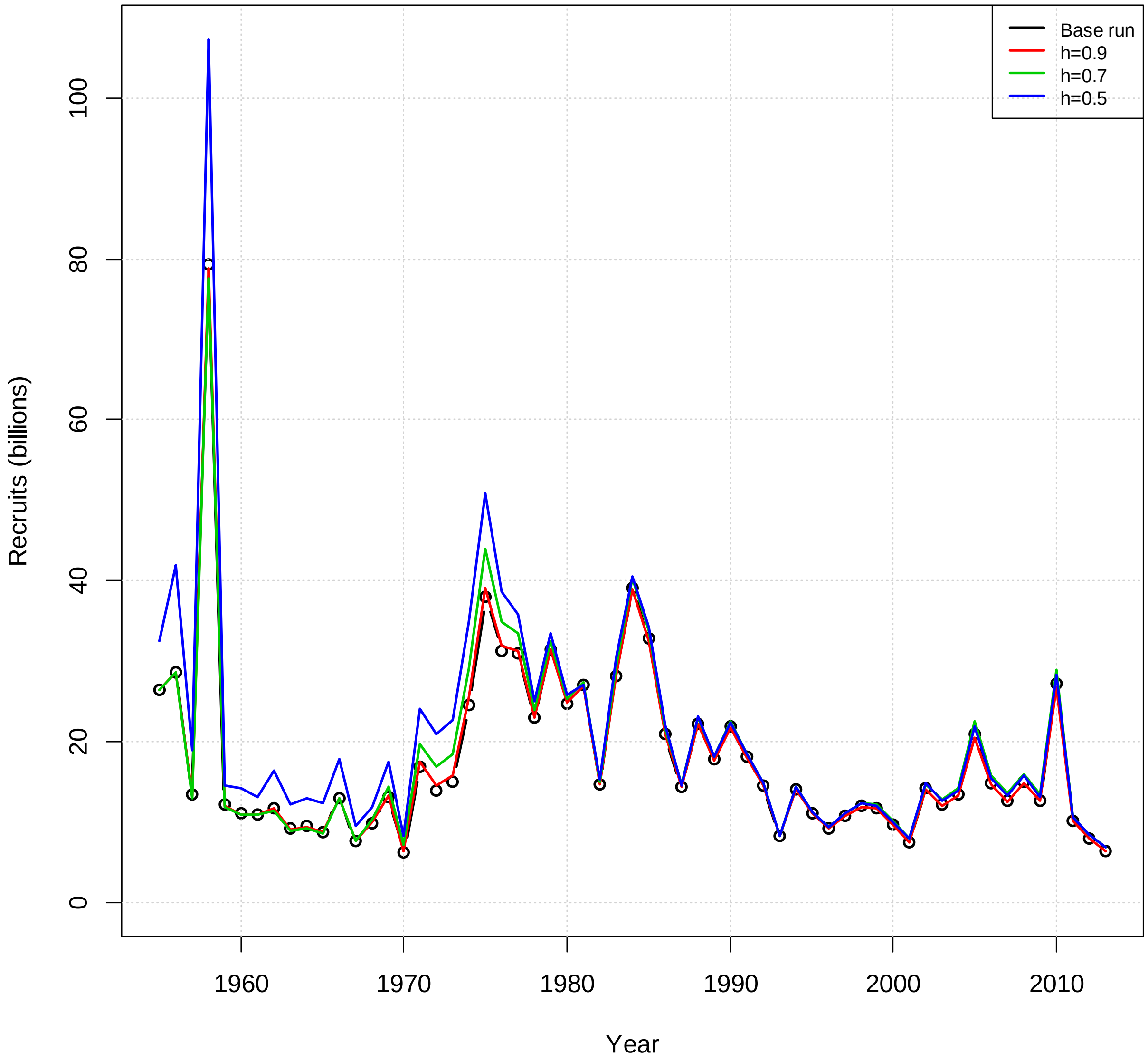


Figure 7.4.1.22. Fecundity over time for sensitivity runs considering differences in growth and life history parameters in the assessment model.

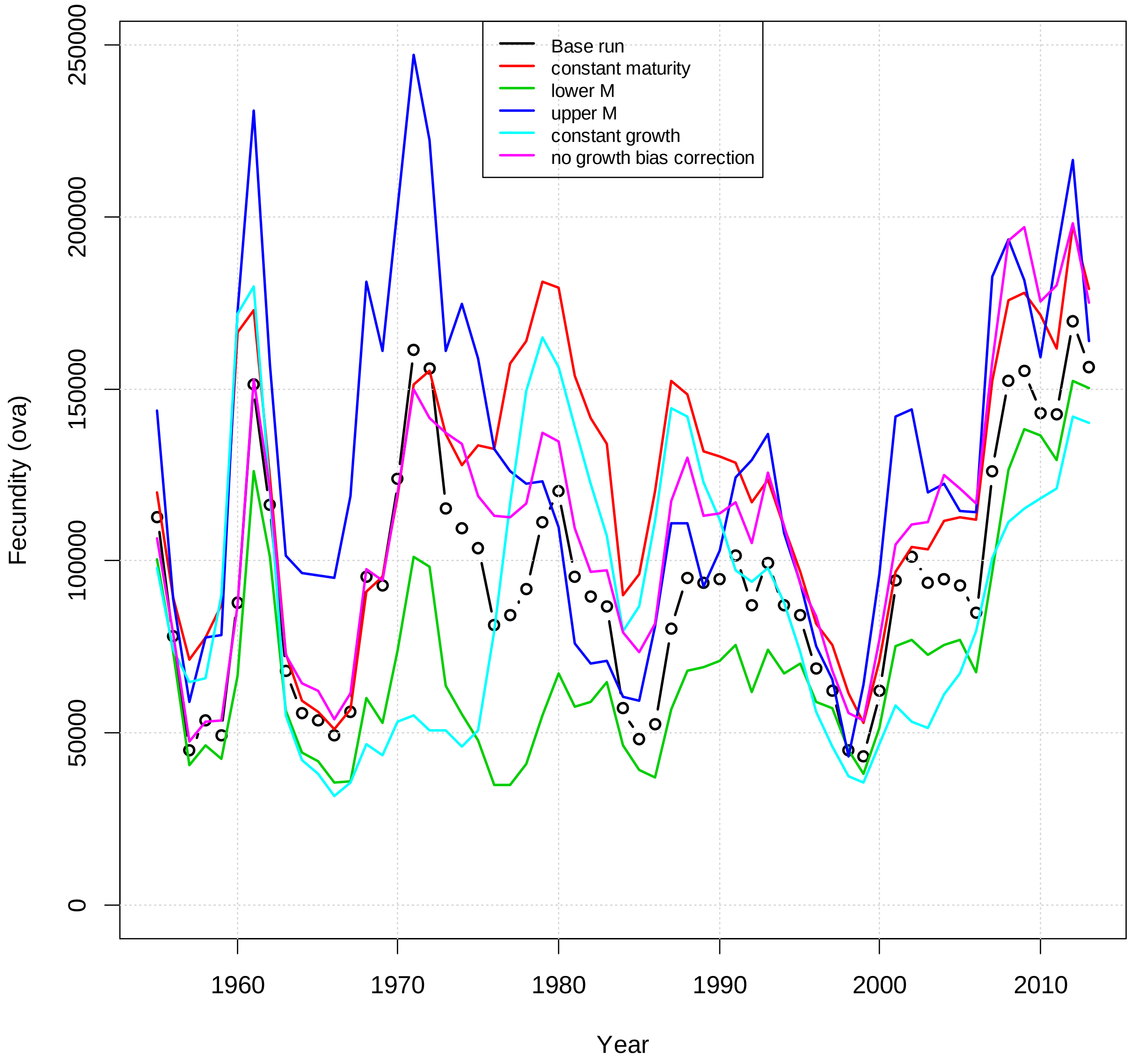


Figure 7.4.1.23. Fecundity over time for sensitivity runs considering differences in indices in the assessment model.

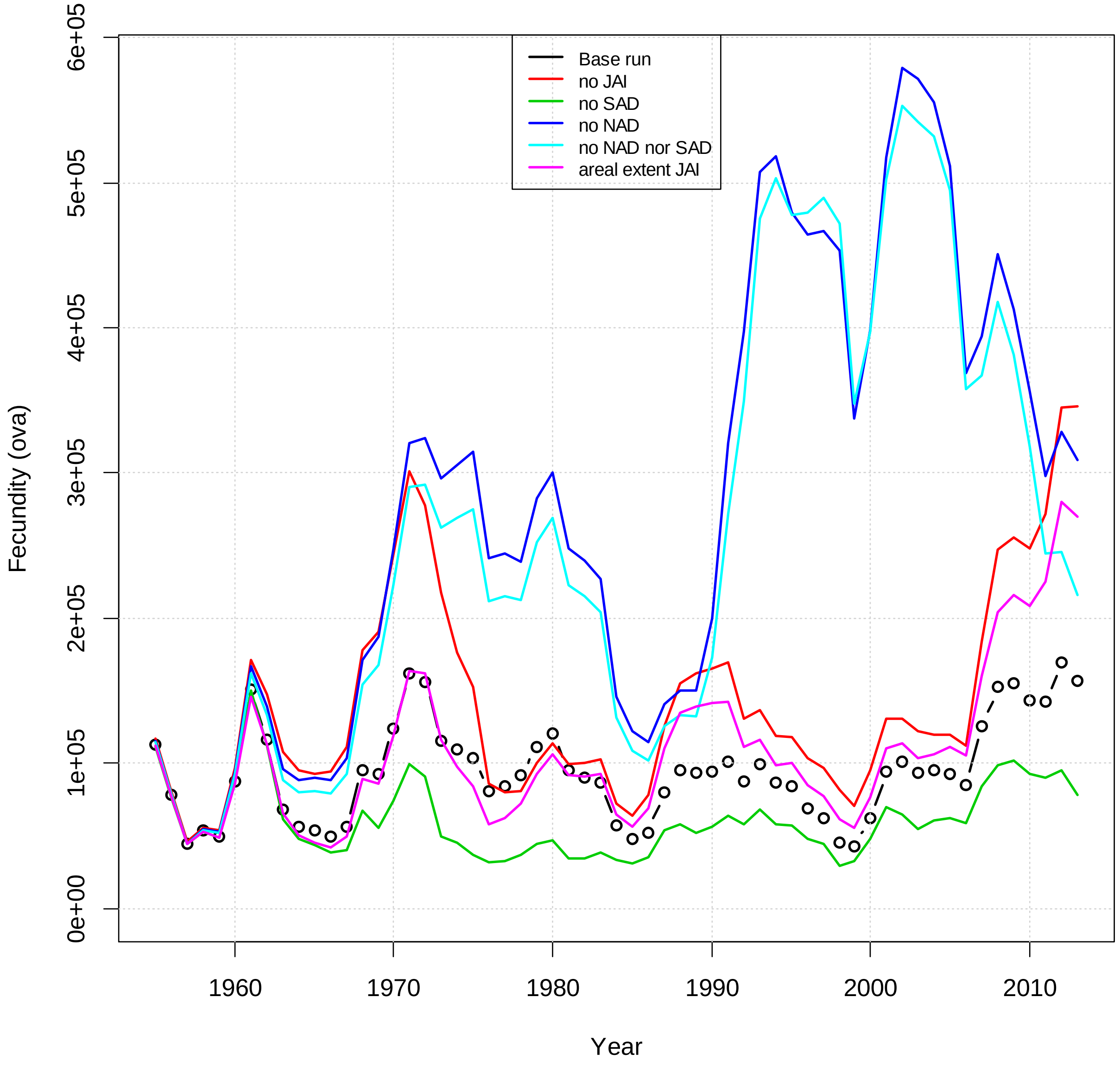


Figure 7.4.1.24. Fecundity over time for sensitivity runs considering differences in fishery selectivity in the assessment model.

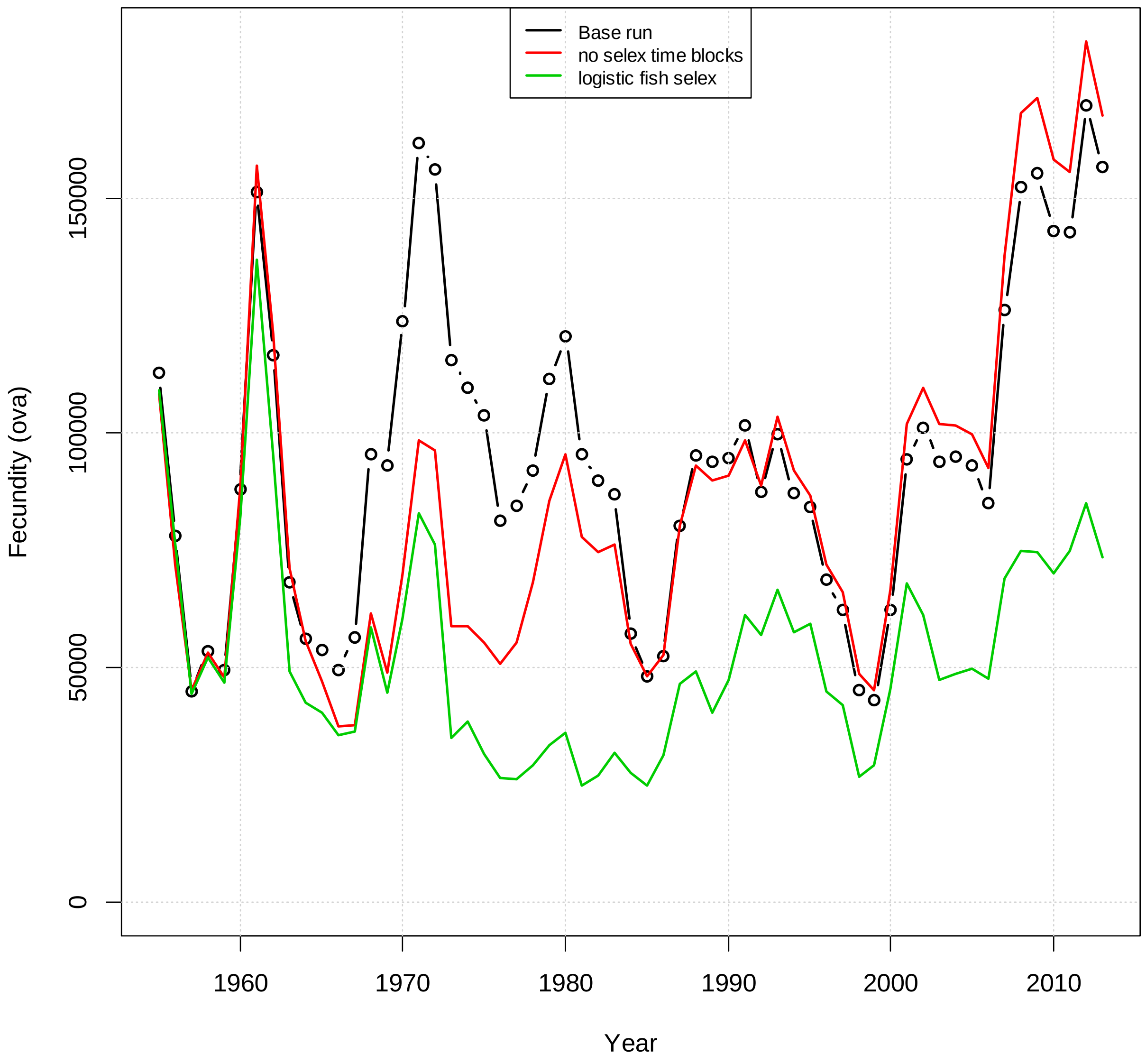


Figure 7.4.1.25. Fecundity over time for sensitivity runs considering differences in ageing uncertainty, catchability for the JAI index, and ages modeled in the assessment model.

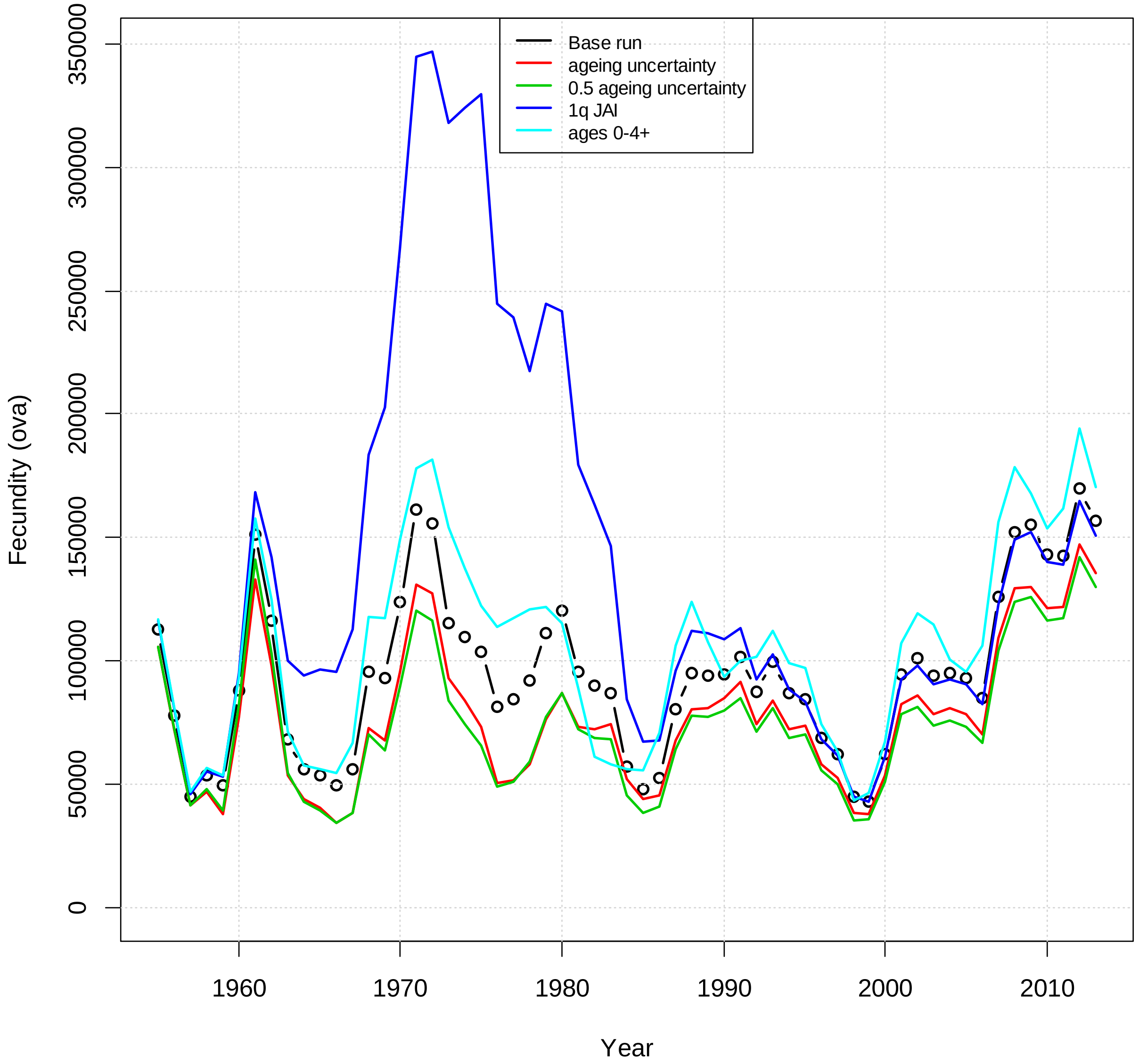


Figure 7.4.1.26. Fecundity over time for sensitivity runs considering differences in start year of the assessment model.

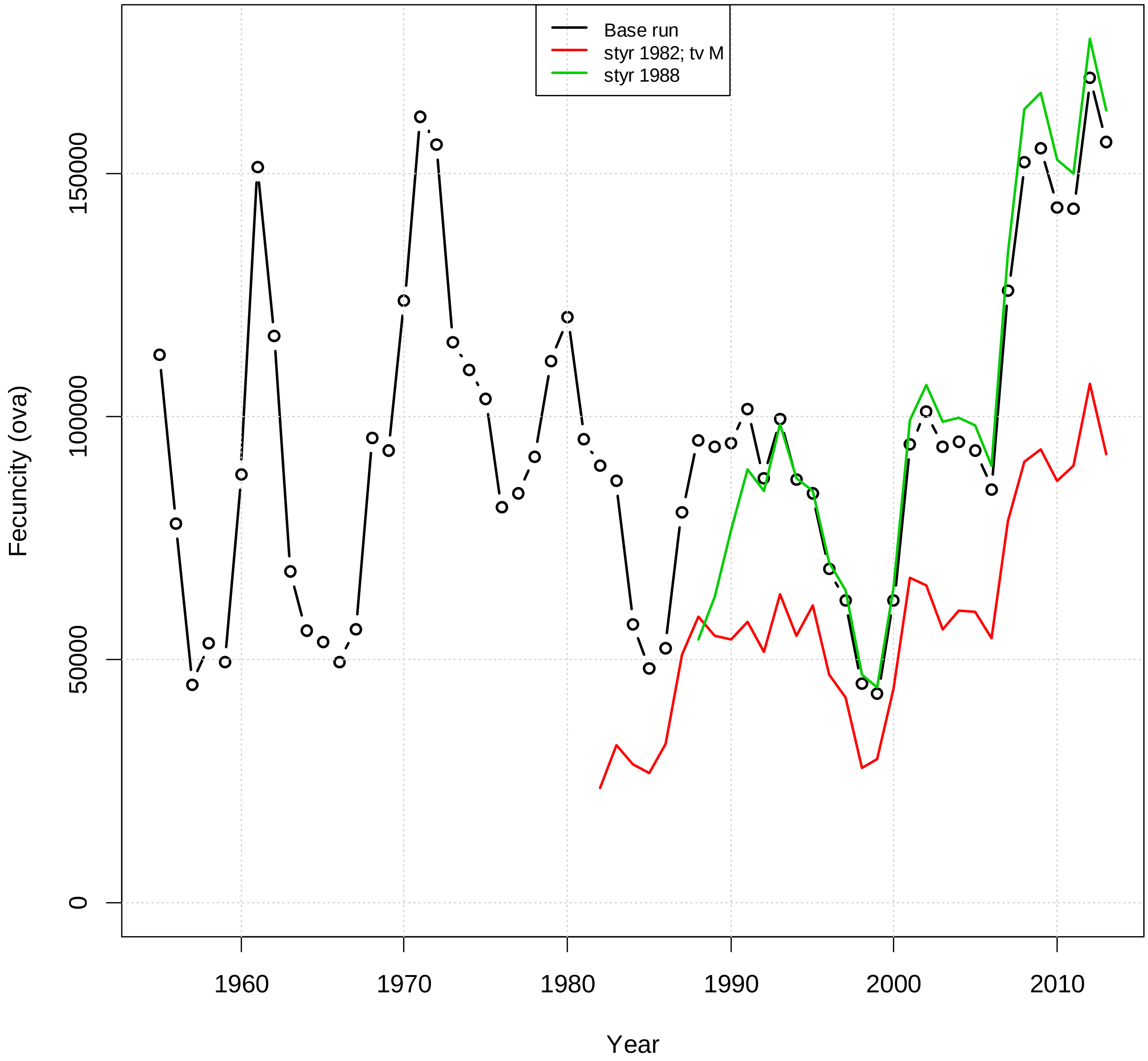


Figure 7.4.1.27. Fecundity over time for sensitivity runs considering differences in weighting of the likelihood components for the assessment model.

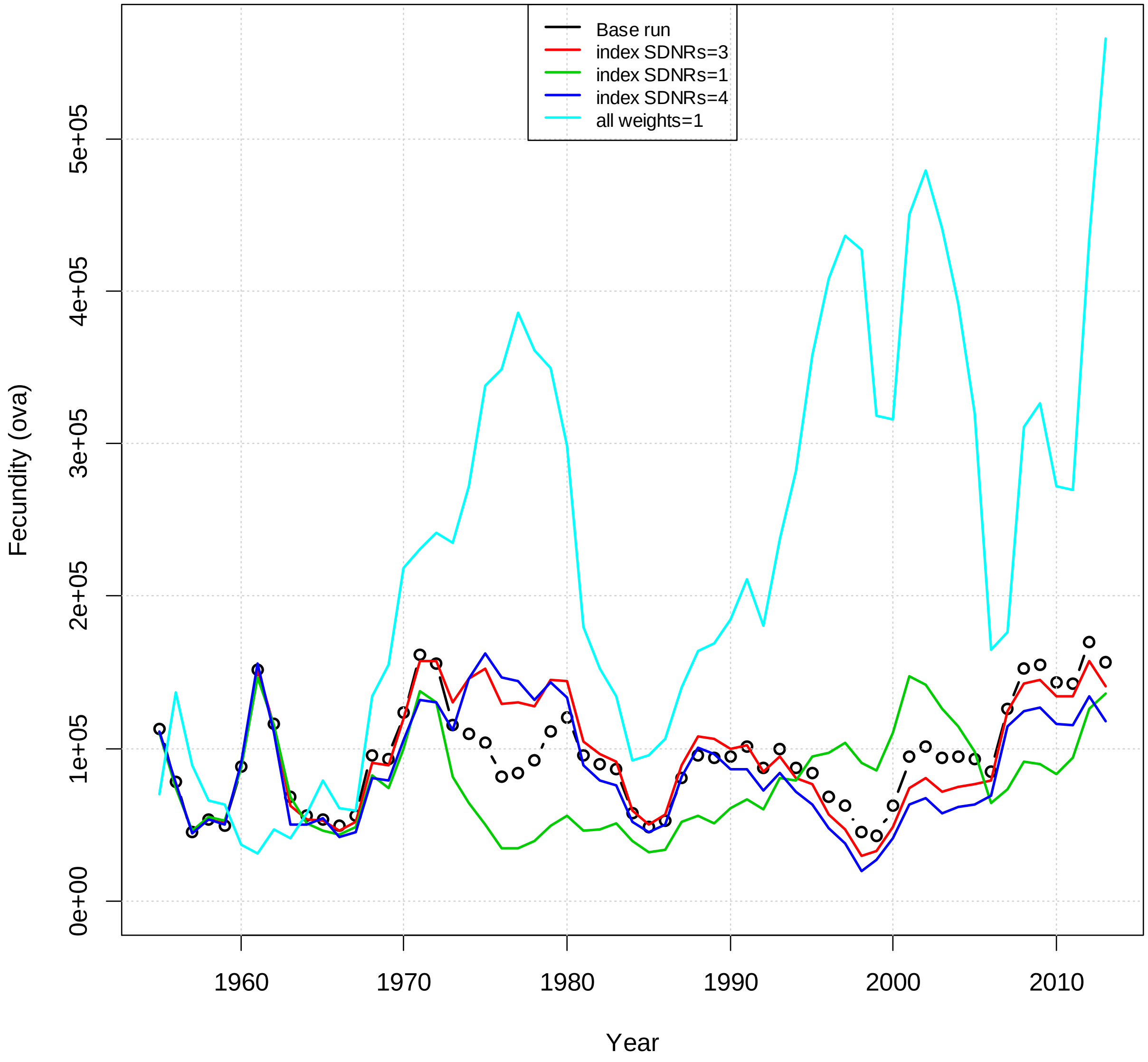


Figure 7.4.1.28. Fecundity over time for sensitivity runs considering differences in steepness.

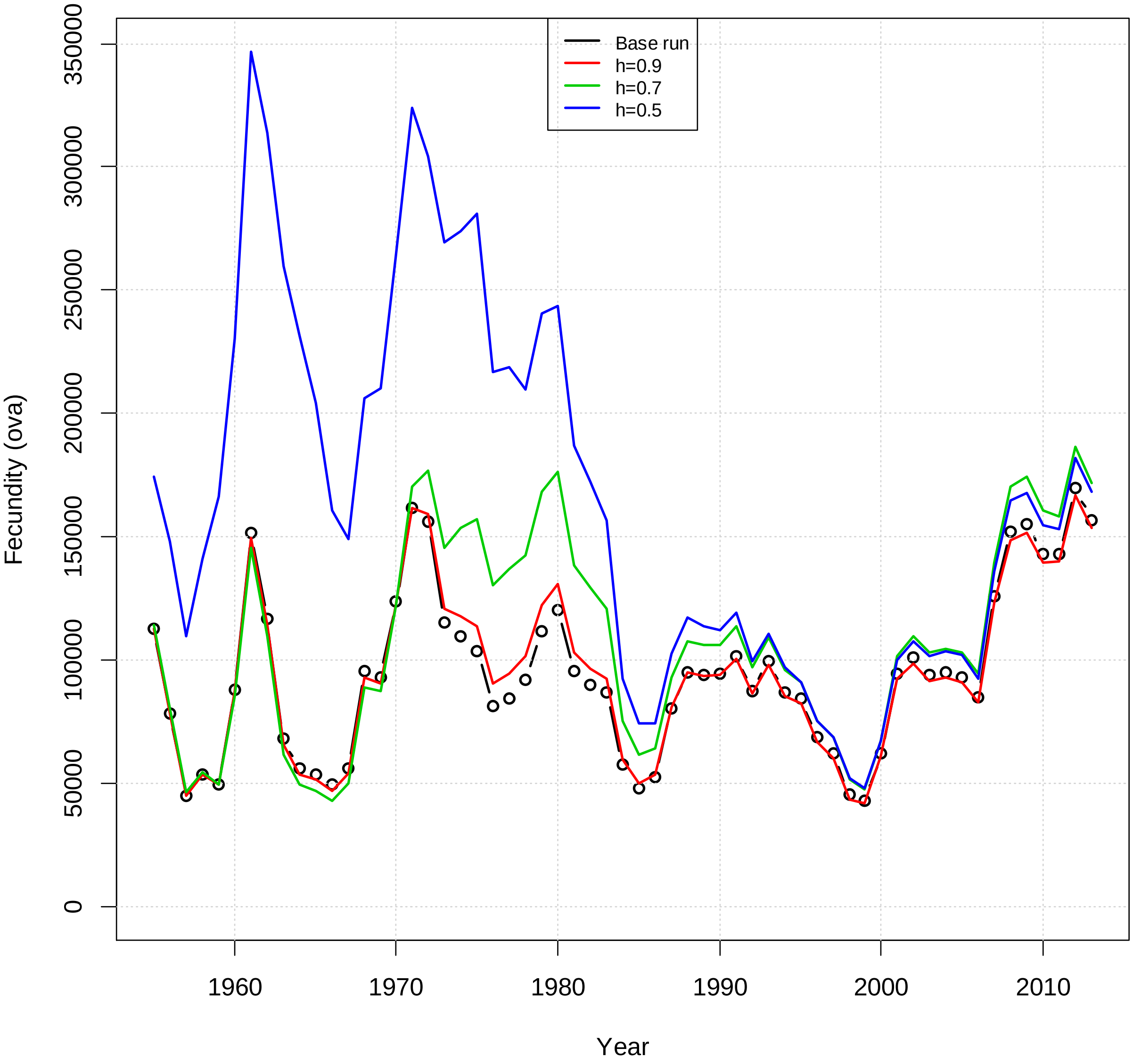


Figure 7.4.1.29. Fit to the recruitment index for sensitivity runs considering differences in growth and life history parameters in the assessment model.

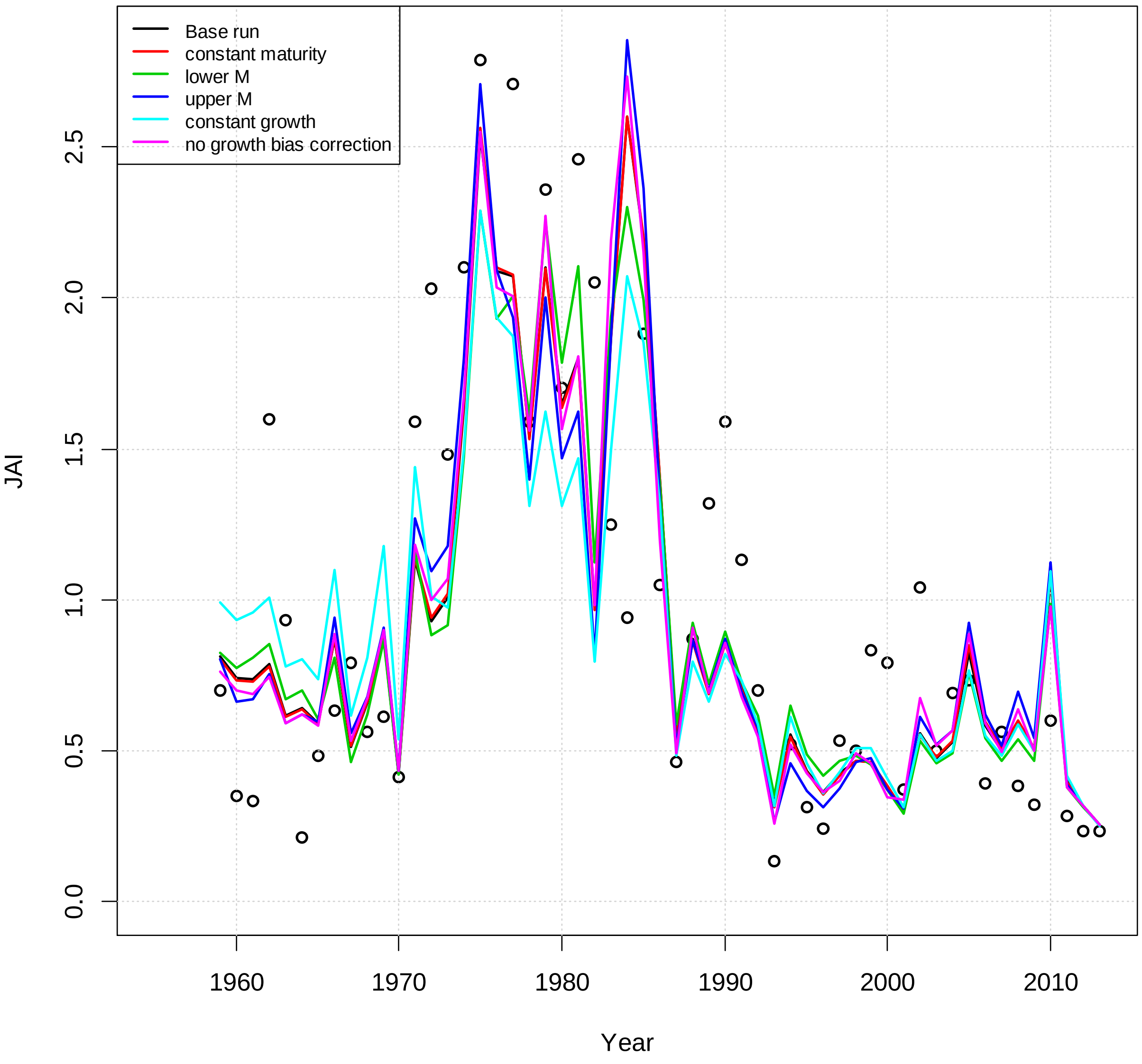


Figure 7.4.1.30. Fit to the recruitment index for sensitivity runs considering differences in indices in the assessment model.

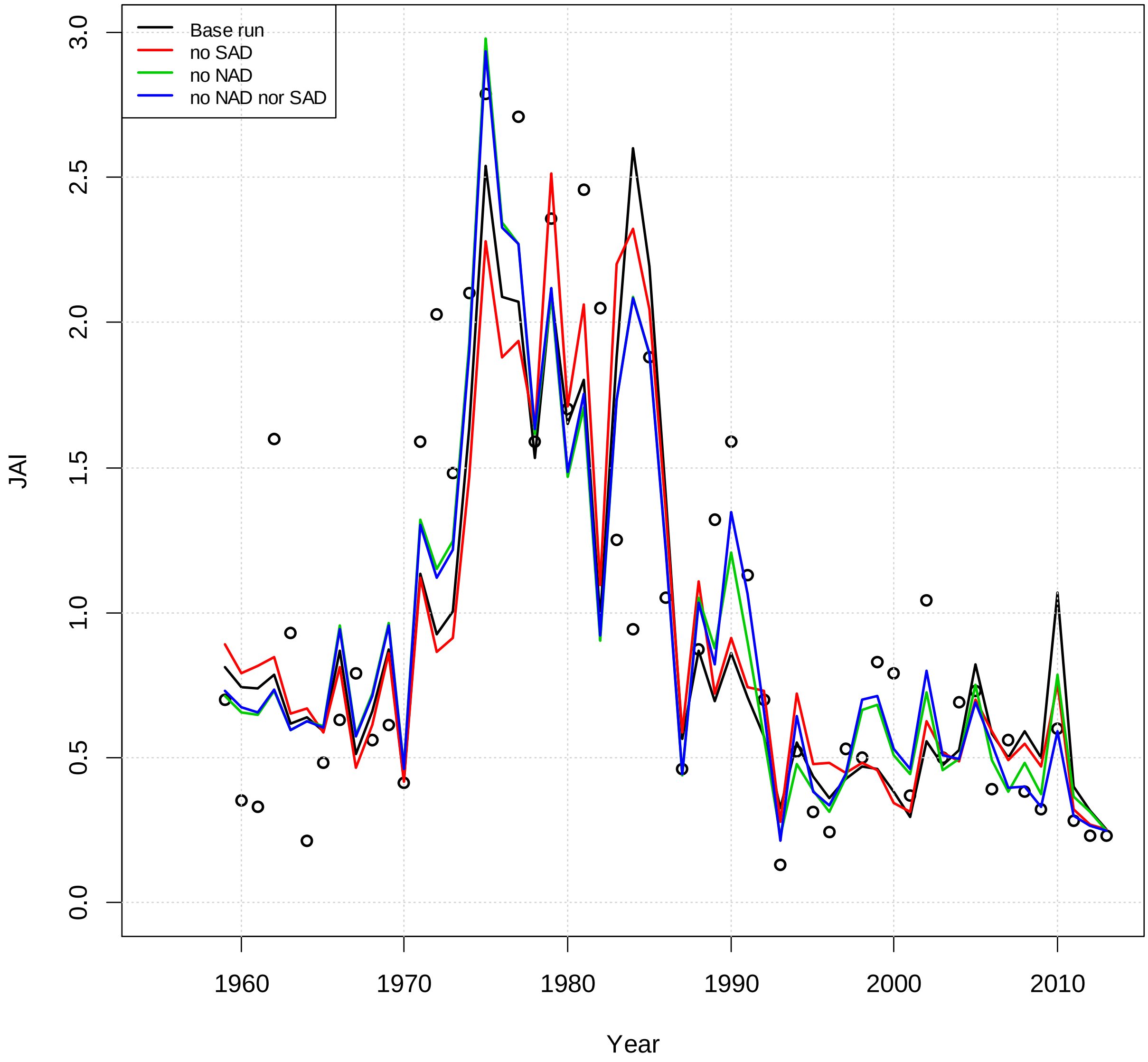


Figure 7.4.1.31. Fit to the recruitment index for sensitivity runs considering differences in fishery selectivity in the assessment model.

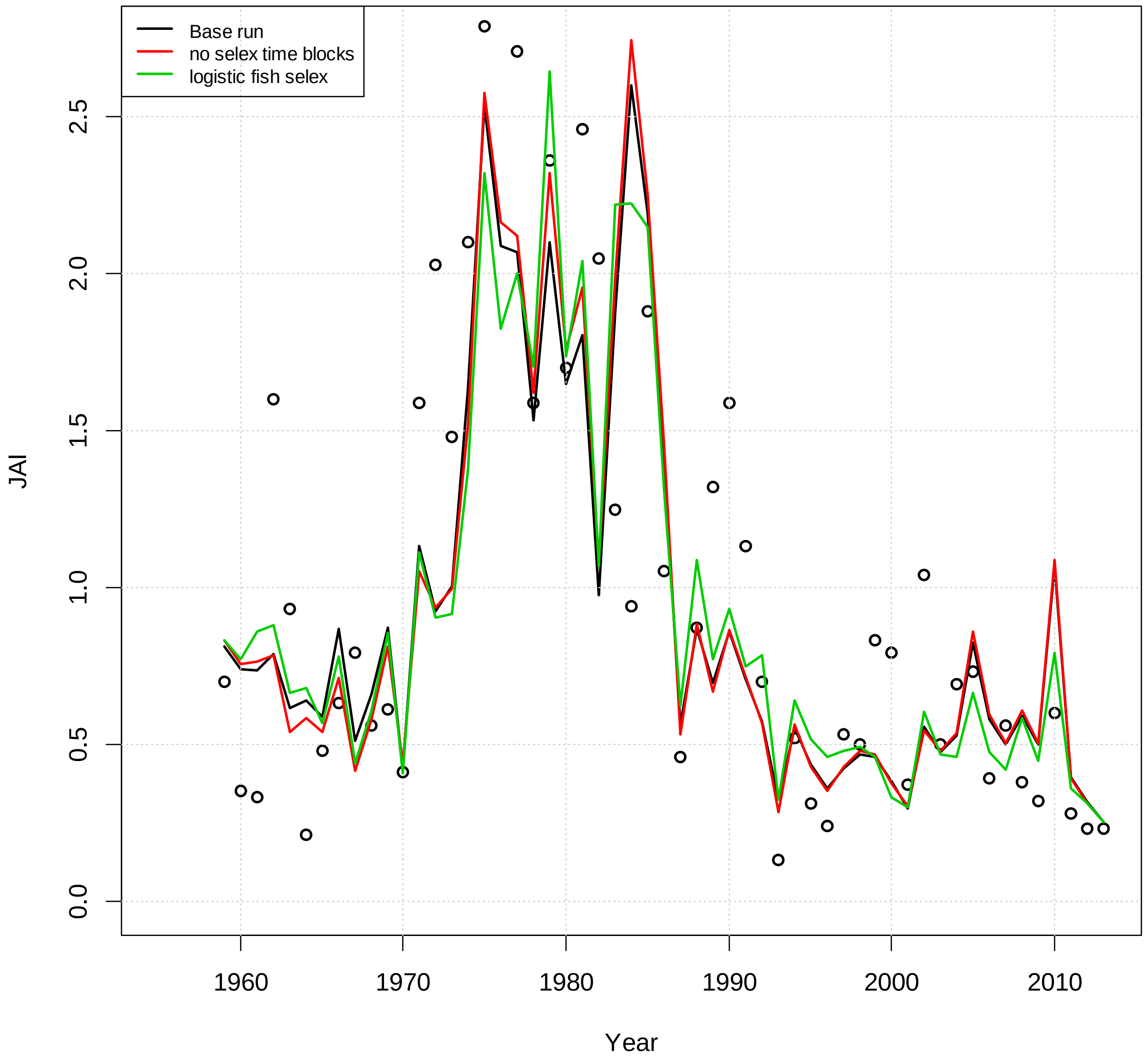


Figure 7.4.1.32. Fit to the recruitment index for sensitivity runs considering differences in ageing uncertainty, catchability for the JAI index, and ages modeled in the assessment model.

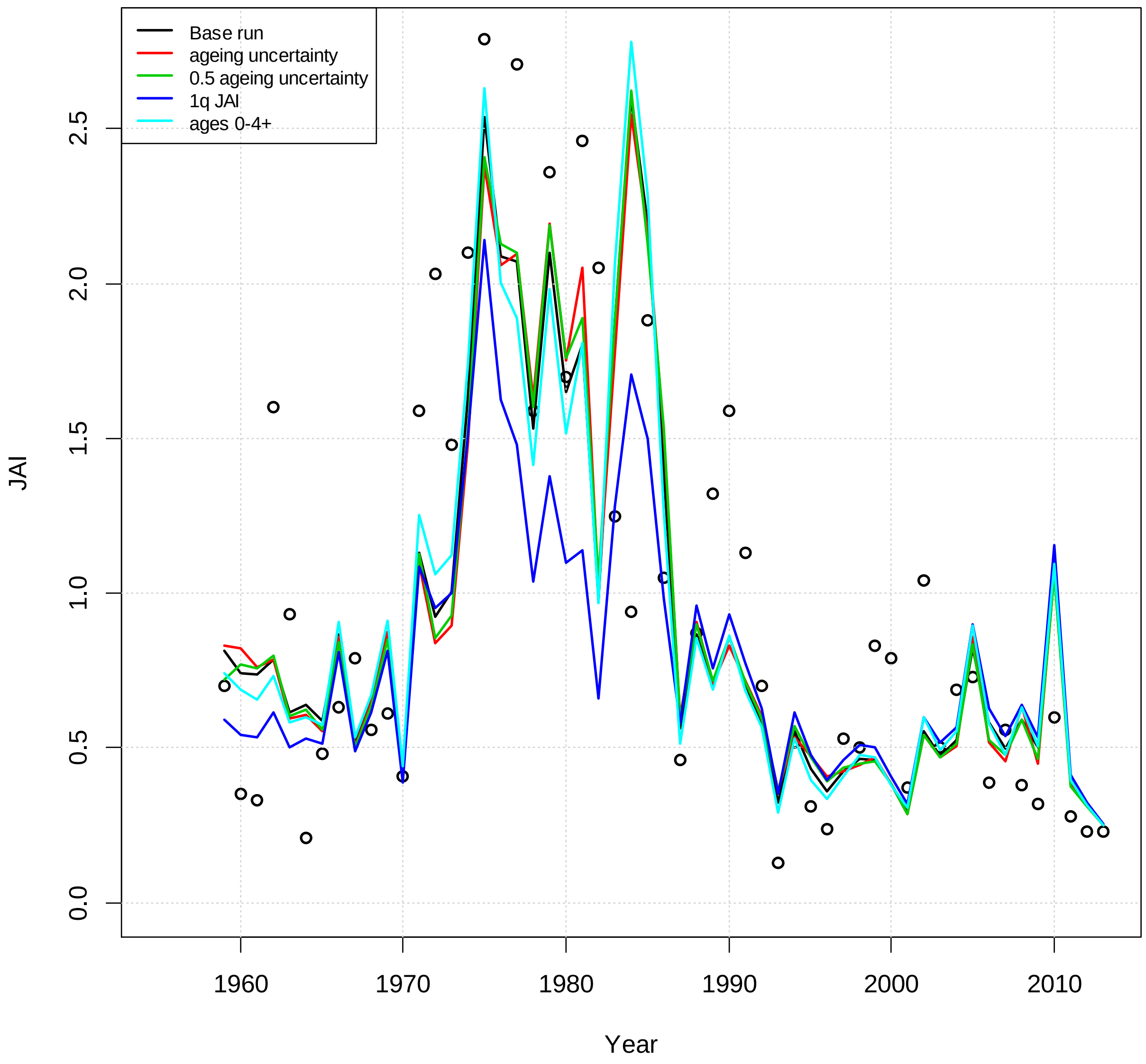


Figure 7.4.1.33. Fit to the recruitment index for sensitivity runs considering differences in start year of the assessment model.

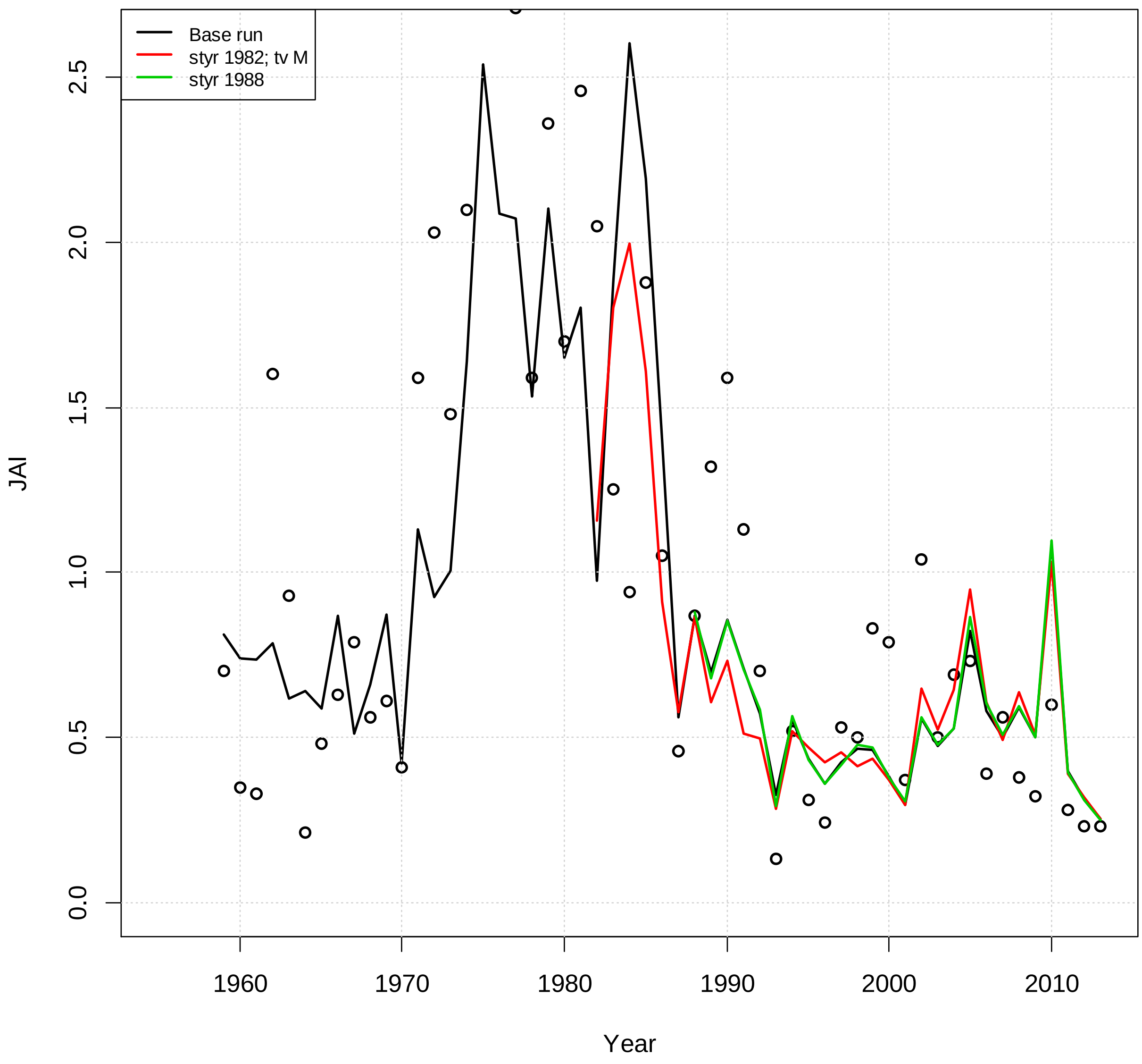


Figure 7.4.1.34. Fit to the recruitment index for sensitivity runs considering differences in weighting of the likelihood components for the assessment model.

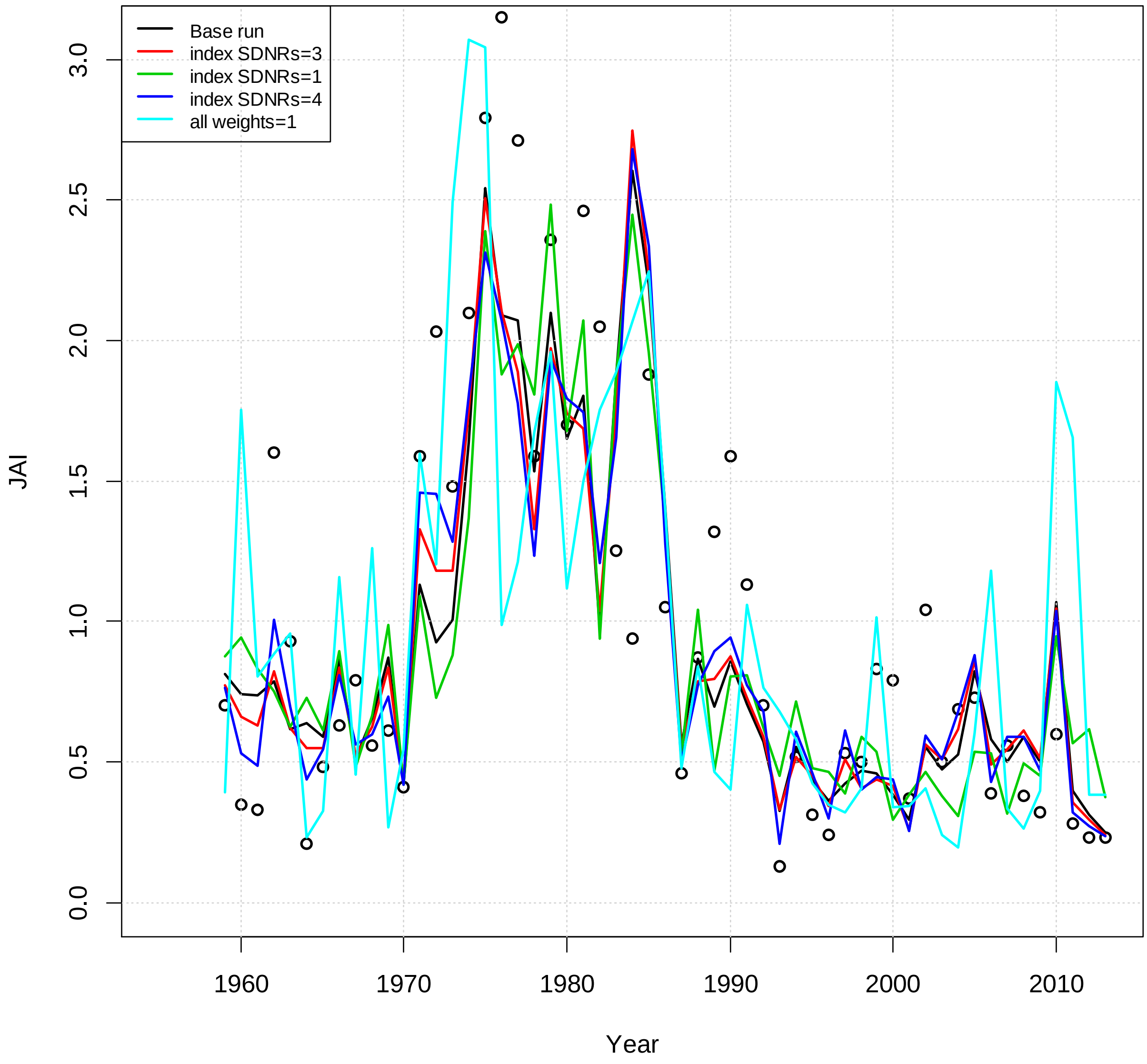


Figure 7.4.1.35. Fit to the recruitment index for sensitivity runs considering differences in steepness.

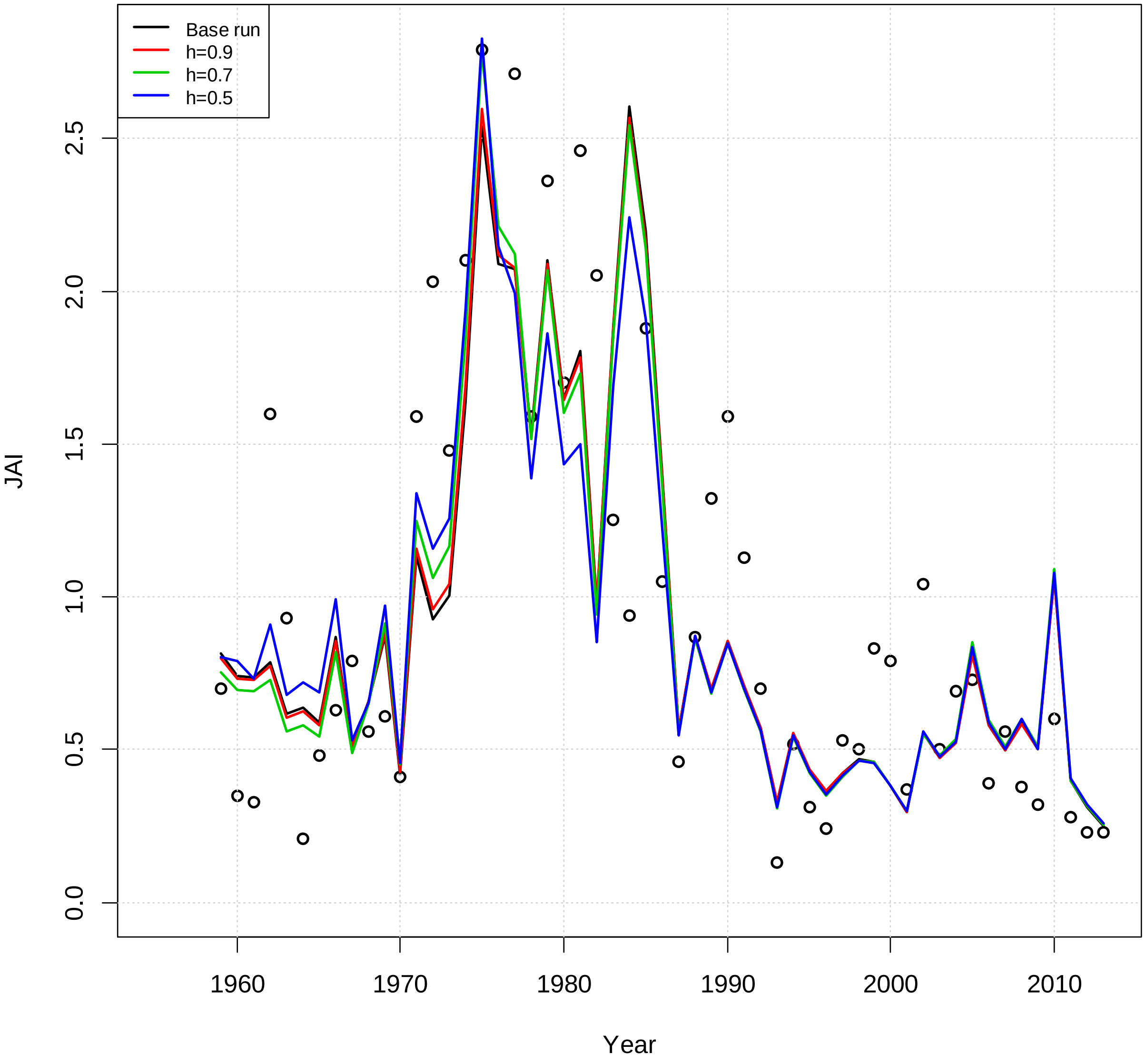


Figure 7.4.1.36. Fit to the SAD index for sensitivity runs considering differences in growth and life history parameters in the assessment model.

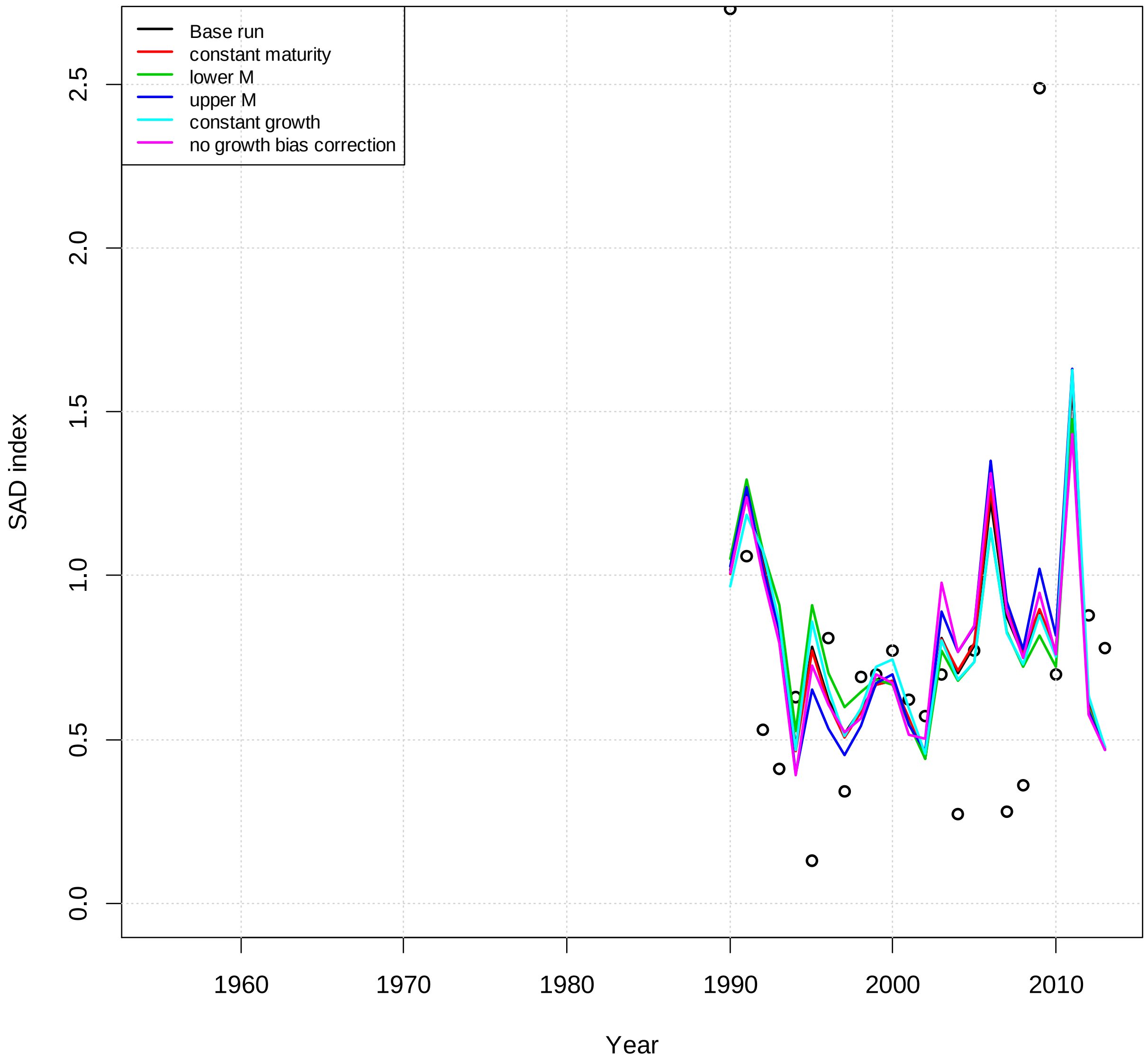


Figure 7.4.1.37. Fit to the SAD index for sensitivity runs considering differences in indices in the assessment model.

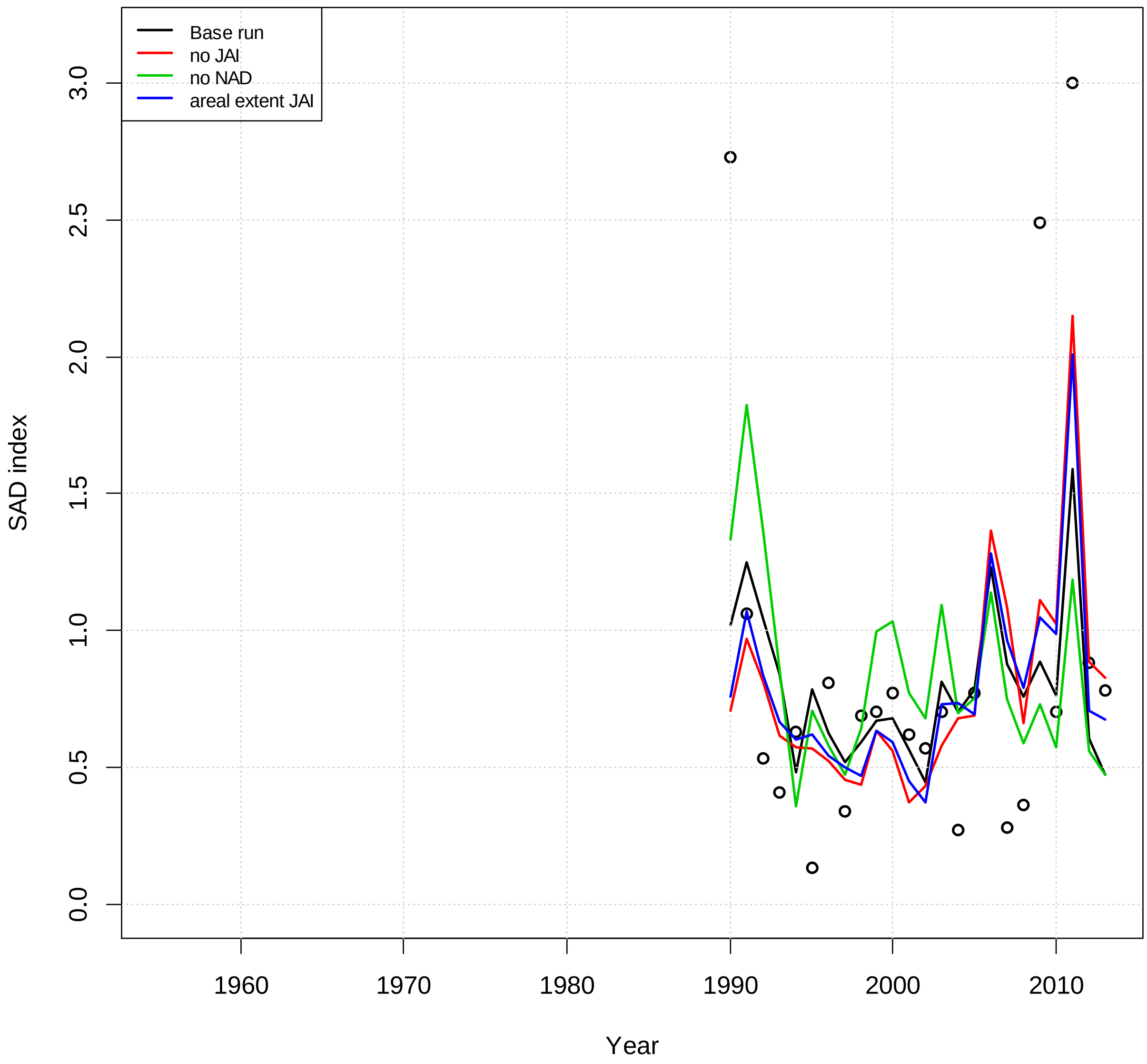


Figure 7.4.1.38. Fit to the SAD index for sensitivity runs considering differences in fishery selectivity in the assessment model.

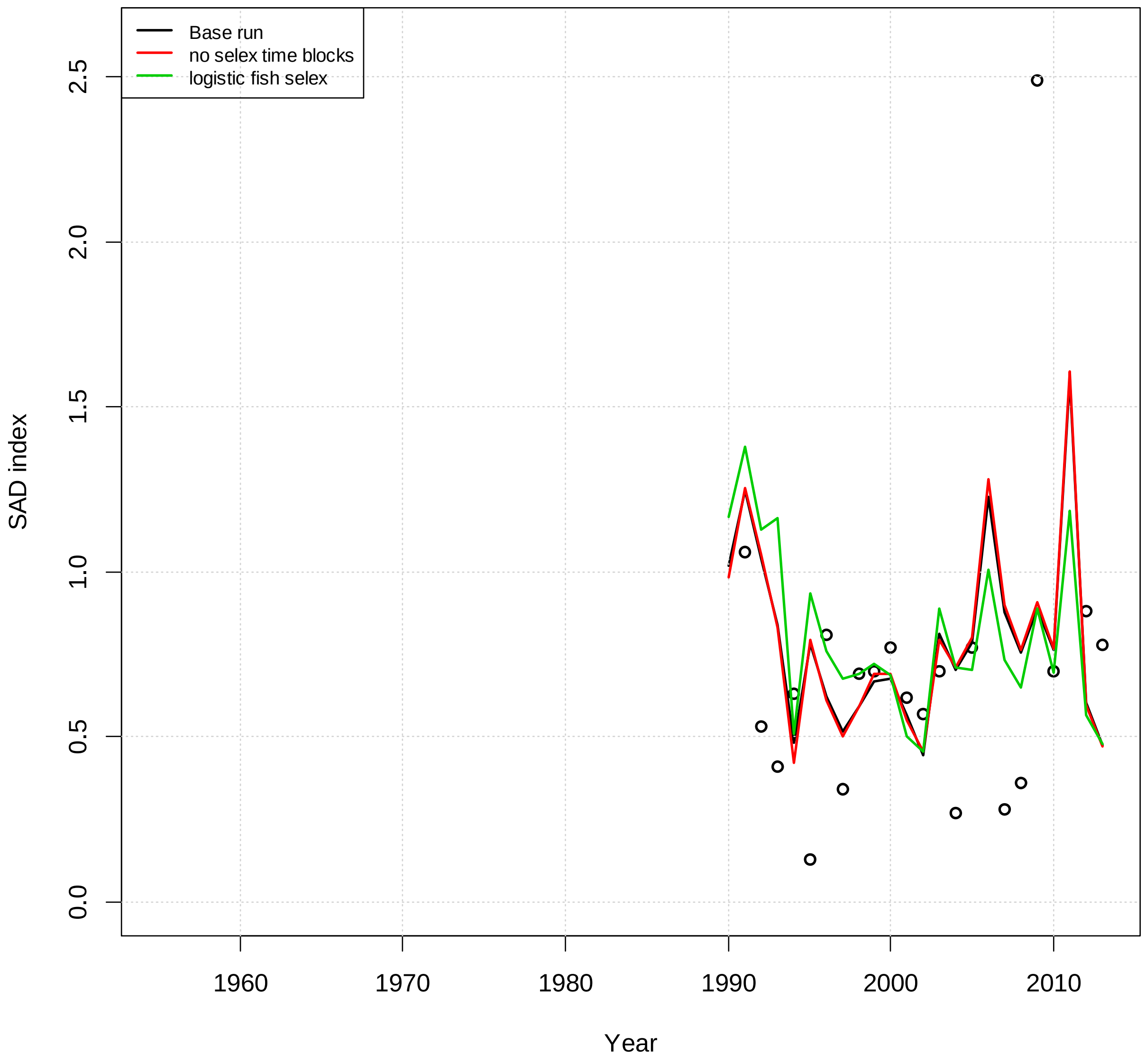


Figure 7.4.1.39. Fit to the SAD index for sensitivity runs considering differences in ageing uncertainty, catchability for the JAI index, and ages modeled in the assessment model.

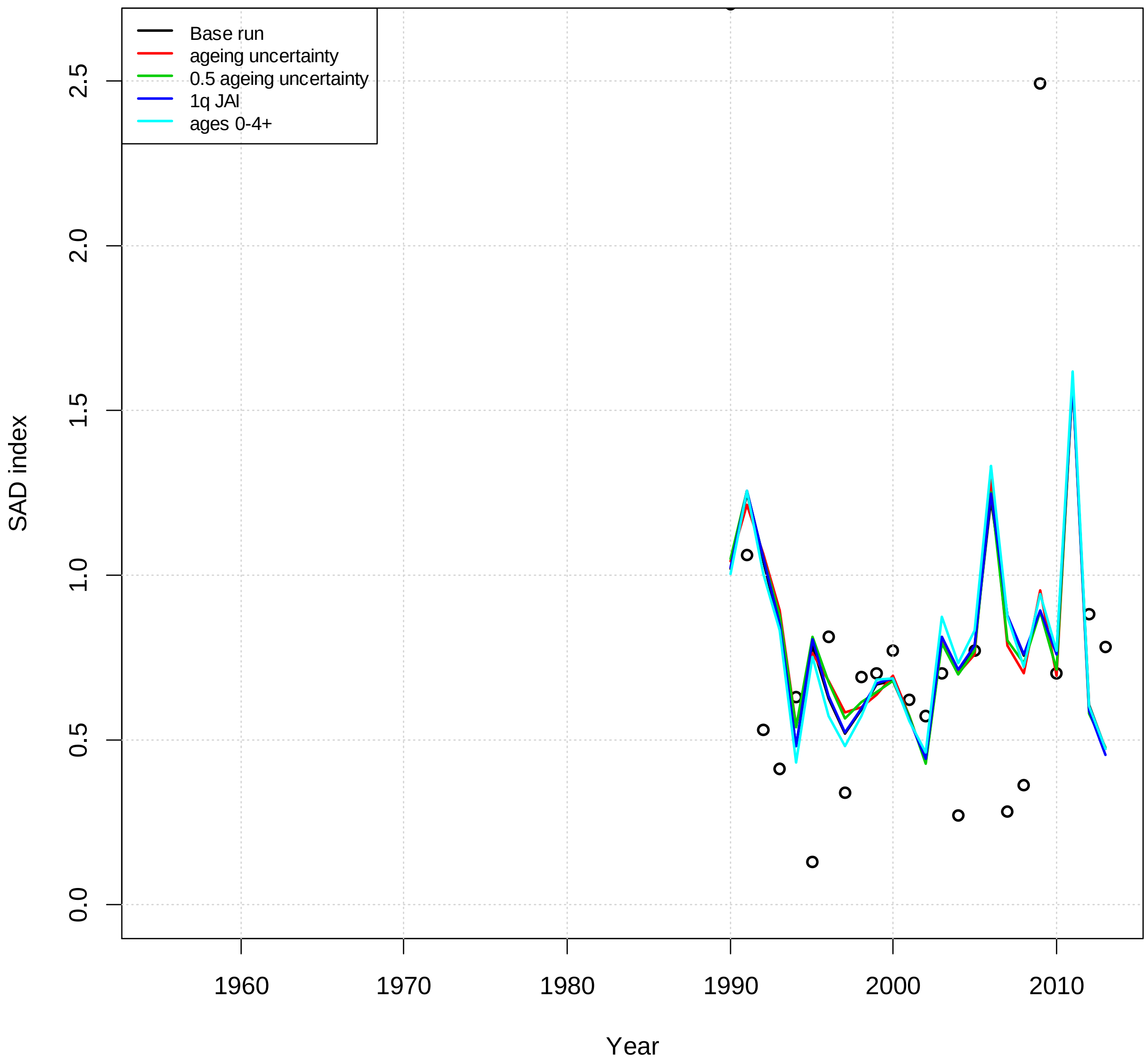


Figure 7.4.1.40. Fit to the SAD index for sensitivity runs considering differences in start year of the assessment model.

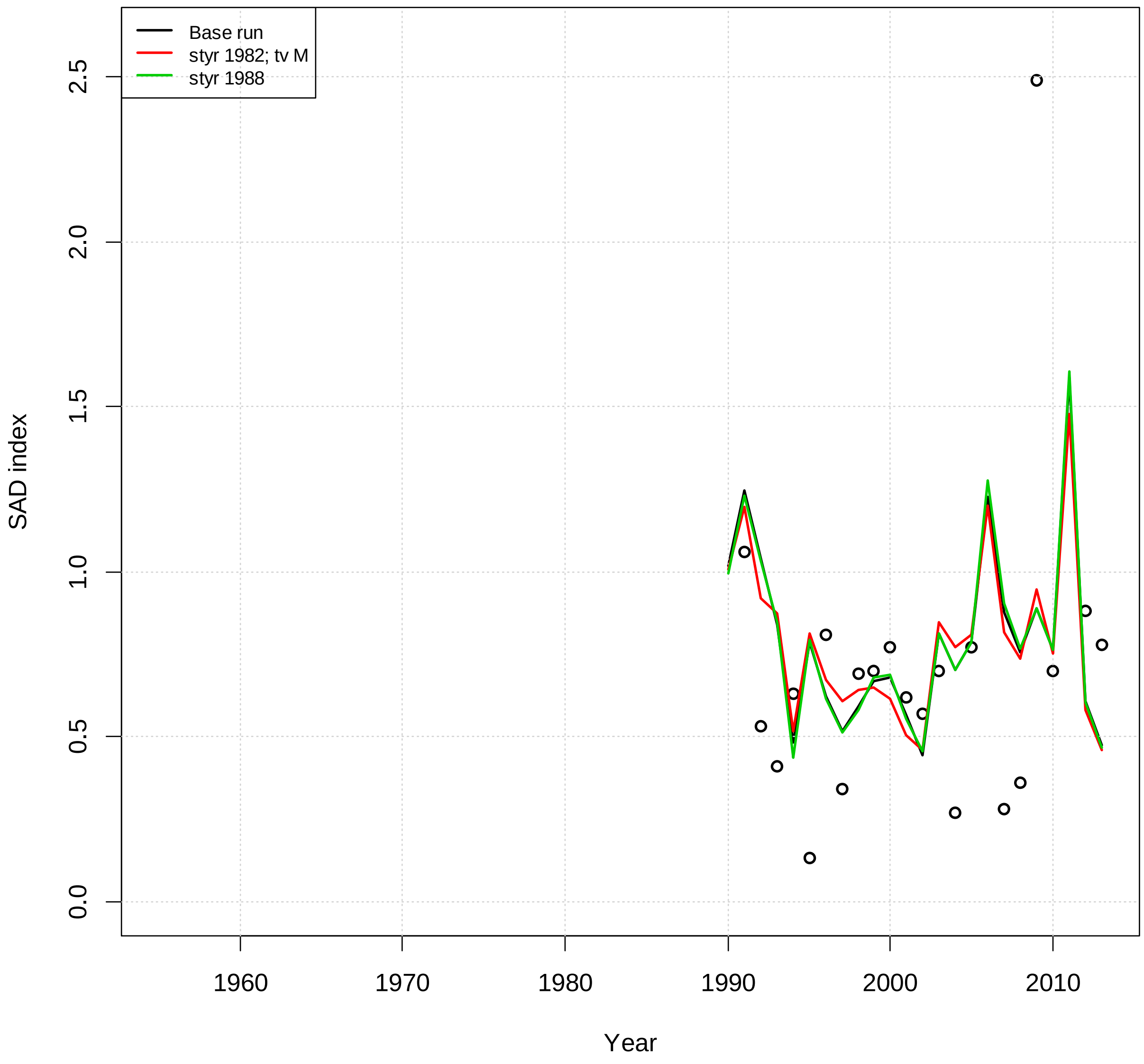


Figure 7.4.1.41. Fit to the SAD index for sensitivity runs considering differences in weighting of the likelihood components for the assessment model.

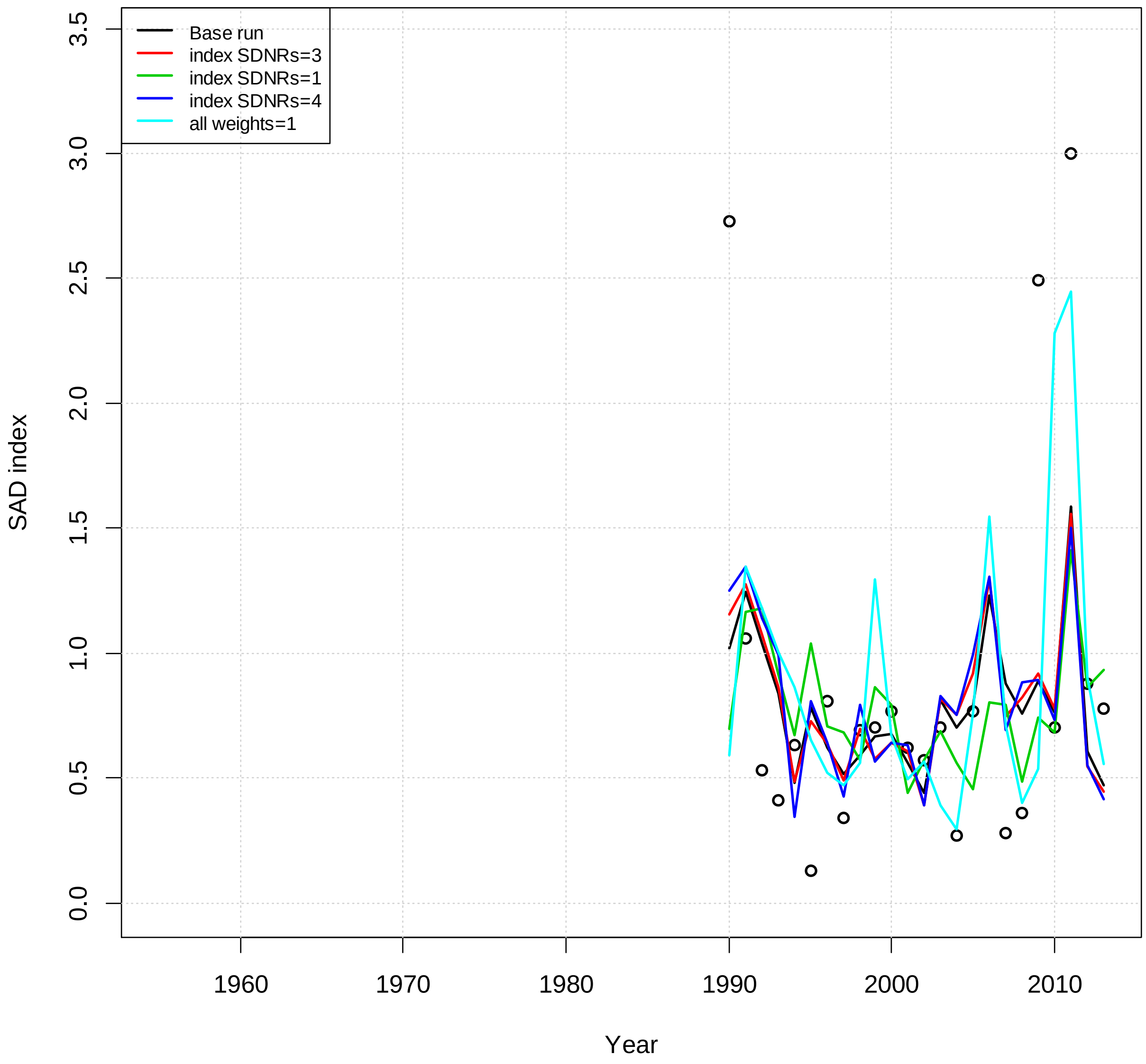


Figure 7.4.1.42. Fit to the SAD index for sensitivity runs considering differences in steepness.

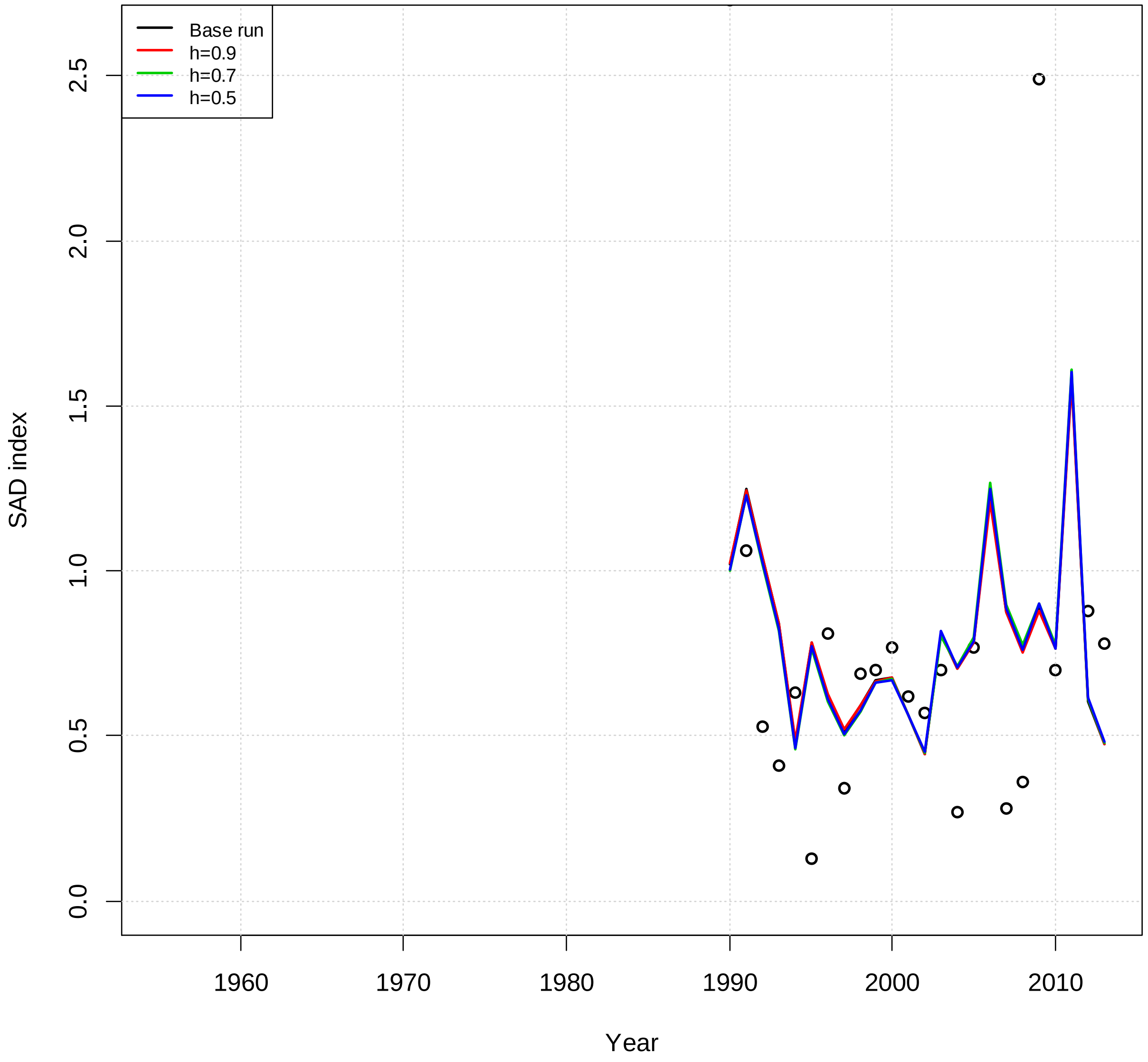


Figure 7.4.1.43. Fit to the NAD index for sensitivity runs considering differences in growth and life history parameters in the assessment model.

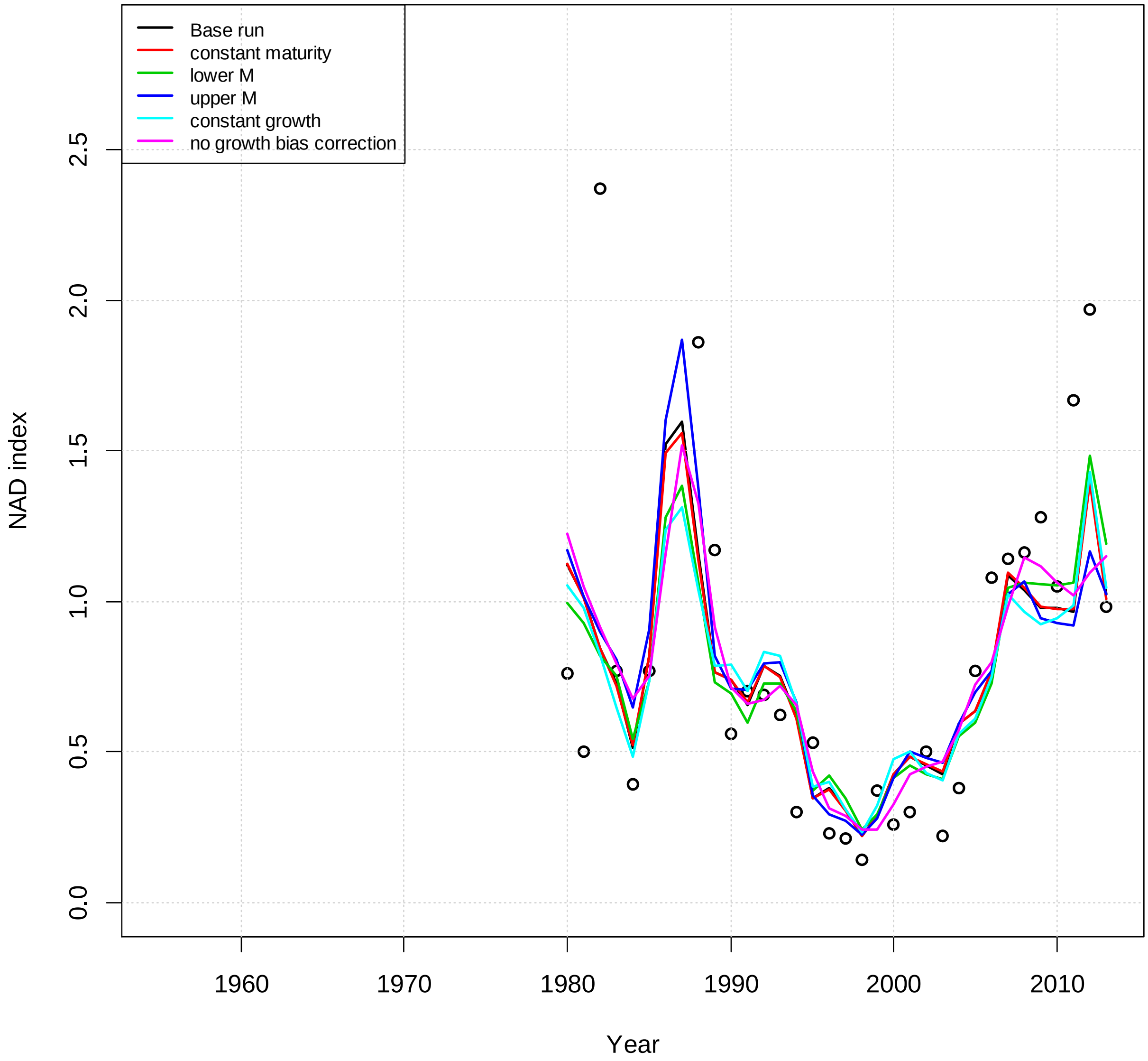


Figure 7.4.1.44. Fit to the NAD index for sensitivity runs considering differences in indices in the assessment model.

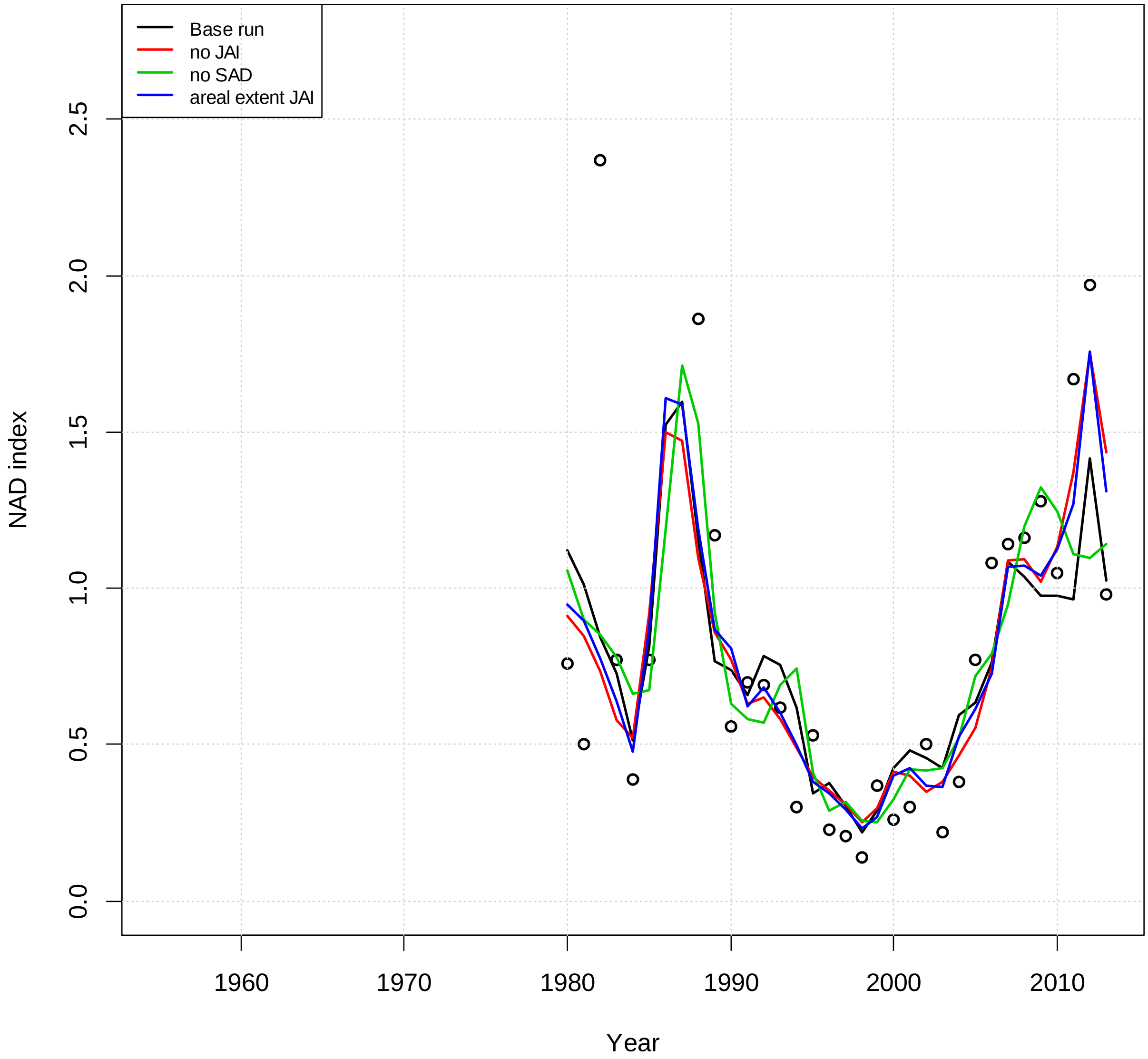


Figure 7.4.1.45. Fit to the NAD index for sensitivity runs considering differences in fishery selectivity in the assessment model.

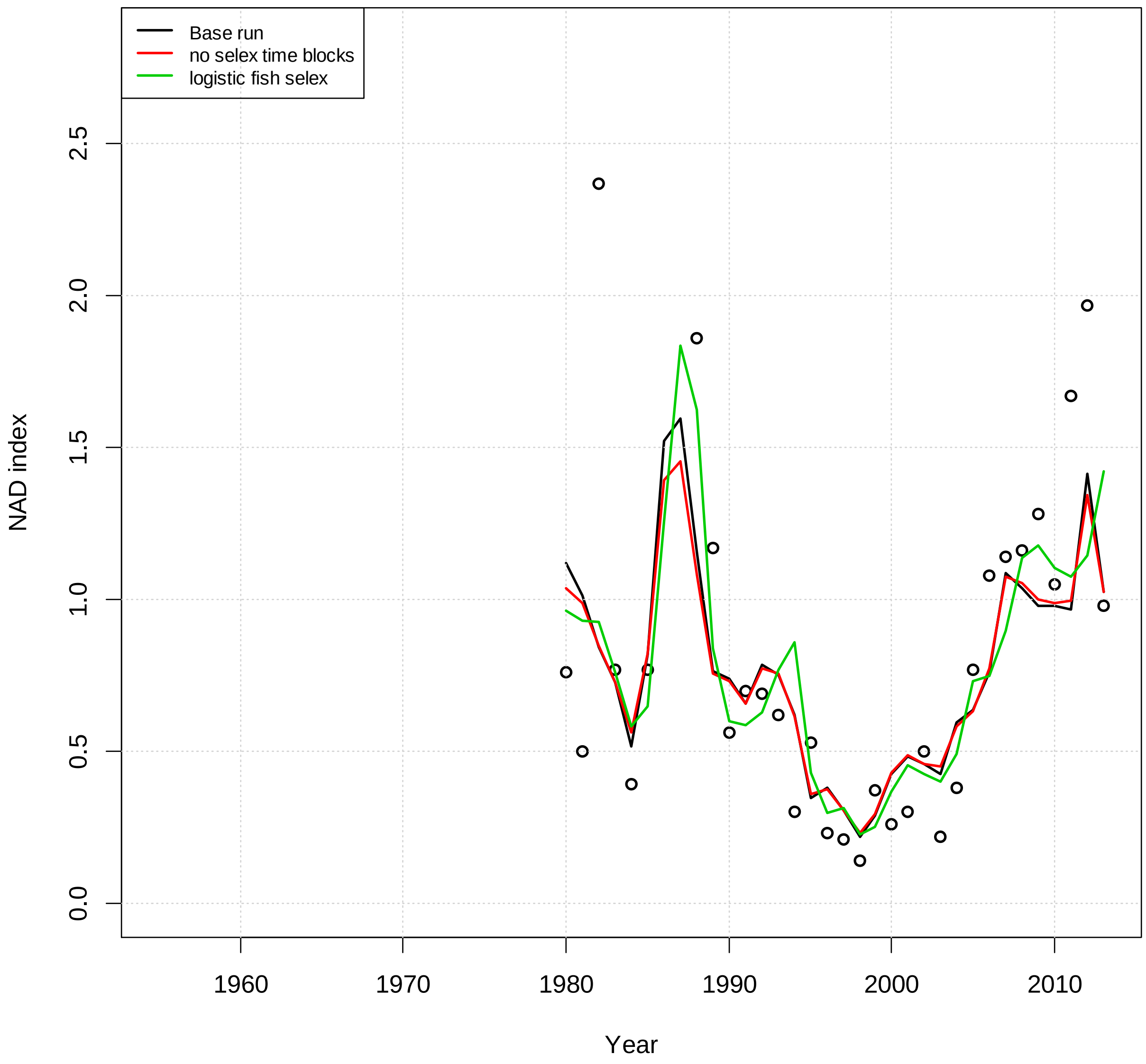


Figure 7.4.1.46. Fit to the NAD index for sensitivity runs considering differences in ageing uncertainty, catchability for the JAI index, and ages modeled in the assessment model.

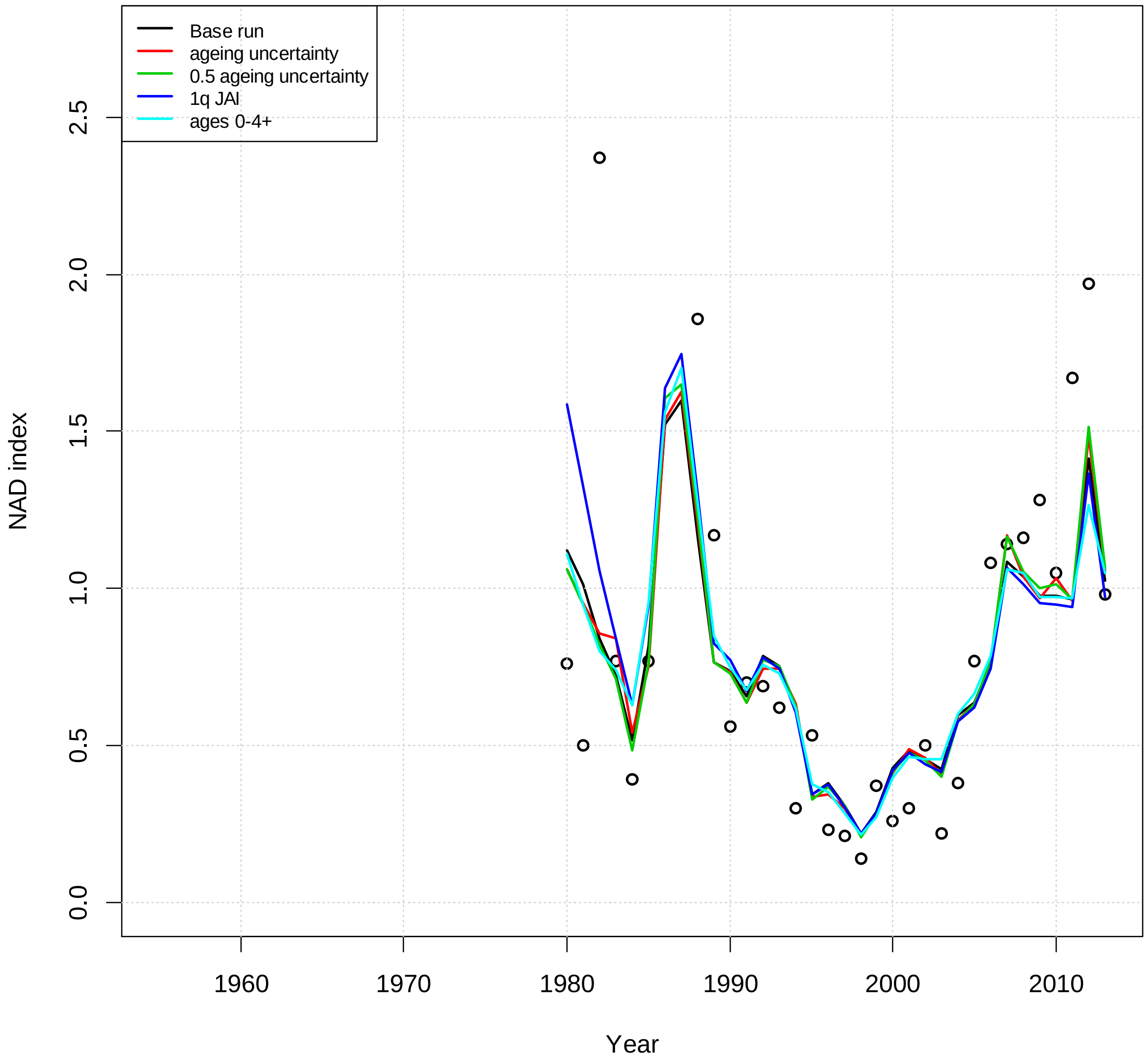


Figure 7.4.1.47. Fit to the NAD index for sensitivity runs considering differences in start year of the assessment model.

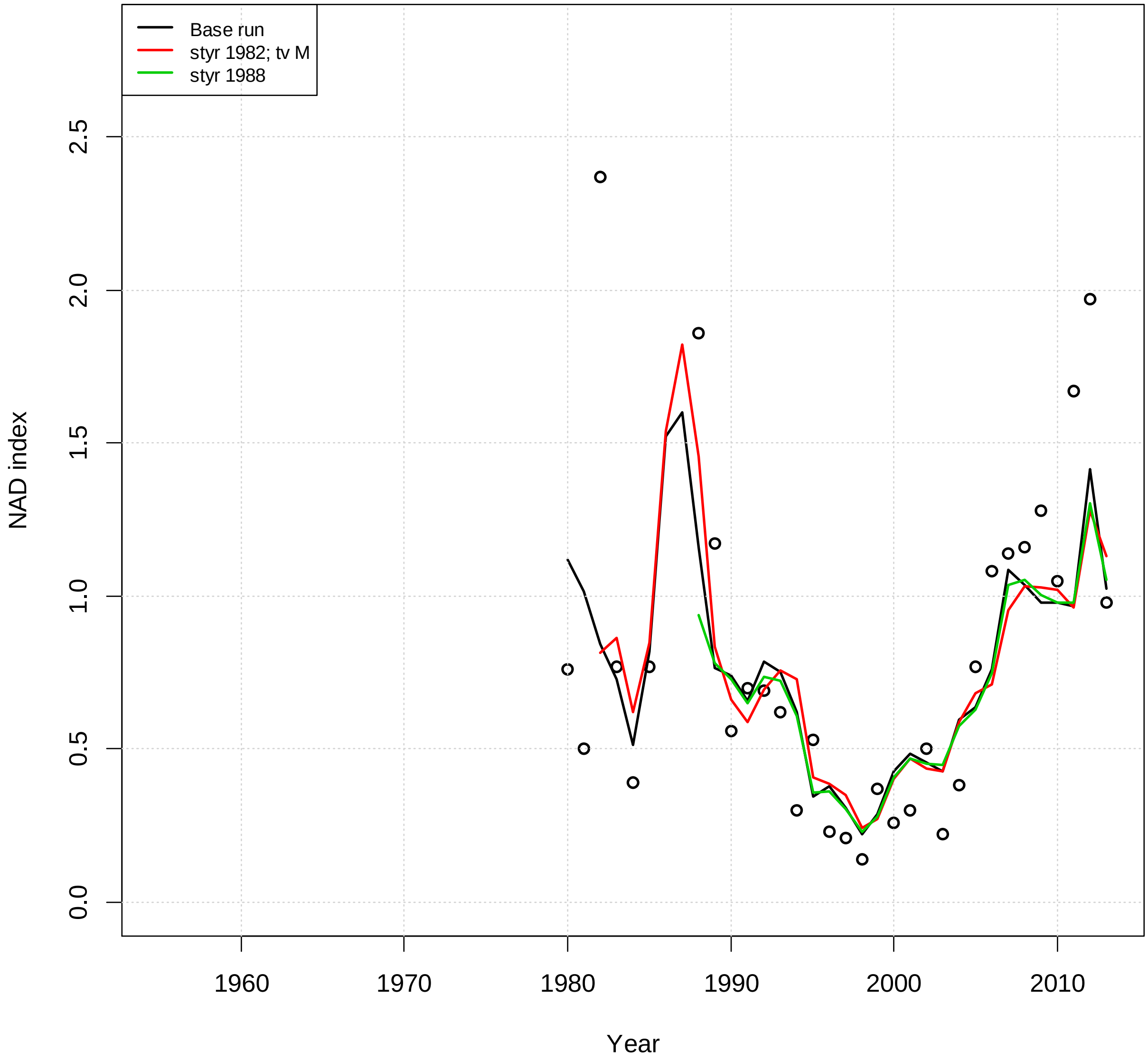


Figure 7.4.1.48. Fit to the NAD index for sensitivity runs considering differences in weighting of the likelihood components for the assessment model.

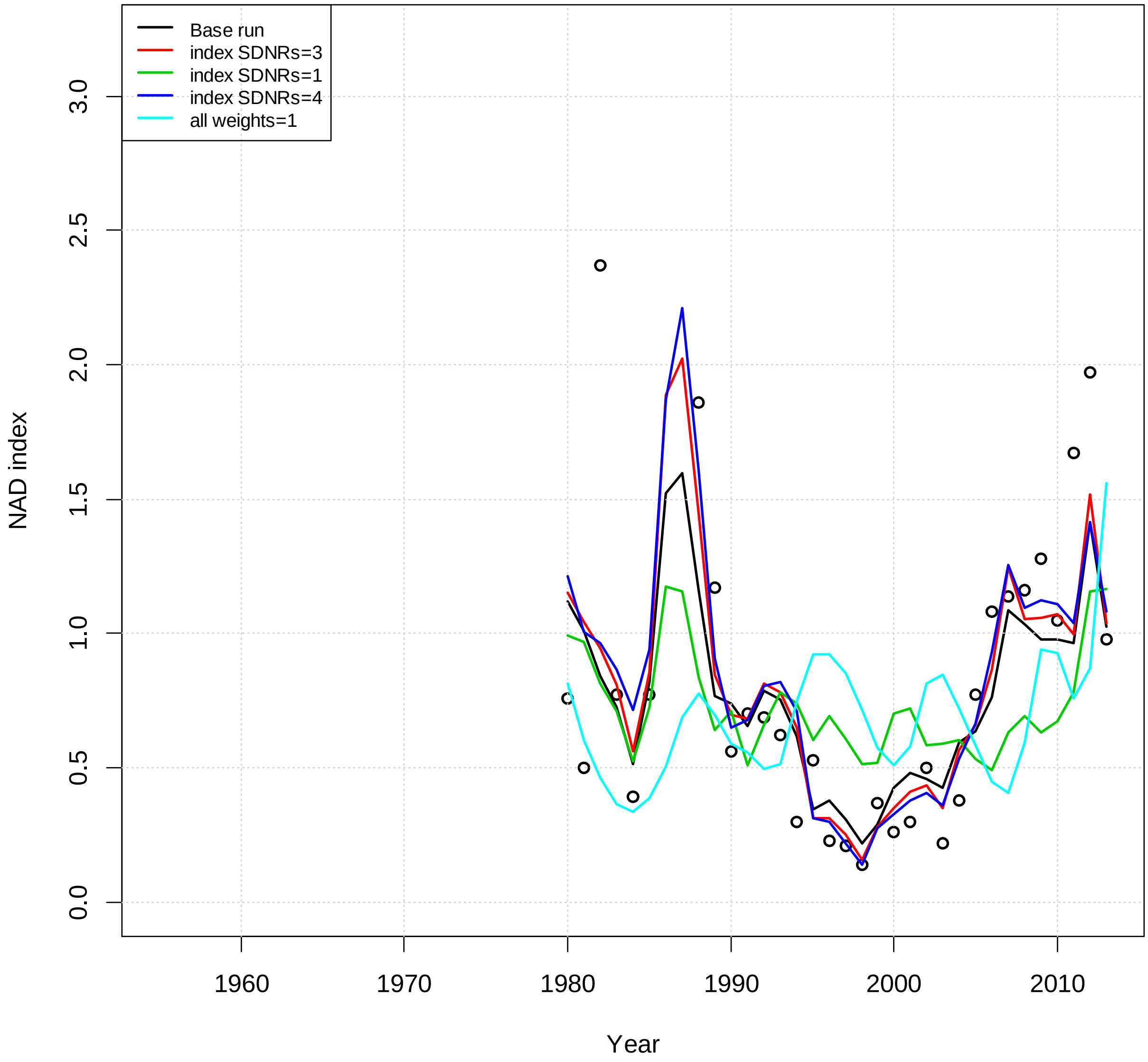


Figure 7.4.1.49. Fit to the NAD index for sensitivity runs considering differences in steepness.

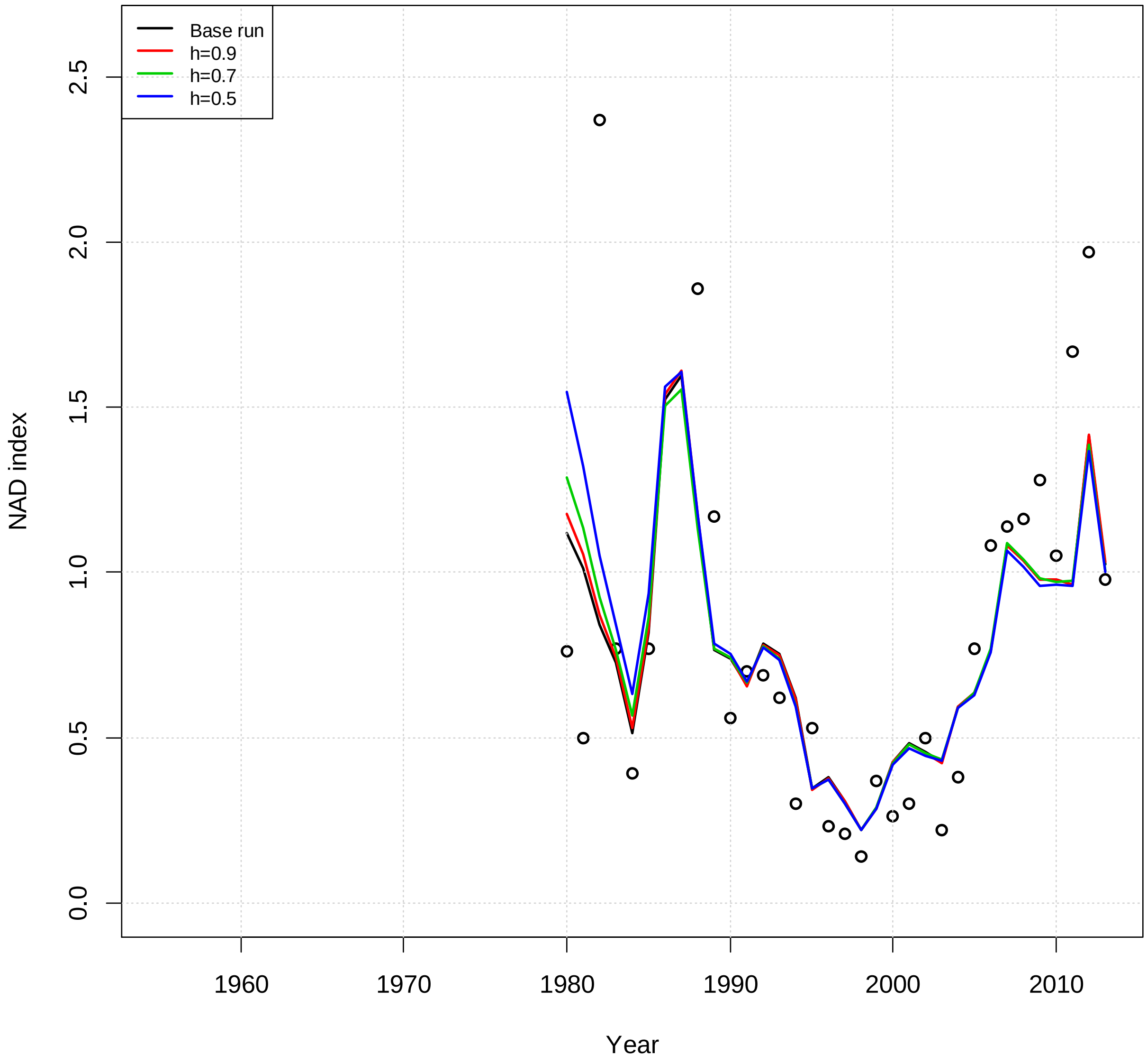
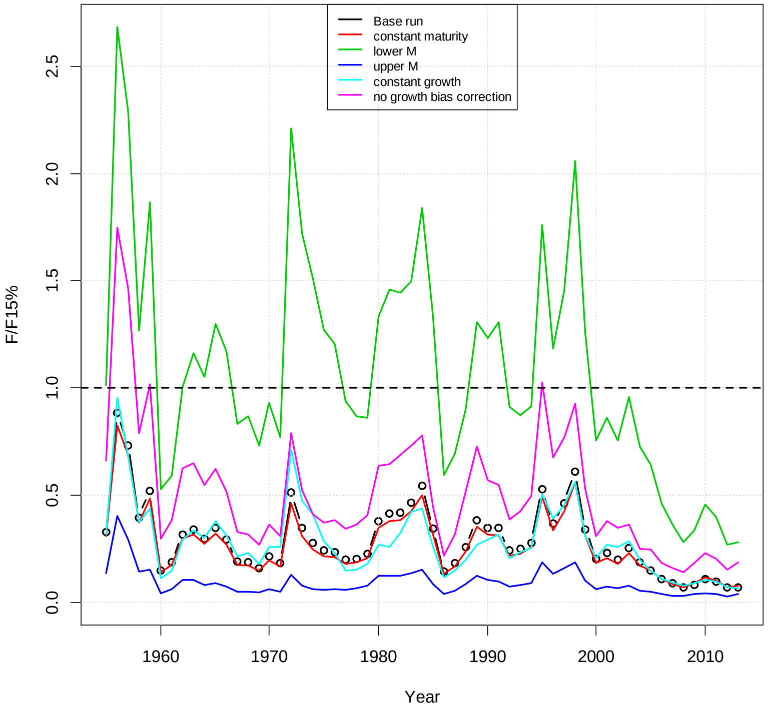


Figure 7.4.1.50. Full F at age-2 (upper) and age-3 (lower) over ***F***$\boldsymbol{F_{15\%}}$ for sensitivity runs considering differences in growth and life history parameters in the assessment model.



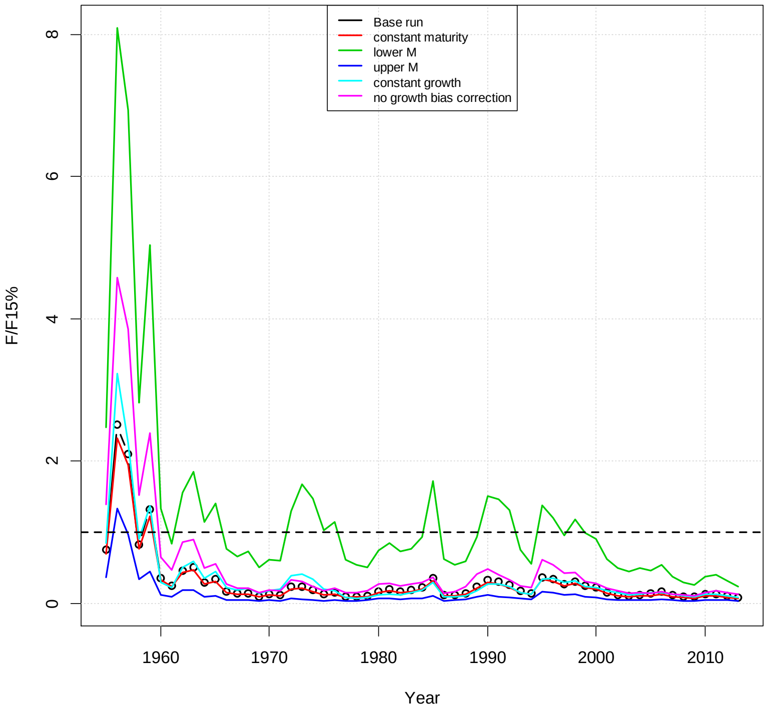
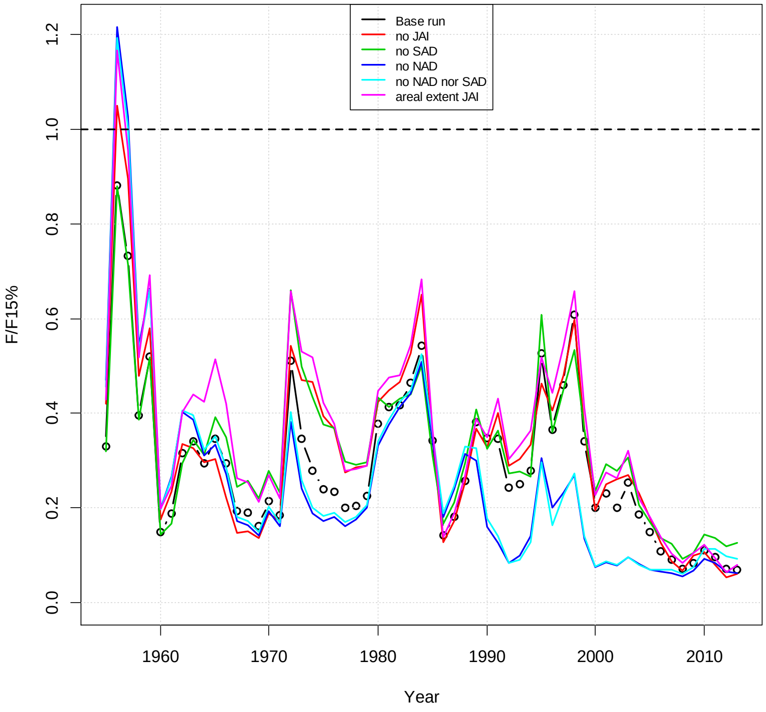


Figure 7.4.1.51. Full F at age-2 (upper) and age-3 (lower) over ***$F_{15\%}$*** for sensitivity runs considering differences in indices in the assessment model.



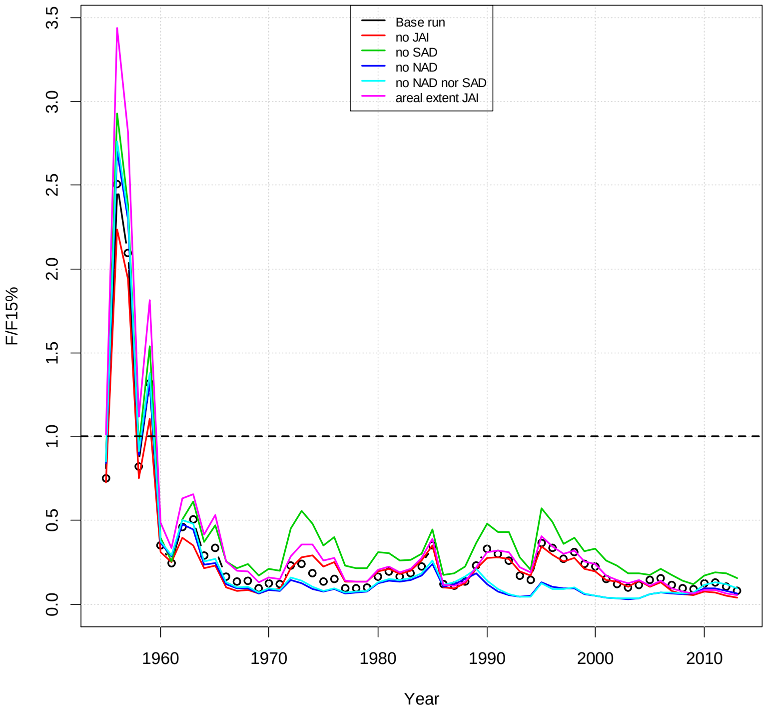
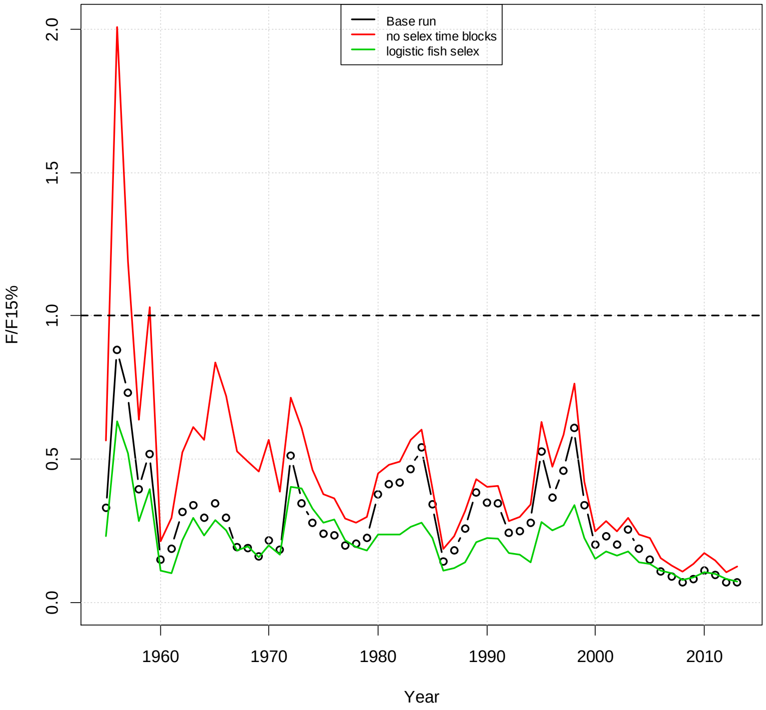


Figure 7.4.1.52. Full F at age-2 (upper) and age-3 (lower) over ***$F_{15\%}$*** for sensitivity runs considering differences in fishery selectivity in the assessment model.



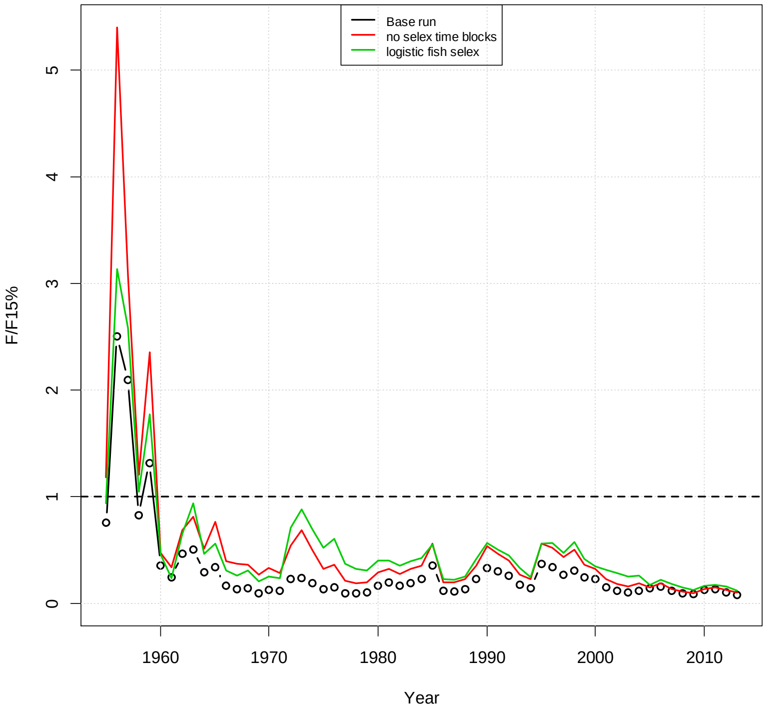
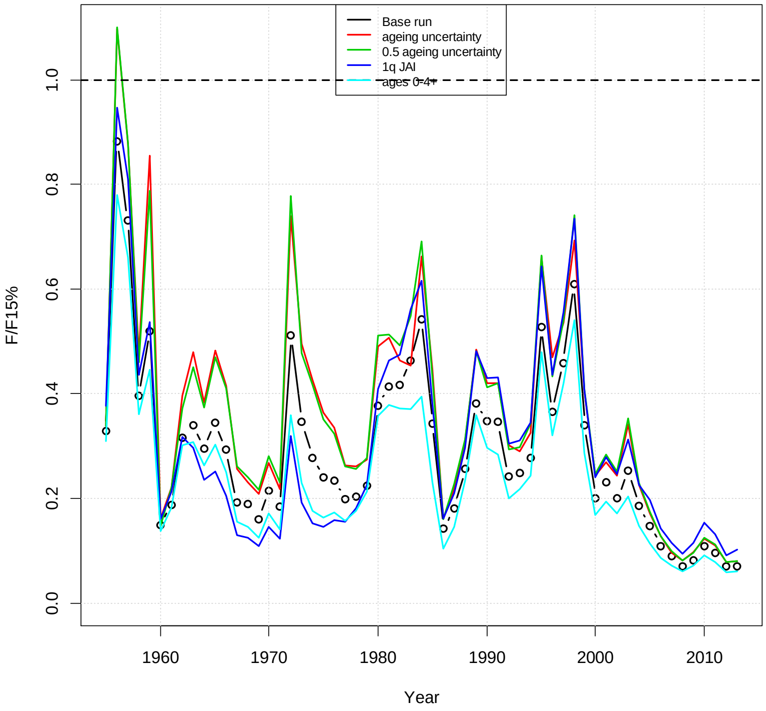


Figure 7.4.1.53. Full F at age-2 (upper) and age-3 (lower) over ***F*$_{15\%}$** for sensitivity runs considering differences in ageing uncertainty, catchability for the JAI index, and ages modeled in the assessment mode



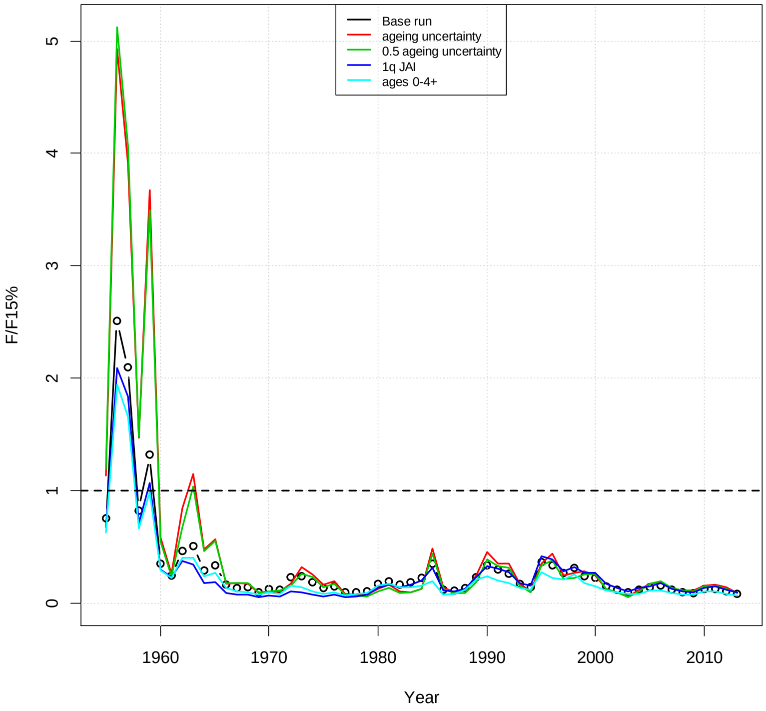
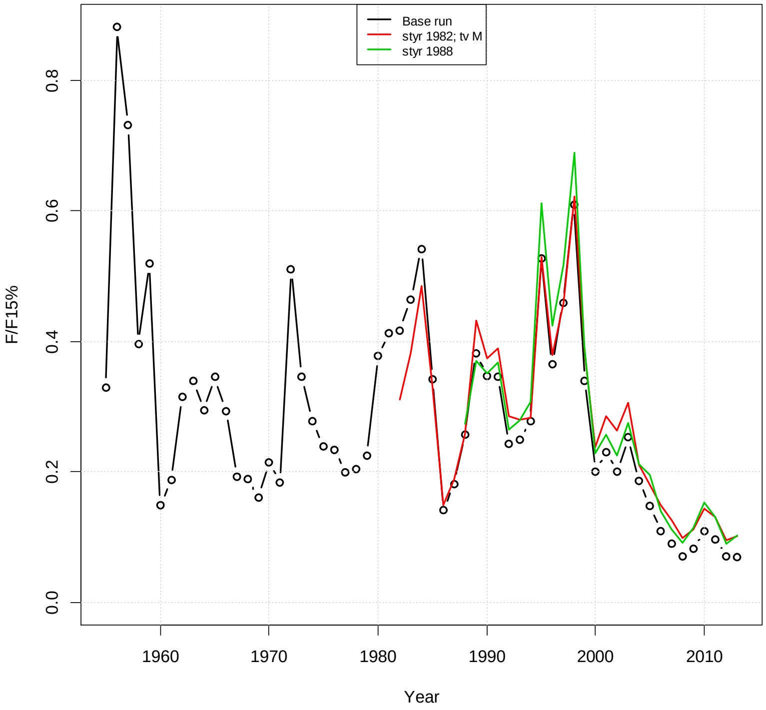


Figure 7.4.1.54. Full F at age-2 (upper) and age-3 (lower) over ***F*$_{15\%}$** for sensitivity runs considering differences in start year of the assessment model.



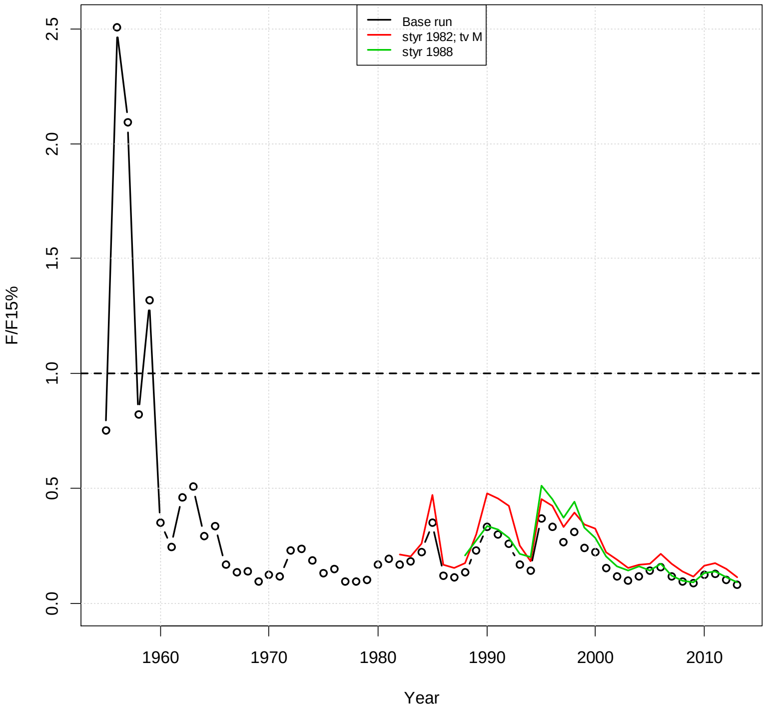
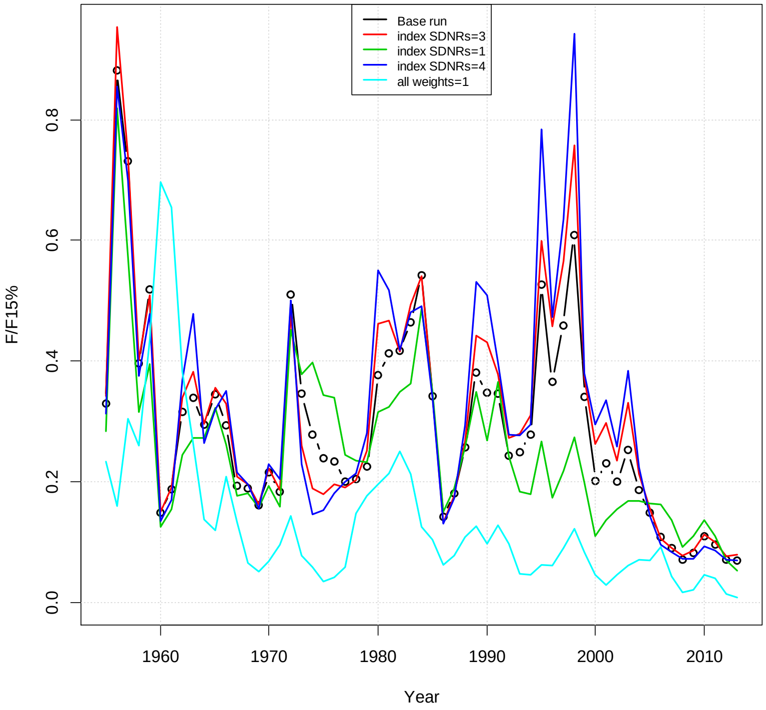


Figure 7.4.1.55. Full F at age-2 (upper) and age-3 (lower) over ***F*$_{15\%}$** for sensitivity runs considering differences in weighting of the likelihood components for the assessment model.



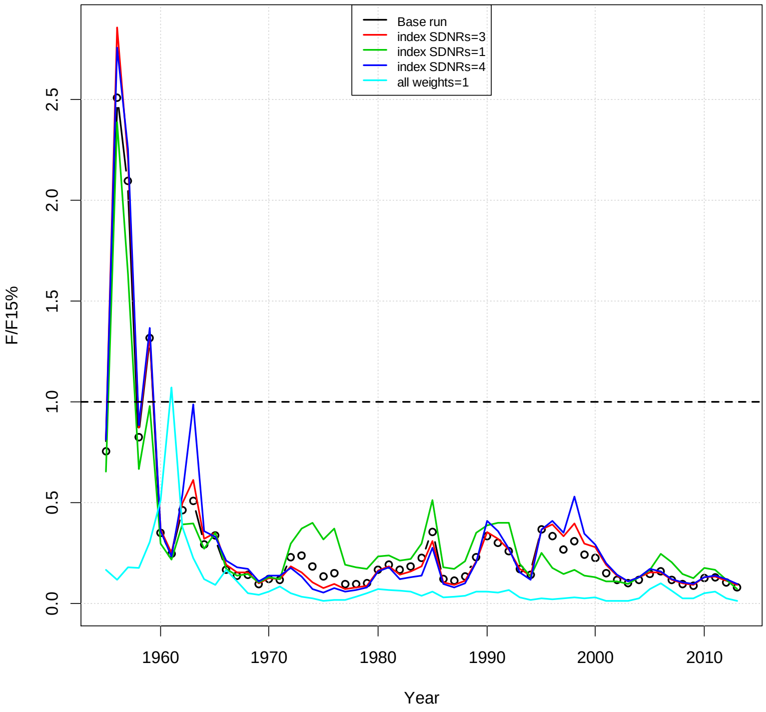
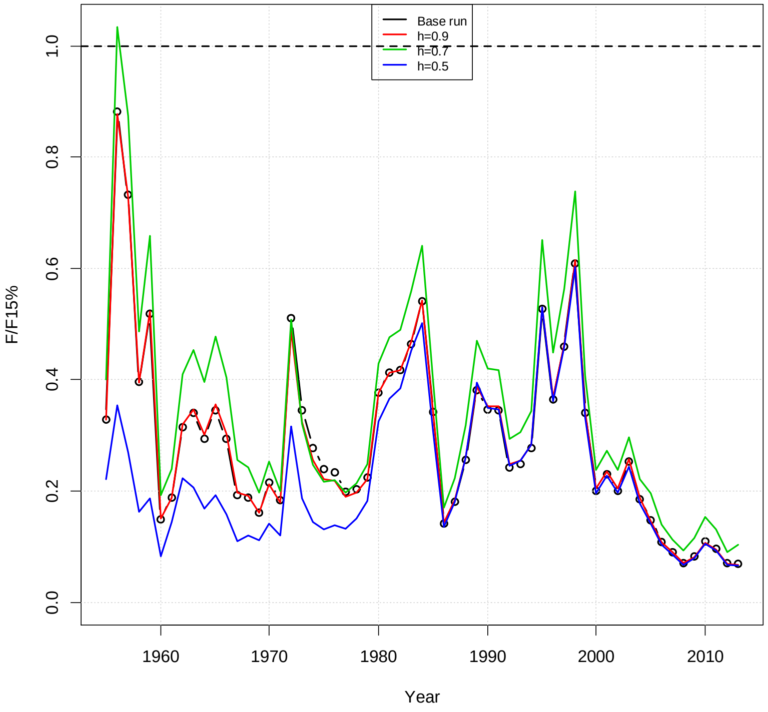


Figure 7.4.1.56. Full F at age-2 (upper) and age-3 (lower) over ***$F_{15\%}$*** for sensitivity runs considering differences in steepness.



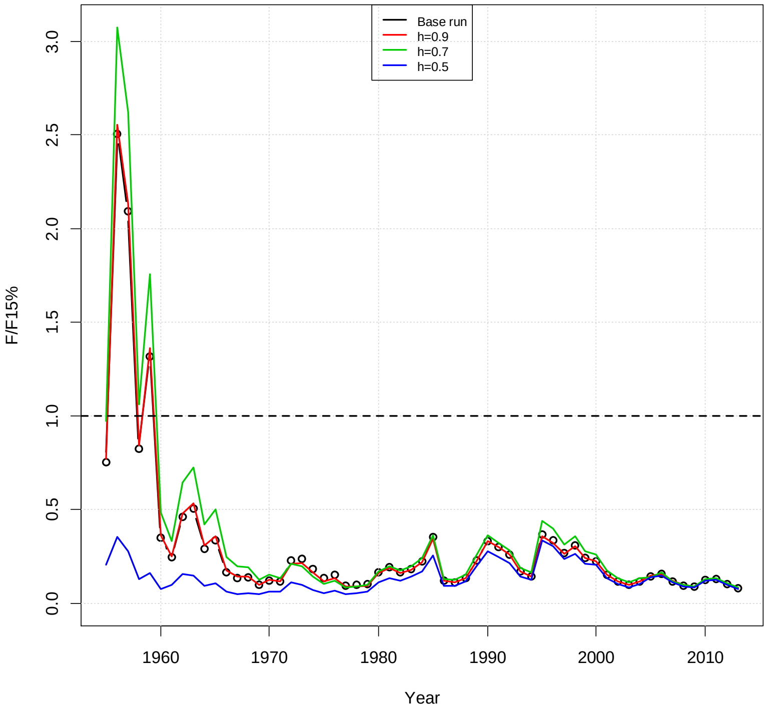
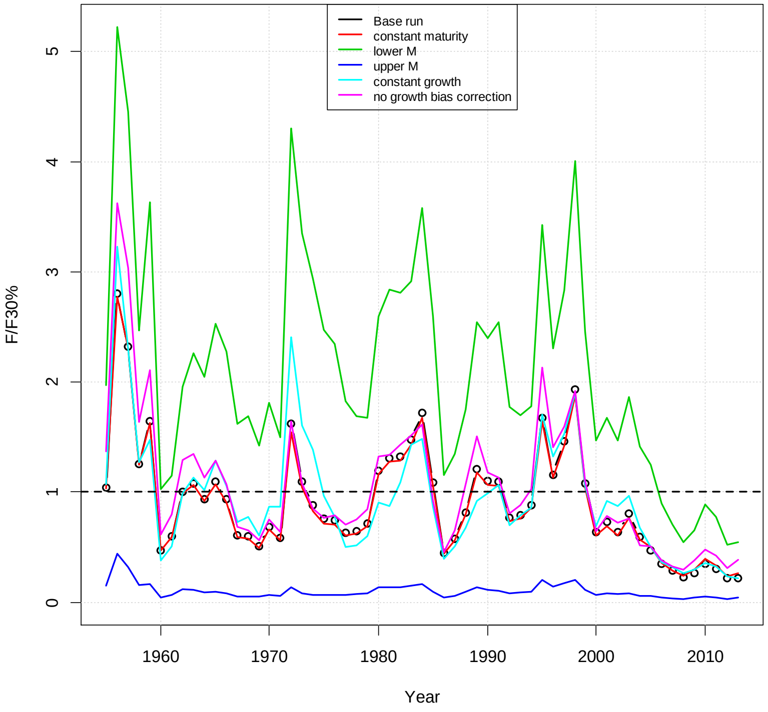


Figure 7.4.1.57. Full F at age-2 (upper) and age-3 (lower) over ***F*$_{30\%}$** for sensitivity runs considering differences in growth and life history parameters in the assessment model.



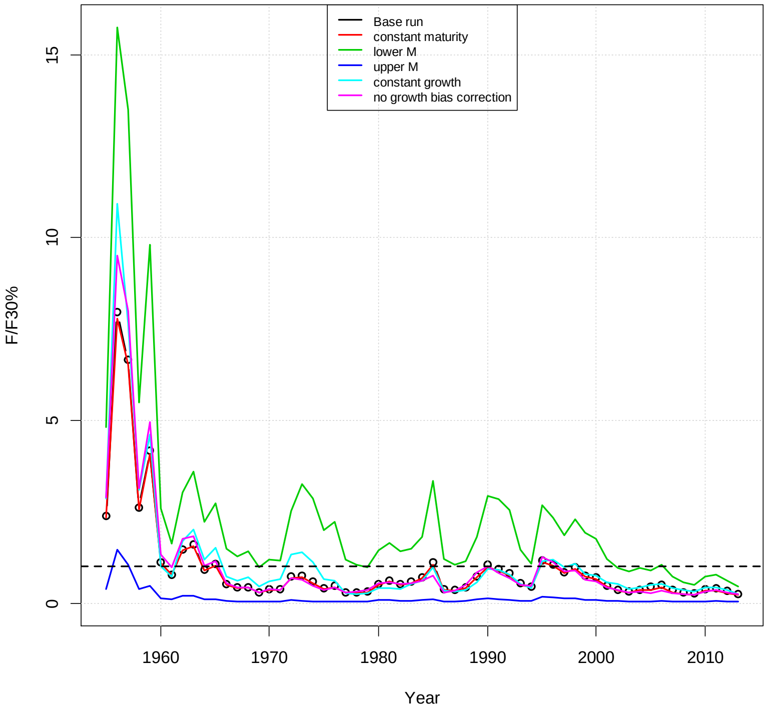
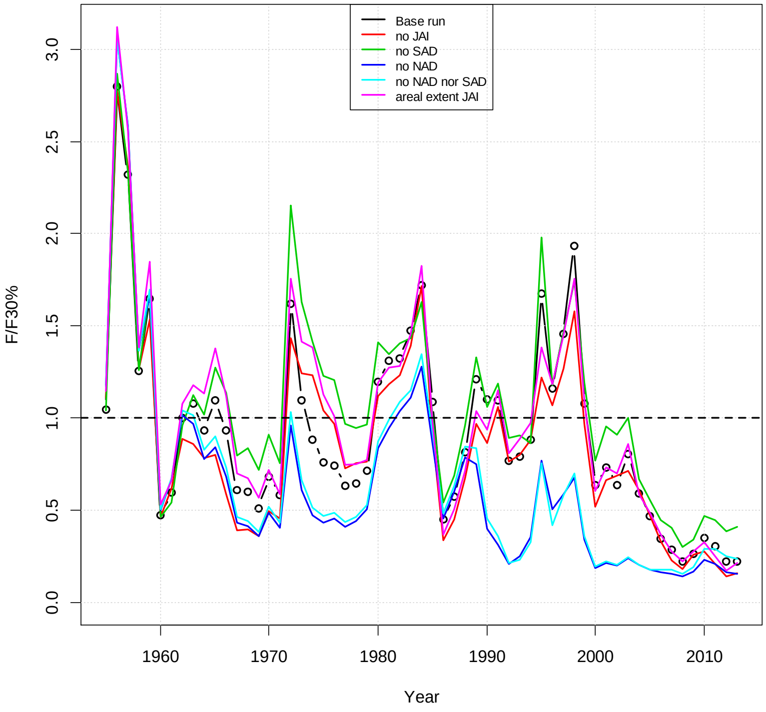


Figure 7.4.1.58. Full F at age-2 (upper) and age-3 (lower) over ***F*$_{30\%}$** for sensitivity runs considering differences in indices in the assessment model.



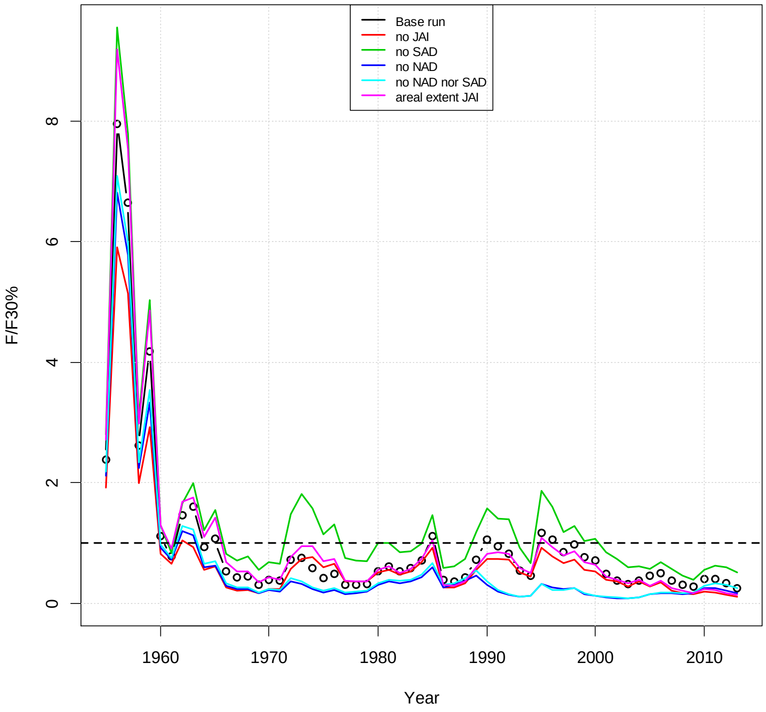
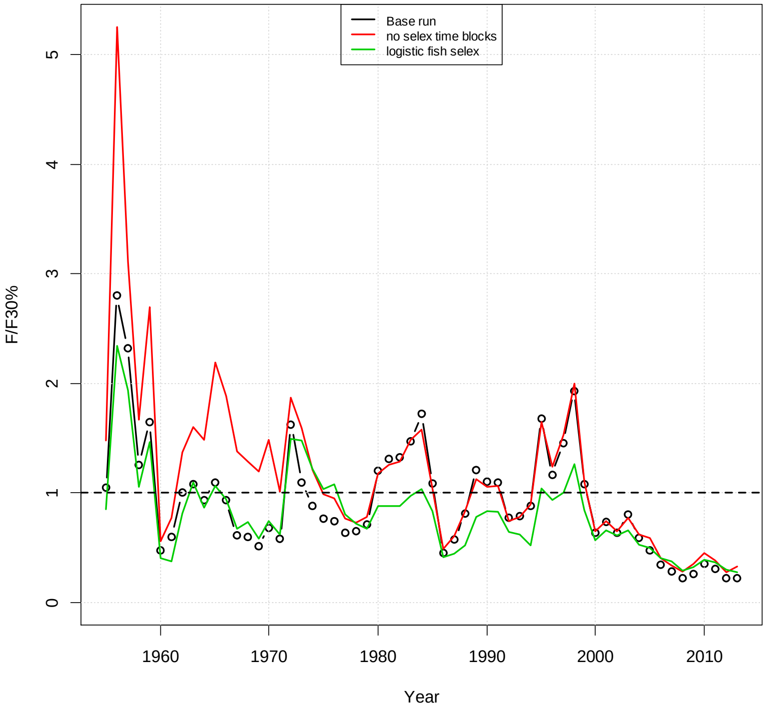


Figure 7.4.1.59. Full F at age-2 (upper) and age-3 (lower) over $F_{30\%}$ for sensitivity runs considering differences in fishery selectivity in the assessment model.



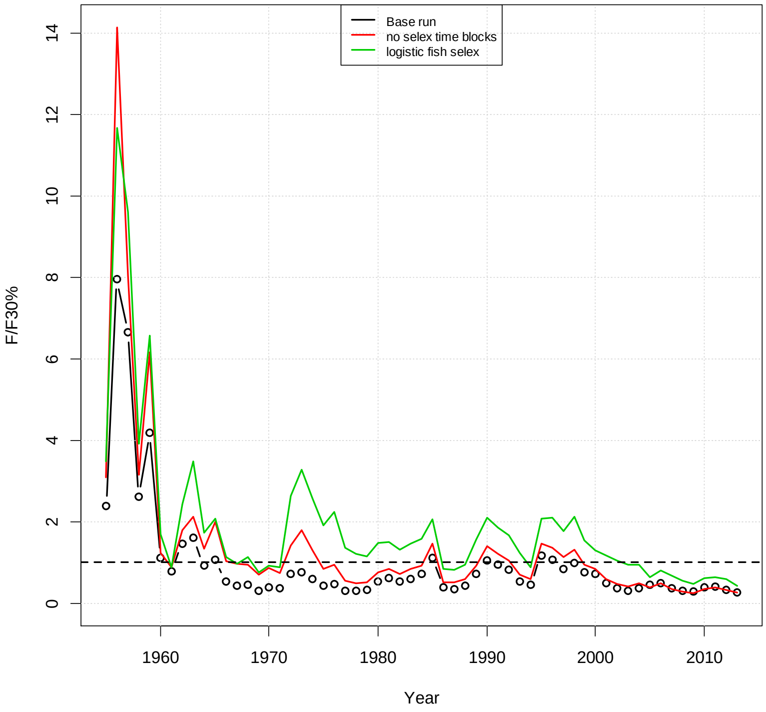
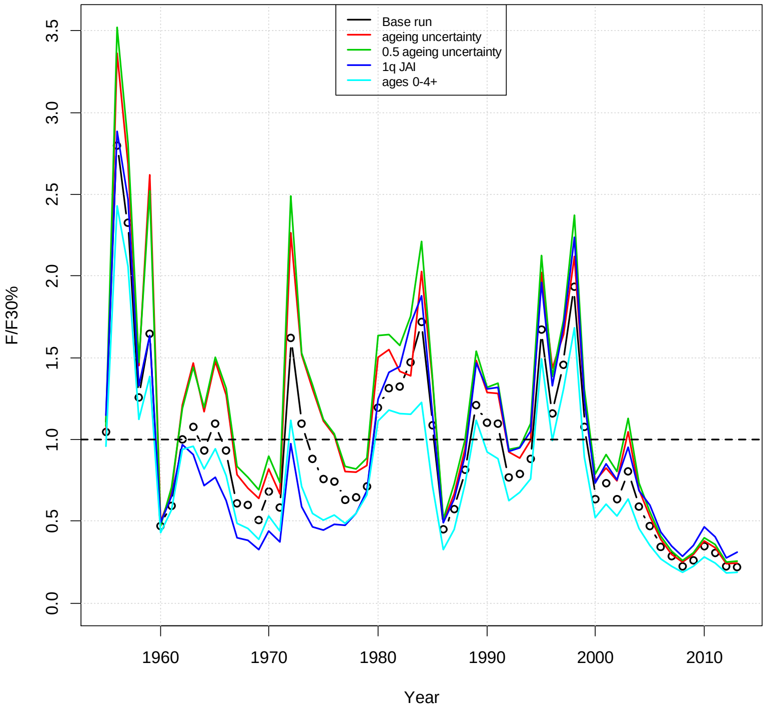


Figure 7.4.1.60. Full F at age-2 (upper) and age-3 (lower) over ***F*$_{30\%}$** for sensitivity runs considering differences in ageing uncertainty, catchability for the JAI index, and ages modeled in the assessment model.



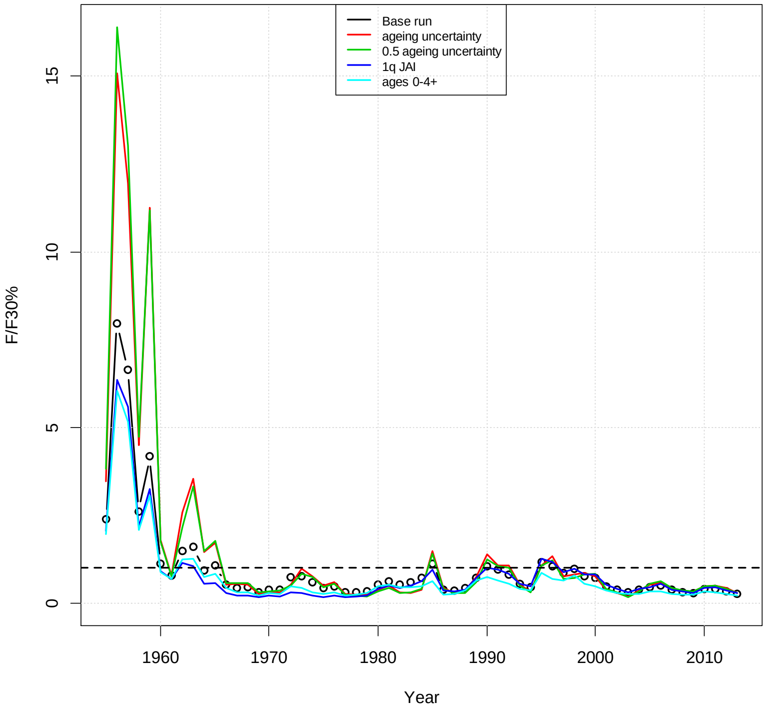
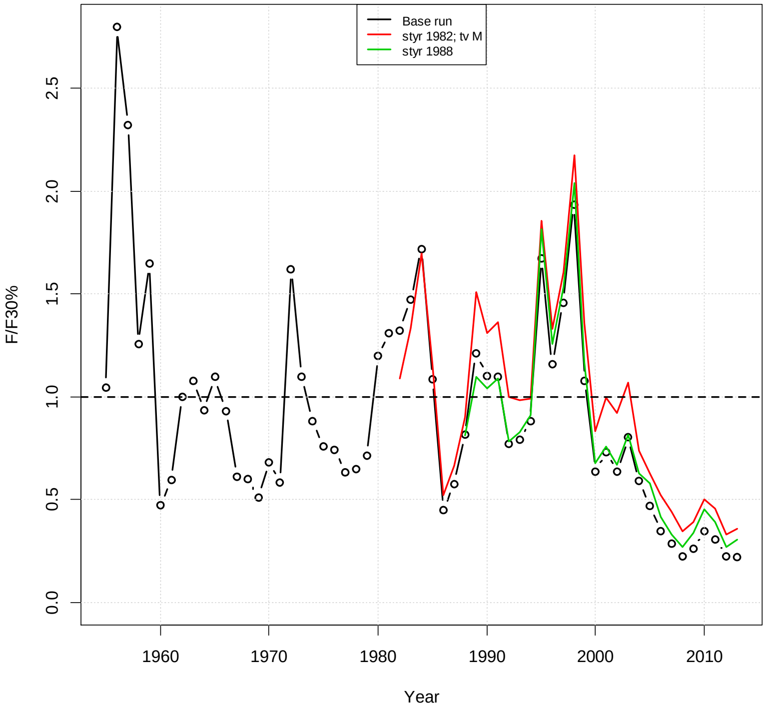


Figure 7.4.1.61. Full F at age-2 (upper) and age-3 (lower) over ***F*$_{30\%}$** for sensitivity runs considering differences in start year of the assessment model.



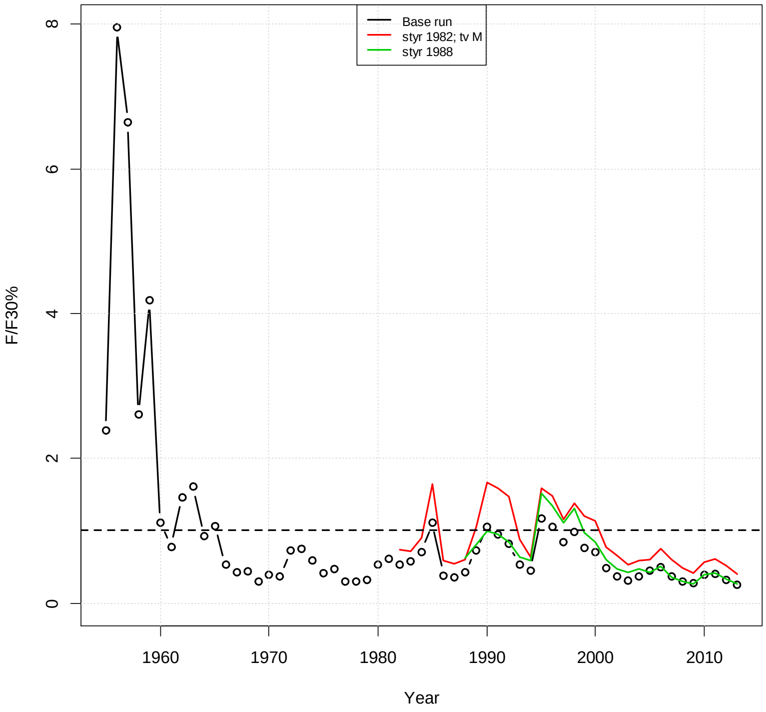
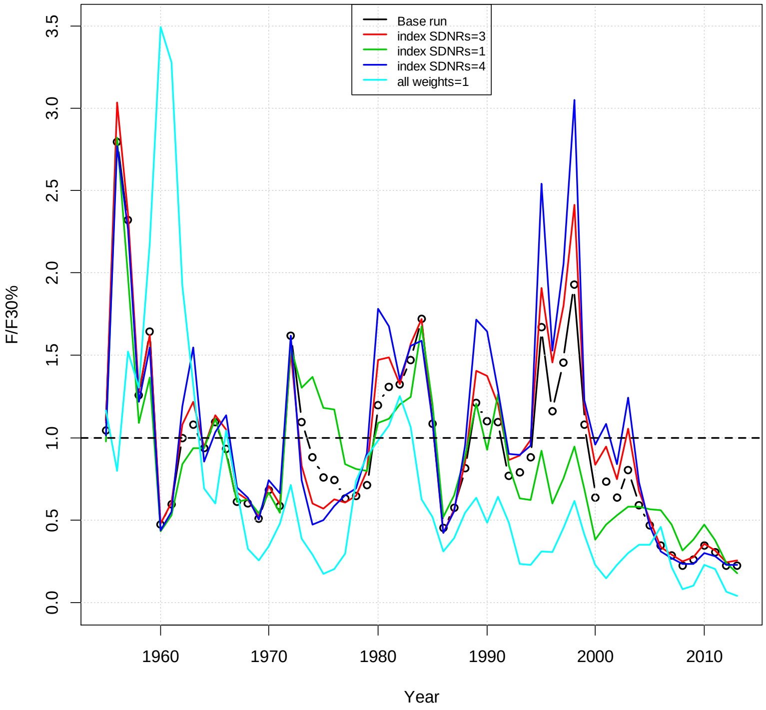


Figure 7.4.1.62. Full F at age-2 (upper) and age-3 (lower) over ***F*$_{30\%}$** for sensitivity runs considering differences in weighting of the likelihood components for the assessment model.



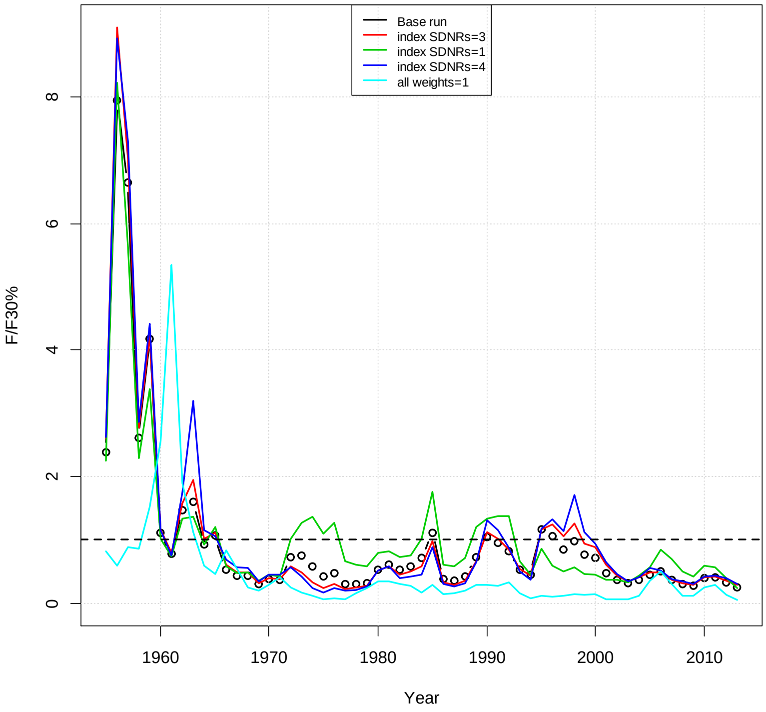
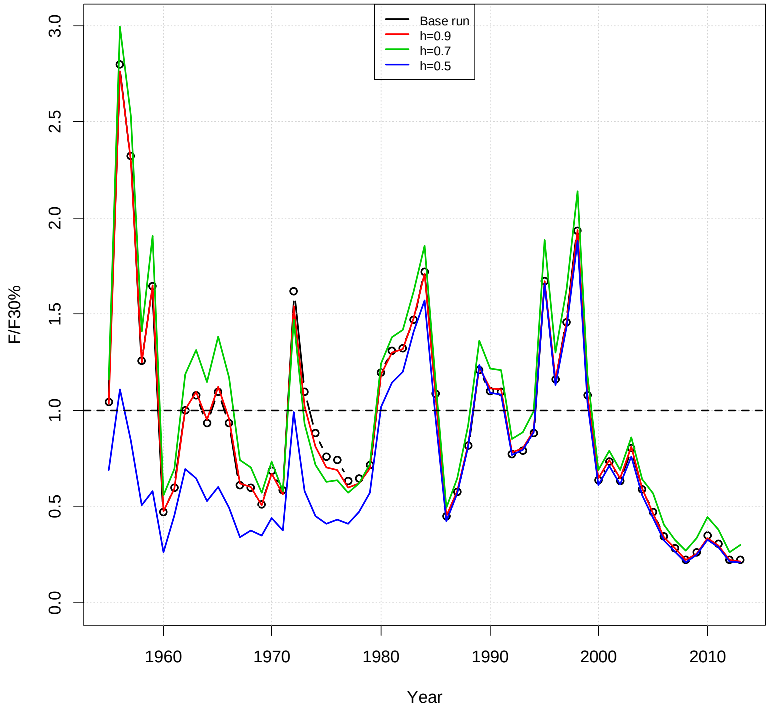


Figure 7.4.1.63. Full F at age-2 (upper) and age-3 (lower) over ***$F_{30\%}$*** for sensitivity runs considering differences in steepness.



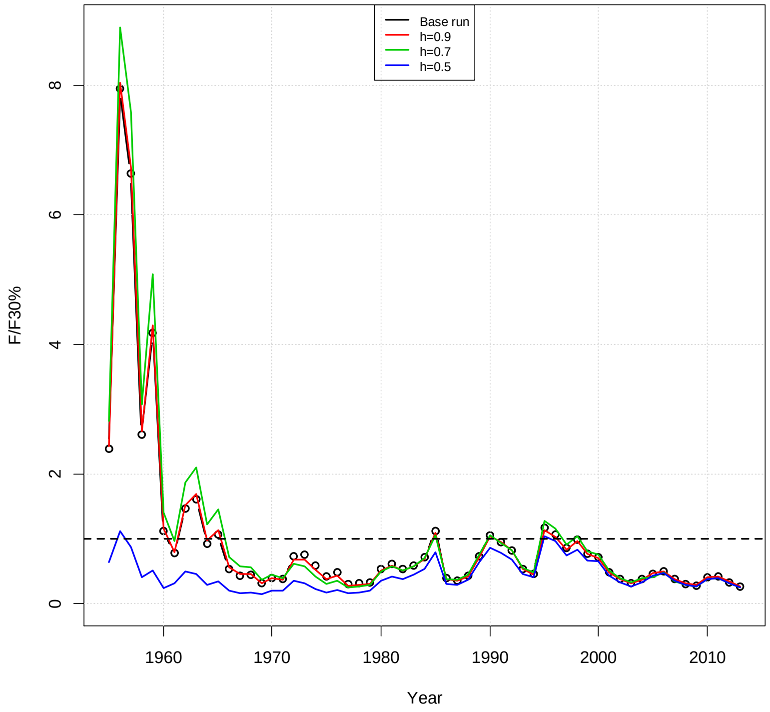


Figure 7.4.1.64. Fecundity over ***$FEC_{15\%}$*** for sensitivity runs considering differences in growth and life history parameters in the assessment model.

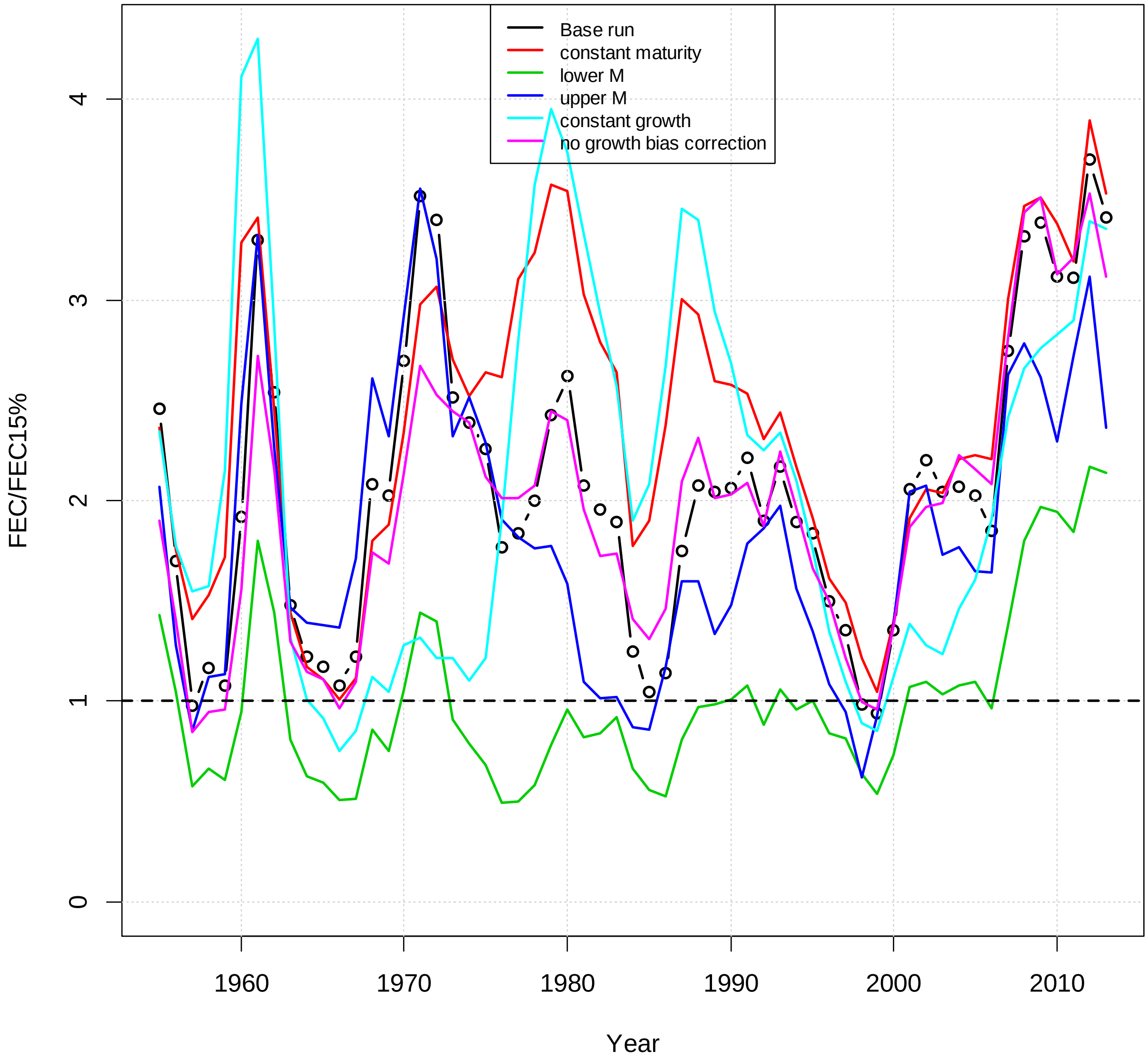


Figure 7.4.1.65. Fecundity over ***FEC***$_{15\%}$ for sensitivity runs considering differences in indices in the assessment model.

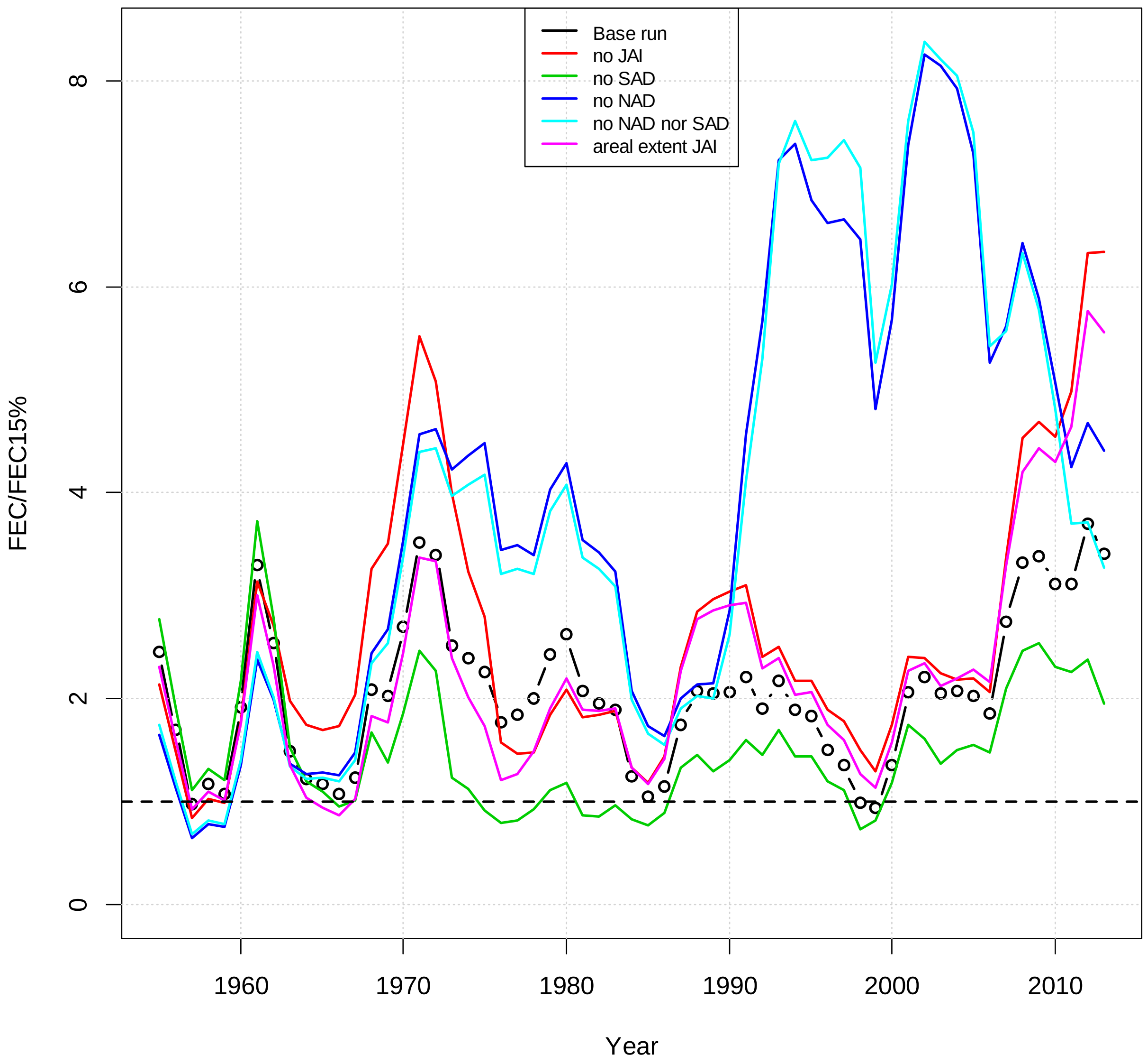


Figure 7.4.1.66. Fecundity over ***FEC*** $_{15\%}$ for sensitivity runs considering differences in fishery selectivity in the assessment model.

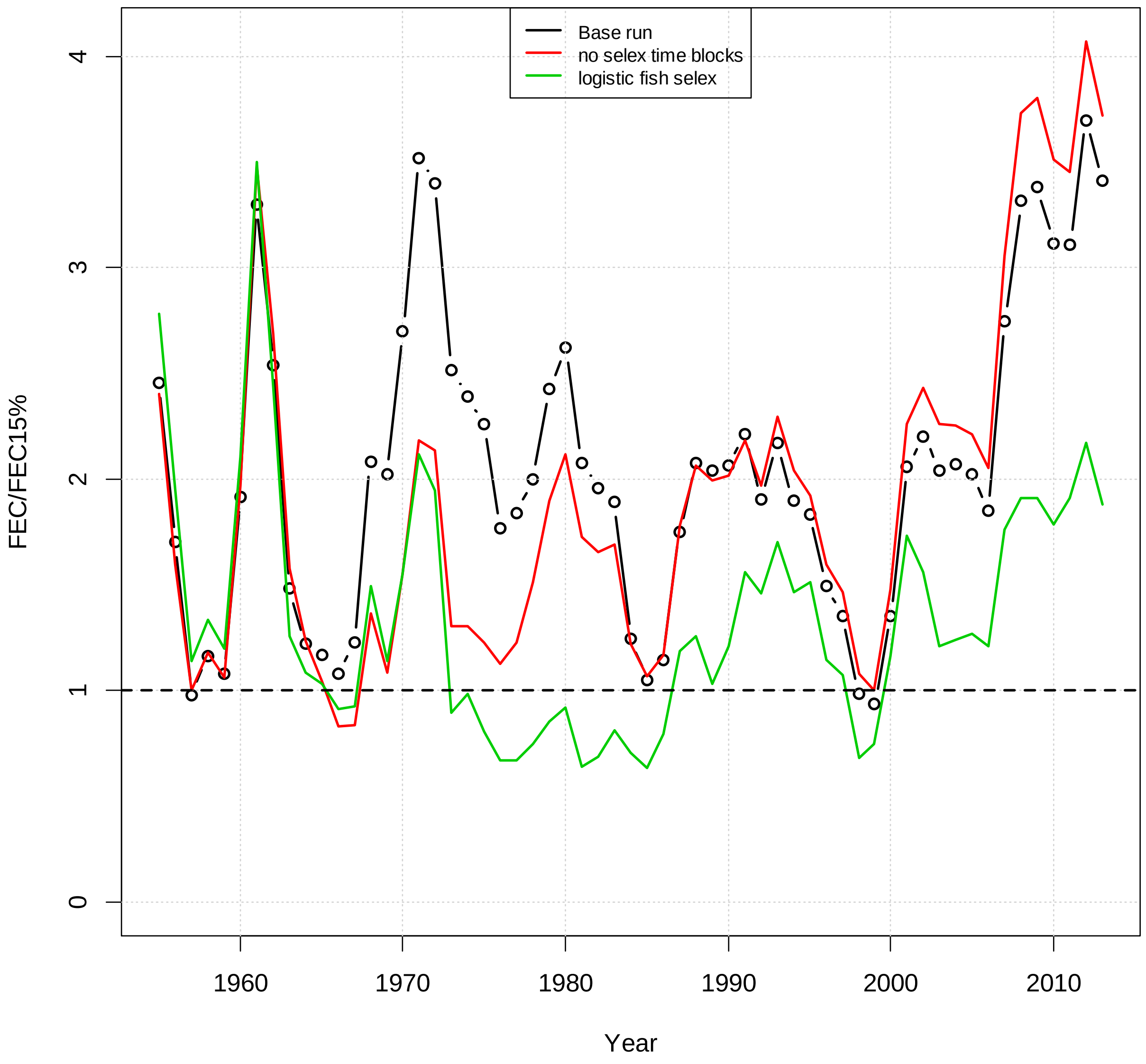


Figure 7.4.1.67. Fecundity over ***$FEC_{15\%}$*** for sensitivity runs considering differences in ageing uncertainty, catchability for the JAI index, and ages modeled in the assessment model.

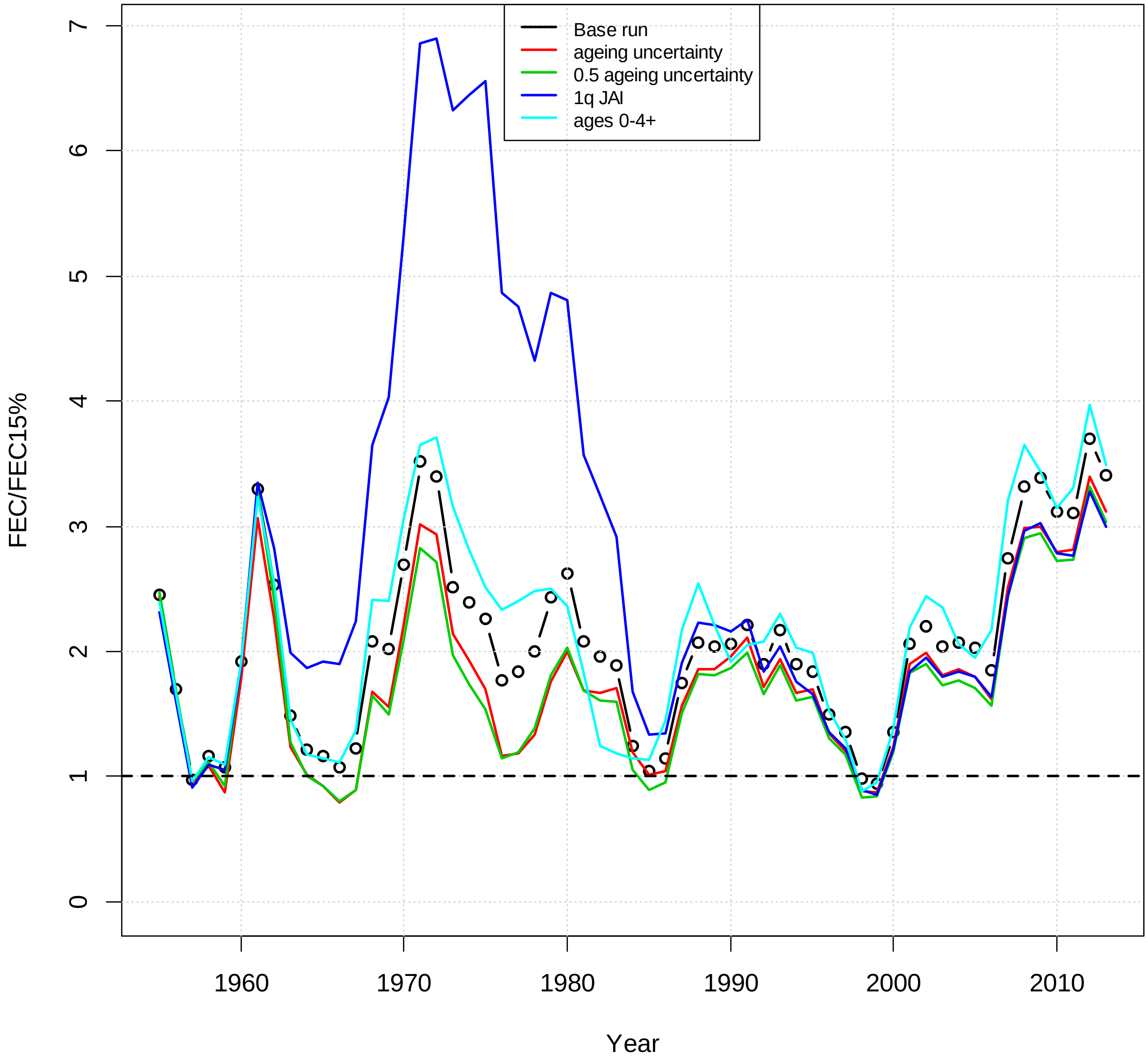


Figure 7.4.1.68. Fecundity over ***$FEC_{15\%}$*** for sensitivity runs considering differences in start year of the assessment model.

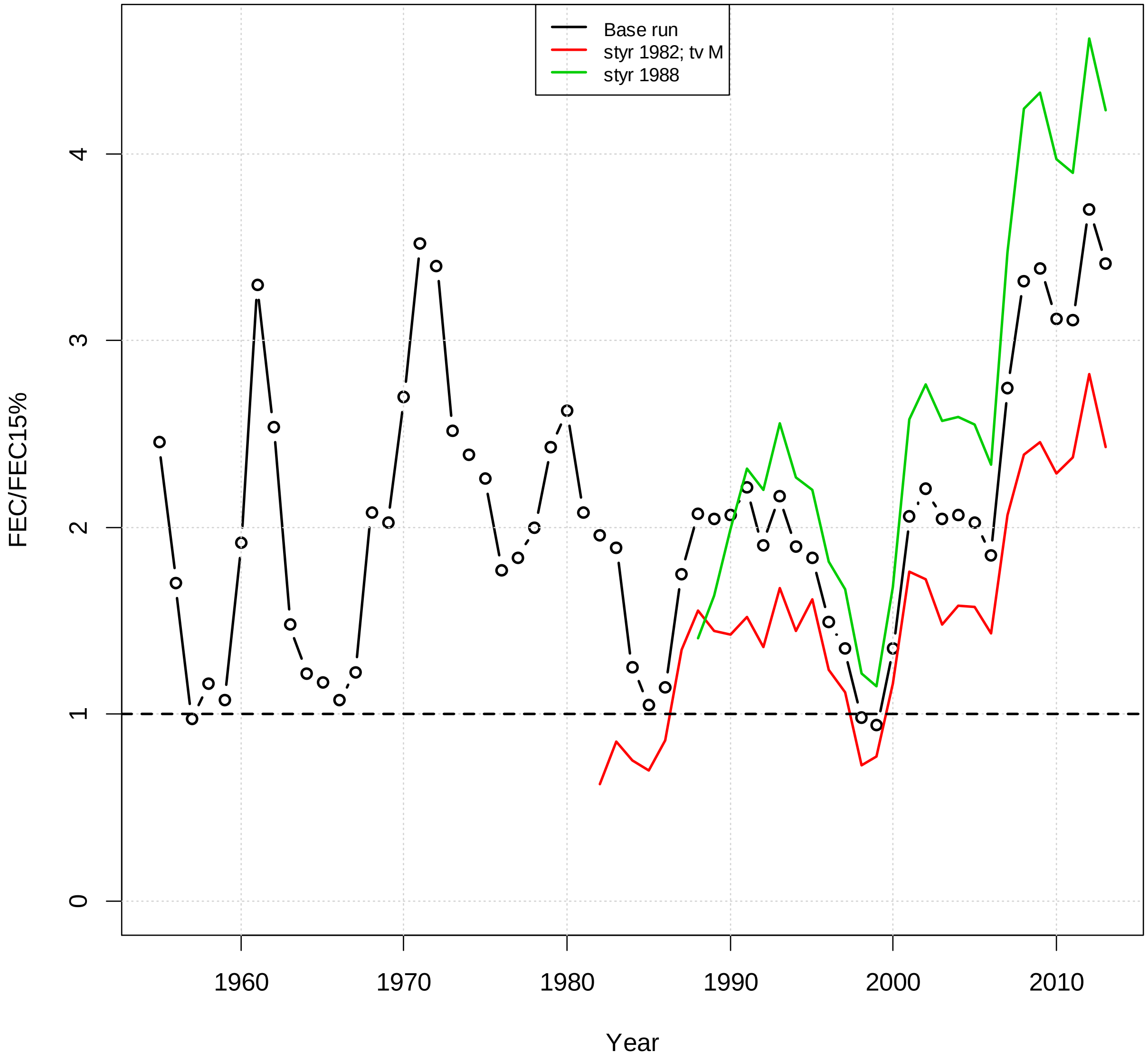


Figure 7.4.1.69. Fecundity over ***FEC$_{15\%}$*** for sensitivity runs considering differences in weighting of the likelihood components for the assessment model.

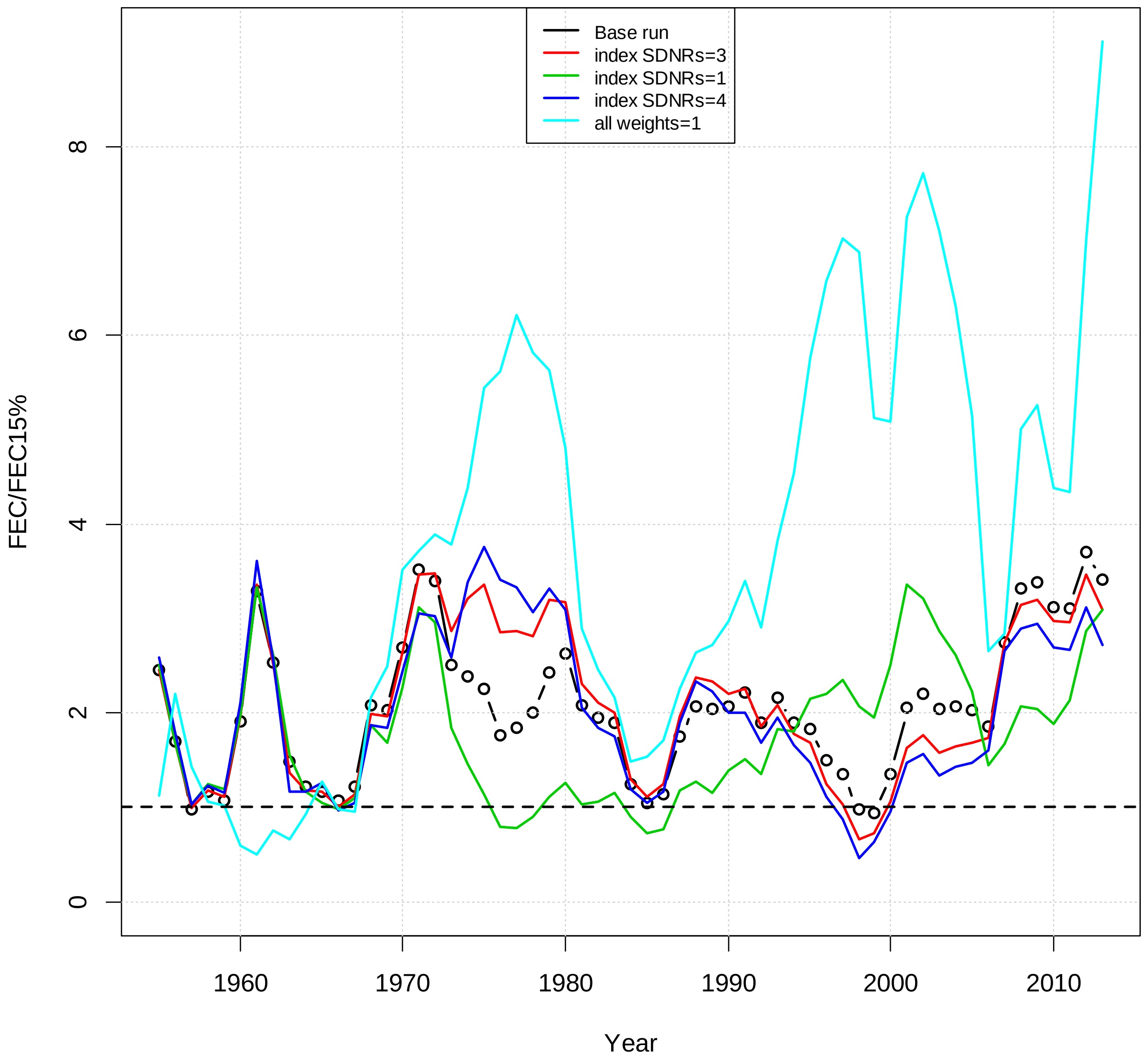


Figure 7.4.1.70. Fecundity over ***$FEC_{15\%}$*** for sensitivity runs considering differences in steepness.

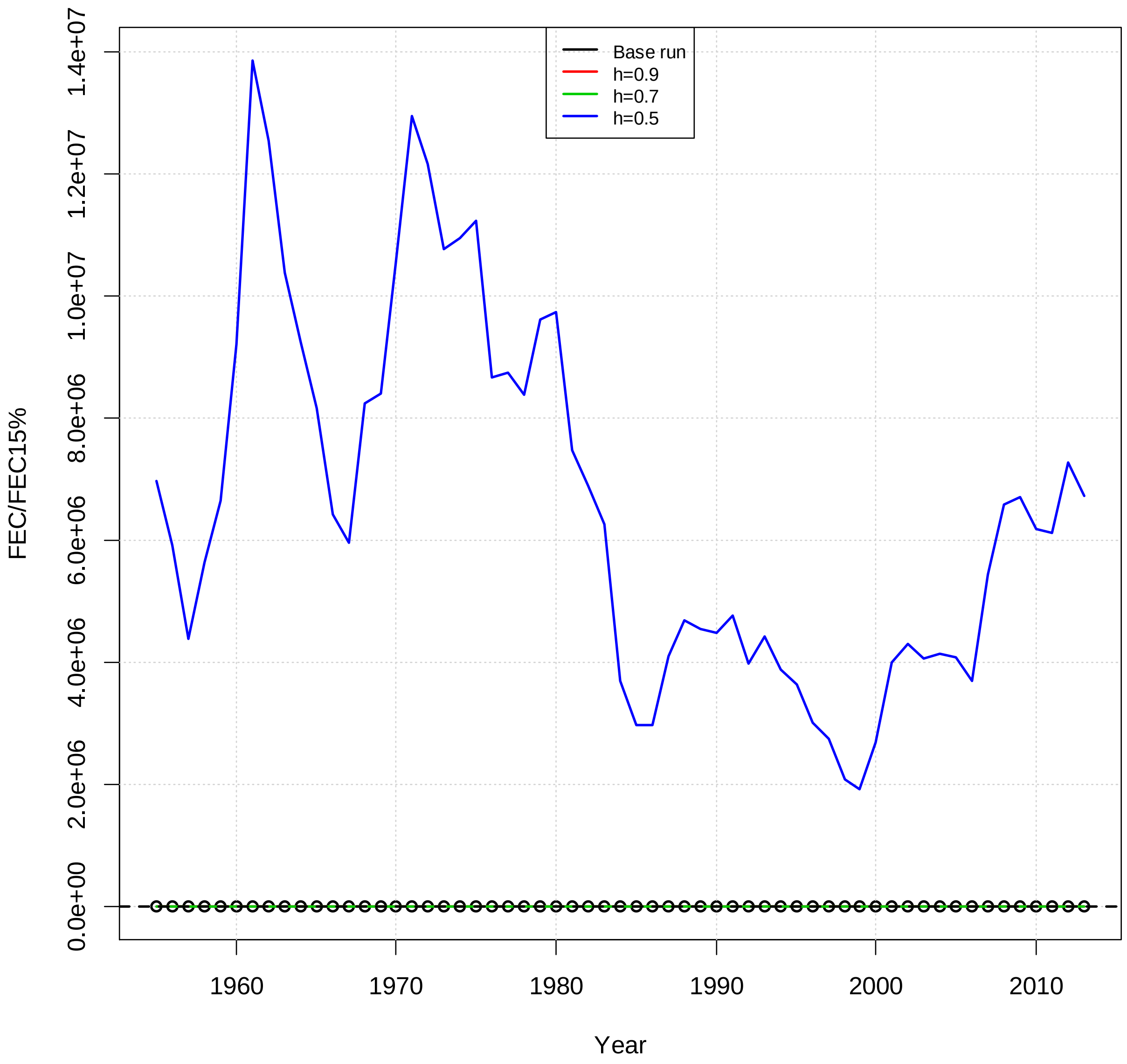


Figure 7.4.1.71. Fecundity over ***$FEC_{30\%}$*** for sensitivity runs considering differences in growth and life history parameters in the assessment model.

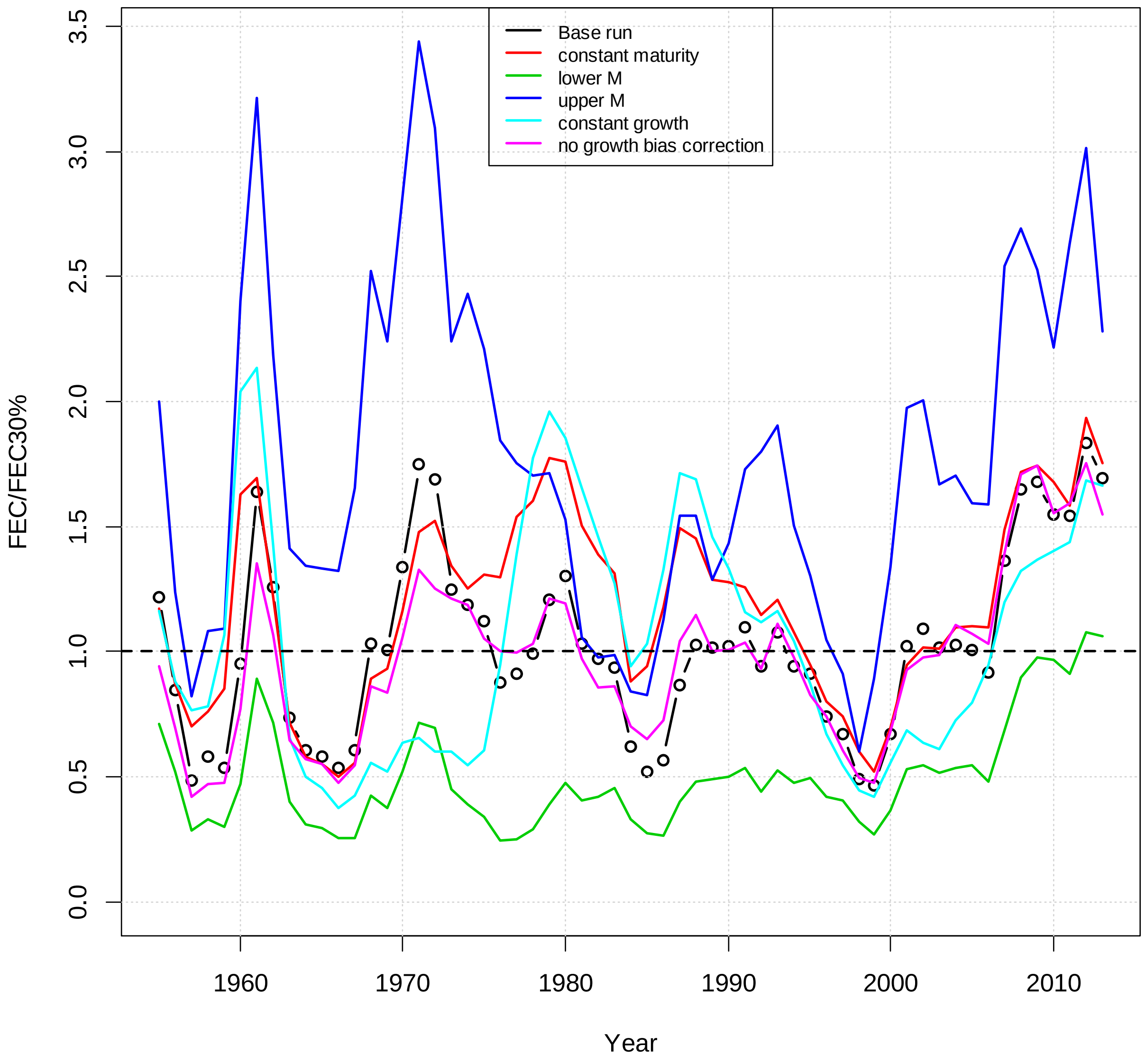


Figure 7.4.1.72. Fecundity over ***$FEC_{30\%}$*** for sensitivity runs considering differences in indices in the assessment model.

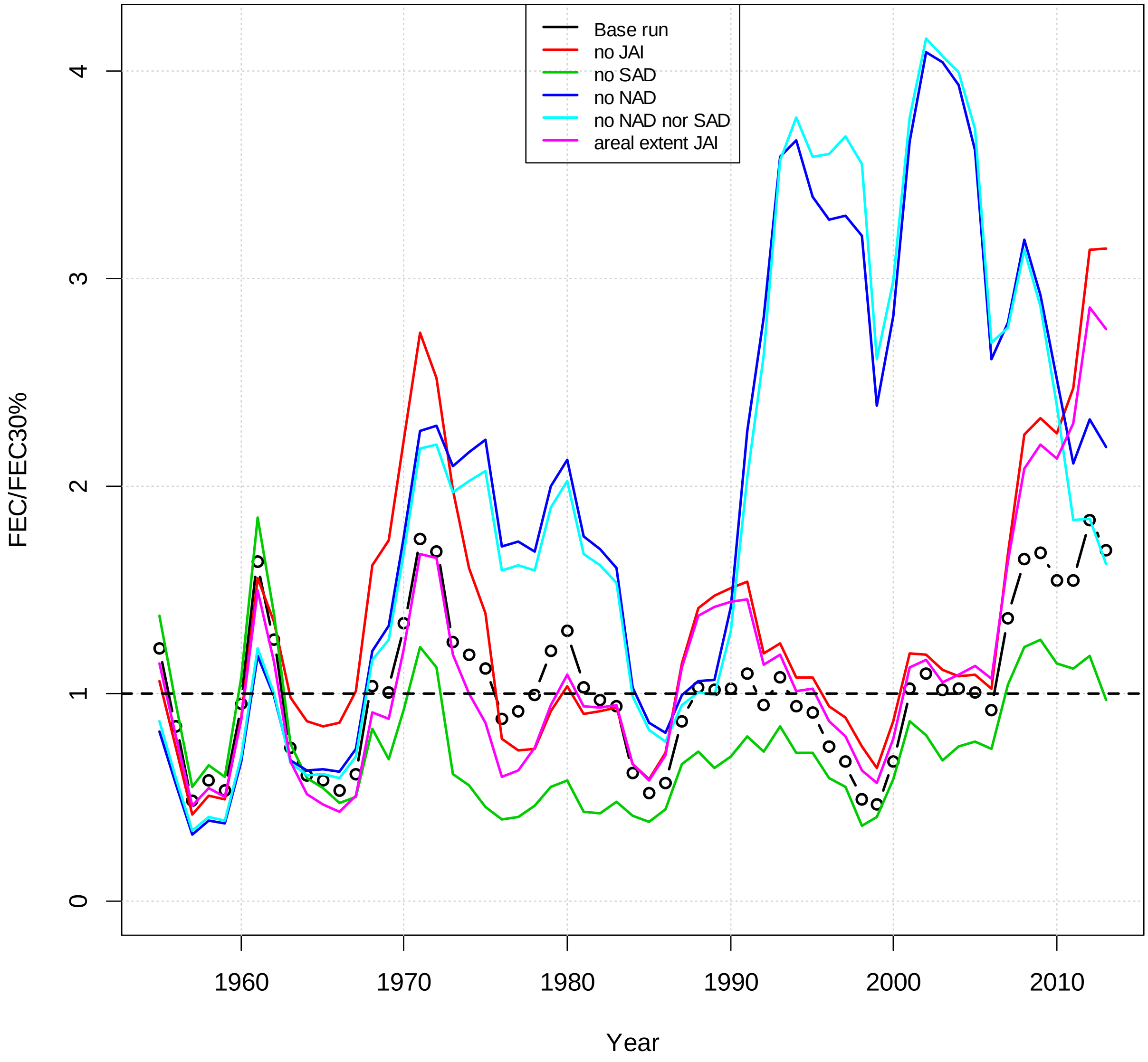


Figure 7.4.1.73. Fecundity over ***$FEC_{30\%}$*** for sensitivity runs considering differences in fishery selectivity in the assessment model.

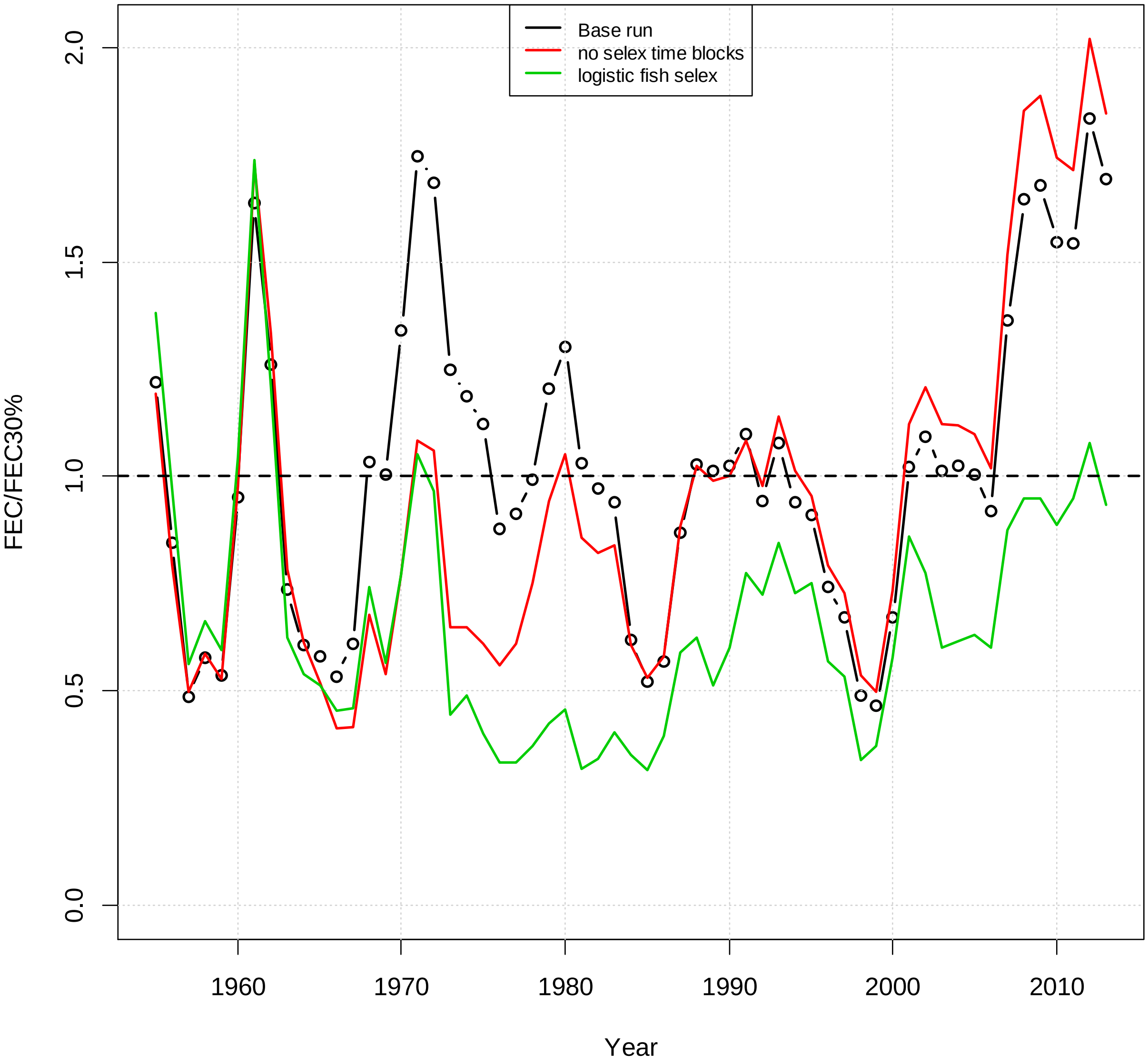


Figure 7.4.1.74. Fecundity over ***FEC$_{30\%}$*** for sensitivity runs considering differences in ageing uncertainty, catchability for the JAI index, and ages modeled in the assessment model.

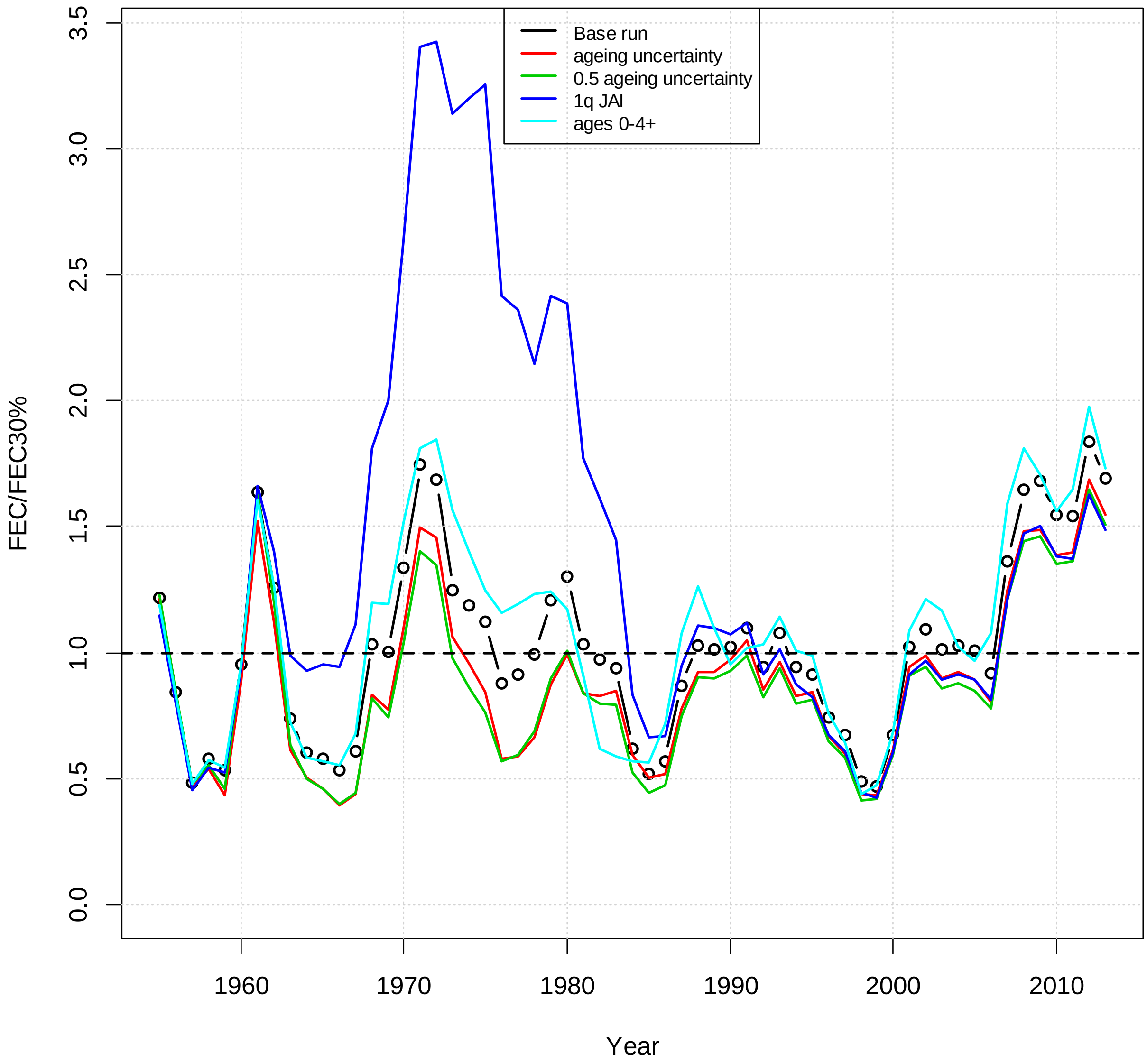


Figure 7.4.1.75. Fecundity over ***FEC*$_{30\%}$** for sensitivity runs considering differences in start year of the assessment model.

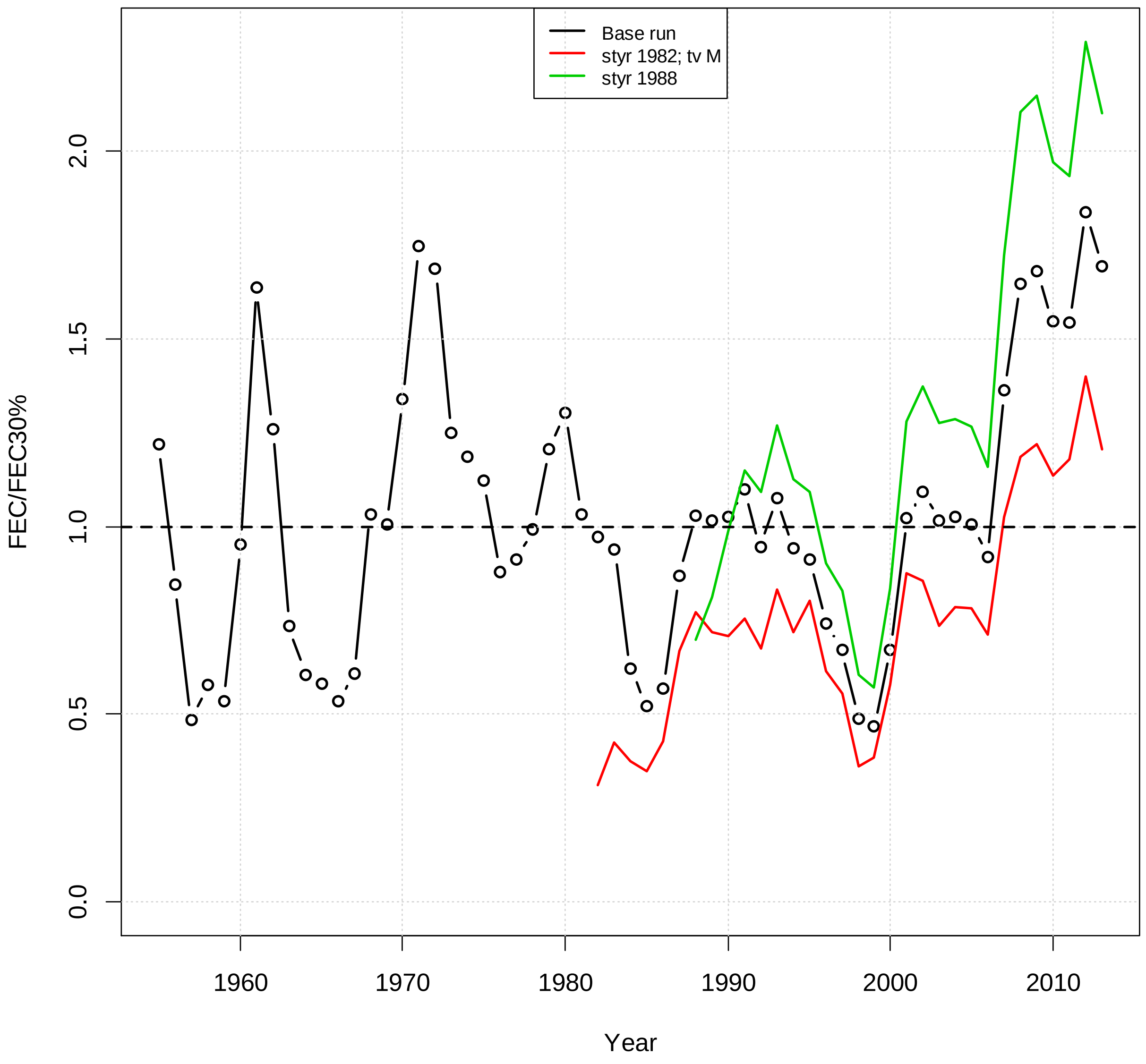


Figure 7.4.1.76. Fecundity over ***$FEC_{30\%}$*** for sensitivity runs considering differences in weighting of the likelihood components for the assessment model.

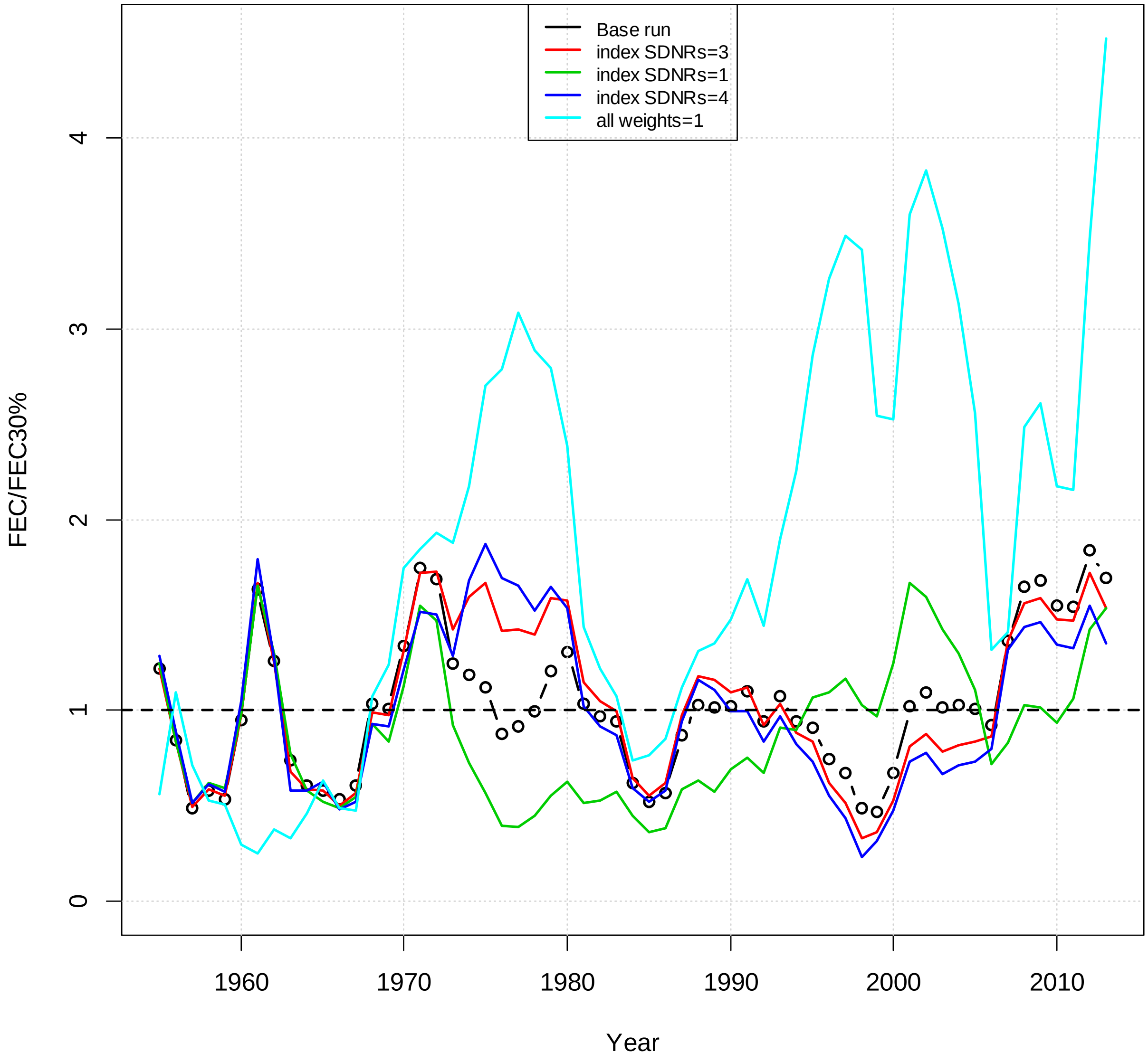


Figure 7.4.1.77. Fecundity over ***$FEC_{30\%}$*** for sensitivity runs considering differences in steepness.

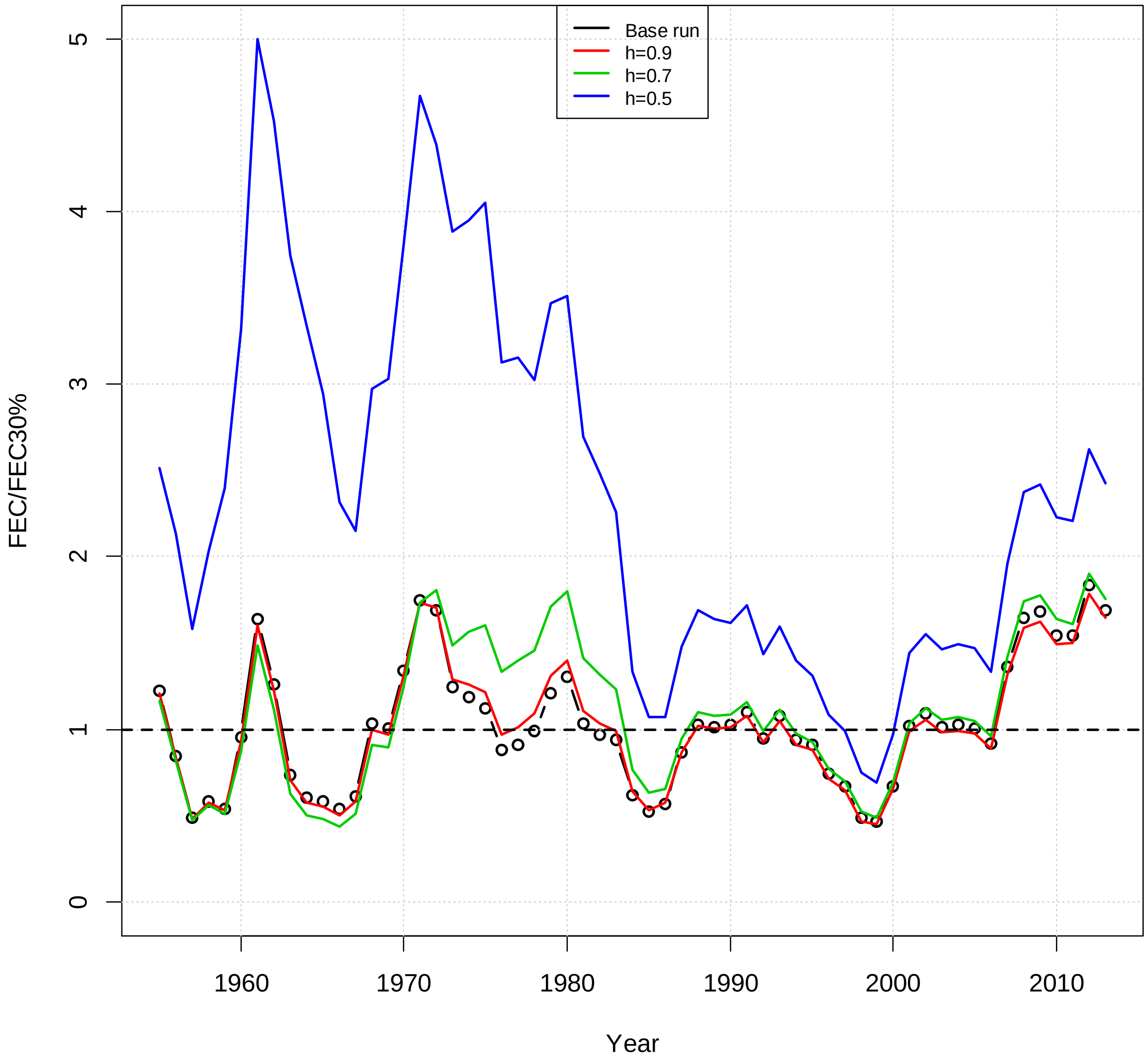
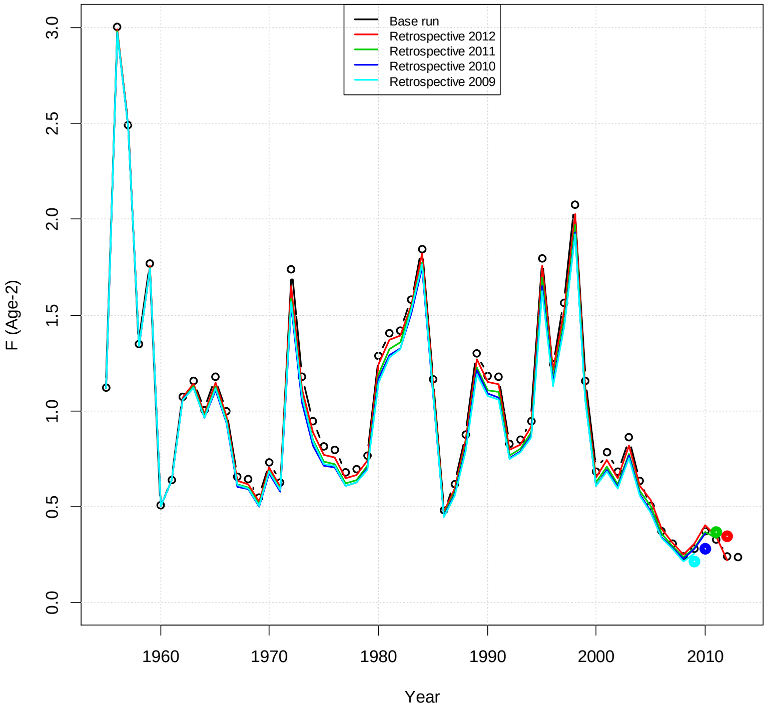


Figure 7.4.2.1. Fishing mortality at age-2 (upper) and age-3 (lower) over time for the retrospective analysis of the assessment model.



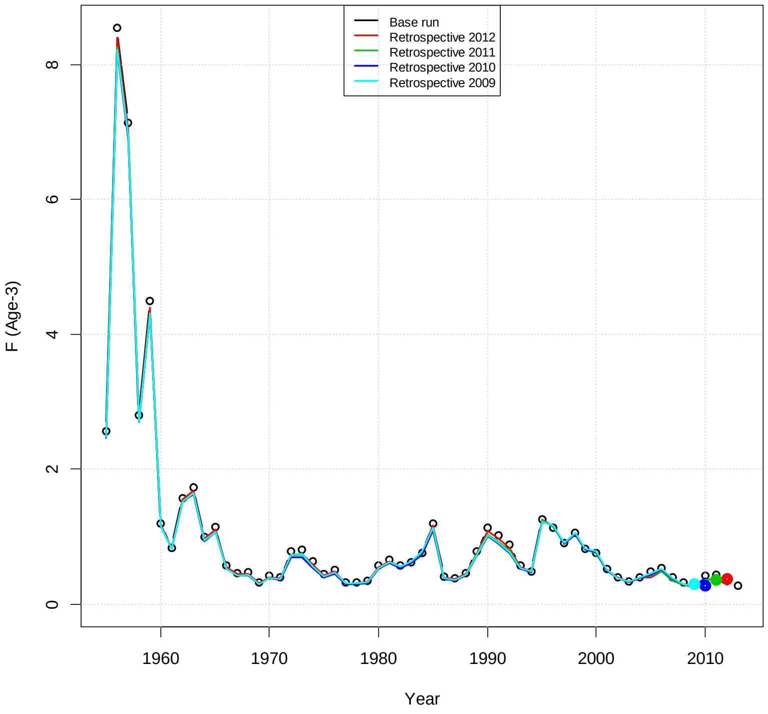


Figure 7.4.2.2. Age-1+ biomass in 1000s mt over time for the retrospective analysis of the assessment model.

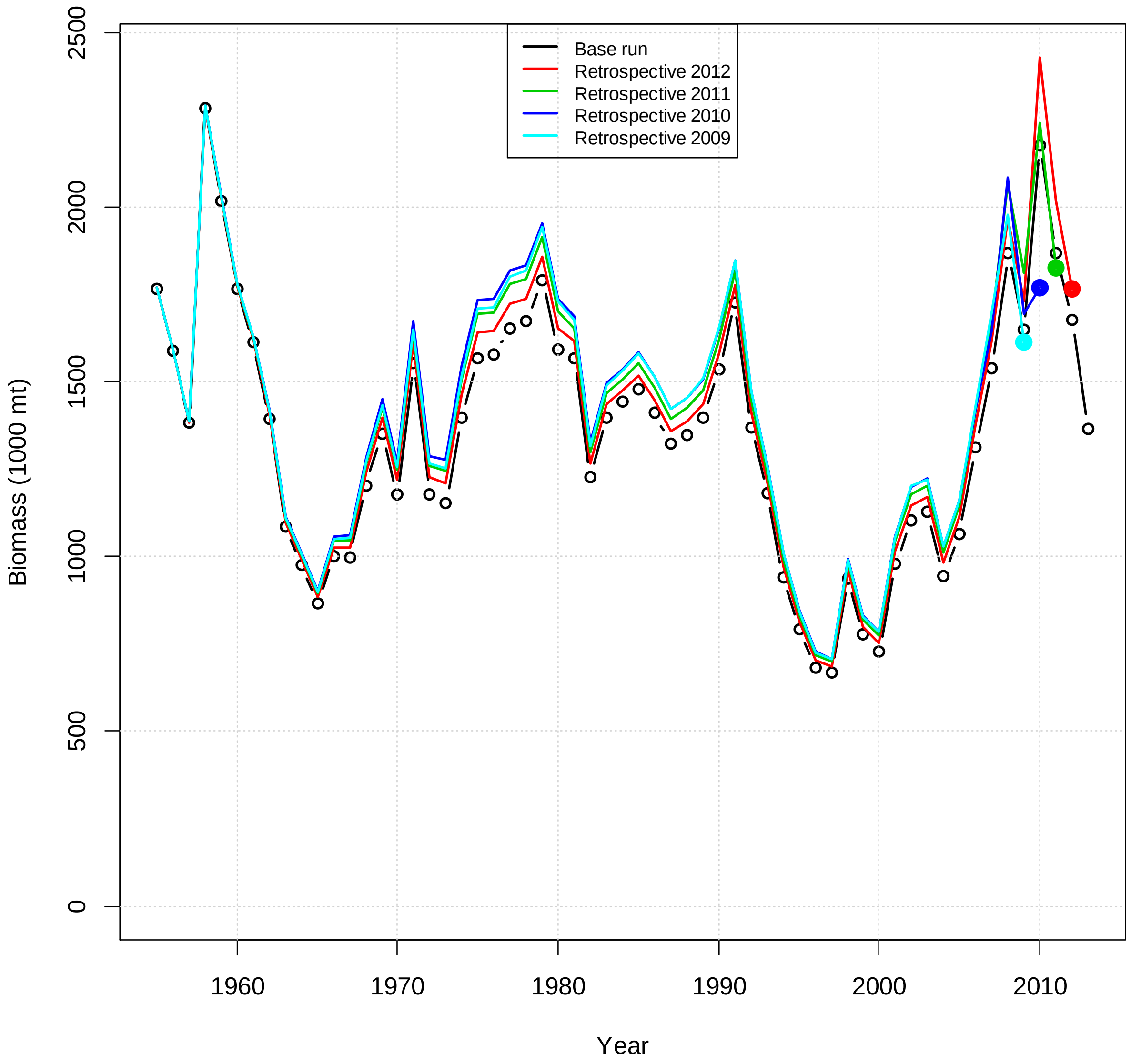


Figure 7.4.2.3. Recruitment over time for the retrospective analysis of the assessment model.

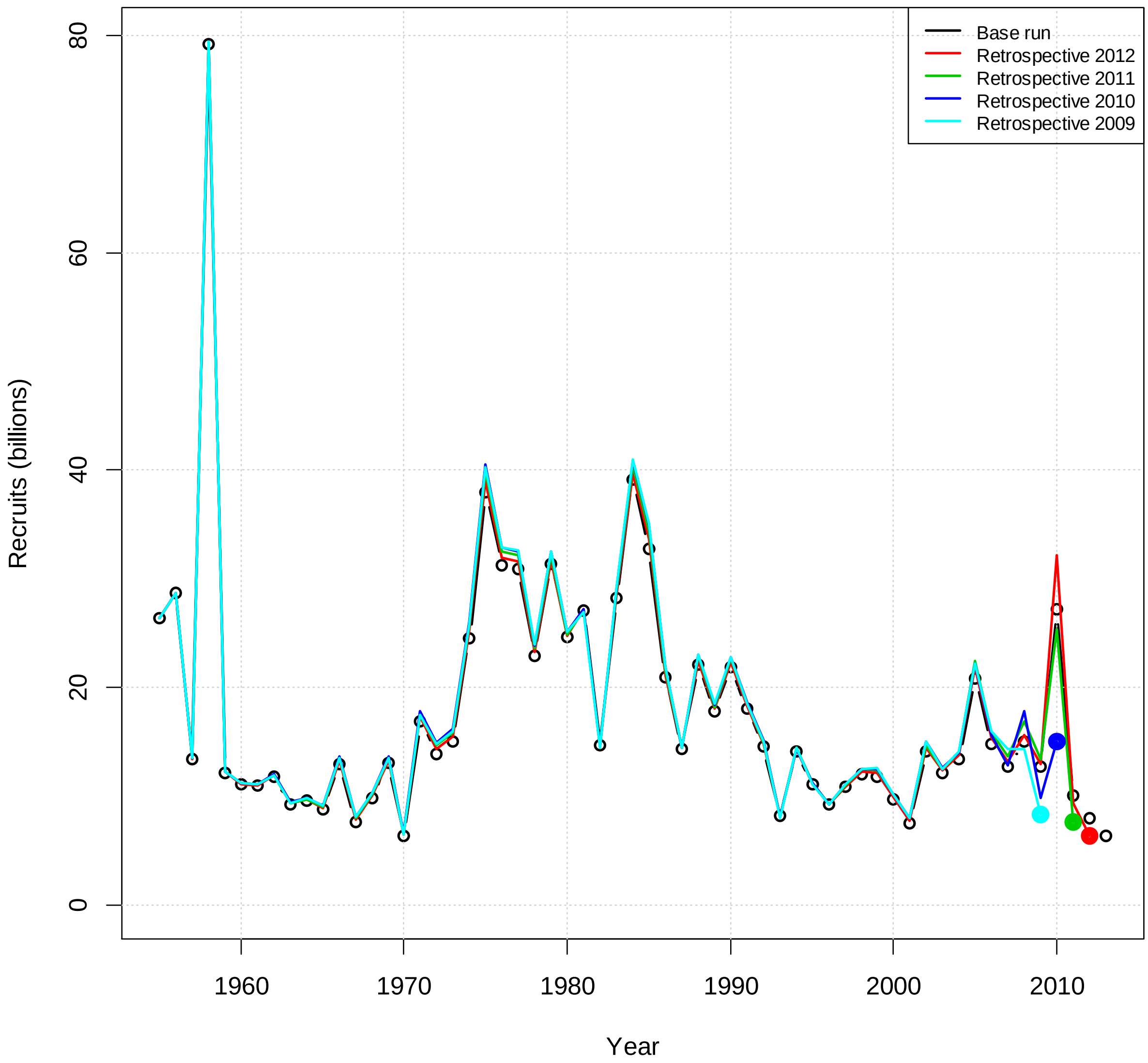


Figure 7.4.2.4. Fecundity over time for the retrospective analysis of the assessment model.

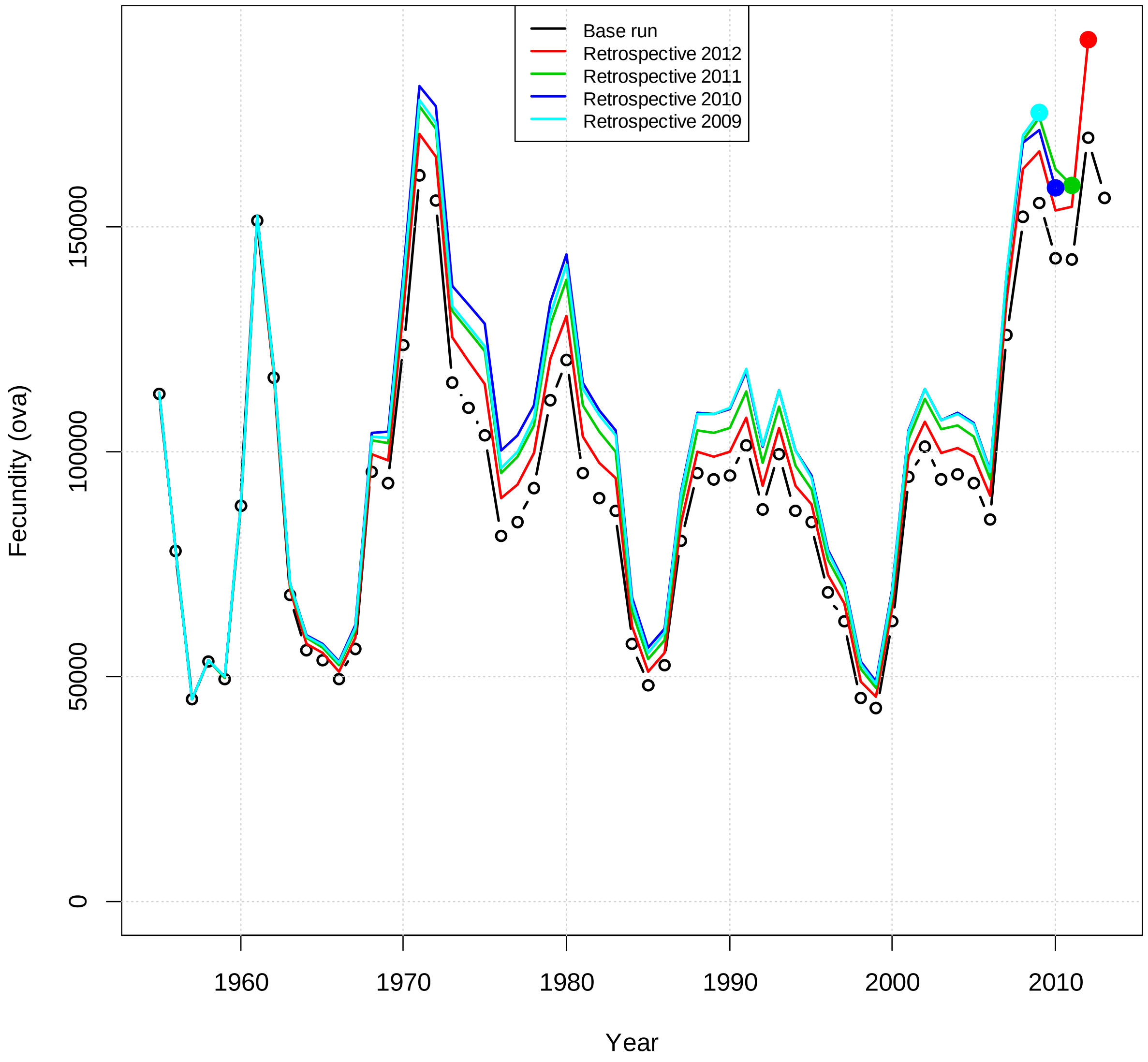


Figure 7.4.2.5. The fit to the JAI index over time for the retrospective analysis of the assessment model.

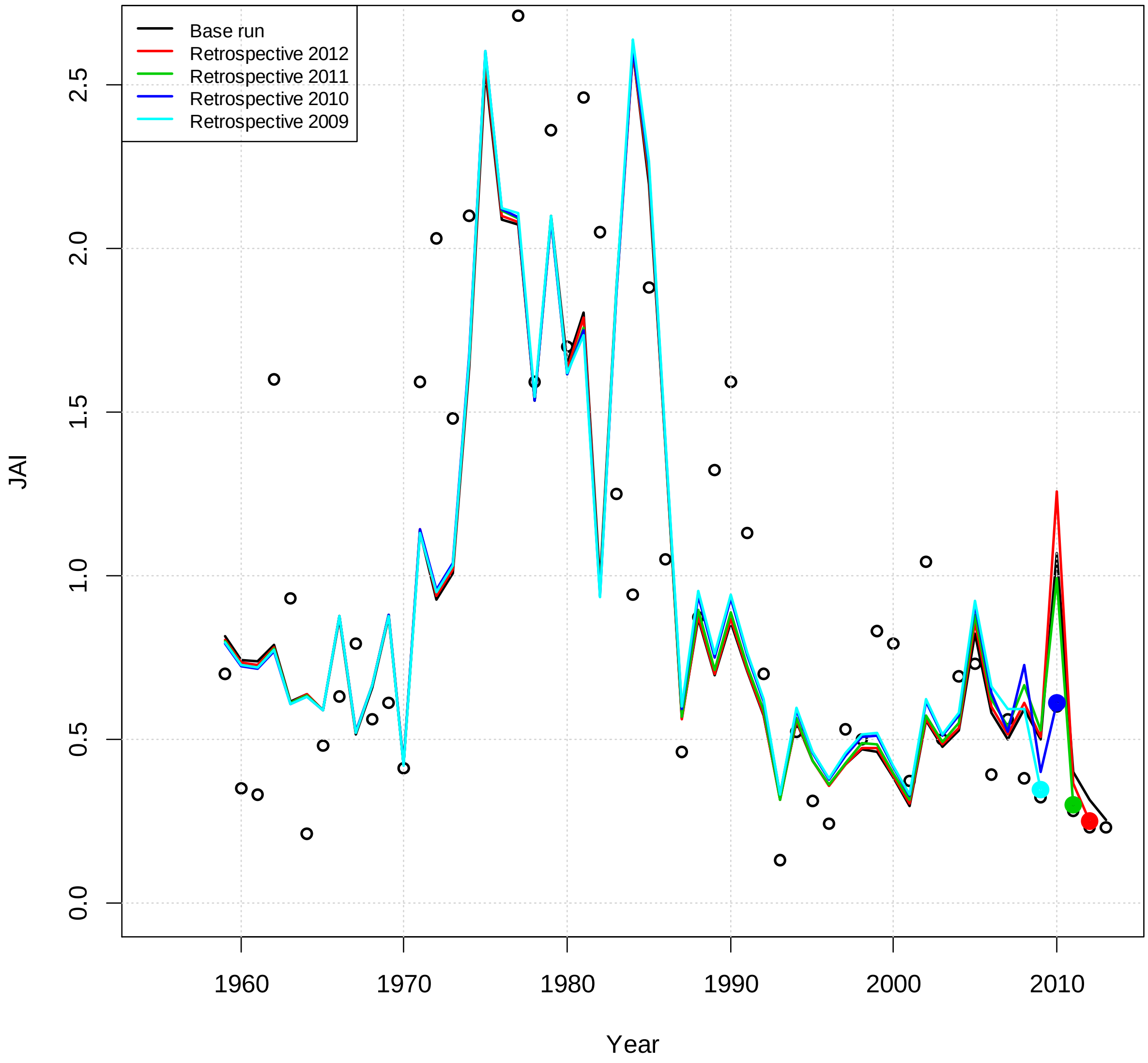


Figure 7.4.2.6. Fit to the SAD index over time for the retrospective analysis of the assessment model.

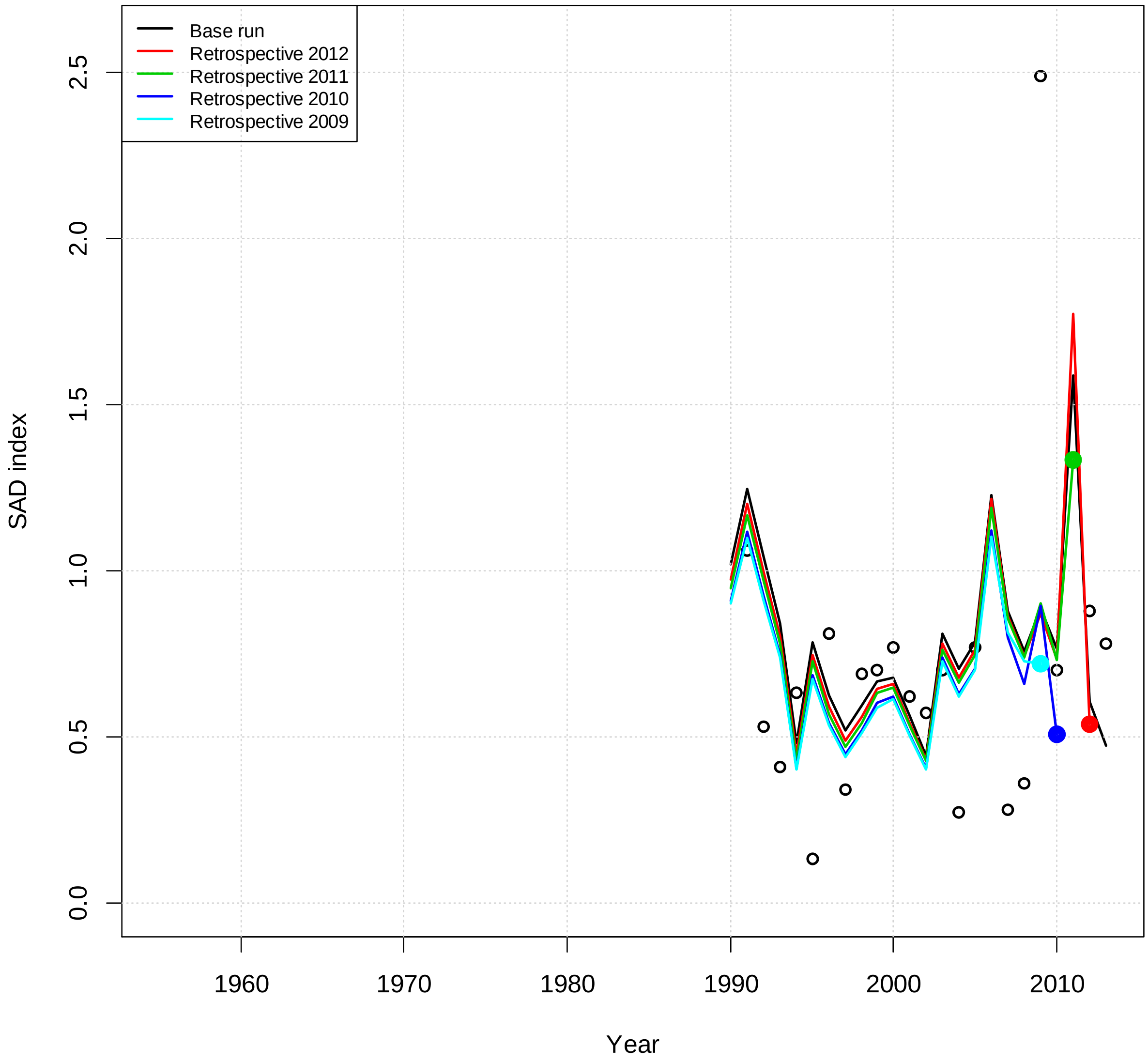


Figure 7.4.2.7. Fit to the NAD index over time for the retrospective analysis of the assessment model.

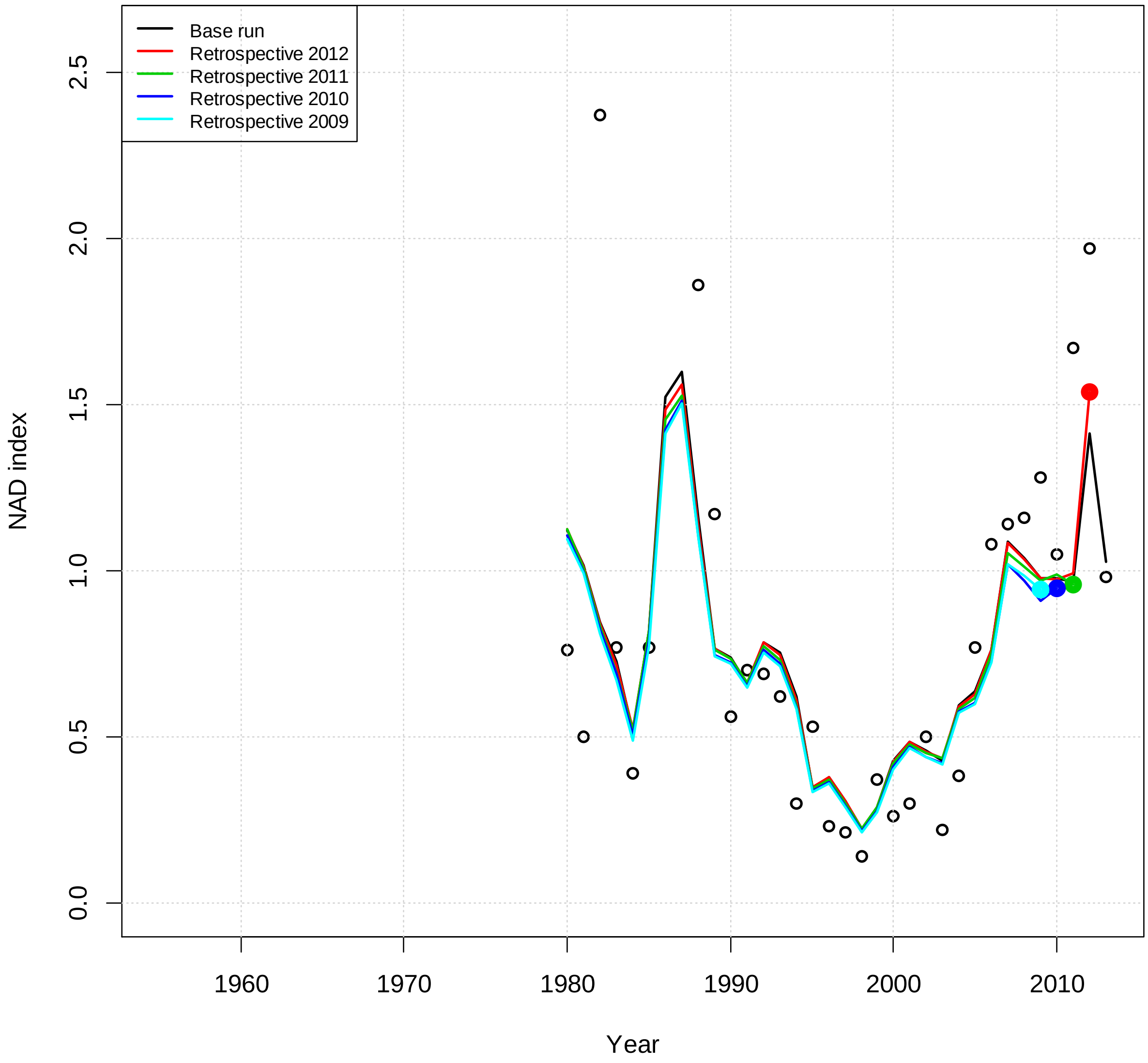


Figure 7.4.2.8. Relative change in F at age-2 (upper) and age-3 (lower) for the retrospective analysis.

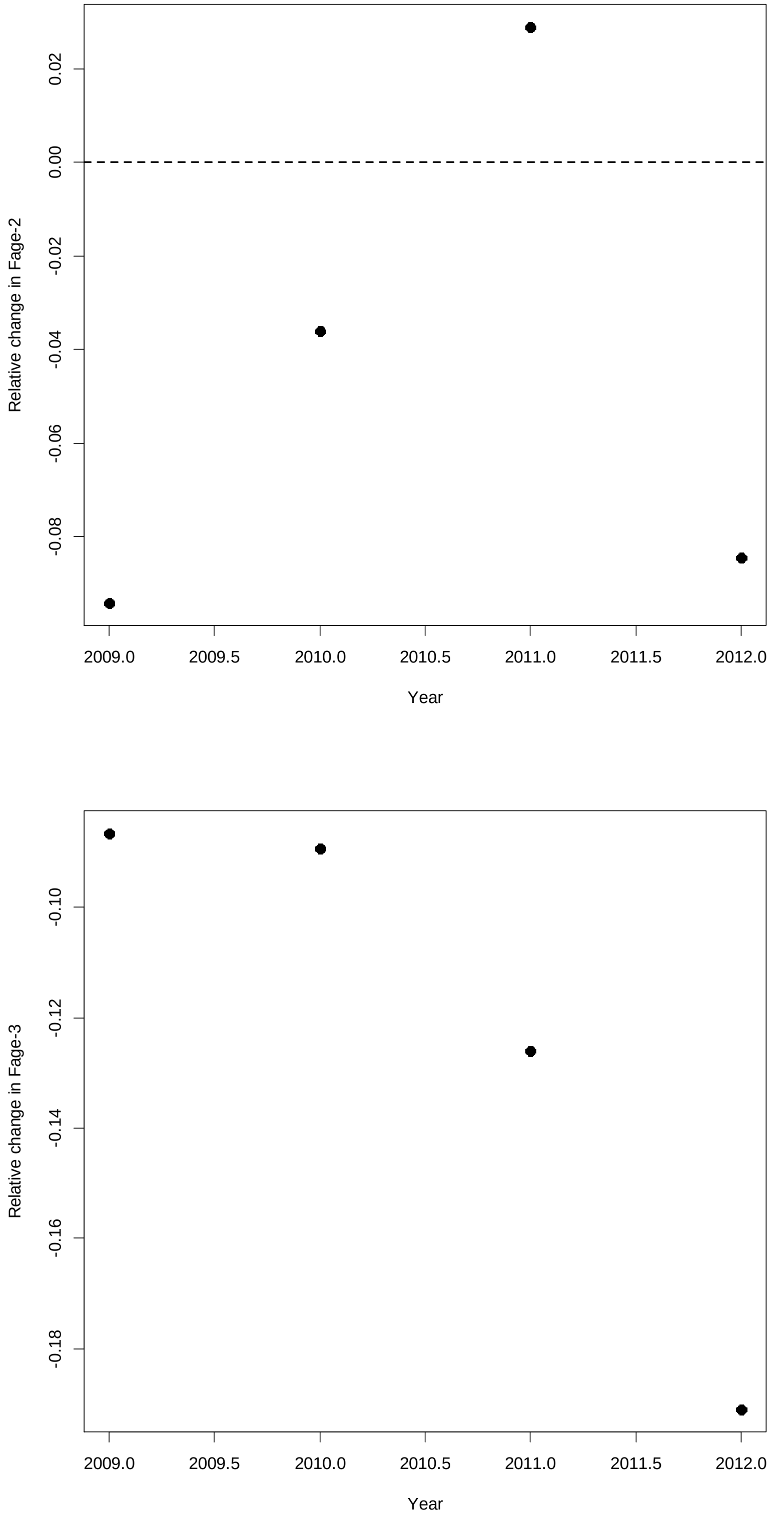


Figure 7.4.2.9. Relative change in biomass for the retrospective analysis.

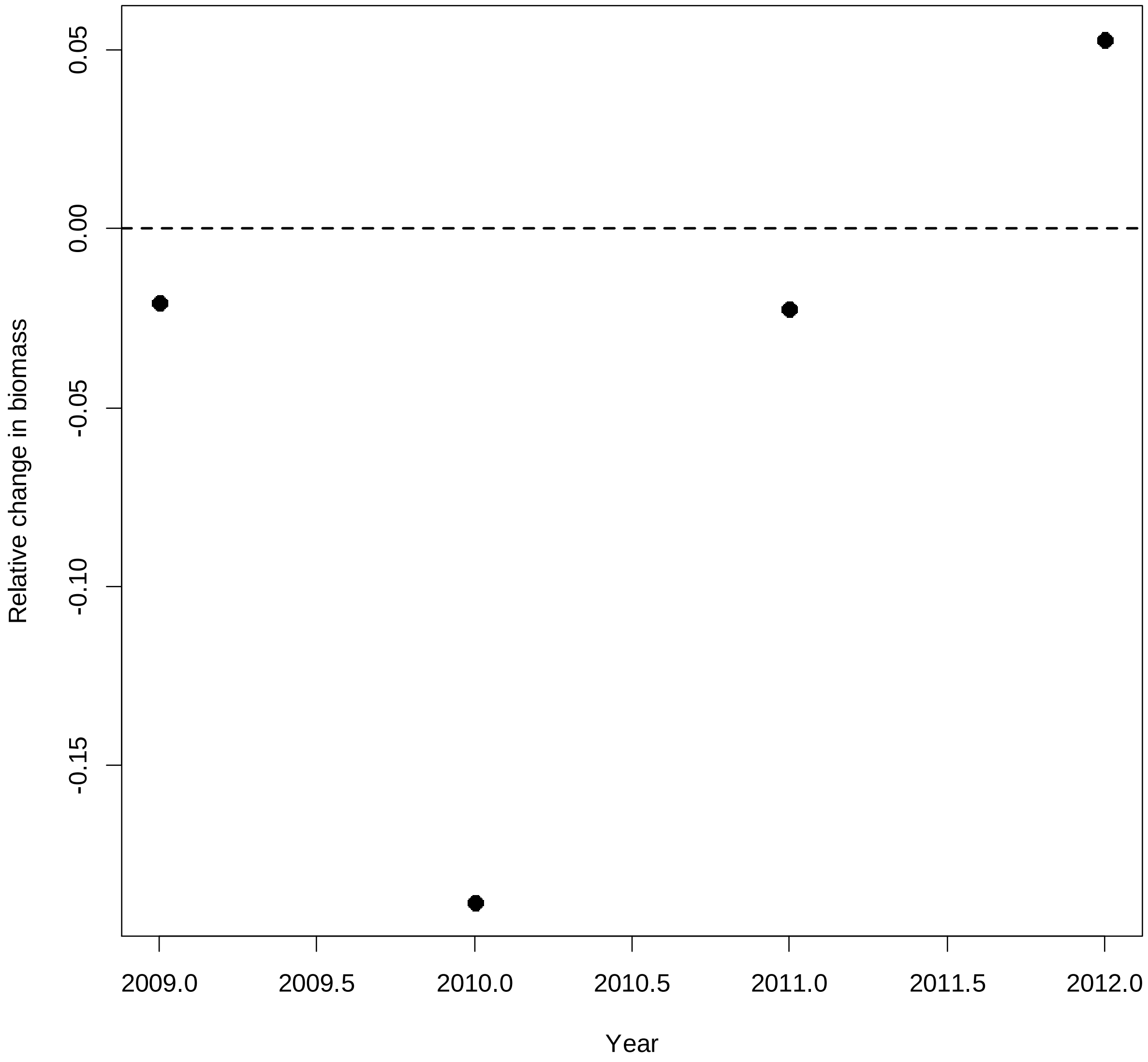


Figure 7.4.2.10. Relative change in recruitment for the retrospective analysis.

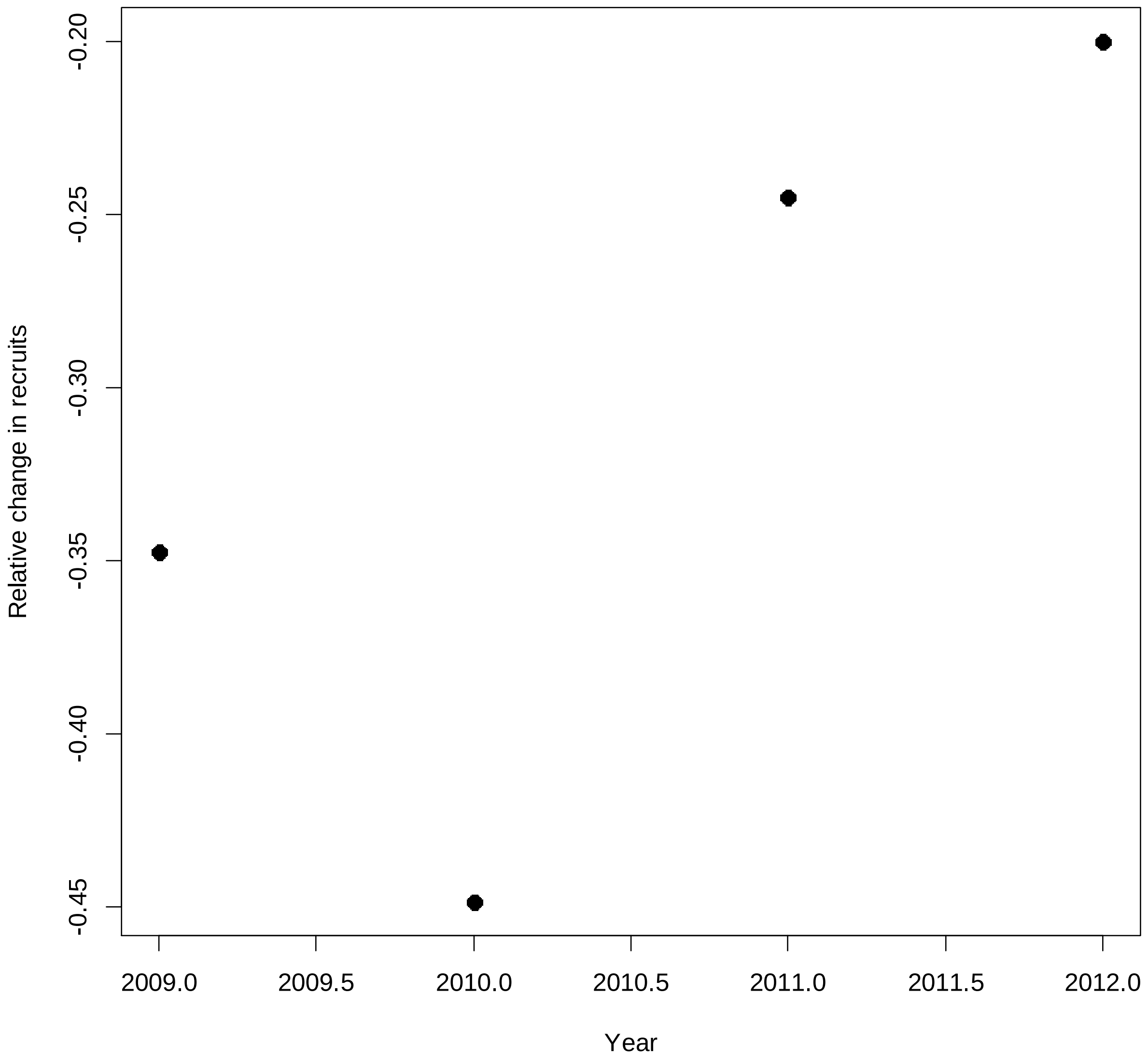


Figure 7.4.2.11. Relative change in fecundity for the retrospective analysis.

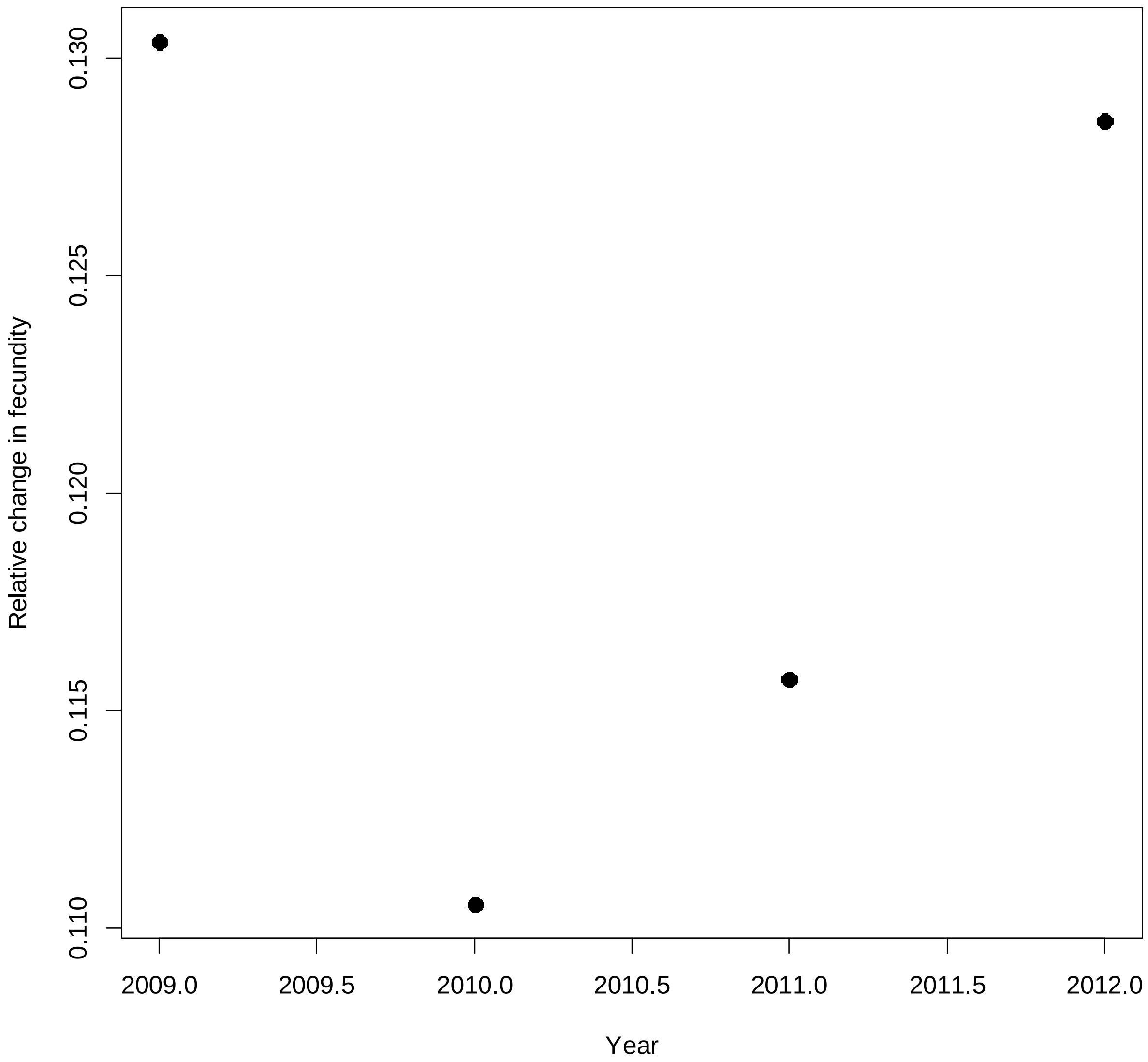


Figure 7.4.2.12. Relative change in the fit to the JAI (recruitment) index for the retrospective analysis.

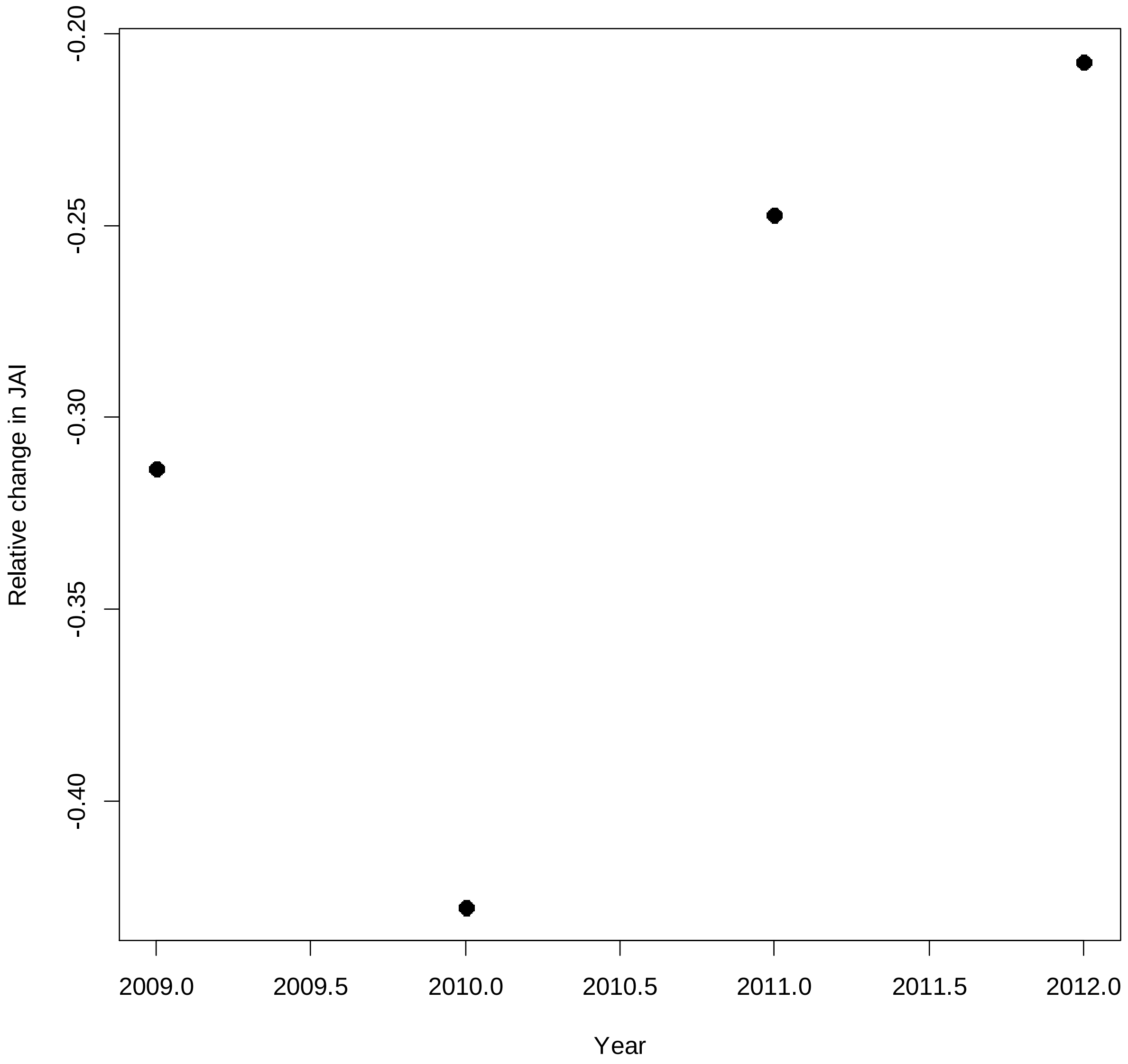


Figure 7.4.2.13. Relative change in the fit to the SAD index for the retrospective analysis.

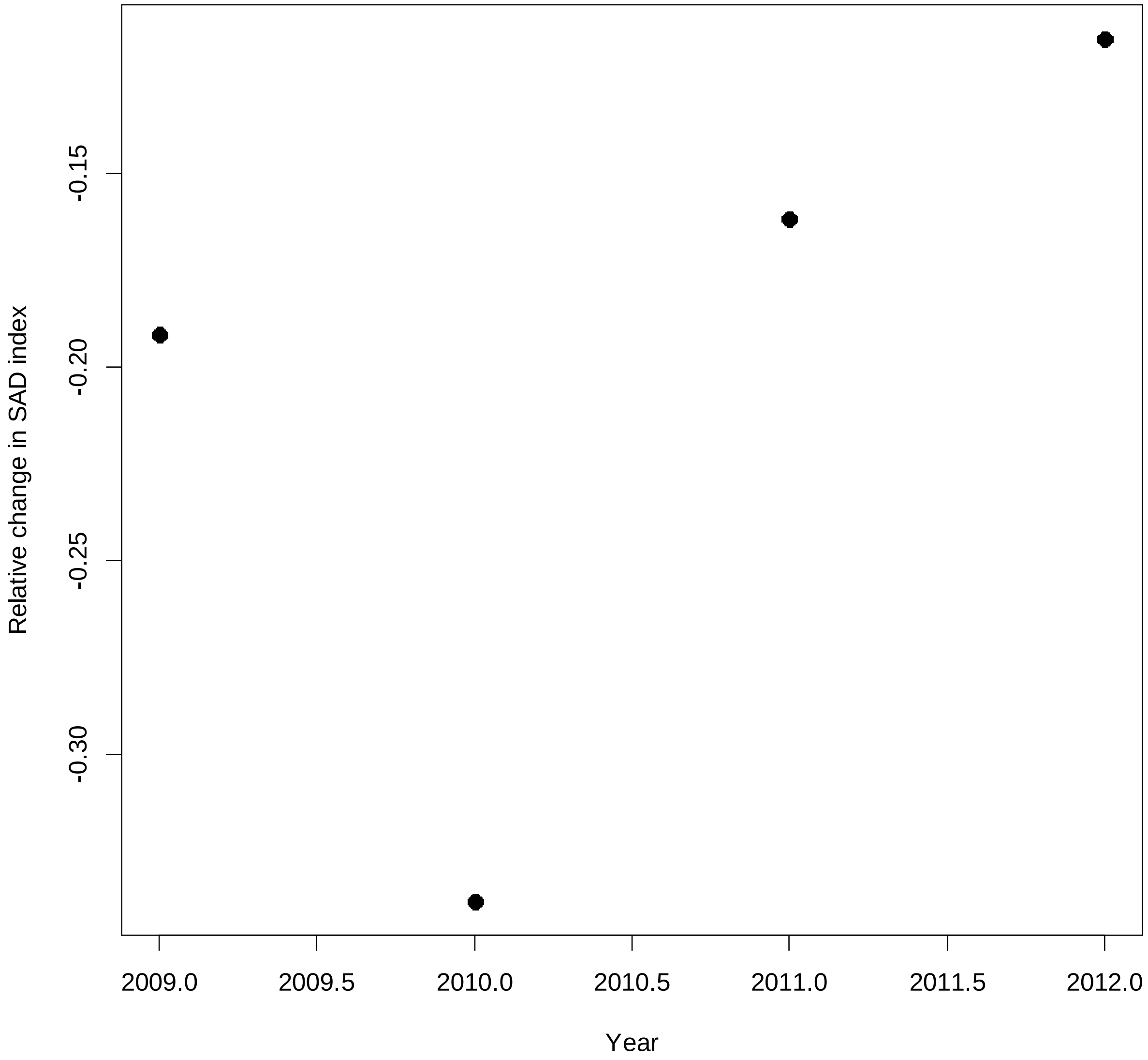


Figure 7.4.2.14. Relative change in the fit to the NAD index for the retrospective analysis.

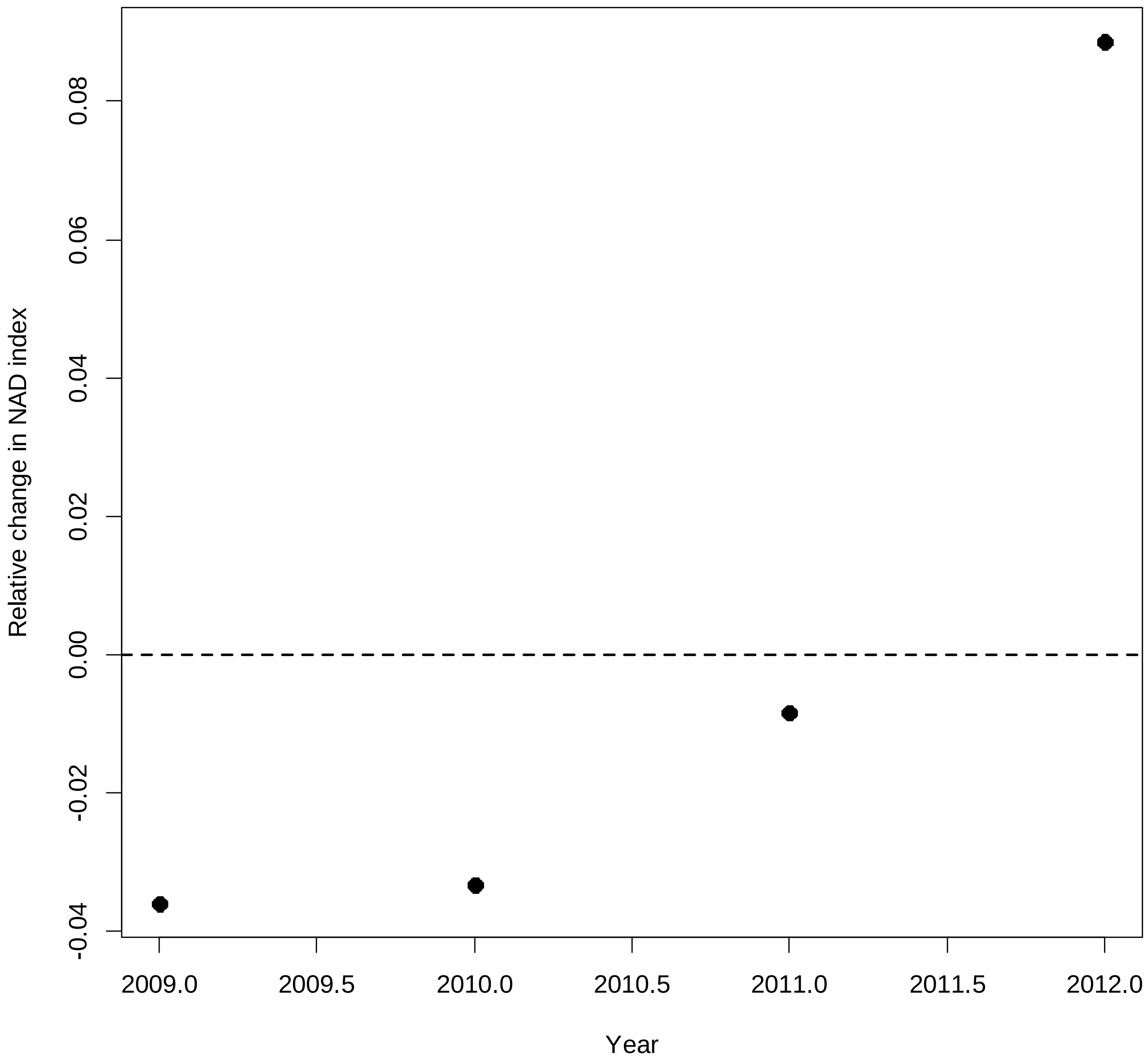
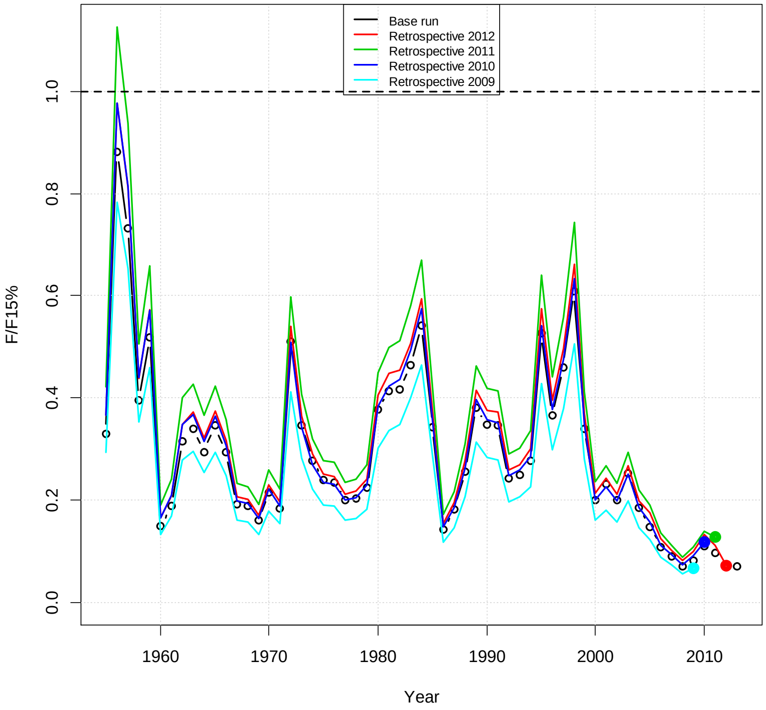


Figure 7.4.2.15. Fishing mortality rate at age-2 (upper) and age-3 (lower) over ***F*$_{15\%}$** for the retrospective analysis.



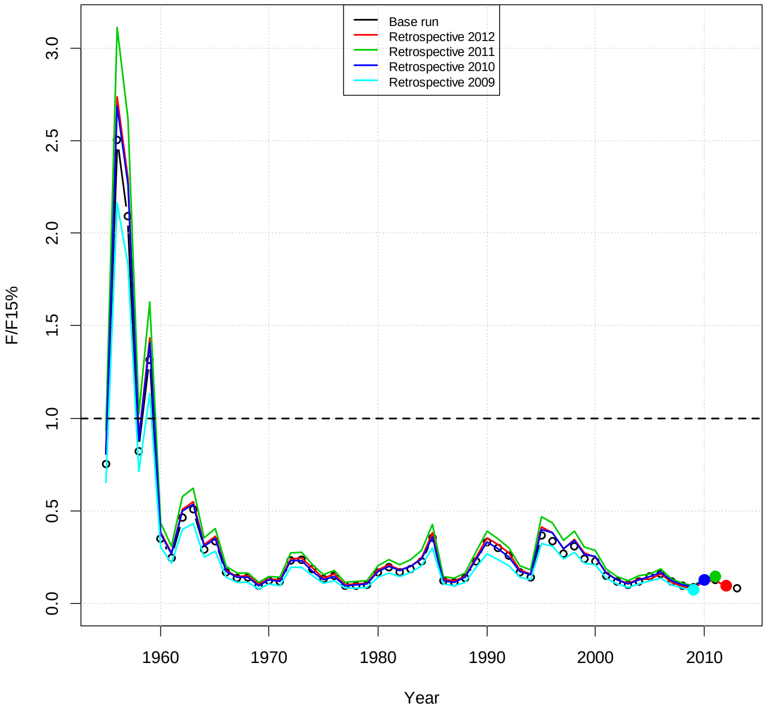
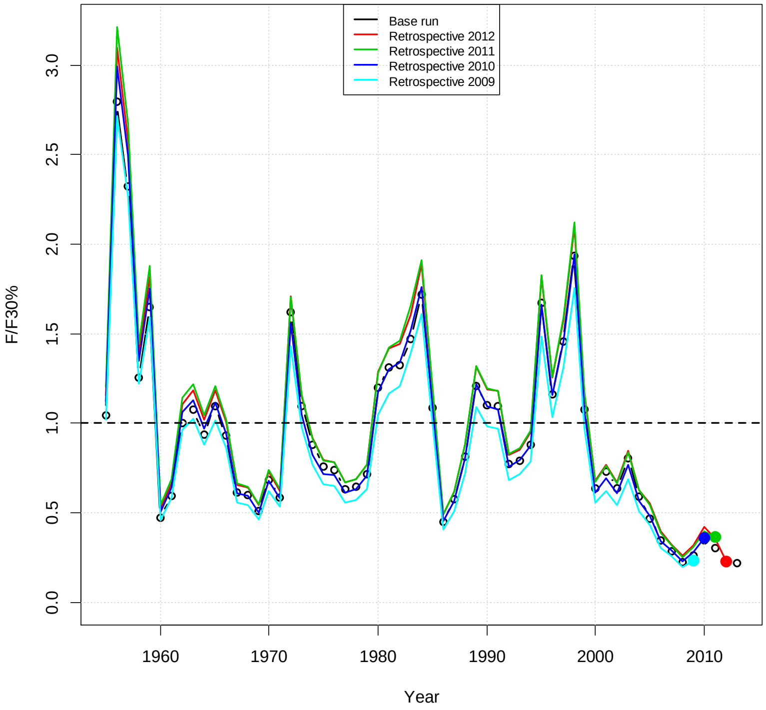


Figure 7.4.2.16. Fishing mortality rate at age-2 (upper) and age-3 (lower) over ***$F_{30\%}$*** for the retrospective analysis.



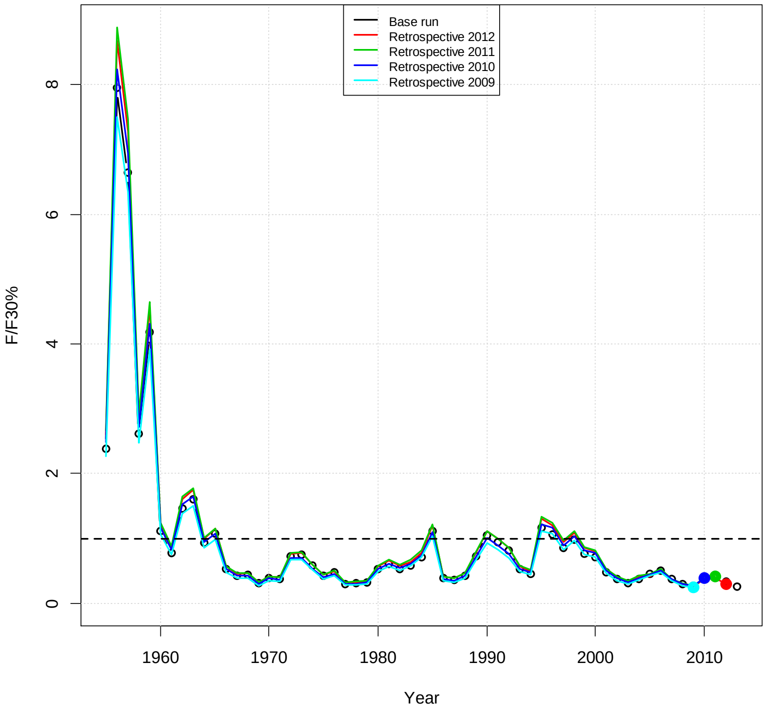


Figure 7.4.2.17. Fecundity over ***FEC$_{15\%}$*** for the retrospective analysis.

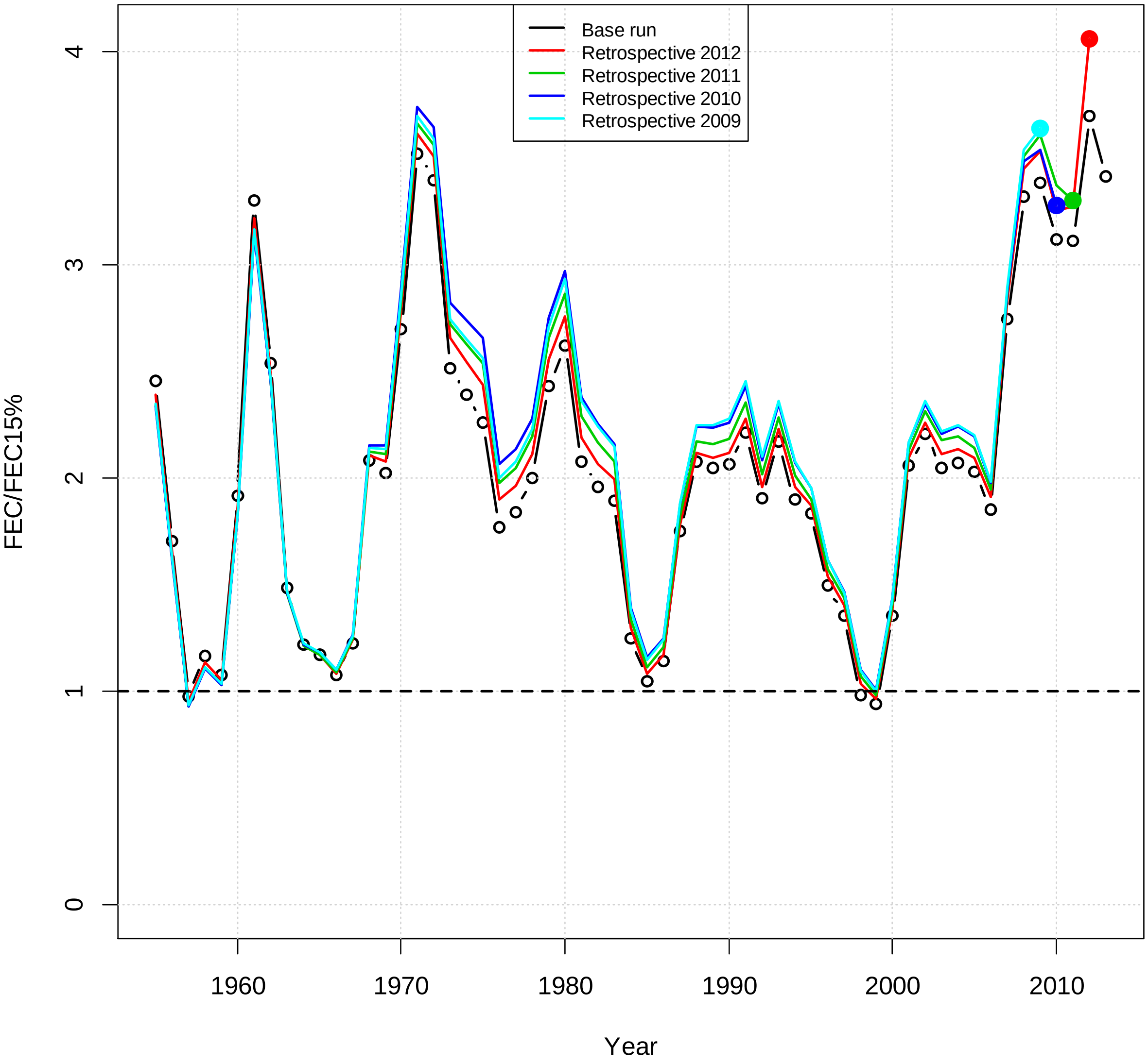


Figure 7.4.2.18. Fecundity over ***$FEC_{30\%}$*** for the retrospective analysis.

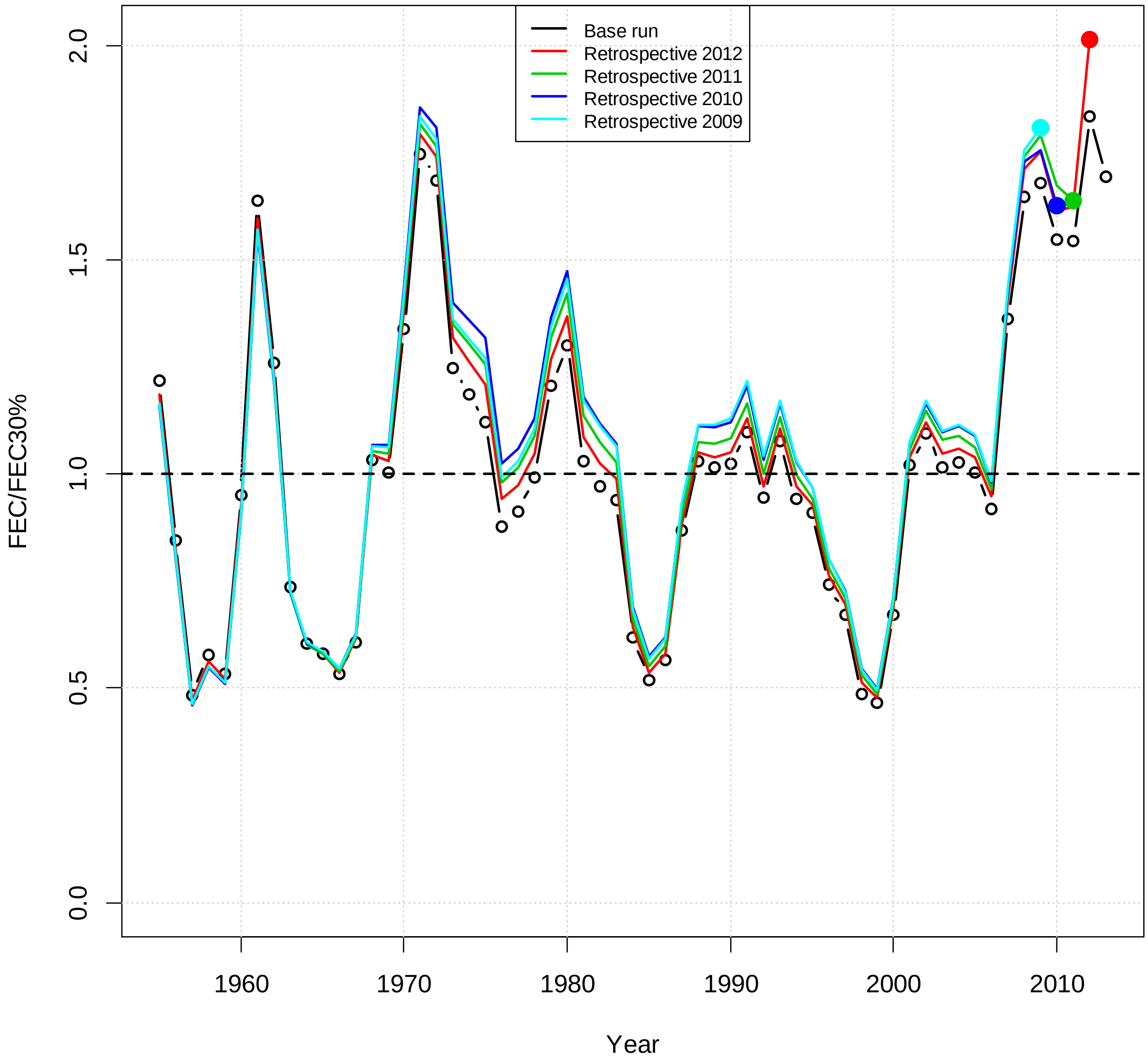


Figure 7.4.3.1. Change in the negative log-likelihood of the southern commercial reduction selectivity for age-4 with the solid green line being the total likelihood change.

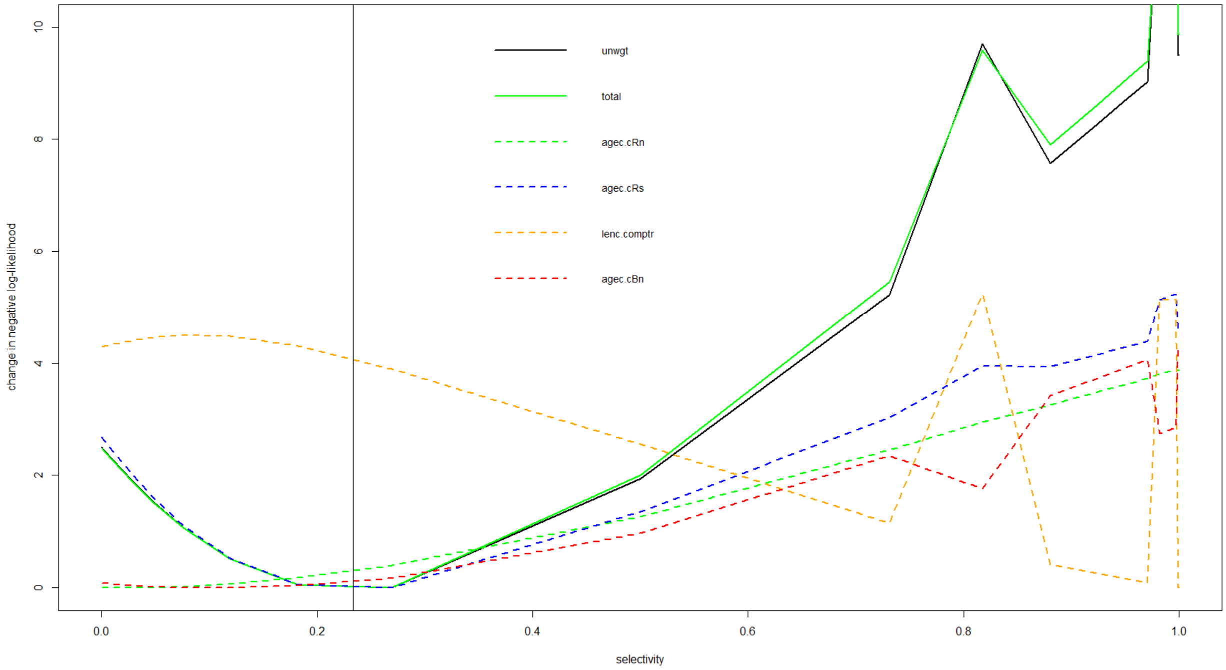


Figure 7.4.3.2. Change in the negative log-likelihood of the southern commercial reduction selectivity for age-5 with the solid green line being the total likelihood change.

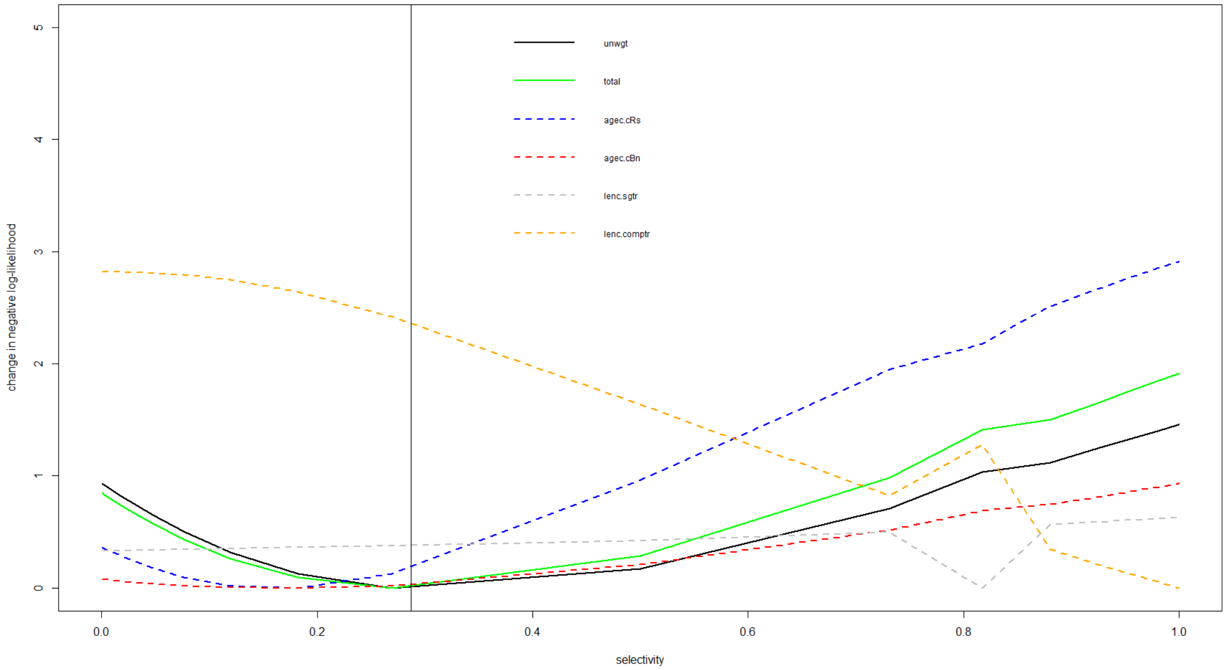


Figure 7.4.3.3. Change in the negative log-likelihood of the northern commercial bait selectivity for age-5 with the solid green line being the total likelihood change.

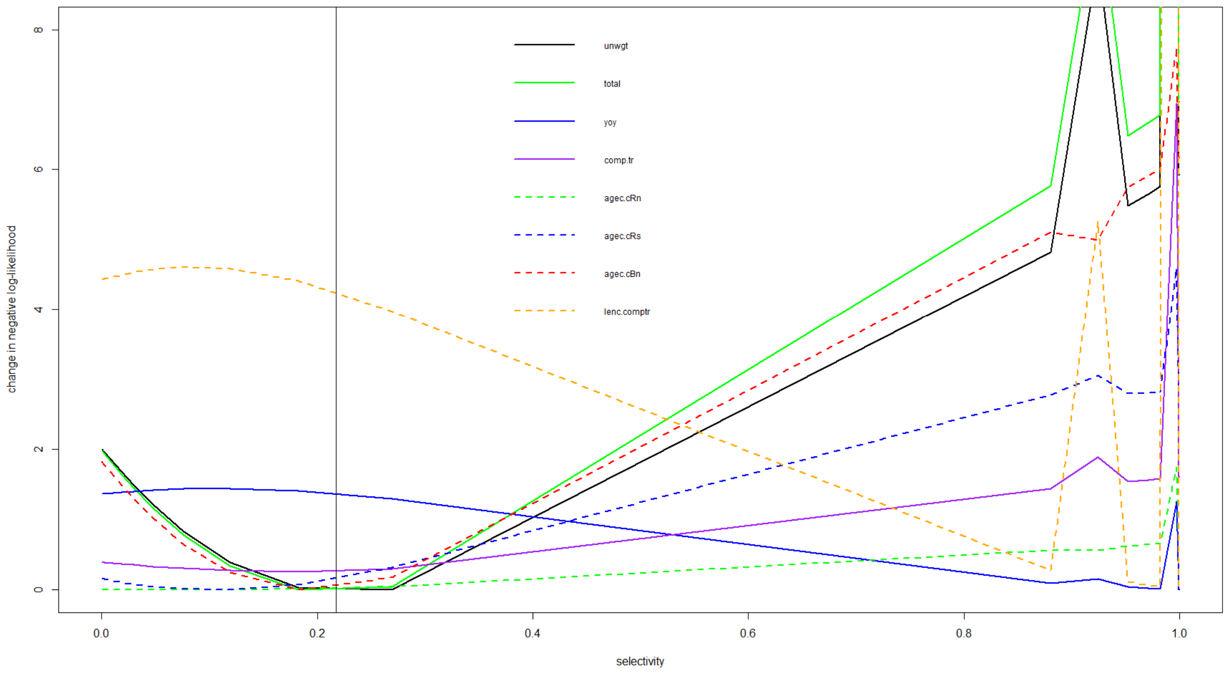


Figure 7.4.3.4. Change in the negative log-likelihood of the northern commercial reduction selectivity for age-5 with the solid green line being the total likelihood change.

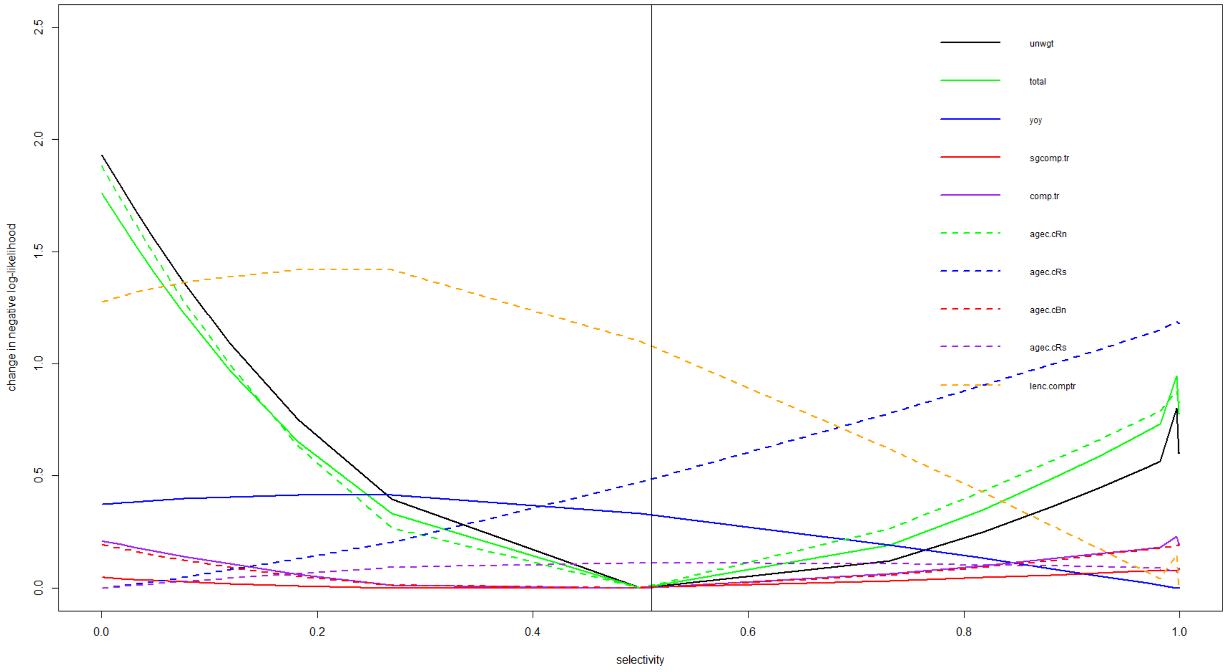


Figure 7.4.3.5. Selectivities estimated for the northern and southern commercial reduction and bait fisheries using the simulation model using the variability in the base run of the assessment model.

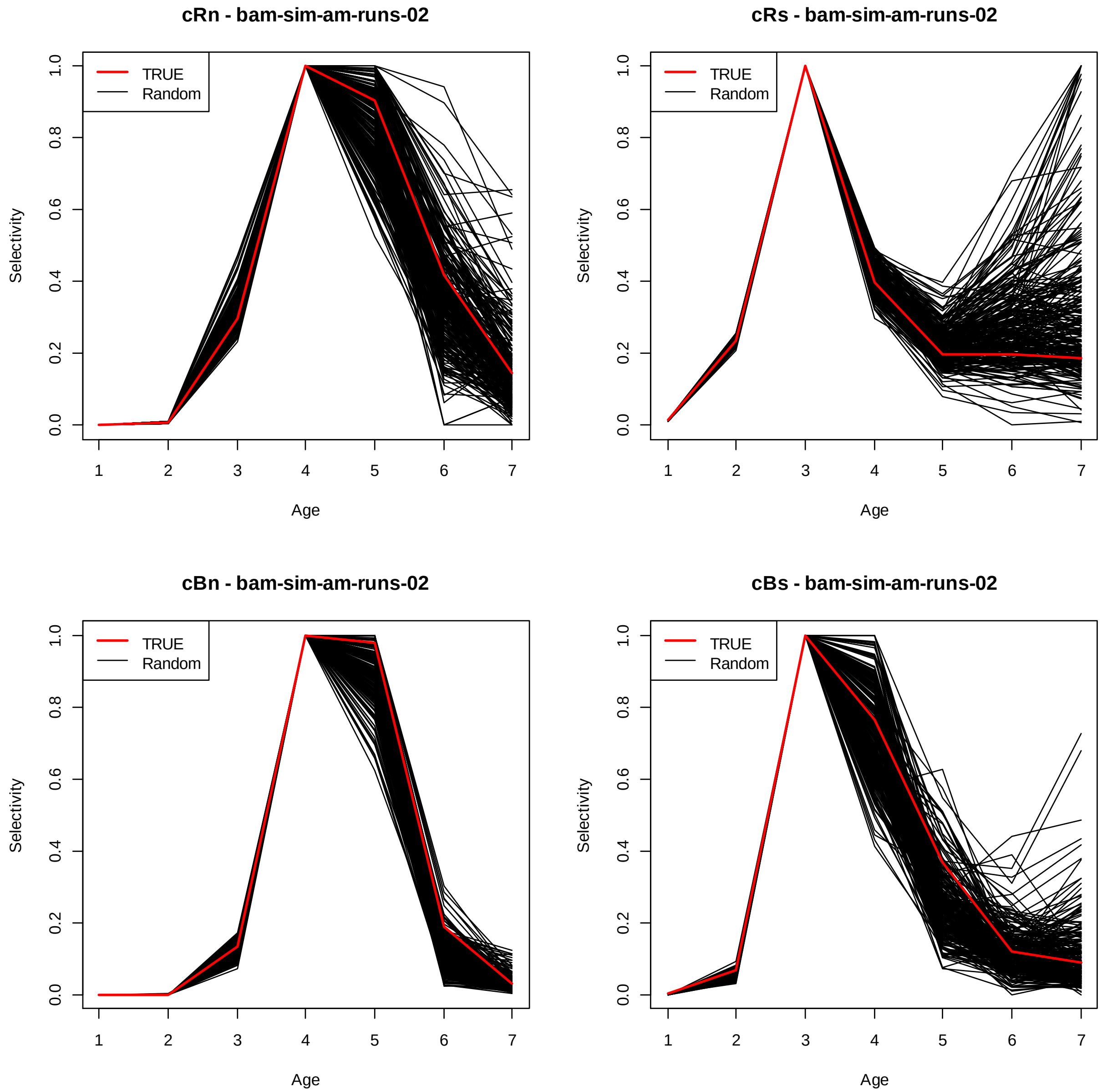


Figure 7.5.1. Fishing mortality at age-2 (upper panel) and age-3 (lower panel) over time for the MCB runs. Gray area indicates 95% confidence interval; black line indicates base run.

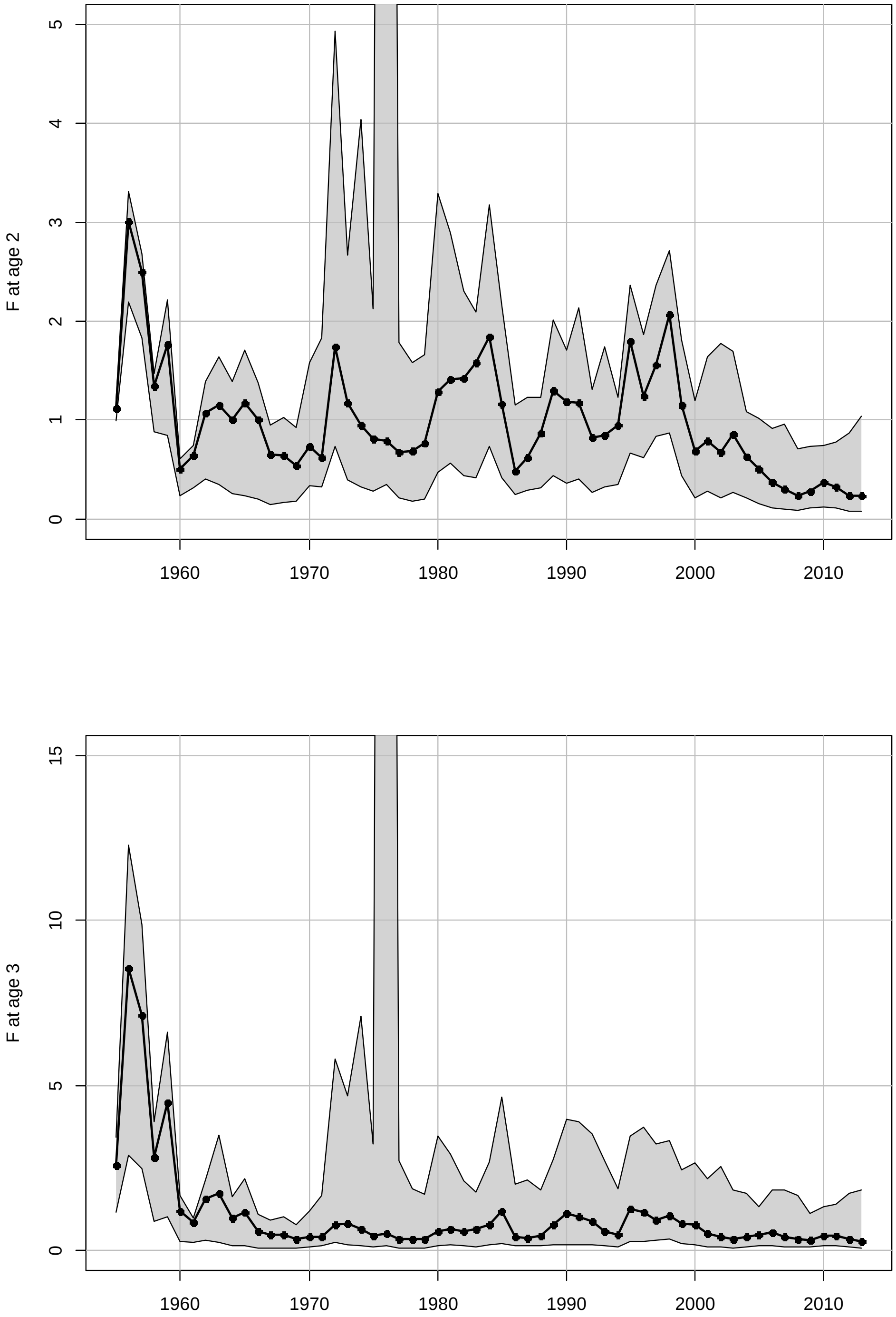


Figure 7.5.2. Age-1+ biomass in 1000s mt over time for the MCB runs. Gray area indicates 95% confidence interval; black line indicates base run.

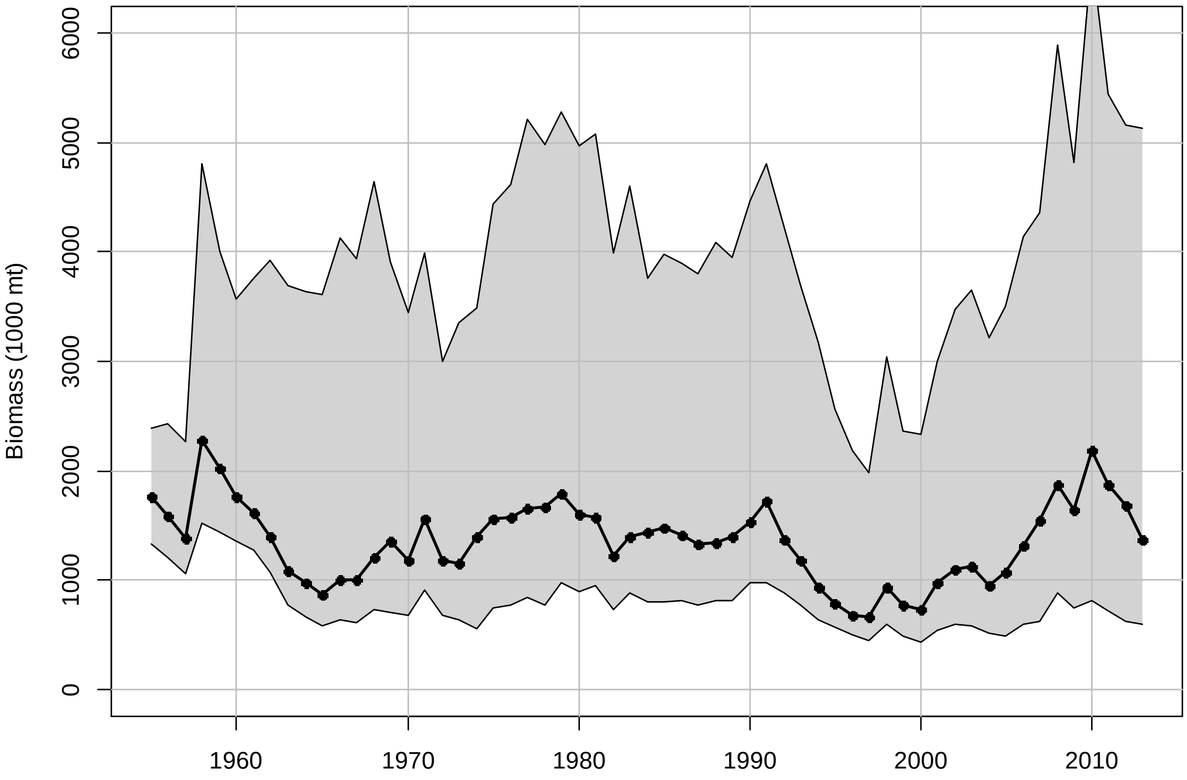


Figure 7.5.3. Recruitment over time for the MCB runs. Gray area indicates 95% confidence interval; black line indicates base run.

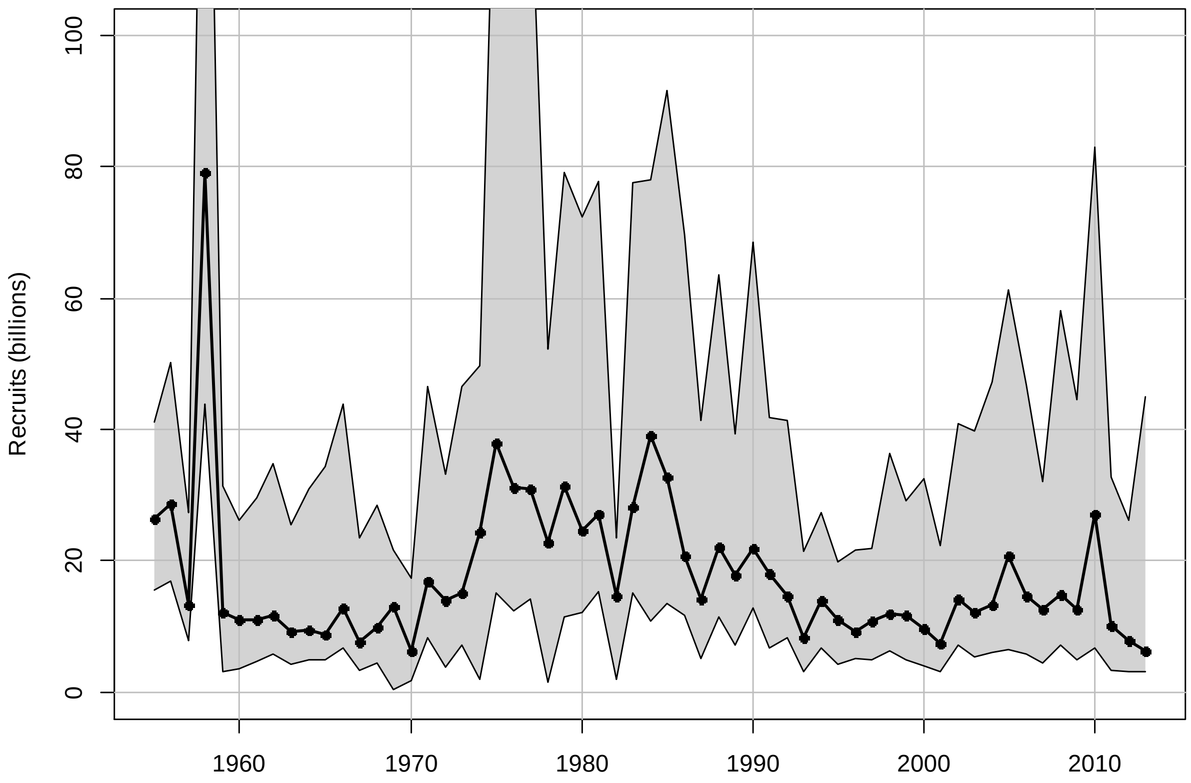


Figure 7.5.4. Fecundity over time for the MCB runs. Gray area indicates 95% confidence interval; black line indicates base run.

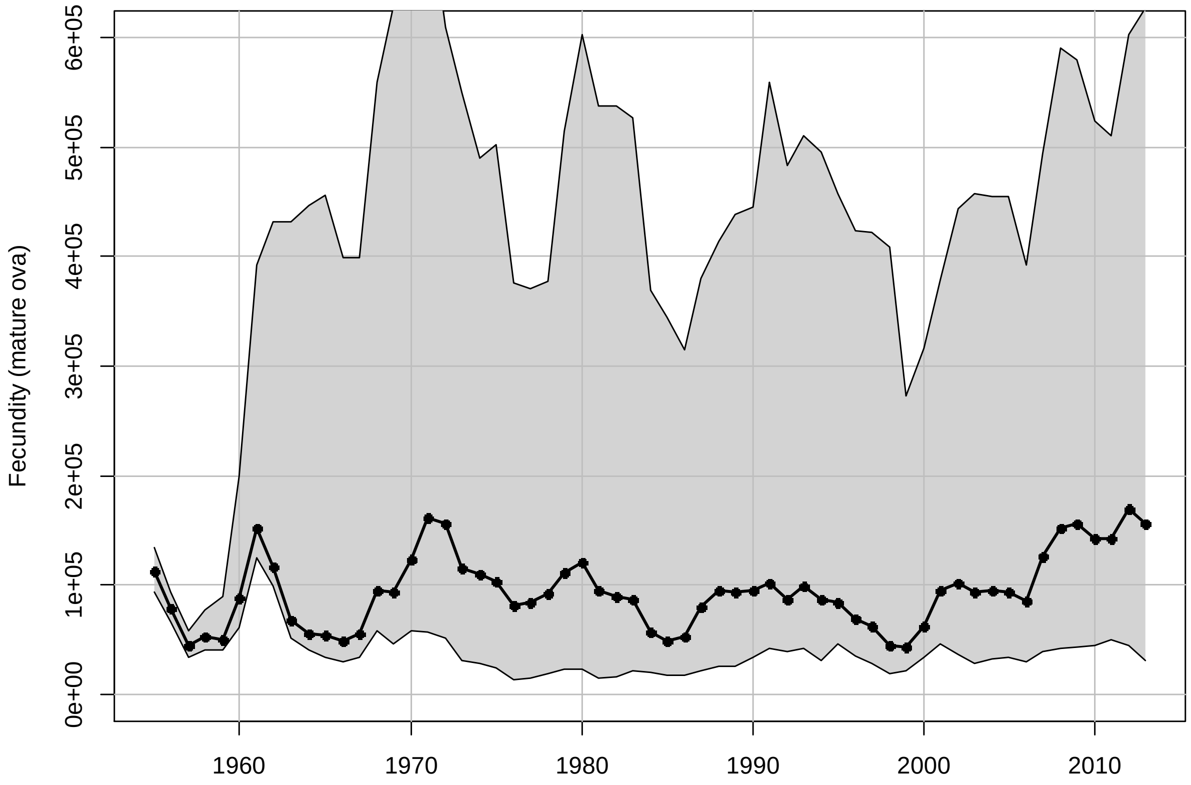


Figure 8.2.1. Fishing mortality at age-2 over time compared to the recommended SPR benchmarks based on the minimum and median ***F*$_{X\%}$** during the time period 1960-2012.

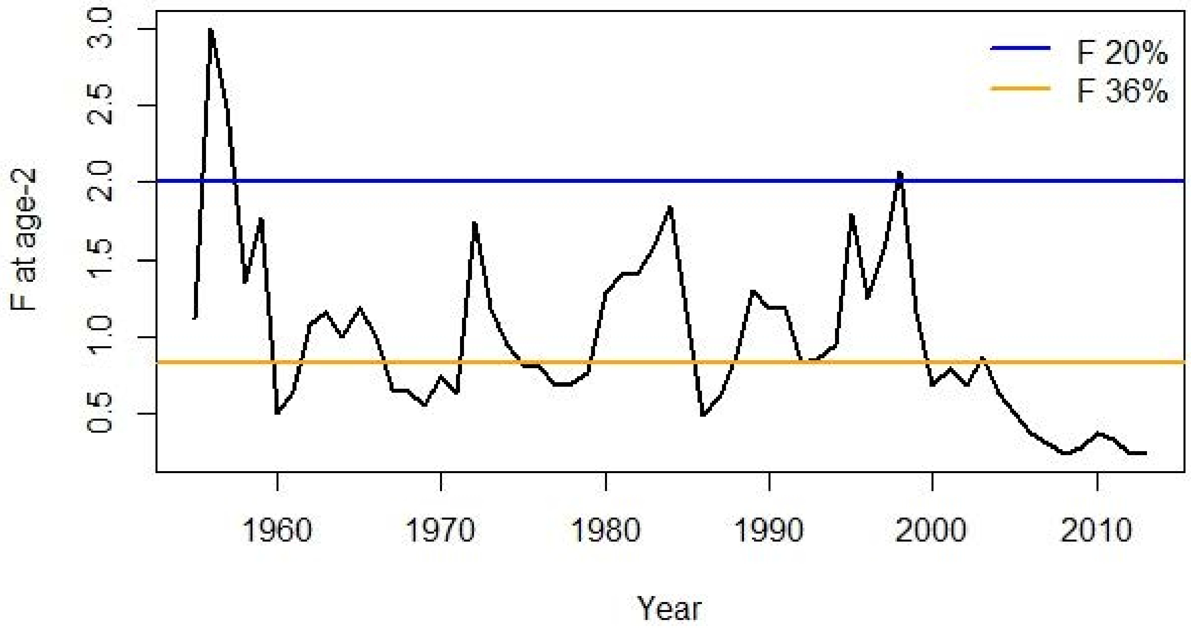


Figure 8.2.2. Fecundity over time compared to the recommended fecundity based benchmarks associated with the SPR benchmarks based on the minimum and median $F_{X\%}$ during the time period 1960-2012.

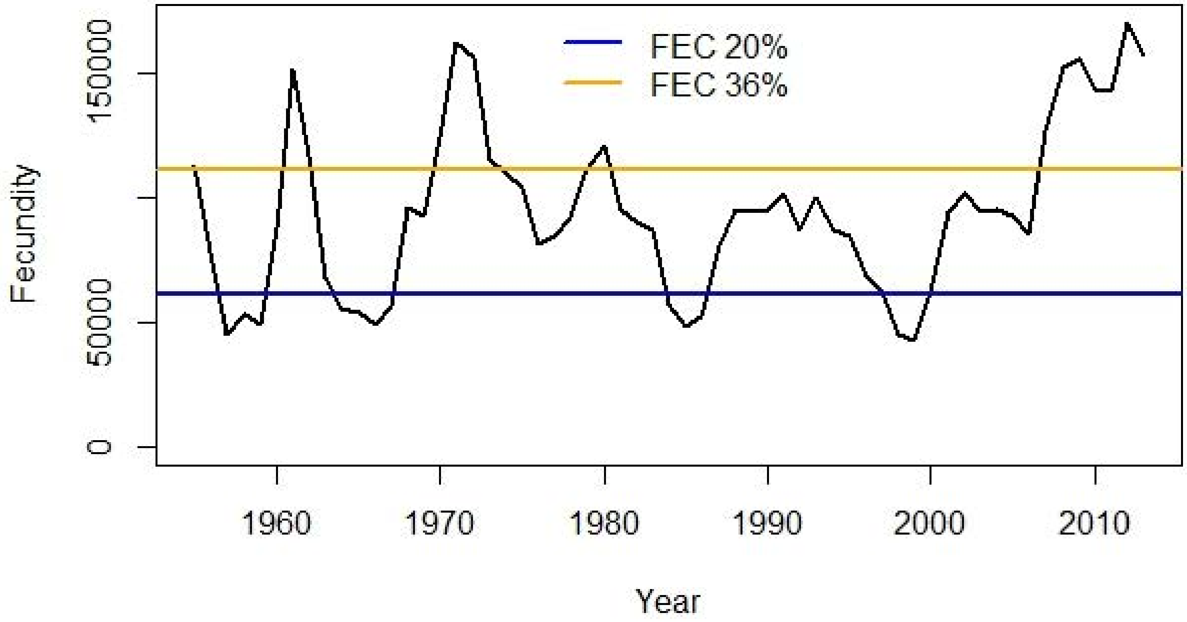


Figure 8.3.1.1. The full fishing mortality rate over time compared to the fishing mortality reference points. Note: the full fishing mortality rate switches between the fishing mortality rate at age-2 and age-3 from year to year depending upon which has the higher rate.

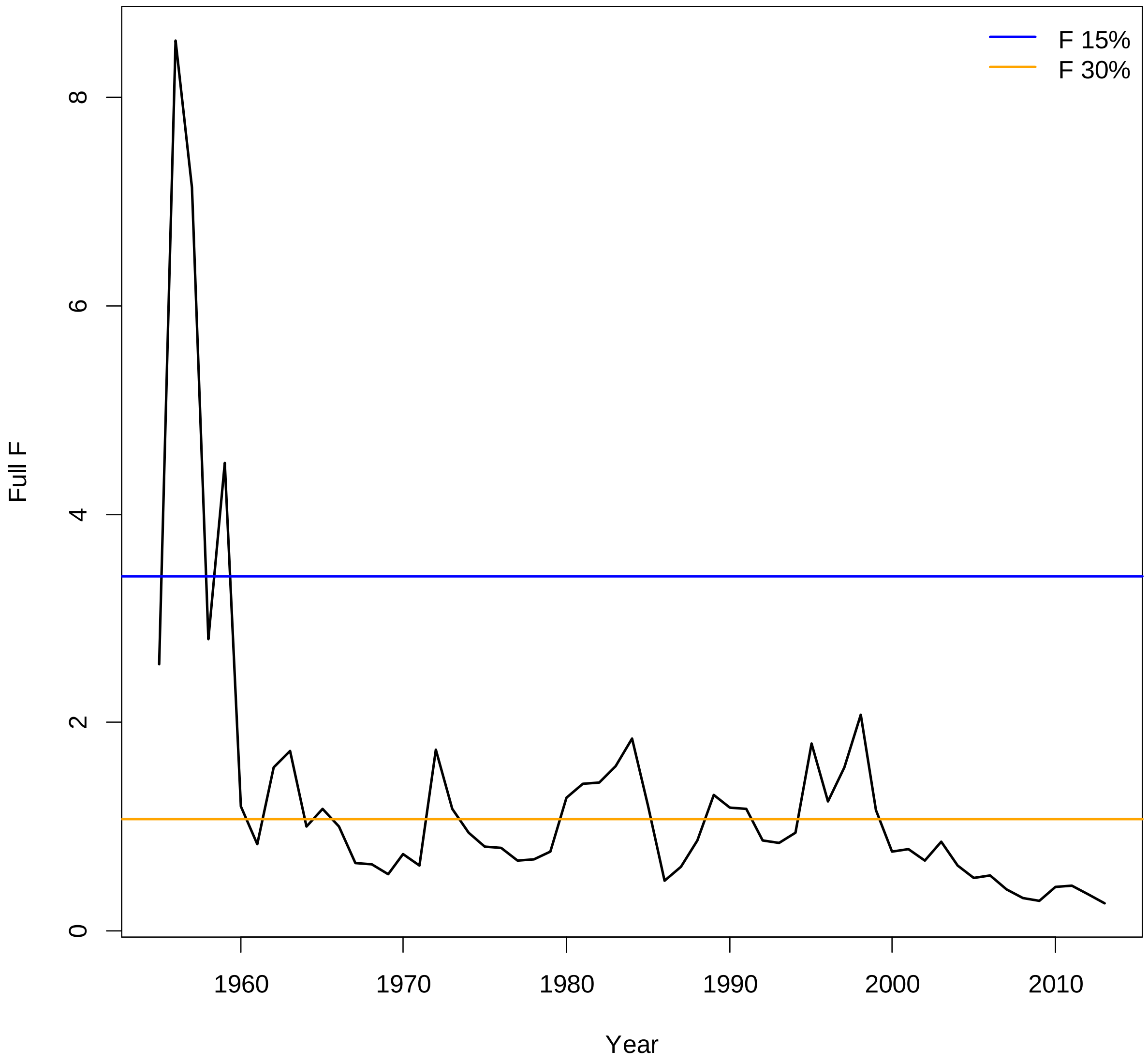


Figure 8.3.1.2. Biomass over time divided by the biomass at F = 0.

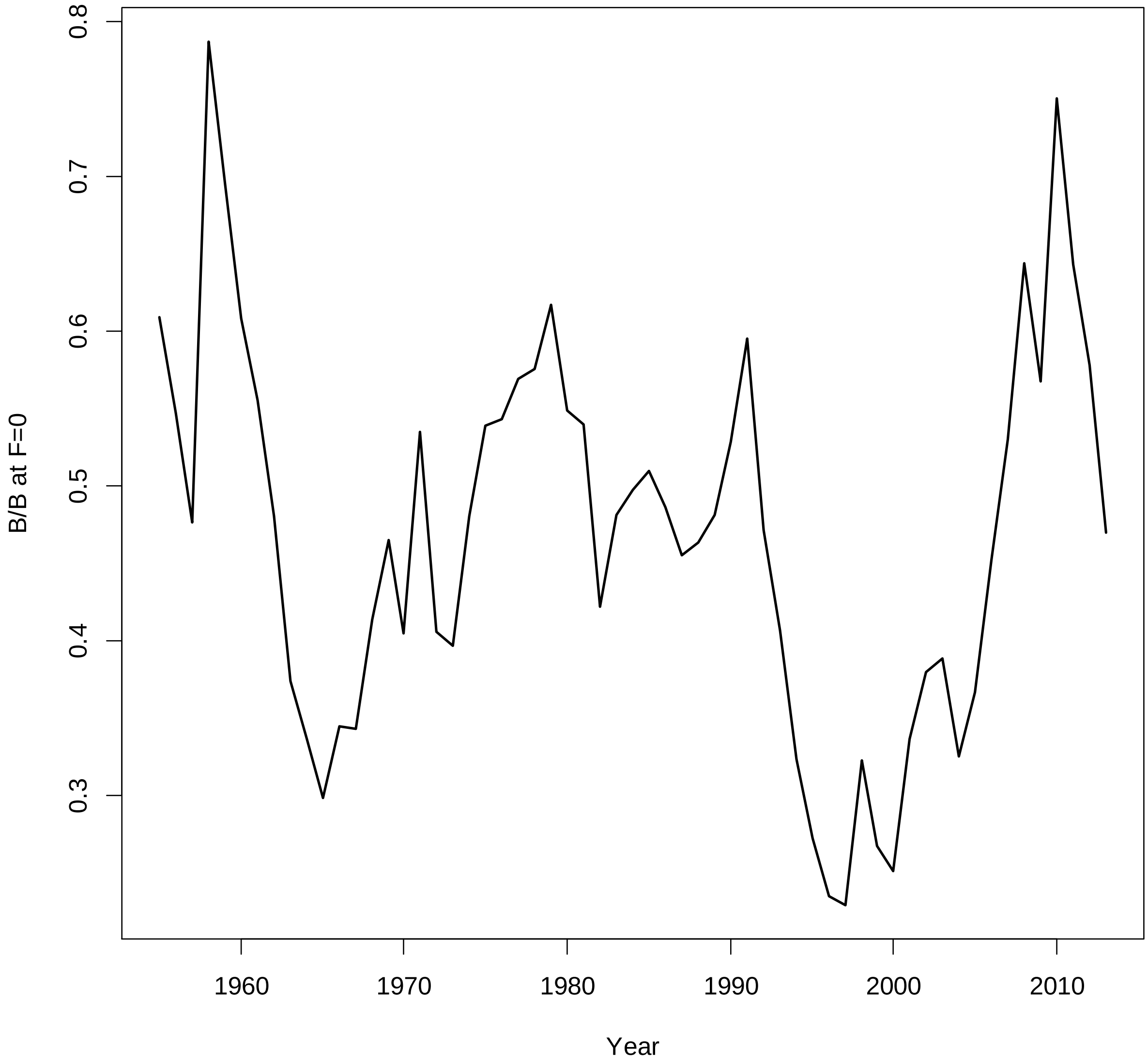
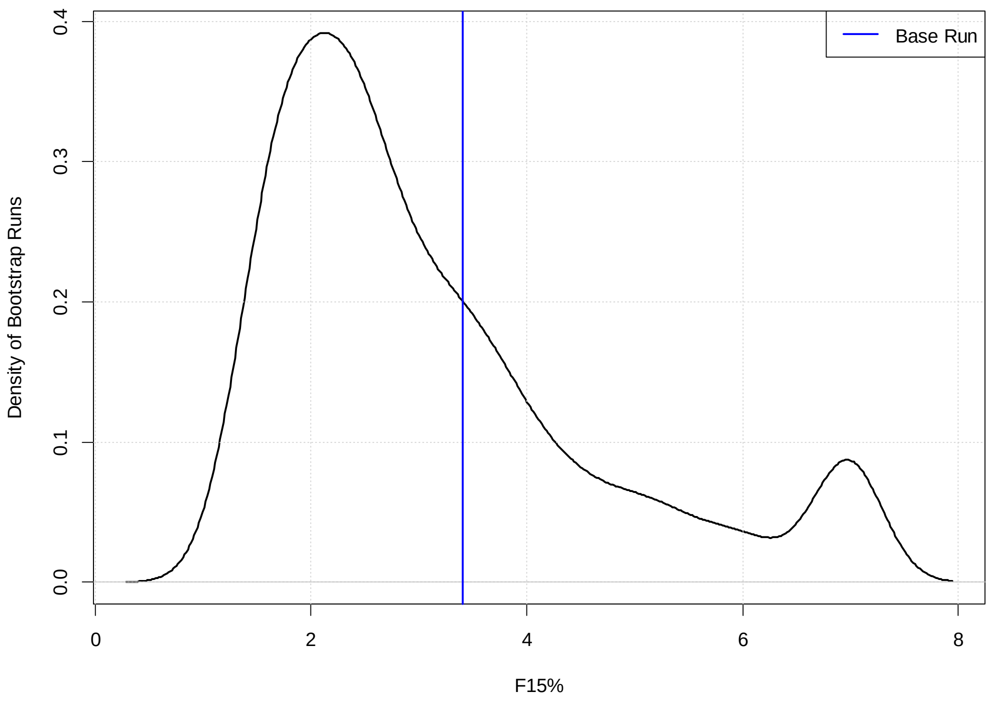


Figure 8.3.2.1. Density plots for the calculated ***$F_{15\%}$*** (above) and ***$F_{30\%}$*** (below) threshold and target benchmarks, respectively, across the base run and MCB runs.



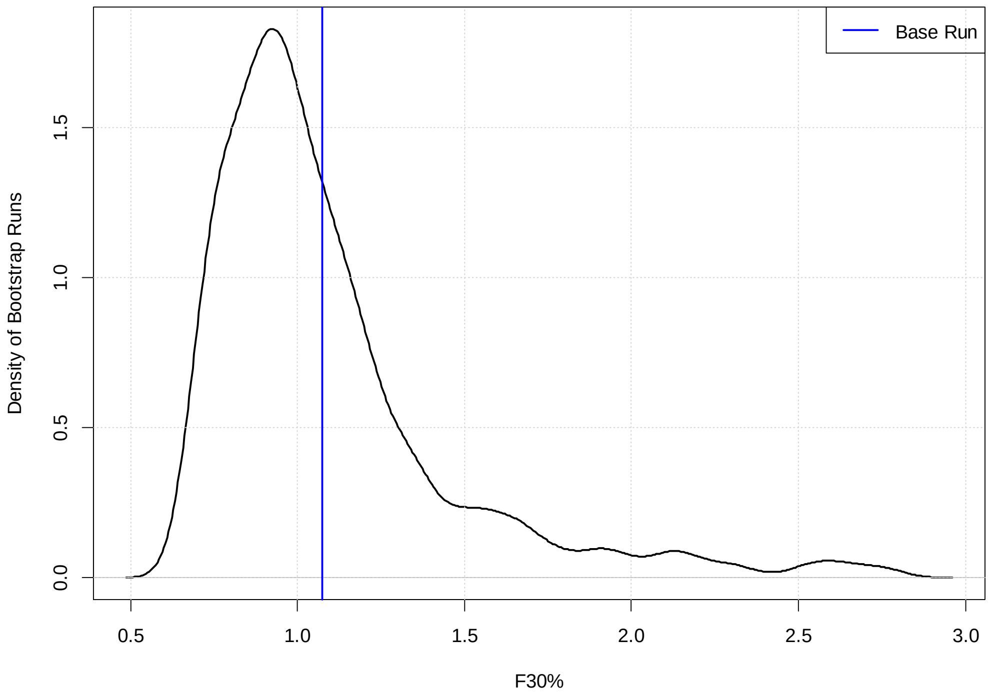
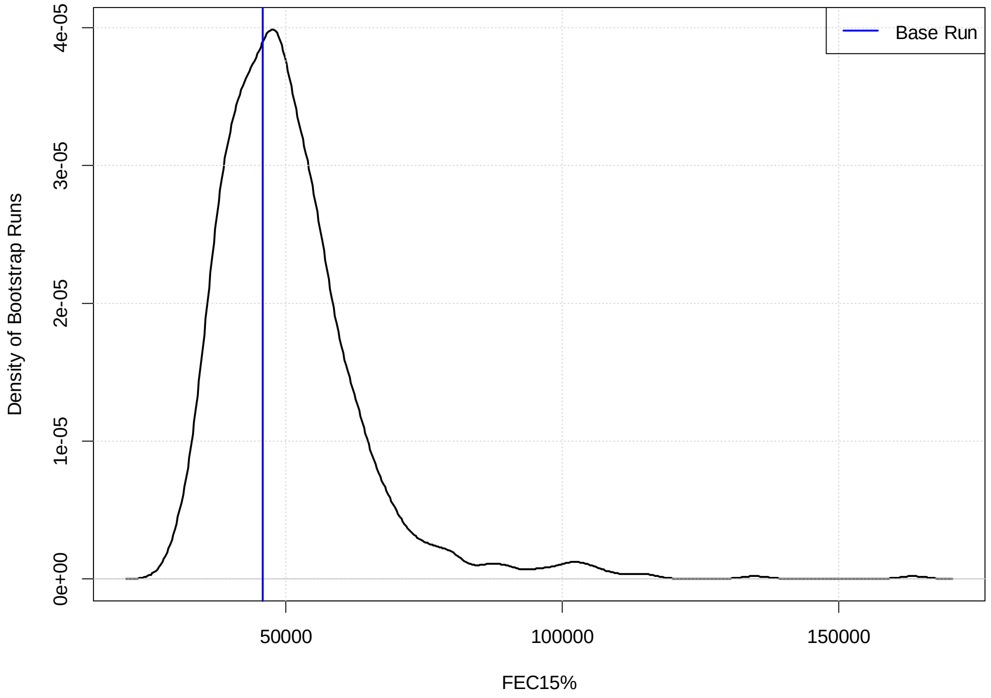


Figure 8.3.2.2. The density plots for the calculated ***FEC*** $_{15\%}$ (above) and ***FEC*** $_{30\%}$ (below) threshold and target benchmarks, respectively, across the base run and MCB runs.



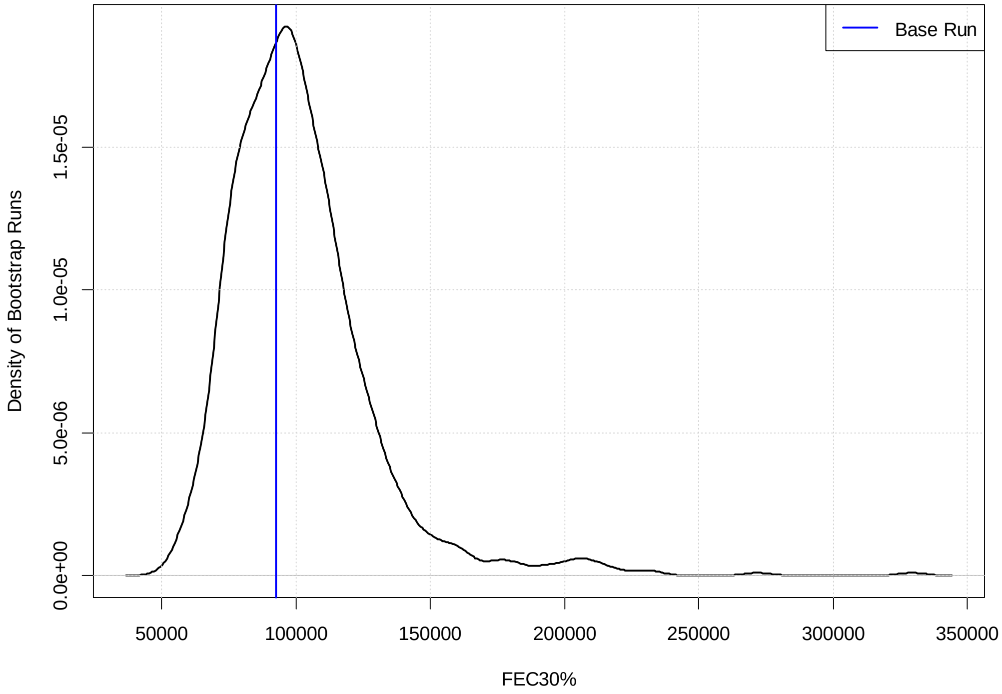


Figure 8.3.2.3. Fishing mortality at age-2 (upper panel) and age-3 (lower panel) over ***F*$_{15\%}$** over time for the MCB runs. Gray area indicates 95% confidence interval; black line indicates base run.

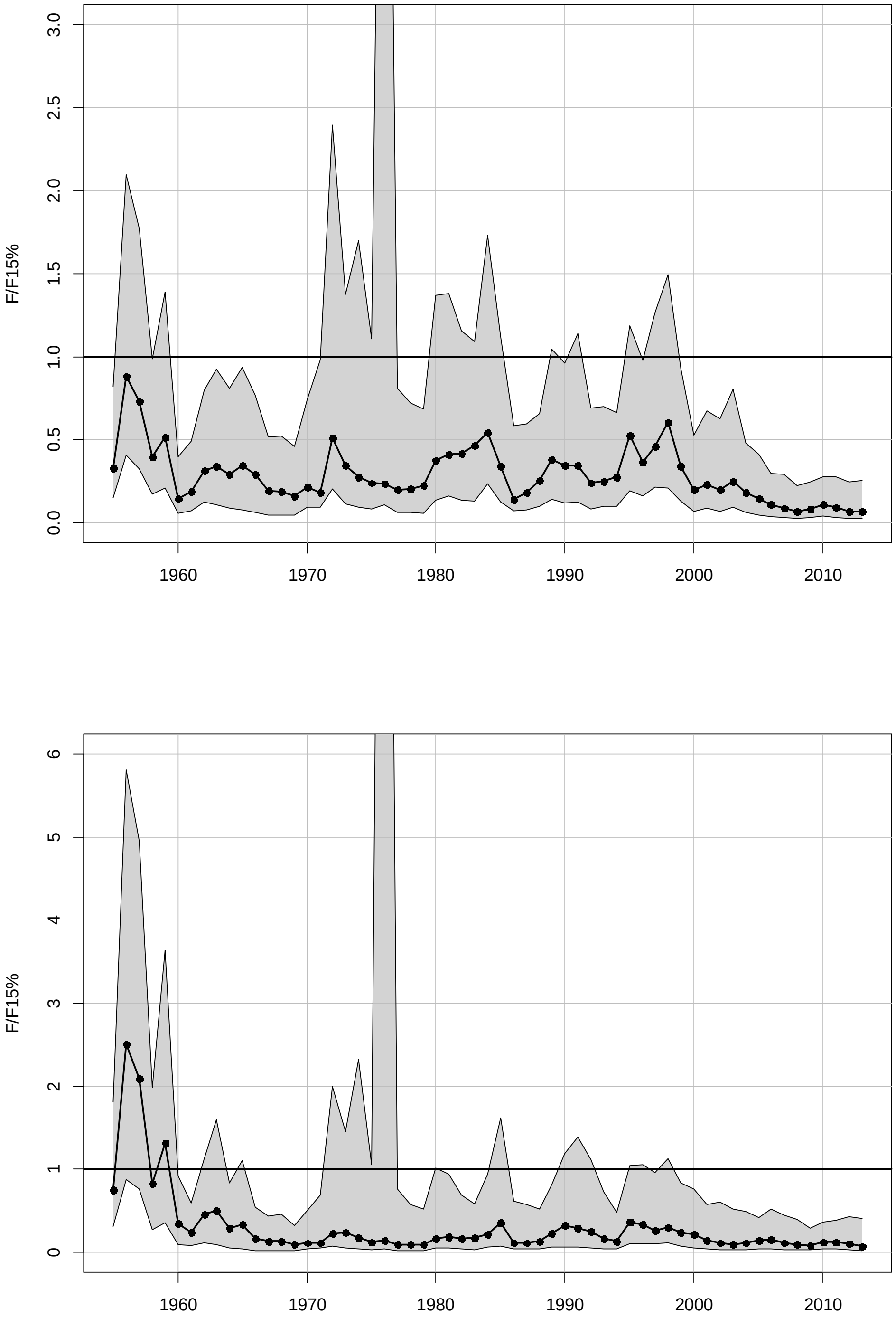


Figure 8.3.2.4. Fishing mortality at age-2 (upper panel) and age-3 (lower panel) over ***$F_{30\%}$*** over time for the MCB runs. Gray area indicates 95% confidence interval; black line indicates base run.

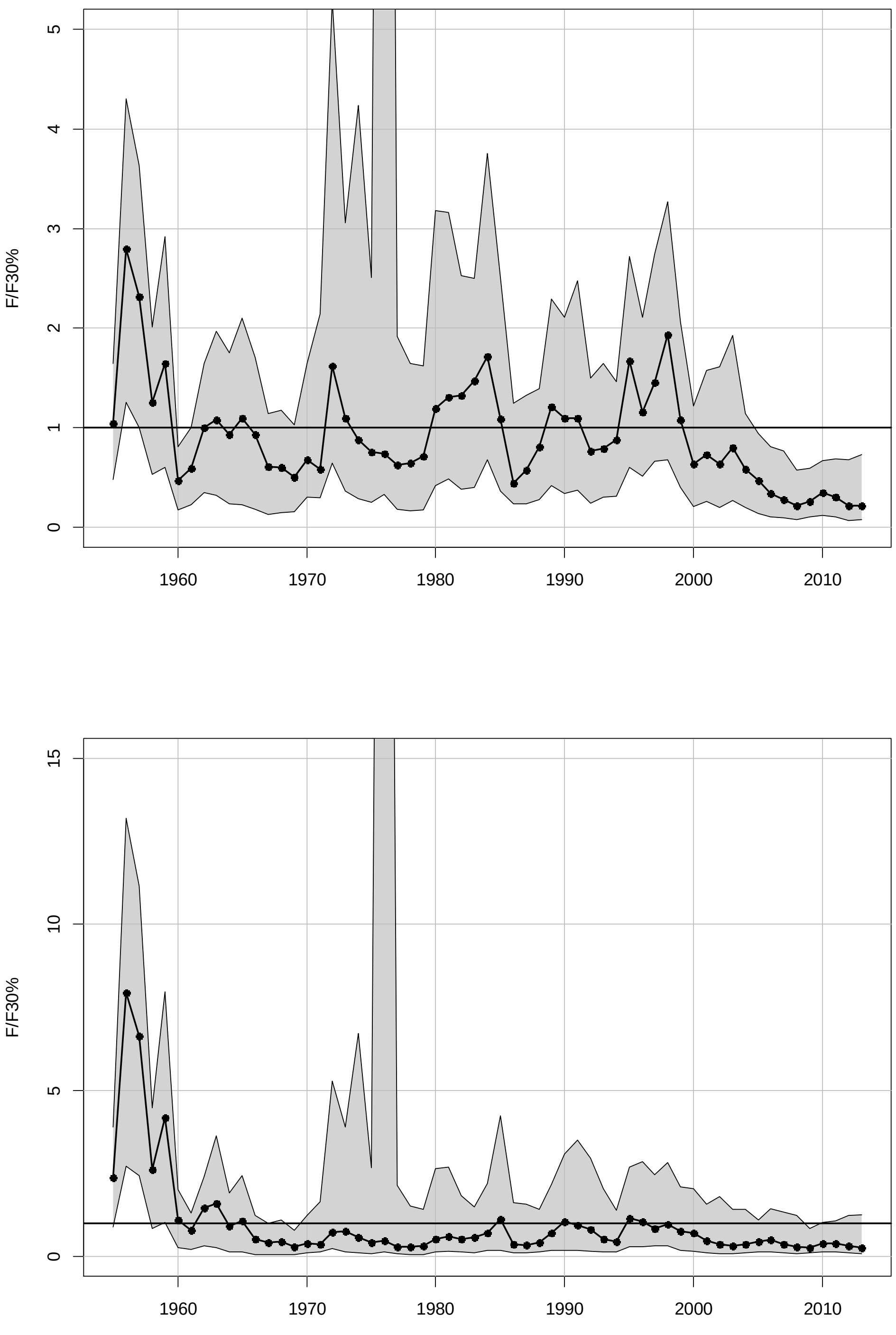


Figure 8.3.2.5. Fecundity over ***FEC*$_{15\%}$** over time for the MCB runs. Gray area indicates 95% confidence interval; black line indicates base run.

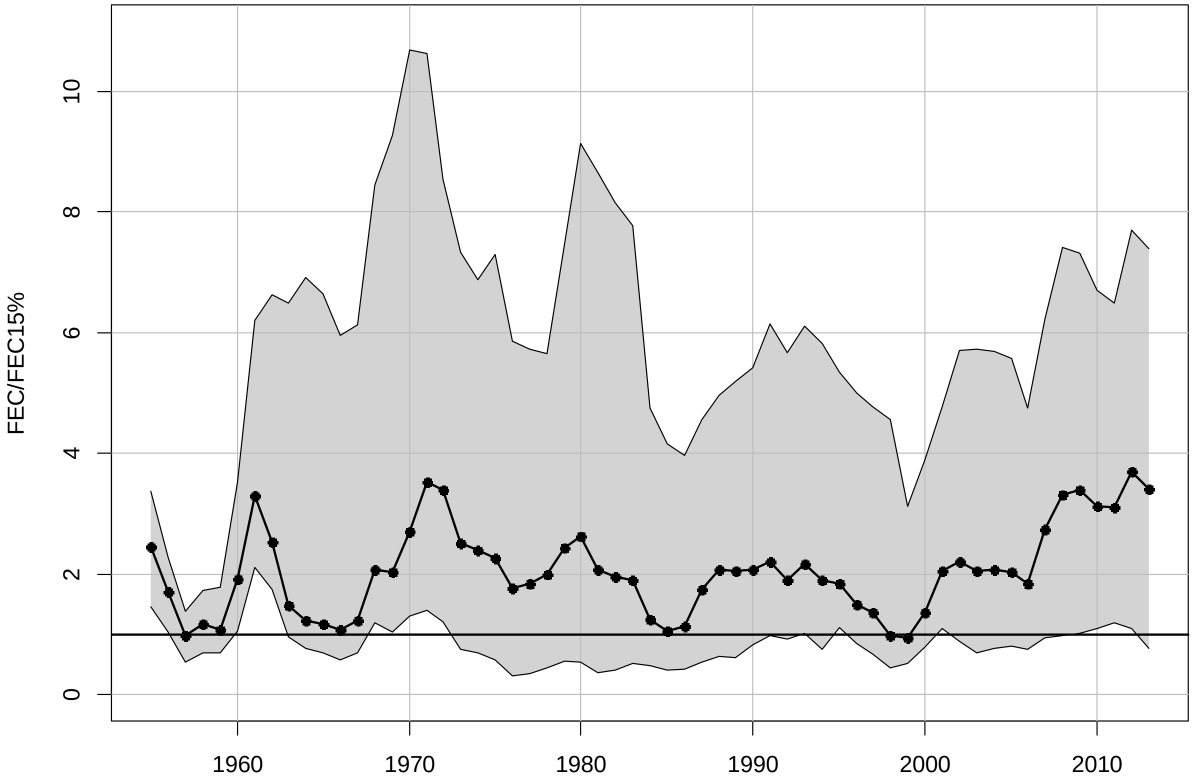


Figure 8.3.2.6. Fecundity over ***$FEC_{30\%}$*** over time for the MCB runs. Gray area indicates 95% confidence interval; black lines indicates base run.

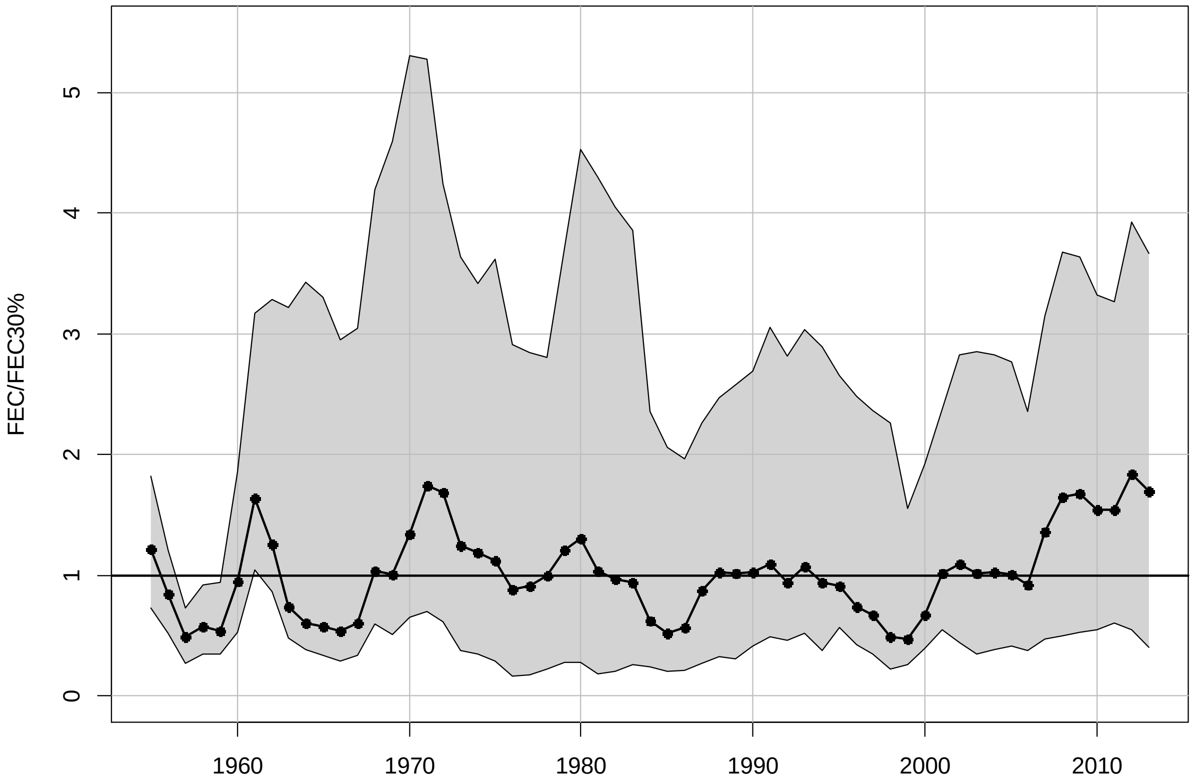


Figure 8.3.2.7. Plot of the terminal year fishing mortality at age-2 (upper panel) and age-3 (lower panel) and the terminal year fecundity relative to their respective threshold benchmarks for the base run and each bootstrap run.

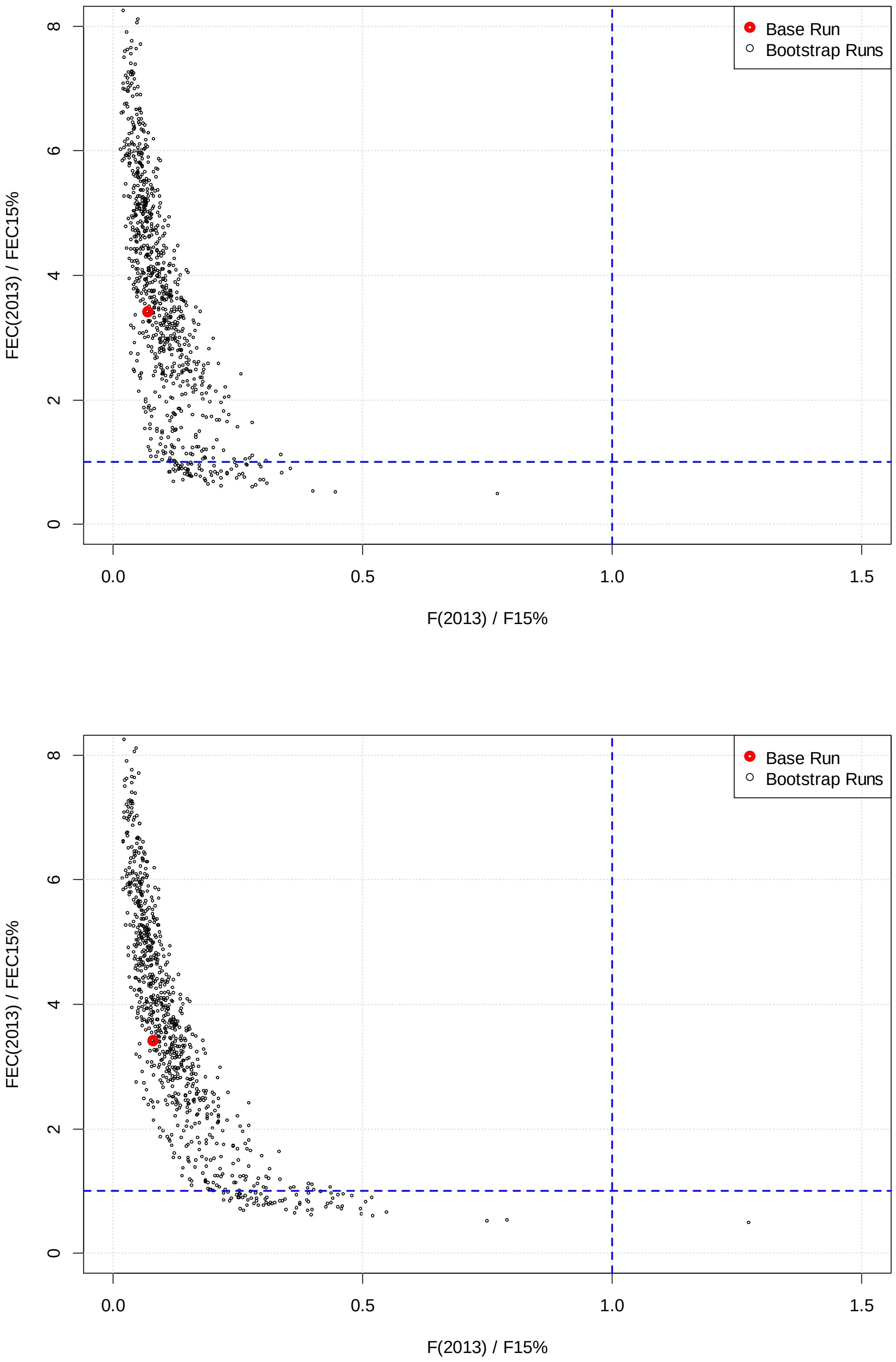


Figure 8.3.2.8. Plot of the terminal year fishing mortality at age-2 (upper panel) and age-3 (lower panel) and the terminal year fecundity relative to their respective target benchmarks for the base run and each bootstrap run.

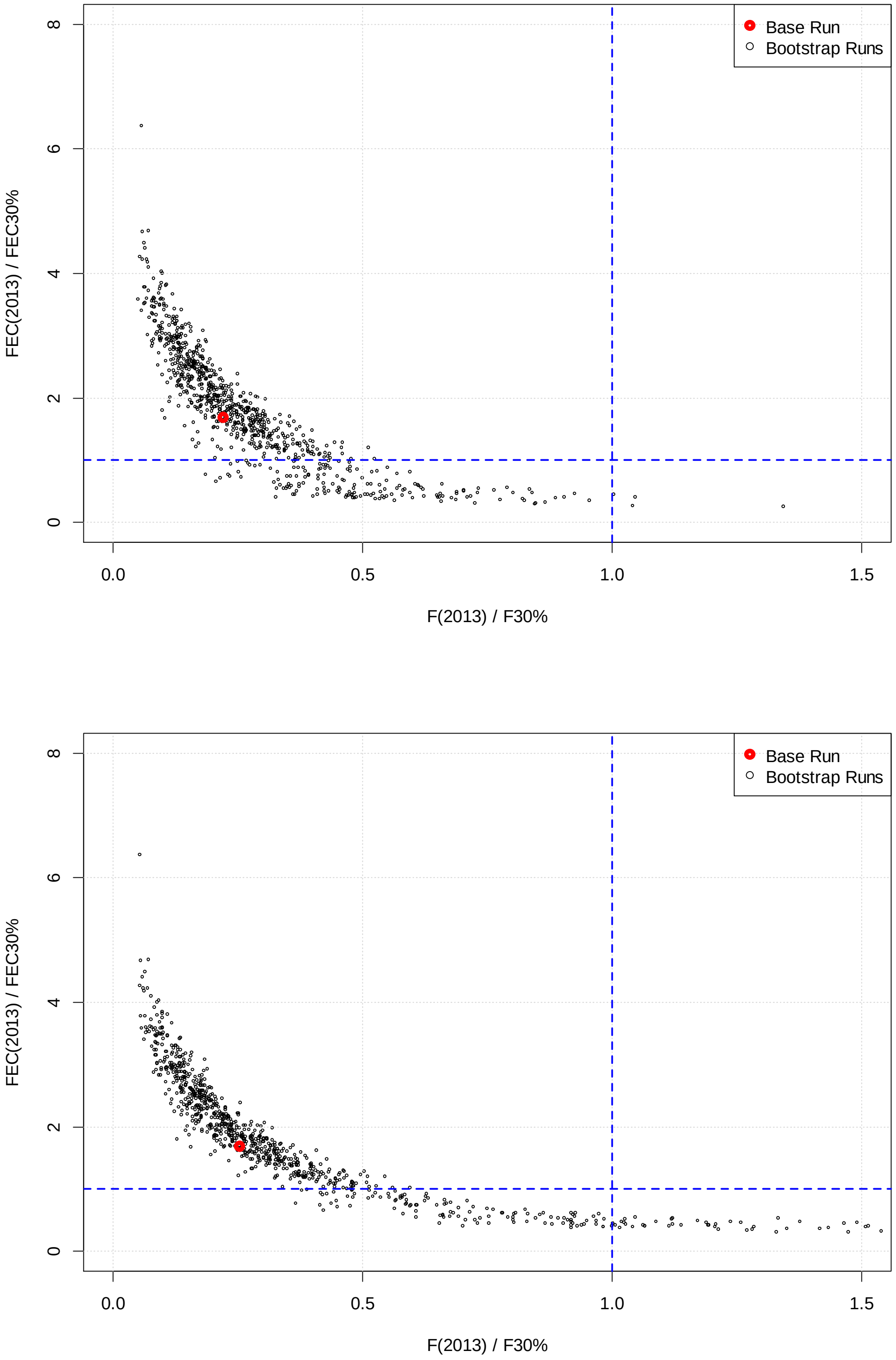


Figure 8.3.2.9. The density plot (above) and cumulative density plot (below) for terminal year fishing mortality at age-2 (left panels) and age-3 (right panels) over the ***F*$_{30\%}$** target benchmark across the base run and MCB runs.

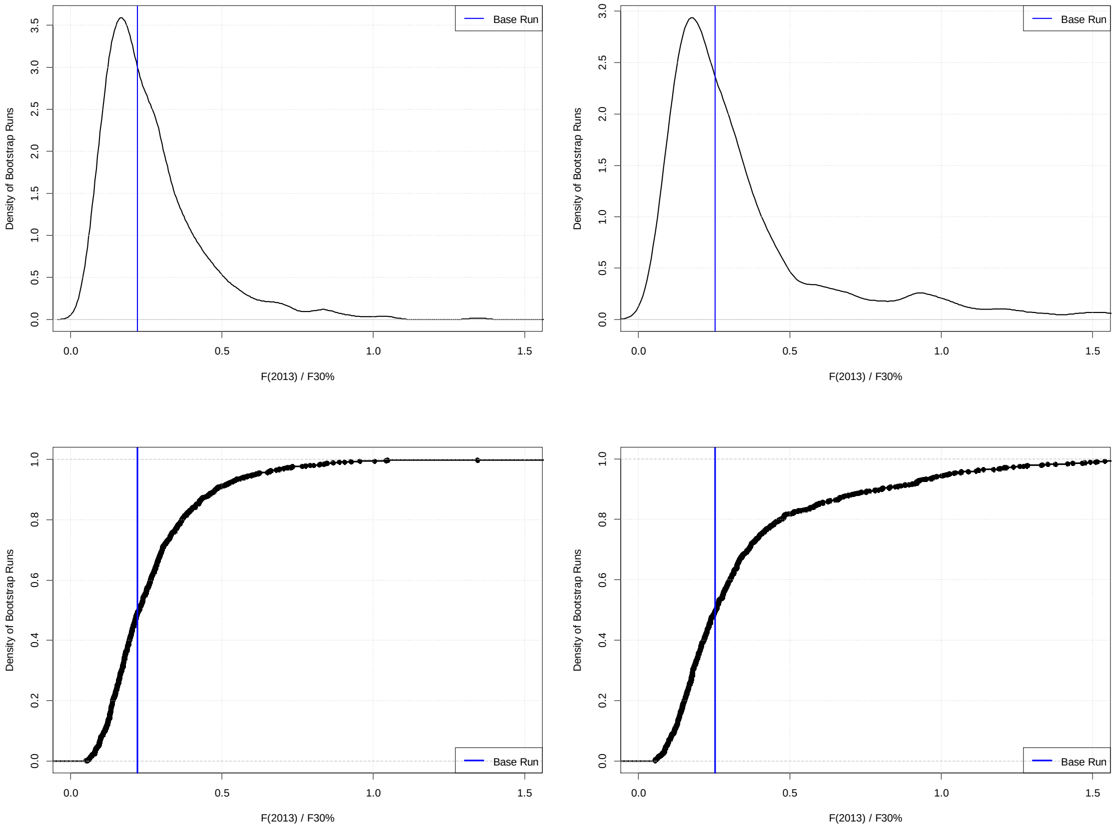


Figure 8.3.2.10. The density plot (above) and cumulative density plot (below) for terminal year fishing mortality at age-2 (left panels) and age-3 (right panels) over the ***$F_{15\%}$*** threshold benchmark across the base run and MCB runs.

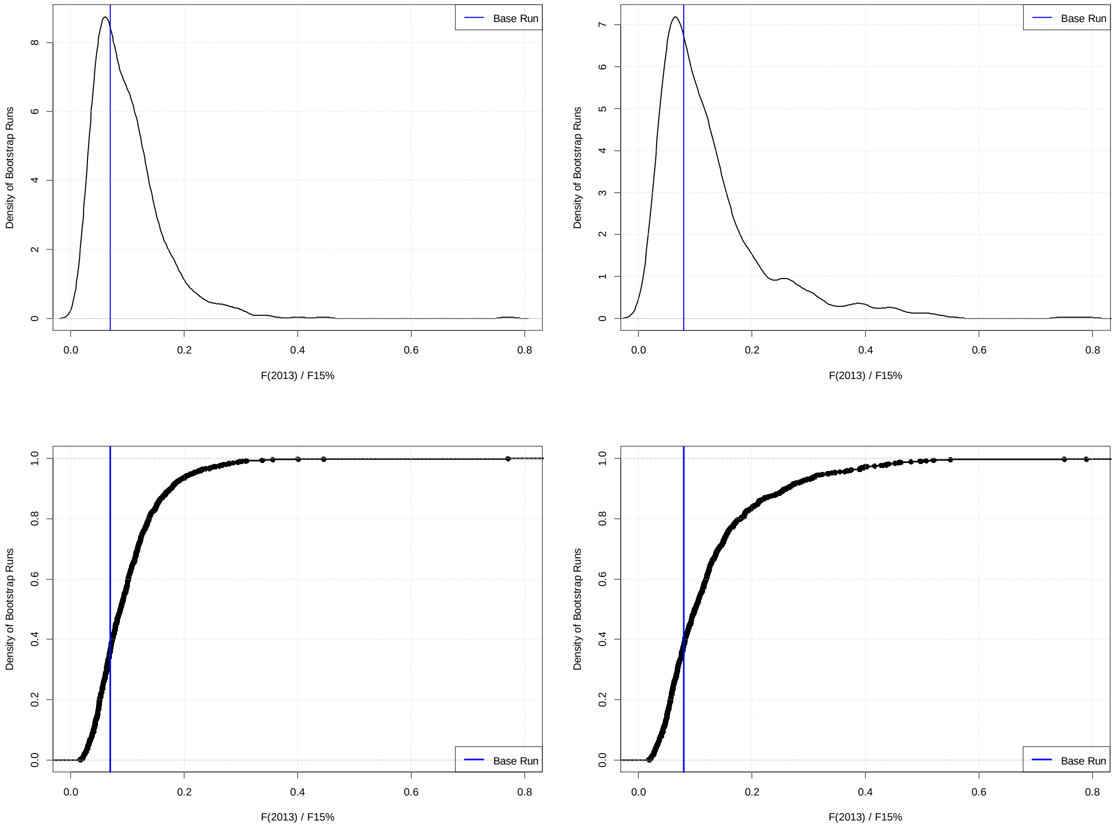
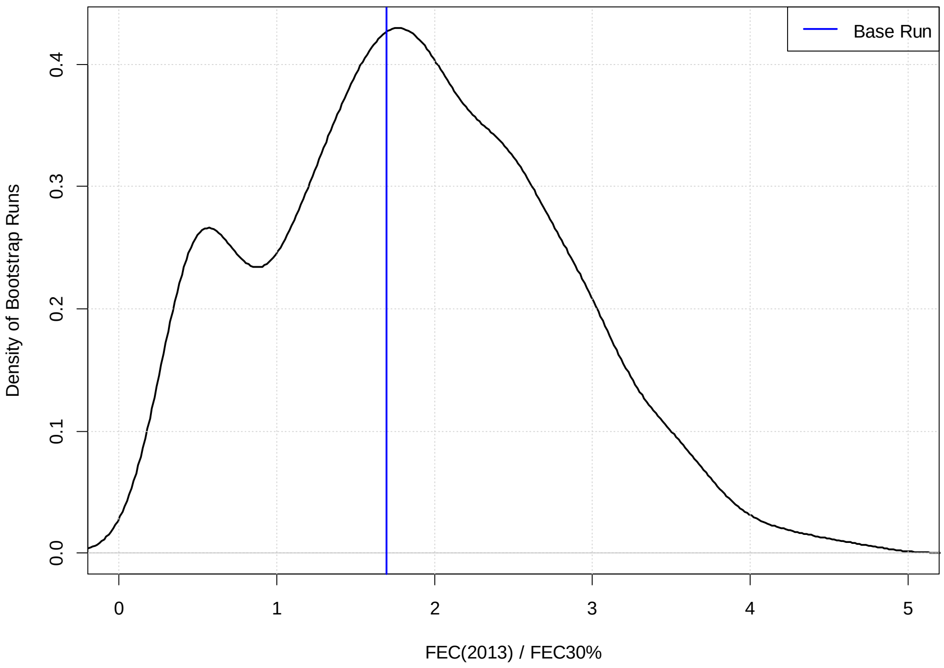


Figure 8.3.2.11. The density plot (above) and cumulative density plot (below) for terminal year fecundity over the ***FEC$_{30\%}$*** target benchmark across the base run and MCB runs.



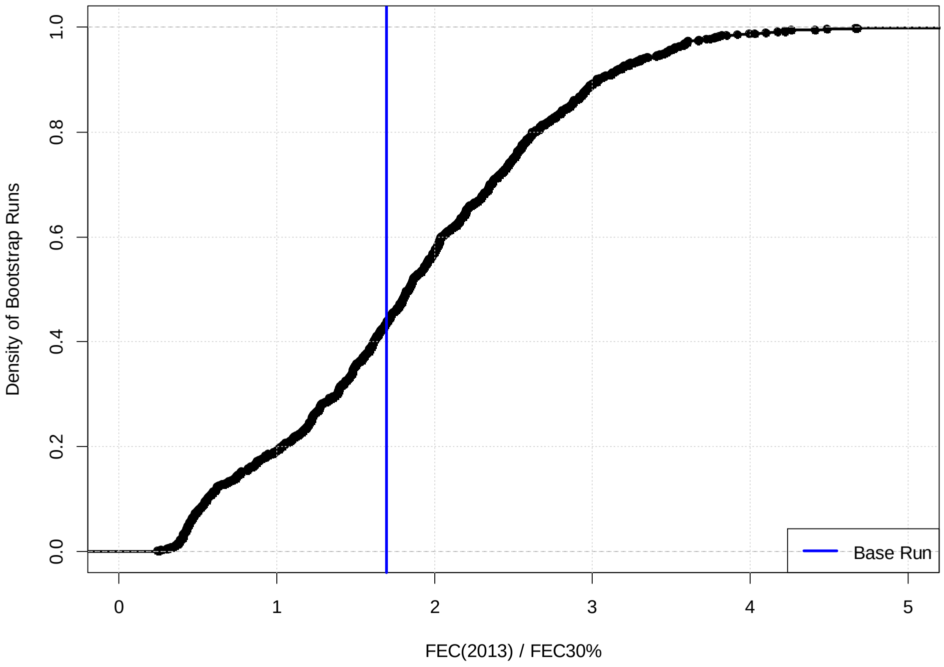
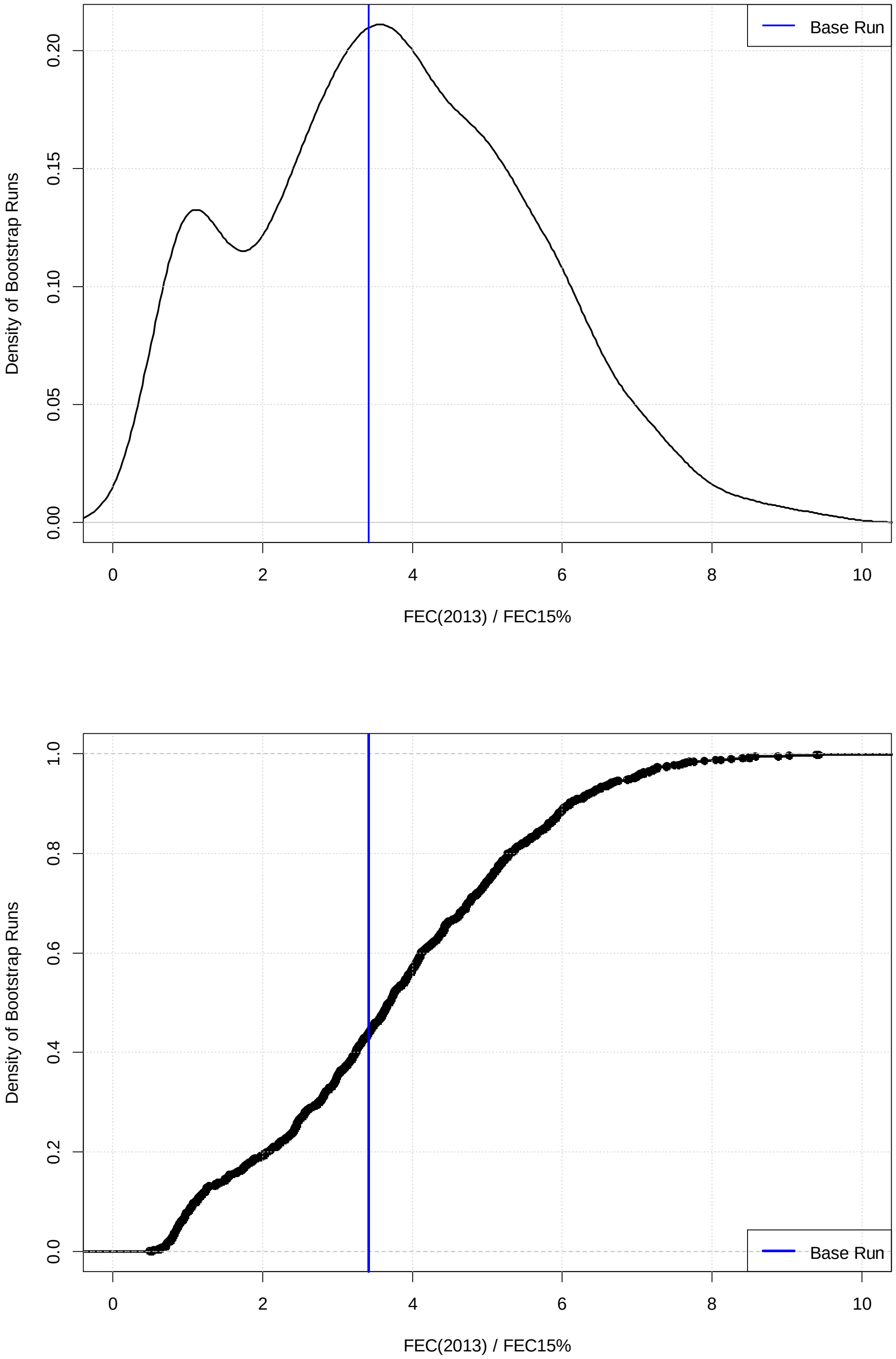


Figure 8.3.2.12. The density plot (above) and cumulative density plot (below) for terminal year fecundity over the ***FEC*$_{15\%}$** threshold benchmark across the base run and MCB runs.



INTRODUCTION

Background

In 2006 the Expanded Multispecies Virtual Population Analysis (MSVPA-X) was developed and peer reviewed to investigate the potential of multi-species management (Garrison et al. 2010, NEFSC 2006). The 2006 base run utilized the best available single-species assessment and diet data for important predator (striped bass, bluefish, and weakfish) and prey (menhaden, other prey) species for the period 1982–2002 from the mid-Atlantic region. An update occurred in 2008 where all data sources were updated through 2006 (ASMFC 2008). The MSVPA-X was partially updated in 2009 and 2012 with new predator and menhaden input data in preparation for the 2010 and 2012 menhaden assessments. This report details how all data sources were updated through 2012 and model configuration was revised in preparation for the 2014 menhaden benchmark.

Overview of changes to base run configuration

Prey length frequency

Length frequencies and size ranges of all of our prey items were updated. Within a prey group, the length frequency of each taxa were averaged together weighting by the relative biomass of each taxa within the model domain. Following the methods described in Garrison and Link (2004) and after reviewing MSVPA visual basic code, we fit a beta distribution to all updated length frequency data (Table 1a; Figure 1). To be consistent with MSVPA code, length data were rounded to the nearest whole centimeter before fitting. The updated prey length frequency curves were substantially different from the 2012 MSVPA, primarily due to changes in prey group membership (Table 1b; Figure 2)

Predator size selectivity

All predator size selectivity parameters were updated following the methods described in Garrison and Link (2004) and Dean (2012). Briefly, size selectivity parameters were developed by fitting a beta function to the frequency distribution prey/predator length ratios, following the methods of Garrison and Link 2004 (Table 2; Figure 3). The Northeast Fishery Science Center’s (NEFSC) Food Habits Database (FHDB) was used to estimate parameters after unidentifiable prey items were removed from the database [specifically, “animal remains,” “boney fish unclassified,” “fish unclassified,” and empty cells (no identification at all)]. Unlike previous updates where parameters were estimated for various size categories of predators (e.g., small, medium, and large predators), for the 2014 update we combined all sizes of predators when estimating selection parameters for parsimony and due to concerns related to low sample sizes for some predator size classes (Figure 4). A review of the literature also suggested that combining all sizes of bluefish and weakfish was appropriate (Garrison and Link 2000).

A comparison of size selectivity parameters and curves used in the 2012 and 2014 updates are provided in Table 2 and Figure 4, respectively. Observed and fitted prey predator ratios for the newly estimated selectivity parameters are provided in Figure 3.

An alternate method of estimating size selection parameters were explored that used literature-reported prey predator length ratios; however, these data proved to be limited in scope and were not available for all predator species. Furthermore, none of the literature reported data were in a format that could be easily used by the MSVPA, which requires the beta distribution.

Prey preference

All prey type preferences (prey preferences) were updated following methods described in NEFSC (2006) and Dean (2012) (Appendix 1 of this document) and see Figure 5. Early runs used prey preferences estimated exactly as described in NEFSC (2006) and Dean (2012); however, the prey preferences yielded predicted diet compositions with unrealistically high levels of benthic invertebrates (BI) and macrozooplankton (ZP) (Figure 6). This resulted from a combination of changes to 1) prey size distributions and predator size selectivity, and the scale of BI and ZP biomass available (Figures 7 and 8). Previous estimates of predator size selectivity effectively removed BI and ZP from the diets of older and larger predators (Figure 9, Appendix 2), whereas the updated size selectivity curves indicated that at least some portion of the BI and ZP biomass was selectable by our larger predators (this was corroborated by a review of predator diet studies). Given that our modeled prey field was dominated by BI and ZP (Figures 8 and 9), even a low spatial overlap and prey preference values resulted in predicted diets with very large fractions of BI and ZP, compared to the average observed diet. Based on these results, we developed a minimum electivity below which prey preference was set to zero (effectively removing them from the predicted diet). In most cases, very low electivity values were derived from only a few observations of a particular diet item and often comprised a very small fraction of the observed diet. However, because the MSVPA uses the rank of the prey electivity values to calculate an index of "general vulnerability" (as opposed to the actual electivity values), an electivity of 0.00000001 will yield the same contribution to the predicted diet as an electivity of 0.01, as long as they are the same rank. This causes prey items that are found in trace amounts in observed diets (and therefore have a positive non-zero electivity value) to be amplified in the predicted diet composition. The minimum electivity cutoffs are an attempt to counteract this bias.

The cutoffs were as follows:

Predator	Electivity cutoff value
Bluefish	0.004
Striped bass	0.003
Weakfish	0.005

The values above are a reasonable compromise, whereas larger cutoffs resulted in capturing too many other prey species (including menhaden) and lower values resulted in not removing BI and ZP from larger predator diets.

Based on the details provided in Dean (2012) (Appendix 1 of this document), we also changed electivities from which our MSVPA prey preferences are calculated. In previous iterations of the MSVPA, type preferences relied on a partially- or nonintersecting set of prey species in the stomachs of predators versus prey species in the environment. For example, in previous MSVPA iterations, type preference for medium forage fish compared the prevalence of river herring, hakes, sandeels, gadids, flounders, mackerel, skates, and other species in the diet of our predators to the availability of squid and butterfish in the environment (see Dean 2012 for more details). For the 2014 update, we rectified this mismatch when developing prey types and compared exactly the same set of prey species in the stomachs of predators and prey species in the environment.

DATA INPUT AND MODEL PARAMETERIZATION

Atlantic menhaden

Commercial Landings and Catch-at-Age (CAA[1])

Reduction fishery: Reduction fishery CAA was updated in the MSVPA-X through 2013 (ASMFC 2014). Landings from the reduction fishery have been provided to and summarized by the NMFS Beaufort Laboratory since 1955. The Beaufort Laboratory has also conducted biological sampling for the reduction fishery since 1955, based on a two-stage cluster design. This sampling is conducted over the range of the fishery, both temporally and geographically. Sampling protocols and estimation of CAA is described in the benchmark stock assessment report for Atlantic menhaden.

Bait fishery: Bait fishery CAA was updated in the MSVPA-X through 2013 (ASMFC 2014). Landings from the bait fishery have been provided by the individual coastal states since 1985 and from the ACCSP database prior to 1985. Sampling protocols and estimation of CAA are described in the benchmark stock assessment report for Atlantic menhaden. Because sampling is much less intense than for the reduction fishery, estimated catch-at-age for the bait fishery is subject to greater uncertainty.

Size and weight at age

The size and weight at age were calculated for January 1st for inclusion into the MSVPA-X (ASMFC 2014). Cohort based biological samples were used to estimate cohort based annual growth parameters. These yearly parameters were then used to provide age and time varying size and weight at age. See the current Atlantic menhaden stock assessment report for a more detailed description of the methods.

Recruitment index

The recruitment index included in the MSVPA was different from the recruitment index included in the final base run of the Atlantic menhaden assessment. However, the indices provided for use here and those in the base run are highly correlated and provide the same overall information. From 1987-2012, a composite index based on aerial extent of each individual index's sampling frame was included (see section 5 of ASMFC 2014). For 1982-1986, a recruitment index based only on data from the MD striped bass seine survey was included. These data were the only recruitment data available for those years.

---

[1] CAA of age 0 Atlantic menhaden in 2011 was 0 fish. This created convergence problems for the MSVPA and so we set CAA of age 0 to 0.05 million fish in 2011, the smallest value that allowed the MSVPA to converge.

The selectivity for these indices was fully selected at age-0 and not selected for any other age.

Adult indices:

Two adult indices of abundance were included in the MSVPA. Both of these indices were the same as those included in the base run of the Atlantic menhaden stock assessment (see section 5 of ASMFC 2014). Specifically, a southern adult index (SAD) included the years 1990 to 2012, and a northern adult index (NAD) included the years 1982-2012. In the assessment, the selectivity for these indices was estimated. Based on that estimation, the selectivity for the indices in the MSVPA was fully selected for age-1 for the SAD and fully selected for age-2 for the NAD.

Striped bass

Striped Bass are modeled as an age-structured predator in the MSVPA-X. Catch-at-age, weight-at-age, and tuning indices for striped bass used in this update of the MSVPA-X were taken from the 2013 ASMFC striped bass benchmark assessment (ASMFC, 2013; NEFSC 2013a).

Catch-at-age

Catch-at-age was estimated using standard methods (ASMFC 2013). Commercial landings-at-age were estimated by applying corresponding length-frequency distributions and age-length keys to the reported number of fish landed by the commercial fishery in each state. Length-frequencies of recreational landings were based on a combination of Marine Recreational Fisheries Statistics Survey (MRFSS) length samples and volunteer angler logbooks. State specific age-length keys were applied, where possible, to length frequencies to estimate number of fish-at-age landed by the recreational fishery. Age composition of the recreational discards was estimated using lengths available from volunteer angler logbooks and American Littoral Society data. State specific methods for estimating age composition of commercial landings, recreational landings, and recreational discards are provided in individual state compliance reports to ASMFC.

Annual weight- and size-at-age

Catch mean weight at age data, which is used to calculate total biomass and spawning stock biomass, was calculated for the period 1998-2002 using all available weight data from MA, NY, MD, VA, NH, and CT (1998-2001) and adding data from RI and DE in 2002 (NEFSC 2008). For 2003-2012, mean weights at age for the 2003-2012 striped bass catches were determined as a result of the expansion of catch and weight at age. Data came from Maine and New Hampshire recreational harvest and discards; Massachusetts recreational and commercial catch; Rhode Island recreational and commercial catch; Connecticut recreational catch; New York recreational catch and commercial landings; New Jersey recreational catch; and Delaware, Maryland, Virginia, and North Carolina recreational and commercial catch. Weighted mean weights at age were calculated as the sum of weight at age multiplied by the catch at age in numbers, divided by the sum of catch at age in numbers. Mid-year weights and sizes at age were converted to January 1st estimates using the NOAA Fisheries Toolbox Rivard calculator (NOAA 2014).

Spatial Distribution

Previous iterations of the MSVPA used total harvest (commercial + recreational) to represent the seasonal and spatial distribution of striped bass along the Atlantic coast. Several shortcomings of this approach were acknowledged during the update process: 1) commercial harvest is a poor indicator of distribution due to seasons, quotas, moratoria and size limits; 2) total harvest does not include information on juvenile fish (sub-legal discards), which have a different spatio-temporal distribution than adults; and 3) it is inappropriate to combine total harvest by weight and proportions-at-age by numbers.

For this update, the spatial distribution of striped bass was described using MRIP estimates of total recreational catch (A+B1+B2) for the Atlantic coast for the period 1981-2012. Catch was assigned to region and season based on the sampling wave and state (see Table D.28 NEFSC 2006b). An alternate analysis that incorporated MRIP estimates of fishing effort was also evaluated but discarded; the seasonal and spatial patterns in recreational CPUE were similar to total catch, with the exception of the Gulf of Maine in winter (Season 1), where CPUE was much greater than total catch. It was believed that this discrepancy was caused by high catch rates on non-migratory "holdover" populations of striped bass in isolated locations and did not indicate that a significant portion of the population resided in the GOM in winter. As such, total recreational catch was used to represent spatial distribution instead of CPUE.

Tuning indices

States provided age-specific and aggregate indices from fisheries-dependent and fisheries independent sources that were assumed to reflect trends in striped bass relative abundance. All juvenile abundance indices included in the 2013 striped bass update were included in the MSVPA-X. Young of year (age-0) indices included those from Maryland, Virginia, New Jersey, and New York. Juveniles (age-1) indices were available for Maryland and New York. Adult age specific indices included the New York ocean haul seine (ages 2-13), New Jersey trawl (ages 2–13+), Delaware River electrofishing spawning stock indices (ages 2–13+), Maryland spawning survey (ages 2 – 15+), and Virginia poundnet (ages 1-13). A number of indices that were used in the past were dropped in this update due to quality consideration or length of the time series.

Natural mortality

Striped bass natural mortality was updated for the MSVPA to be consistent with the single species assessment. The MSVPA requires natural mortality for all ages (0+), while the single species assessment only models age 1+ abundance. Natural mortality for age 0 striped bass was set equal to that of age 1 natural mortality:

Age	0	1	2	3	4	5	6	7+
M	1.13	1.13	0.68	0.45	0.33	0.25	0.19	0.15

Weakfish

Catch-at-age

Weakfish are modeled as an age-structured predator in the MSVPA-X. Catch-at-age data were supplied either individually by state, or by estimating CAA from length-frequency data and applying regional length-weight and age-length relationships as appropriate (ASMFC 2006, Part A; NEFSC 2009). For the SARC-reviewed MSVPA-X model (NEFSC 2006), the fishery CAA matrix included commercial and recreational landings, and recreational discard estimates. Commercial discard estimates were not included in the CAA matrix until the 2008 MSVPA-X update (ASMFC 2008). For this update, CAA again includes removals from all four sectors (commercial and recreational harvest and discards) covering the period 1982 to 2012 for ages 1 through 6+ (Table 4).

A benchmark stock assessment for weakfish in 2009 revised and updated estimates of harvest at age for the period 1981 to 2006 (Table 4; see NEFSC 2009 for details). Recent (2007-2012) recreational harvest estimates and CAA were calculated as in the 2009 stock assessment; however, because of some changes in fishery regulations and data availability, commercial data were treated using slightly different methods than in the past. For the SARC review and 2008 update, commercial harvest weight was converted to numbers at size using state-year-season-gear specific biological samples where available. Recently, population declines and regulation changes have severely limited weakfish harvest, and the number of biological samples has dropped dramatically as a result. Therefore, harvest weight from 2008-2012 was converted to numbers at size using region-wide sample data (region-year-season). Commercial discards for 2008-2012 were calculated using multi-year ratios from the 2009 stock assessment for appropriate gear-species combinations, but implementation of trip limits in 2010 required calculation of additional discards for that year. The NMFS Commercial Fisheries Database System (CFDBS) was queried for trips that landed weakfish from 2005-2009. The trip limit from 2010 was applied to these trips to estimate harvest had the trip limit been in place in those years. The ratio of "restricted" 2005-2009 harvest to report 2005-2009 harvest was calculated and applied to 2010-2012 reported harvest to estimate harvest if the trip limits had not been in effect. The difference between 2010-2012 reported harvest and estimated "unrestricted" harvest was added to the discard estimates developed from the multi-year gear-species combinations.

Annual weight- and size-at-age

As with the 2008 update, annual size- and weight-at-age estimates for this update were calculated using year-specific von Bertalanffy parameters developed by Vaughan (unpublished data) for the period from 1992-1999 based upon otolith data (Kahn 2002b and D. Vaughan, SEFSC, personal communication) and 2001 to 2012 (NEFSC 2009; J. Brust, pers. comm.; Table 4). The 1992 estimates were applied for the period from 1982 to 1991. For 2000, estimates from 1999 and 2001 were averaged. All January 1st (cf mid-year) estimates were used in the MSVPA.

Tuning indices

The most recent weakfish stock assessment that uses VPA as the preferred method (ASMFC 2006) was tuned using fishery dependent CPUE from the federal recreational fisheries survey. A more recent weakfish assessment included additional indices for tuning the VPA, but VPA was not selected as the preferred assessment model (NEFSC 2009). The MSVPA update therefore uses only the recreational fishery dependent indices to tune the weakfish model. An age aggregated index of CPUE for ages 2+ was developed using catch (numbers) per private/rental boat trip in the Mid-Atlantic region. The Mid-Atlantic region is the center of the weakfish stock, and the private/rental sector is a highly mobile fleet, able to maintain contact with the stock throughout the season (***i.e.*** the index is less likely to be biased by lack of spatial overlap during certain seasons; ASMFC 2006). In addition, age specific indices of harvest per unit effort (HPUE) were developed for ages 3-6+ using the same criteria (number per Mid-Atlantic private/rental boat trip; Table 4).

Spatial Distribution

Weakfish seasonal spatial distribution was updated using recreational CPUE data from the MRFSS/MRIP database. Because fishery independent data sources do not exist for weakfish in all regions and seasons a recreational fishery dependent) abundance index was used. Low abundance, and therefore catch rates, in recent years required the use of data from earlier years with higher abundance. Data from 1981 to 1989 were used because abundance was high and there were no regulations in place to constrain harvest. Validity of the results using these data is contingent upon the assumption that the recent declines affected all regions equally, and that length frequency of discards were the same as harvested fish. There are no data on discard lengths during this period, but the lack of minimum size regulations and the incidence of harvested fish at small (<10”) sizes tends to support this assumption.

The MRFSS database was queried for total catch (A + B1 + B2) in numbers by state, year, wave (2-month period), and fishing area (inland, ocean < 3 miles, ocean > 3 miles). Fishing effort, defined as the number of trips where weakfish was targeted or caught, was queried for the same strata from the ACCSP “recreational advanced” query tool to allow calculation of CPUE by state, year, wave, area. CPUE was then parsed to CPUE at length based on MRFSS length frequency data at the state, year, and wave level. Length frequencies at the area level are not reliable due to low sample size, so this method assumes length frequency was same for all areas within a state/year/wave cell. Data were subset by MSVPA region, and CPUE at size was estimated as the average across all years for each region and wave.

Raw biological data for weakfish from the 1980s is not available, so CPUE at size was converted to CPUE at age using multiyear age-length keys from recent years (2004 – 2007, NEFSC 2009). This assumes size at age has not varied considerably over time. ALKs were developed for early (Jan-June) and late (July-Dec) seasons and applied to the appropriate waves of CPUE at size (early = waves 2-3; late = waves 4-6) to estimate wave- and region-specific CPUE at age.

Average weight at age for the years 1981-1989 was taken from the 2009 weakfish stock assessment VPA input file to convert CPUE at age in numbers to CPUE at age in weight. Wave specific CPUEs were converted to MSVPA season CPUEs as Season 1 =

Wave 2; Season 2 = average W2 and W3, Season 3 = average W4 and W5, and Season 4 = average W5 and W6. Absolute CPUEs were then converted to relative CPUE (***i.e.*** standardized to 1.0) for each region, season, and age.

Bluefish

Bluefish in the MSVPA is modeled as a biomass predator. Biomass estimates for the 2012 update were taken from the 2011 bluefish stock assessment update (1982-2010 values from Table 11 in NEFSC 2011). January 1st biomass estimates for the 2014 update were taken from the 2013 bluefish stock assessment update (1982-2012 values from Table 10 in NEFSC 2013b).

In previous iterations of the MSVPA, a review of bluefish diet information based upon the NEFSC food habits database[2] indicated significant breaks in bluefish diets in three size/age classes: 10-30 cm (ages 0-1), 30-60 cm (ages 2- 3), and >60 cm (ages 4+) (ASMFC 2008); the size range of each of the age ranges was updated for the present assessment based on updated mean size at age data (NEFSC 2013b): 10-33 cm (ages 0-1), 33-55 cm (ages 2- 3), and >55 cm (ages 4+). These three size classes were used in the MSVPA-X model to account for ontogenetic changes in feeding selectivity and consumption parameters. A review of the literature for the present update suggested that bluefish diet might not change as notably as initially suspected (Figure 2 in Garrison and Link 2000), but the age groupings were nonetheless retained. Predator size selection in 2014 was updated using all sizes of bluefish (Garrison and Link 2000).

The proportion of the total biomass in each age class was estimated from the age-specific ASAP biomass estimates from the 2013 bluefish stock assessment update (Table 10 in NEFSC 2013b; i.e., for each of the three size classes, the sum of annual biomasses within the size class ÷ total biomass across all years and ages). For the 2014 update, these input values were: Size 1 = 0.043; Size 2 = 0.149; Size 3 = 0.807.

Spatial Distribution

Spatial and temporal distribution of bluefish was determined using estimates of weight per unit effort from the MRIP, including Type 9 B2 records. The availability of discard length frequency data limited the time frame for this analysis to 2005-2012, inclusive. Due to limited discard length frequency data in season 1 (only 1 fish was measured), we applied season 1 + season 2 discard length frequencies to season 1 B2 numbers. Seasons and MRIP wave were connected as follows:

Season	MRIP wave
1	1 & 2*0.5
2	2*0.5 & 3
3	4 & 5*0.5
4	5*0.5 & 6

---

[2] http://www.nefsc.noaa.gov/pbio/fwdp/databases.html#survey

where, for example, 2*0.5 indicates that ½ of the catch of wave 2 was assigned to season 1, and ½ was assigned to season 2. Catch was assigned to Chesapeake Bay as follows: all catch in waters classified as Chesapeake Bay, inland Virginia, and inland Maryland.

Numbers at length were converted to weight at length via seasonal length-weight conversion coefficients from the NEFSC bottom trawl (spring, applied to seasons 1 & 2: a = 0.00001017208, b = 3.031723; fall, applied to seasons 3 & 4: a = 0.00001388681, b = 2.994005). Ages for each of three size classes were assigned based on seasonal mean sizes at age:

Size	Age	Season 1 & 2 size range	Season 3 & 4 size range
1	0 & 1	≤ 33 cm	≤ 37 cm
2	2 & 3	34-55 cm	38-57 cm
3	4+	> 55 cm	> 57 cm

Effort was used for all trips where the angler identified bluefish as their primary or secondary target for the trip.

Other prey (non-menhaden)

Zooplankton

The coastwide biomass of macrozooplankton was previously estimated by taking the unweighted average copepod density of Chesapeake, Delaware and Narragansett Bays (Monaco and Ulanowicz 1997) and extrapolating to the total area of each region. By assuming a single mean density over the entire model domain, this method did not provide a very informative estimate of spatial overlap, nor did it yield a realistic measure of copepod availability for calculating prey preference. Furthermore, the only taxon represented in Monaco and Ulanowicz (1997) were copepods, despite being compared to the prevalence of shrimps, euphausiids, mysids, etc. in the diet data.

Because of these discrepancies, the biomass of zooplankton here are described using the MARMAP/ECOMON shelf-wide plankton surveys, which provided estimates of zooplankton density across a wide range of taxa by year, season, and region (Table 5). These surveys operate in all of our regions except for the Chesapeake Bay. Fortunately, the Chesapeake Bay Program conducts plankton sampling throughout the bay and from these data a single annual zooplankton density of 10.3 t/km^2 was used represent the biomass of zooplankton in this region (Christensen et al. 2009). The following taxonomic groups were included in this prey category: copepods, euphausiids, mysids and amphipods. Care was taken to include the same taxa in diet data as with the estimate of biomass.

The size distribution of this prey group was estimated by fitting symmetric triangle distributions to literature values of the minimum and maximum size of each of 14 primary species. These triangle distributions were then averaged together, weighting by the relative abundance of each species from the MARMAP/ECOMON dataset.

Benthic invertebrates

In previous iterations of the MSVPA, there were three primary taxa included in this prey category: isopods, polychaetes, and amphipods. For this update, amphipods were moved to the Zooplankton category because those datasets were thought to be more representative of the amphipod biomass available. Regional density estimates for the remaining benthic invertebrate taxa (isopods and polychaetes) were developed from a systematic benthic sampling program of the U.S. Atlantic continental shelf described in Wigley and Theroux (1981) and Theroux et al. (1998). While these estimates of benthic invertebrate biomass are based upon several decades old data, there is not a more recent broad scale estimate of benthic biomass available over the U.S. Atlantic continental shelf. The size distribution of this prey category was estimated by fitting symmetric triangle distributions to the minimum and maximum sizes of the most common taxa observed. These triangle distributions were then averaged together, weighting by the relative abundance of each taxa in the model domain (Table 5).

Benthic crustaceans

This group includes blue crab, American lobster, rock crab, and Jonah crab. These species make up a small, but consistent, proportion of the diet of striped bass, bluefish, and weakfish (NEFSC 2006). In the 2014 base run, revised estimates of total annual total benthic crustacean biomass were obtained by summing estimates for all four species (Table 5).

<u>Blue crab:</u> Blue crab population estimates were available only for the largest, commercially exploited populations of blue crab in Chesapeake Bay, Delaware Bay, and North Carolina. Estimated biomass was summed across all three areas. Blue crab found in predator stomachs do not exceed the size of approximately 60 mm (R. Latour, VIMS ChesMMAP, personal communication); therefore, only total biomass of blue crab <=60 mm in size was included in the analysis (Table 5).

Annual estimates of absolute abundance of age 0 (<60 mm carapace width) blue crab in Chesapeake Bay were obtained from MD Department of Natural Resources (personal communication with Glenn Davis) and are based on winter dredge blue crab survey, which is conducted annually by MD DNR and Virginia Institute of Marine Science (VIMS) since 1990. Survey details are provided in Sharov et al. (2003). Carapace width - weight relationship for blue crabs reported in Sharov et al. (2003) was applied to juvenile size frequency distribution to estimate average weight (grams) of age 0 crab. Average weight was multiplied by estimate of absolute abundance of Age 0 crabs at the start of the year to arrive at biomass estimate of Age 0 crabs. Relative changes (%) in age 0 abundance in MD DNR blue crab trawl survey by quarter were used to estimate quarterly biomass as a product of age 0 crab biomass at the start of the year and the % of age 0 abundance in trawl survey in each quarter relative to the abundance in the first quarter.

For Delaware Bay, estimates of recruit biomass (<120 mm crabs) were obtained from the 2013 blue crab assessment for Delaware Bay (Wong 2013). This assessment was based on a catch-survey model (Collie and Sissenwine 1983), incorporating observation and process error and producing annual estimates of absolute abundance, biomass, and fishing mortality rates from 1979 through 2013. An average size frequency distribution from the Chesapeake Bay was applied to Delaware Bay recruit estimates to obtain biomass of crabs <=60 mm carapace width. Quarterly estimates of biomass were derived by applying quarterly percent biomass distribution derived for the Chesapeake Bay.

Stock assessment of blue crab in North Carolina was conducted by Eggleston et al. (2004). A Collie - Sissenwine catch survey model was used to estimate absolute abundance of recruits (CW<127 mm) and post-recruits (CW=>127 mm). Total abundance estimates for 1988-2002 were distributed by 10 mm size groups using an average size frequency distribution observed in Chesapeake Bay. Mean weights at size were applied to number of crabs per size group to produce biomass by size. No stock assessment was completed between 2003 and 2013. Total population biomass estimates for these years were approximated by dividing the total annual harvest by the average exploitation rate observed in 1989-2002 period (0.66). Total annual population biomass was multiplied by the average percent (11%) of age 0 biomass relative to the total population biomass estimated for the Chesapeake Bay to arrive at age 0 biomass in NC. Quarterly distribution of age 0 biomass was completed using percentages estimated for the Chesapeake Bay.

Lobster: Abundance estimates for lobsters were obtained from the 2009 American lobster stock assessment (ASMFC 2009). This assessment used a statistical length-, sex-, and season-structured model to estimate recruitment, abundance, and biomass of lobster 53-227 mm carapace length in each of three stock units (Gulf of Maine, Georges Bank, and the portion of the range south of Cape Cod). Diet data indicated that lobster <60 mm are primarily found in striped bass stomachs; however, the lobster assessment does not estimate abundance of animals <53mm. Therefore, several adjustments were made. First, the estimate of total abundance of lobster in the 53 and 58 mm carapace length bins (≥53 mm and <63 mm) in each sex and season was multiplied by the weight of lobster by size bin, sex, and stock area to obtain a base estimate of lobster biomass in the two smallest assessment model length bins. Biomass estimates were then down-weighted by the proportion of lobster biomass in the NEFSC trawl survey that was caught inside vs. outside the MSVPA model area (~75%). Only data from years prior to the vessel change in 2009 were used. Biomass estimates were then inflated by the proportion of lobster biomass in the NEFSC spring and fall trawl surveys caught inside the MSVPA area that were less than 53 mm CL to account for the portion of the lobster stock too small to estimate by the stock assessment (~22%). Finally, total biomass of males and females in each season were summed across stock units (Table 5).

Jonah Crab: In order to develop spatial and temporal overlap estimates among Jonah Crabs (JC) and predators, a matrix of proportional biomass by region and season was developed. We elected to prune benthic crustacean (BC) biomass to include only BC biomass actually available to our predators[3]. Based on a review of the FHDB and Figure 6 from Nelson et al. (2003), we estimated only BC biomass ≤ 6 cm.

We used two sources of data to estimate regional and seasonal JC biomass[4]. The NEFSC bottom trawl survey and NEAMAP. The spring NEFSC trawl (February through May, inclusive, but most data were from March and April) was used to characterize seasons 1 and 2; the fall survey (September through December, inclusive, but most data were from September and October) was used to characterize seasons 3 and 4. No adjustment was made to catches to account for the 2009 NEFSC vessel change (Miller et al. 2010). For NEAMAP, the April and May cruises were used to characterize seasons 1 and 2; September and October cruises were used to characterize seasons 3 and 4. Survey tow stations were assigned to MSVPA regions using GIS (by M Dean).

NEFSC swept area weight per unit effort (WPUE) estimates assumed a trawl swept area of $a = 0.0408$ km^2 (Rago and Sosebee 2011) and a gear efficiency of 100%. Total aggregate weight (all years, 1982-2012, combined) of the catch was apportioned among numbers at length using length-weight relationships from the NEFSC trawl (average of male and female and spring and fall estimates: $a = 0.000168$, $b = 2.8757$). This produced season and region specific WPUE/a estimates. Identical methods were applied to NEAMAP trawl data (all years, 2007-2013), except that we used an assumed trawl swept area of $a = 0.025$ km^2. Season-, region-, trawl-specific WPUE/a estimates were then averaged based on the number of tows in each season and region, the area of each region, and the number of years of data from each survey. Season and region weighted WPUE/a estimates were then multiplied by the area of each MSVPA region. For a more detailed summary of our approach, see Dean (2012). The proportion of biomass of JC by year and season is provided in Table 5.

In addition to spatial and temporal distribution, we also estimated a time series of seasonal biomass, required for the model run. Identical methods to those described above were used, with two exceptions: 1) estimates were year-specific (cf aggregate all years combined), and 2) given the differing periods of time over which the various surveys have been conducted, only the NEFSC trawl data were used, as it covers the entire 1982-2012 time series.

Rock Crabs: Identical methods to those provided above for JC were applied to rock Crabs (RC) with four exceptions or modifications. First, unlike JC, RC have been collected in Chesapeake Bay and so ChesMMAP data (2002-2012) were incorporated into the weighted average WPUE/a estimate. ChesMMAP data were apportioned into seasons as follows: March = season 1, April-June = Season 2, July-September = season 3, and October-November = season 4. Second, as noted above a time series of RC seasonal

---

[3] We could also have let the MSVPA's size selection capabilities prune out all unsuitable BC biomass. However, size selection in the MSVPA is predator- and not prey- specific, so size selection could have allowed for very large BC in the diet of our predators whereas the FHDB and literature shows this is not the case. Note that with our approach size selection is still applied to our BC biomass estimates.

[4] There are no records of JC being collected in the Chesapeake Bay (ChesMMAP).

biomass is also needed for the MSVPA; since RC are found in Chesapeake Bay (whereas JC were not), but we only have ChesMMAP data from 2002-2012, we used the mean seasonal biomass from ChesMMAP to fill the remainder of the time series in Chesapeake Bay (i.e., mean seasonal biomass from 2002-2012 was used to fill in 1982-2012 in Chesapeake Bay). This CB biomass was then added to the entire coastal estimate of seasonal biomass derived from NEFSC trawl data. Third, total aggregate survey-specific weights of the catch were apportioned among numbers at length using length-weight relationships from the NEFSC trawl for RC (average of male and female and spring and fall estimates: a = 0.0002170, b = 2.7222). Fourth, for the NEFSC trawl, factors of 3.343 and 2.511 were applied to convert spring and fall Albatross IV to Henry B. Bigelow catch numbers, respectively (Miller et al. 2010)[5]. The proportion of biomass of RC by year and season is provided in Table 5.

Benthic crustacean length frequency was estimated from rock and Jonah crabs only due to the limited length range of this prey category (1-6 cm, inclusive). We used seasonal biomass at size (1-cm bins from 1 to 6 cm) from the NEFSC bottom trawl for rock and Jonah crabs. Biomass at length was averaged across seasons and crab species, weighted by the average annual MSVPA total domain biomass estimates. The resulting length frequency is depicted in Figure 1.

Atlantic herring

Population size at age was made available via the 2012 SAW SARC benchmark report (NEFSC, 2012). This was then converted to biomass by 2 cm length bins using the same commercial samples to generate the catch-at-age matrix (ME DMR). To apportion biomass inside and outside the model's domain, as well as apportion biomass by model domain area and season, the NEFSC bottom trawl survey was used to first calculate swept area biomass in each area/quarter and year. Next, an average of that proportion was taken across years. Finally, the total yearly biomass was apportioned accordingly (Table 5). Because the NEFSC trawl survey occurs in quarters 2 and 4, proportions for quarter 1 and quarter 3 were borrowed from quarters 2 and 4 respectively.

Medium forage fish – butterfish, sand lance, scup, squids, and white perch

Butterfish (*Poronotus triacanthus*): The biomass estimates for butterfish were developed by taking the weight per tow from the NEFSC trawl survey (NEFSC, personal communication), and stratifying that data by year, season, and area (areas as defined in this document; Table 5). This was done for all stock areas with the exception of Chesapeake Bay. These stratified biomass estimates were then divided by the number of tows in that year in each area, multiplied by the assumed area of a tow (0.0408 km^2), and then that value was multiplied by the squared kilometers for each individual stock area.

Stock Area	Stock Area km^2
Gulf of Maine	79,741
Mid Atlantic	17,787
North Carolina	25,967

---

[5] Catches of JC were insufficient to estimate conversion factors for JC (Miller et al. 2010).

Chesapeake Bay	11,610
New England	15,266

This area swept value was then divided by 1,000 to convert from kilograms to metric tons (equation 1).

The Chesapeake Bay information was collected from the ChesMMAP trawl survey and stratified by year and season. The tow information was already calculated as an area swept calculation for each tow. The ChesMMAP survey began in 2002, so for years prior to 2002, the Chesapeake Bay information was calculated by determining an average proportion of catch by season between the Chesapeake Bay and the other stock areas from 2002 – 2012, and applying this proportion to the calculated total for the other stock area annual biomass estimates (equation 2). The biomass in the Chesapeake for 2002 through 2012 was calculated as noted above and per equation 1.

$$Area\ Swept\ Biomass = \frac{\left(\frac{\sum w_{sa,yr,season}}{tw_{sa,yr,season} * A_{tw}} * A_{sa}\right)}{1000} \qquad (1)$$

where $w_{sa,\,yr,\,season}$ = weight of the species in kilograms for a tow in a stock area (sa), year (yr), and season; $tw_{sa,\,yr,\,season}$ = number of tows in a given year, stock area, and season; A_{tw} = area of a tow in square kilometers (0.0408 km^2); A_{sa} = area of the stock area in square kilometers

$$AB\ Chesapeake_{1982-2001} = \sum AB_{sa,yr,season} * \frac{\sum_{2002}^{2012} \frac{\sum w_{CB,yr,season}}{\sum AB_{sa,yr,season}}}{11} \qquad (2)$$

where *AB Chesapeake* = the area swept biomass for the Chesapeake for the indicated years; $AB_{sa,yr,season}$ = area swept biomass for each stock area (Gulf of Maine, North Carolina, Mid Atlantic, and New England) in each year and season; $w_{CB,\,yr}$ = weight of the species in kilograms for the Chesapeake by year and season (calculated from weight of ChesMMAP tows times the total area of the Chesapeake)

Longfin squid (*Loligo pealeii*): The biomass estimates for longfin squid were developed by taking the weight per tow from the NEFSC trawl survey (NEFSC, personal communication), and stratifying that data by year, season, and area (areas as defined in this document). This was done for all stock areas with the exception of Chesapeake Bay. These stratified biomass estimates were then divided by a catchability (*q*) of 0.45 as in the 2008 MSVPA update. This *q* adjusted biomass was then divided by the number of tows in that year in each area, multiplied by the assumed area of a tow (0.0408 km^2), and then this value was multiplied by the squared kilometers for each individual stock area (See Butterfish section above). This area swept value was then divided by 1,000 to convert from kilograms to metric tons (equation 3; Table 5).

The Chesapeake Bay information was collected from the ChesMMAP trawl survey and stratified by year and season. The tow information was already calculated as an area swept calculation for each tow by the survey investigators. The ChesMMAP survey began in 2002, so for years prior to 2002, the Chesapeake Bay information was calculated by determining an average proportion of catch by season between the Chesapeake Bay and the other stock areas from 2002 – 2012, and applying this proportion to the calculated total for the other stock area annual biomass estimates (equation 2). The biomass in the Chesapeake for 2002 through 2012 was calculated as noted above and per equation 3.

$$Area\ Swept\ Biomass = \frac{\left(\frac{\Sigma \frac{w_{sa,yr,season}}{q}}{tw_{sa,yr,season} * A_{tw}} * A_{sa}\right)}{1000} \qquad (3)$$

where q = catchability value; $w_{sa,yr,season}$ = weight of the species for a tow in kilograms in a stock area (sa), year (yr), and season; $tw_{sa,yr,season}$ = number of tows in a given year, stock area, and season; A_{tw} = area of a tow in square kilometers (0.0408 km^2); A_{sa} = area of the stock area in square kilometers

Shortfin squid (*Illex illecebrosus*): The biomass estimates for shortfin squid were developed by taking the weight per tow from the NEFSC trawl survey (NEFSC, personal communication), and stratifying that data by year, season, and area (areas as defined in this document). This was done for all stock areas with the exception of Chesapeake Bay. After review of the filtered trawl survey dataset, it was found that there were no shortfin squid caught in the survey areas as defined in this document.

The Chesapeake Bay information was collected from the ChesMMAP trawl survey and stratified by year and season. The tow information was already calculated as an area swept calculation for each tow by the survey investigators. As was the case for the NEFSC trawl survey, no shortfin squid were caught by the ChesMMAP survey. Given that shortfin squid were not found in the two surveys used to account for this prey item, shortfin squid are not included as a prey item in the assessment.

Sand Lance (*Ammodytes americanus* and *Ammodytes dubius*): The biomass estimates (Table 5) for sand lance (American and northern sand lance combined) were developed by taking the weight per tow from the NEFSC trawl survey (NEFSC, personal communication), and stratifying that data by year, season, and area (areas as defined in this document). This was done for all stock areas with the exception of Chesapeake Bay. These stratified biomass estimates were then divided by a catchability (q = 0.0204 (Greenstreet et al 2006) value. This q adjusted biomass was then divided by the number of tows in that year in each area, multiplied by the assumed area of a tow (0.0408 km^2), and then this value was multiplied by the squared kilometers for each individual stock area (See Butterfish section above). This area swept value was then divided by 1,000 to convert from kilograms to metric tons (equation 3).

The Chesapeake Bay information was collected from the ChesMMAP trawl survey and stratified by year and season. The tow information was already calculated as an area swept calculation for each tow by the survey investigators. The ChesMMAP survey began in 2002, so for years prior to 2002, the Chesapeake Bay information was calculated by determining an average proportion of catch by season between the Chesapeake Bay and the other stock areas from 2002 – 2012, and applying this proportion to the calculated total for the other stock area annual biomass estimates (equation 2). The biomass in the Chesapeake for 2002 through 2012 was calculated as noted above and per equation 3.

Scup (*Stenotomus chrysops*): The annual biomass estimates for scup (Table 5) were developed by taking the estimated annual biomass from the 2012 update assessment for scup (Terceiro 2012). To then stratify this into seasons, stock areas, and years the weight per tow from the NEFSC trawl survey (NEFSC, personal communication) was used to develop stratified proportions of catch. These proportions were then applied to the annual biomass estimate from the stock assessment. This was done for all stock areas with the exception of Chesapeake Bay, where this same procedure was used but the proportions were developed from the ChesMMAP survey.

White Perch (*Morone americana*): No assessment of coastwide white perch abundance has been completed, and no fisheries-independent surveys covering the spatial domain of the MSVPA reliably catch white perch. Thus, white perch biomass (Table 5) could only be estimated by making assumptions regarding the rate of harvest producing the landings reported to the NMFS (NMFS 2014a and 2014b). With no coastwide estimate of harvest rate, the most parsimonious assumption was that the fishery harvested at a sustainable rate of 30%. Biomass $B_{whiteperch}$ was estimated as

$$B_{white\ perch} = harvest/0.30.$$

The seasonal spatial distribution of fishery harvest was assumed to be proportional to the seasonal spatial distribution of the population. Harvest statistics were obtained from NMFS fisheries statistics (NMFS 2014a and 2014b).

White perch proportional biomass-at-length estimates were calculated using von Bertalanffy growth model predictions of length at age, a length-weight conversion (Froese and Pauly 2000), and proportional numbers at age predicted by a simple population projection model,

$$prop\ B_{age} = \left(weight_{age} * N_{age-1} * e^{-\left(Z_{age-1}\right)}\right) / \sum_{\max age}^{1} weight_{age} * N_{age}.$$

Total mortality at age (Z_{age}) in the population projection model was the sum of age-specific Lorenzen (2005) M and the harvest rate described above.

Bay Anchovy

Biomass Estimates: An estuary and coastal biomass density (mt·km^{-2}) estimate was obtained for each season in all of the five MSVPA model regions. For the 2011 update of the MSVPA model, all estuary biomass densities were based on Chesapeake Bay values (Jung and Houde 2004) and all coastal densities were based on the New Jersey Ocean

Trawl Survey. In this iteration, each biomass estimate was derived from data specific to each MSVPA region, area (estuary or coastal), and season when available then extrapolated out to more accurate GIS-based estimates of size (km^2) for each estuary and coastal area. This is the most notable difference between the 2011 and 2014 calculations and using site-specific density estimates is considered an improvement over the previous method.

Biomass from all regions were based on fisheries independent surveys conducted in that region, except for Chesapeake Bay in which total biomass estimates were available in the literature (Jung and Houde 2004) and coastal Gulf of Maine in which no survey captured sufficient numbers of Bay Anchovy to be used. The raw biomass densities from each survey were divided by a catchability value q to obtain adjusted biomass densities. As an initial parameterization, a q of 0.1 was used for all inshore trawl surveys and a value of 0.01 for all surveys conducted in coastal waters. When data were unavailable for a particular season and region combination, it was estimated based on the relative densities observed across seasons from an adjacent region. Once a seasonal biomass density ($mt \cdot km^{-2}$) was determined for all region-area combinations, the densities were multiplied by area sizes to obtain absolute biomass (mt). The coastal and estuarine estimates for each region were then added together for total seasonal and regional biomass, which were then used to calculate the seasonal proportions of biomass in each region (Table 5).

In North Carolina, the estuary density was estimated from the NCDMF bottom trawl survey conducted in Pamlico Sound. The densities were simply the seasonal average of catch rates in all tows. The North Carolina coastal density was taken as the average seasonal biomass densities from SEAMAP (seasons 2-4), NEAMAP (seasons 2 and 4), and NEFSC (season 1) trawl surveys.

The Mid Atlantic estuary densities were derived from Delaware Bay Trawl and Delaware River Seine Surveys conducted by the NJDEP. Each of these surveys provided catch in numbers, which were converted to biomass based on the length frequency in each sample and a length-weight conversion equation (a=0.00436, b=3.18 from FishBase). For the trawl survey, density was calculated using an area swept of 3,234.365 m^2 assuming a trawl distance of 0.357 nautical miles and a headrope length of 4.8768 m. The coastal biomass estimates were based on monthly average biomass densities from the NJ Ocean Trawl Survey, averaged across available months in each season.

The estuary biomass estimate for the New England region was based on Connecticut surveys of Long Island Sound and available in the appendix of a performance report to the Federal Aid in Sport Fish Restoration grant F-54-R-32. The report provided the total weight (kg) of bay anchovy captured in all tows each year from 1999-2012, which were converted to biomass density by dividing by the number of tows each year and assuming an average area swept of 0.024 km^2 (also in SFR report). No seasonal data were available in the report therefore the annual estimate was adjusted by season based on the relative densities between seasons in the Mid-Atlantic region. That is, the seasonal estimates in New England estuaries varied according to the seasonal change in the Mid-

Atlantic, with an average equal to the annual density from the CT trawl survey. The coastal density was based on the biomass densities in the NEFSC trawl survey.

In the Gulf of Maine, bay anchovy are collected by the Massachusetts Division of Marine Fisheries trawl survey that has been conducted since 1978. On average, approximately 300 fish were estimated to be caught in each tow since 1978. This numerical density was converted to biomass density by assuming a body weight of 0.14 g (based on average length of 30 mm) and an area swept of 17,624 m^2. No seasonal estimates of catch rates were provided, therefore the average annual density estimate was converted to seasonal values based on the relative densities between seasons in the New England region. The only coastal survey in this region that captured bay anchovy was the NEFSC trawl survey, however it occurred in such low numbers that the survey was deemed to be uninformative. Therefore, the coastal biomass densities were assumed to less than the New England biomass in the same proportion as New England is lower than the Mid Atlantic. This was meant to account for the decline in bay anchovy biomass at the northern end of its range.

Biomass Indices: Seasonal biomass indices (combined over all regions) were developed by first standardizing each index (z-score transformation) and then averaging across the indices that were conducted in the same MSVPA region and area (estuary or coast). Grand estuary and grand coastal indices were generated by averaging across regions and then used to back fill missing years in the regional indices. The region-area specific indices were then scaled to a mean of 1 and multiplied by the region-area-seasonal biomasses calculated from the density measurements described above, using the same region-area index for each season. Because the survey indices and combined region-area trends were annual, the seasonal trends within a region and area differ only in the magnitude of biomass as calculated from density estimates. Total seasonal biomass trend in a region was the sum of estuary and coastal biomass trends. The total seasonal biomass over the model domain was the sum of biomass across regions within each season.

For North Carolina, the estuary index was the NCDMF Pamlico Sound trawl survey and the coastal indices included SEAMAP, NEAMAP, and NEFSC trawl surveys. In Chesapeake Bay, the VIMS trawl and seine surveys, MD juvenile fishes seine survey, and MD CBFI trawl and seine surveys were included. For the Mid-Atlantic region all estuary indices were from Delaware Bay or Delaware River and included the New Jersey Delaware River seine, NJ Delaware Bay trawl, DE midwater trawl, DE inland trawl, and DE estuary trawl surveys. The coastal surveys used in the Mid Atlantic were the NJ Ocean Trawl Survey, NEAMAP, and NEFSC trawl surveys. The CT Long Island Sound survey was the only estuary survey included for the New England region with the NEFSC and NEAMAP trawls used for the coastal area. Lastly, the MA trawl survey and NEFSC trawl survey were used as indices for the estuary and coastal area respectively.

Sciaenids

Spot and croaker were updated with new estimates through 2012 (Table 5). Total annual spot and croaker biomass estimates were summed to create the other prey class called sciaenids.

Croaker: Biomass-at-age and length-at-age estimates from 1991-2008 were obtained from updated assessment results (ASMFC 2010). Note these estimates do not include shrimp bycatch. The seasonal spatial distribution and proportional biomass at length for Atlantic croaker was estimated following the same methodology used for white perch (Table 5).

Spot: Methodology to estimate spot biomass (Table 5), spatial distribution, and proportional biomass at length followed that of white perch.

Predator diets

A review of published literature and survey datasets was conducted to achieve as complete dataset of diet composition as possible for the modeled predators. Over 500 diet composition records were assembled from 28 unique data sources, representing over 42,000 individual stomach samples (Figure 10). A database was created to house these data in a standardized format that automatically calculates average diet compositions for each predator size/region/season combination. Data sources were averaged together; weighted by the study area, number of years, and number of stomachs examined.

Temperature

Monthly average temperatures were obtained from buoy data along the U.S. Atlantic coast and locations in the Chesapeake Bay (http://www.ndbc.noaa.gov/to_station.shtml) through 2012. These averages typically include approximately 15 years of temperature observations. Seasonal averages were calculated for winter (Jan-Mar), spring (Apr-Jun), summer (Jul-Sept), and fall (Oct-Dec) in each of five regions (Gulf of Maine, Southern New England, Mid-Atlantic Bight, Chesapeake Bay, and North Carolina) and weighted by the relative distribution of predator biomass in each. For this update, data from seven buoys were used (Table 6); CHLV2, TPLM2, and FPSN7 had stopped recording since last update.

RESULTS

Striped bass

Overall total striped bass consumption increased as the striped bass population increased (Figure 11) and then remained stable but highly variable from about 1996 to the present. The same is true for consumption of menhaden in particular (Figure 12). Menhaden as a percentage of striped bass diet has increased slightly since about 2000 to about 16%, whereas prior to 2000, striped bass diet consisted on average of about 10% menhaden (Figure 11). The dominance of benthic invertebrates and macrozooplankton in the diet of striped bass diet (Figure 11) is due in large part to the model predicted diets of young striped bass ages 1-4. The numerical dominance of young striped bass combined with their predicted diet results in the patterns seen in Figure 11.

Estimates of menhaden consumption by striped bass decreased dramatically from the 2012 update (Figure 12). This reduction is in part due to a changed striped bass single species assessment and resulting biomass (Figure 13). In the most recent peer reviewed report (ASMFC 2013) population abundance at age, and overall population abundance and biomass changed from previous assessments. This change is reflected in the MSVPA-X as a reduction in consumption of menhaden by striped bass (Figure 12) and is a result of increased abundance of smaller striped bass, which have a lower propensity to consume menhaden (Figure 14). The decline in consumption of menhaden is also a result of updating predator size selectivities and prey length frequencies compared to the 2012 update (Figure 15).

Figure 14 shows reasonable agreement between striped bass diet predicted by the MSVPA and the diet seen in our diet data base (see Appendix 3 for season-, year-, and predator-age-specific model predicted diets). The largest difference is in the younger ages of striped bass (ages 1 through 4, inclusive), where menhaden is a fraction of striped bass diet relative to what is seen in the diet data. The large fractions of ZP and BI in the diets of age 7, 9, and 10 striped bass result from our electivity cutoffs (Table 3: and please see above).

Weakfish

Overall total weakfish consumption has declined since the start of the time series as a result of stock declines. Overall weakfish is not an important predator on menhaden (Figures 11, 12, and 16) due in part to the small population size and lack of consumption even at higher population levels (Figure 11). At present, weakfish have little influence on the menhaden population total M_2 (Figure 17).

Figure 18 shows that the MSVPA tends to underestimate menhaden in the diets of young weakfish and overestimate consumption in the diets of older weakfish (see Appendix 3 for season-, year-, and predator-age-specific model predicted diets). Part of this pattern is related to predator size selectivity. The electivity cutoffs (Table 3) we used did not capture macrozooplankton in the diets of weakfish and hence, given the dominance of ZP in the environment (Figure 7 and 8), ZP tended to dominate the diets. As weakfish grow, predator size selectivity begins to phase ZP out of weakfish diets, as other prey items of more suitable size (clupeids and bay anchovies for example) become more selectable (Appendix 2).

Weakfish consumption, like striped bass, also shows a change from the 2012 update of the MSVPA-X. In the 2012 update, an unrealistic drop in menhaden consumption by weakfish was seen 1988 to 1989. With this update it can be seen that consumption of menhaden by weakfish may have been over-estimated prior to 1988. This over estimation was in part resolved when updated weakfish size at age was corrected with the most recent information available (J. Brust personal communication; Figure 13). The overall effect of this correction was to reduce the historical removals of menhaden by weakfish to levels more in line with recent observations (Figure 12).

Bluefish

Bluefish, currently the only biomass predator in the MSVPA, shows a propensity to consume high amounts of menhaden particularly earlier in the time series due to high abundance (Figures 11 and 12). While consumption of menhaden by bluefish has declined over the time series, in part as a result of declining bluefish biomass, bluefish are still an important predator on menhaden. Overall bluefish has a higher impact of regulation of the menhaden population when compared to either striped bass or weakfish at present (Figure 17).

Bluefish biomass from about 2005 through 2012 has decreased relative to bluefish biomass over the same time period from our 2012 update (Figure 13); this lower bluefish biomass appears to have translated into lower consumption of menhaden over this same time period in the present update (Figure 12).

Figure 19 shows that, similar to weakfish, the MSVPA tends to underestimate menhaden in the diets of young bluefish and overestimate consumption in the diets of older bluefish. As with weakfish, part of this pattern is due to predator size selectivity. In the case of bluefish, our electivity cutoff (Table 3) captures menhaden for small (size 1 in Figure 19) bluefish, thereby excluding menhaden from size 1 bluefish diets. BI and ZP are also captured by the prey preference cutoff for all sizes of bluefish, thereby excluding them from bluefish diets. This is reasonably consistent with results from our diet data base (Figure 19). The length frequency of bay anchovies overlaps nearly completely with predator size selectivity of small bluefish and so bay anchovies become a large part of the predicted diet (especially in the absence of BI and ZP), which is in good agreement with our diet database. Moreover, the trend in the proportion of bay anchovies in the diets of all bluefish is, in general, in good agreement with our diet database. It is important to note that Figure 19 is an average diet overall years (31) and all seasons (4) used in the model. The MSVPA generates season and year specific diet compositions (i.e., 31 x 4 = 124 figures similar to the MSVPA predicted diet depicted in Figure 19; all 124 combinations for each predator are provided in Appendix 3); in general, where those season and year combinations align closely with the time period most representative of our average diet (Figure 19), there is good agreement between the MSVPA predicted diet and our diet database (this is true for striped bass and weakfish diets as well). Note too that the MSVPA predicted diet composition changes over time with changes in prey biomass (Appendix 3).

Atlantic menhaden

Over the model's time series, the MSVPA-X shows a decline in abundance of 0+ menhaden. This is in part due to the continued lower recruitment as first discussed in the previous update (ASMFC 2012).

Total population abundance (ages 1+) of Atlantic menhaden remained mostly unchanged in this update (Figure 20) with the notable exception of decreased abundances in the recent period. As always, estimates in the terminal year are the most uncertain. A retrospective pattern is not seen with this update, though retrospective variability is apparent (Figure 20) and highlights the uncertainty in the terminal year estimates of the population. These uncertainties are no doubt carried through to estimates of M_2 for menhaden.

When comparing M_2 from our 2012 and 2014 run some slight differences are seen. With this update M_2 is lower from about 1985-1996 and again in the most recent time period. This time period coincides with dramatic changes to menhaden consumption by our predators between the two updates (Figure 12). Overall, this update resulted in little net change in menhaden M_2 from previous updates.

It should be noted that trends in menhaden biomass, abundance, and fishing mortality estimated by this MSVPA update differ from the most recent estimates of menhaden abundance, biomass, and fishing mortality estimated by the single species base model, the Beaufort Assessment Model (BAM; ASMFC 2014). These differences are the result of single species modeling changes such as the inclusion of area-specific fleets, selectivity assumptions, and the inclusion of new, fishery-independent indices.

CONCLUSIONS

The final configuration of the MSVPA included such changes as updating spatial overlap, predator and prey population sizes, predator size selectivities, and type preferences. Before a final alteration to prey preferences, M_2 was unrealistically low (for example, M_2 on age 0 menhaden averaged approximately 0.2 over the times series). The very low M_2 was driven principally by our new predator selectivity curves that now captured BI and ZP for all ages of our predators – given the dominance of BI and ZP[6] in our prey field (Figure 7 and 8), the feeding model filled the diets of our predators with BI and ZP. Of note, we could not reproduce the predator selectivities used in prior runs of the MSVPA. As a reasonable next step we established an electivity cutoff below which we assumed prey preference = 0 (Table 3); this measure was designed to target BI and ZP, exactly the prey items that were excluding nearly all other prey from the diets of our predators. This single change resulted in an M_2 (and hence total M) that was similar to our 2012 estimates, more biologically realistic, and very similar to the M that was used in the final base run of the menhaden single species assessment (ASMFC 2014). Sensitivity runs that explored the impact of changing the electivity cutoff values and re-estimating predator size selectivities as a function of predator size category resulted in only small changes to M2 from our final MSVPA base run (i.e., M2 estimates from our final base run are robust to changes in predator size selectivity and electivity cutoff values). That is, from numerous model runs, two M_2 trajectories were apparent: 1) an unrealistically low M_2 or 2) a biologically sensible M_2 (and hence total M) very similar to that used in the final menhaden base run. All MSVPA runs fit into these two categories.

---

[6] The combined fraction of total biomass that consists of either BI or ZP remained very similar between the 2012 and 2014 updates, though, the fractions of these two prey groups reversed (Figure 8).

Because of this, the menhaden SAS concluded that the configuration of the BAM with these changes was preferred approach, and that the results of the MSVPA-X should be excluded as it was unable to capture these changes. In addition, a comparison of average *M*-at-age estimated by the MSVPA and that of life history-based *M* estimates (e.g., Lorenzen) were quite similar (ASMFC 2014). Therefore, M_2s from the MSVPA-X were not included in the final base run of BAM. However a sensitivity run with the output of the MSVPA-X was included in the assessment for comparison (ASMFC 2014).

REFERENCES

Atlantic States Marine Fisheries Commission (ASMFC). 2006. Stock assessment report for weakfish. Atlantic States Marine Fisheries Commission Stock Assessment Report.

____. 2008. Update of the Multispecies Virtual Population Analysis. Atlantic States Marine Fisheries Commission. 54p.

____. 2009. American lobster stock assessment report for peer review. ASMFC Stock Assessment Report No. 09-01 (Suppl.).

____. 2010. Atlantic croaker 2010 benchmark stock assessment. Atlantic States Marine Fisheries Commission Stock Assessment.

____. 2012. Atlantic menhaden stock assessment update. Atlantic States Marine Fisheries Commission Stock Assessment.

____. 2013. Update of the Striped Bass Stock Assessment using Final Data. October 2013. ASMFC Striped Bass Technical Committee. 74 p.

____. 2014. Atlantic menhaden stock assessment report for peer review. December 2014. ASMFC Atlantic menhaden Technical Committee.

Christensen, V., A. Beattie, C. Buchanan, H. Ma, S. Martell, R. Latour, D. Preikshot, M. Sigrist, J. Uphoff, C. Walters, R. Wood, and H. Townsend. 2009. Fisheries Ecosystem Model of the Chesapeake Bay: Methodology, Parameterization, and Model Exploration. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service. NOAA Technical Memorandum NMFS-F/SPO-106, 146 p.

Collie, J.S., and M.P. Sissenwine. 1983. Estimating population size from relative abundance data measured with error. Can. J. Fish. Aq. Sc. 40:1871-1879.

Dean, M. 2012. Input data for including spiny dogfish as a biomass predator in the MSVPA-X application for Atlantic Menhaden, a report to the ASMFC Multispecies Technical Committee (*Appendix A to this report*).

Eggleston D.B., E. G. Johnson. and J. E. Hightower 2004. Population Dynamics and Stock Assessment of the Blue Crab in North Carolina Final Report for Contracts 99-PEG-10 and 00-FEG-11 to the North Carolina Fishery Resource Grant Program, North Carolina Sea Grant, and the North Carolina Department of Environmental Health and Natural Resources, Division of Marine Fisheries. Department of Marine, Earth & Atmospheric Sciences. North Carolina State University Raleigh, NC 27695-8208

Froese, R. and D. Pauly, Editors. 2000. FishBase 2000: concepts, design and data sources. ICLARM, Los Baños, Laguna, Philippines. 344 p.

Garrison, L. P. and J. S. Link. 2000. Dietary guild structure of the fish community in the Northeast United States continental shelf ecosystem. Marine Ecology Progress Series 202: 231:240.

Garrison, L.P, and J.S. Link. 2004. "An expanded multispecies virtual population analysis approach (MSVPA-X) to evaluate predator–prey interactions in exploited fish ecosystems." Atlantic States Marine Fisheries Commission, Arlington, VA.

Garrison, L.P., J.S. Link, D.P. Kilduff, M.D. Cieri, B. Muffley, D. Vaughan, A. Sharov, B. Mahmoudi, and R.J. Latour. 2010. An expansion of the MSVPA approach for quantifying predator-prey interactions in exploited fish communities. ICES Journal of Marine Science 67:856-870.

Greenstreet, S.P.R, E. Armstrong, H. Mosegaard, H. Jensen, I.M. Gibb, H.M. Fraser, B.E. Scott, G.J. Holland, J. Sharples. 2006. Variation in the abundance of sandeels Ammodytes marinus off southeast Scotland: an evaluation of area-closure fisheries management and stock abundance assessment methods. ICES Journal of Marine Science 63:1530–1550.

Jung, S. and E.D. Houde. 2004. Recruitment and spawning-stock biomass distributions of bay anchovy in Chesapeake Bay. Fishery Bulletin, U.S. 102:63-77.

Kahn, D.M. 2002. Weakfish growth analysis, based on 2000 samples from point net and long haul seine in Chesapeake Bay and Pamlico sound. Report to the ASMFC Weakfish Technical Committee. 21 June 2002.

Lorenzen, K. 2005. Population dynamics and potential of fisheries stock enhancement: practical theory for assessment and policy analysis. Philosophical Transactions of the Royal Society B: Biological Sciences 360:171-189.

Miller, T.J., C. Das, P.J. Politis, A.S. Miller, S.M. Lucey, C.M. Legault, R.W. Brown, and P.J. Rago. 2010. Estimation of Albatross IV to Henry B. Bigelow calibration factors. NEFSC Ref Doc 10-05. 230 pp.

Monaco ME, Ulanowicz RE (1997) Comparative ecosystem trophic structure of three

U.S. mid-Atlantic estuaries. *Mar. Ecol. Prog. Ser.* 161: 239-254.

Nelson, G., B. C. Chase, J. Stockwell. 2003. Food habits of striped bass (*Marone saxatilis*) in coastal waters of Massachusetts. *Journal of Northwest Atlantic Fishery Science* 32:1-25.

Northeast Fisheries Science Center (NEFSC). 2006. 42nd Northeast Regional Stock Assessment Workshop (42nd SAW) stock assessment report, part B: Expanded Multispecies Virtual Population Analysis (MSVPA-X) stock assessment model. U.S. Dep. Commer., Northeast Fish. Sci. Cent. Ref. Doc. 06-09b; 308 p.

____. 2008. 46th Northeast Regional Stock Assessment Workshop (46th SAW) Assessment Report. U.S. Dep. Commer., Northeast Fish. Sci. Cent. Ref. Doc. 08-03a; 252 p.

____. 2009. 48th Northeast Regional Stock Assessment Workshop (48th SAW) Assessment Summary Report. US Dept Commer, Northeast Fish Sci Cent Ref Doc. 09-10; 50 p.

____. 2011. Bluefish 2011 stock assessment update. Coastal/Pelagic Working Group, National Marine Fisheries Service; 41 p.

____. 2012. 54th Northeast Regional Stock Assessment Workshop (54th SAW) Assessment Summary Report. US Dept Commer, Northeast Fish Sci Cent Ref Doc. 12-14; 40 p. Available from: National Marine Fisheries Service, 166 Water Street, Woods Hole, MA 02543-1026, or online at http://www.nefsc.noaa.gov/nefsc/publications/

____. 2013. 57th Northeast Regional Stock Assessment Workshop (57th SAW) Assessment Report. US Dept Commer, Northeast Fish Sci Cent Ref Doc. 13-16; 967 p. Available from: National Marine Fisheries Service, 166 Water Street, Woods Hole, MA 02543-1026, or online at http://nefsc.noaa.gov/publications/

____. 2013. Bluefish 2013 stock assessment update. Coastal/Pelagic Working Group, National Marine Fisheries Service; 38 p.

NMFS (National Marine Fisheries Service). 2014a. Commercial Fisheries Statistics. <http://www.st.nmfs.noaa.gov/st1/commercial>

NMFS (National Marine Fisheries Service). 2014b. Recreational Fisheries Statistics. http://www.st.nmfs.noaa.gov/recreational-fisheries/access-data

NOAA. 2014. Rivard weights calculation module of NOAA Fisheries Toolbox. http://nft.nefsc.noaa.gov/Rivard.html Accessed May 2014.

Rago, P., & Sosebee, K. 2011. Update on the Status of Spiny Dogfish in 2011 and Initial

Evaluation of Alternative Harvest Strategies. Mid-Atlantic Fishery Management Countil-Science and Statistical Committee.

Sharov, A. F. J. H. Vølstad, G.R. Davis, B.K. Davis, R.N. Lipcius and M.M. Montane. 2003. Abundance and exploitation rate of the blue crab (Callinectes sapidus) in Chesapeake Bay. Bull. Mar. Sci. 72(2) : 543 - 565.

Terceiro M. 2012. Stock Assessment of Scup (*Stenotomus chrysops*) for 2012. US Dept Commer, Northeast Fish Sci Cent Ref Doc. 12-25; 104 p.

Theroux, R. Wigley, R. Título (1998): Quantitative composition and distribution of the macrobenthic invertebrate fauna of the continental shelf ecosystems of the Northeastern United States: NOAA Technical report NMFS. 140. 240 p.

Wigley, R. L. and Theroux, R. (1981), Atlantic continental shelf and slope of the United States; macrobenthic invertebrate fauna of the Middle Atlantic Bight region; faunal composition and quantitative distribution, United States Geological Survey, Professional Paper, 529-N:1-198, 124.

Wong, R. 2013. 2013 Assessment of the Delaware Bay Blue Crab (Callinectes sapidus) Stock. Delaware Department of Natural resources and Environmental Control, Division of Fish and Wildlife, 89 Kings Highway, Dover, DE 19901.

Table 1A. Length frequency parameters used to construct length frequencies in the 2012 and 2014 MSVPA updates.

2012 update

Prey name/group	Minimum size	Maximum size	Size alpha	Size beta
Bay anchovy	2	11	12.45	9.69
Benthic crustacean	1	21	6.54	3.35
Benthic invertebrates	1	6	3.29	3.32
Clupeids	7	39	4.87	3.46
Macrozooplankton	1	4	4.74	2.73
Medium forage fish	1	27	1.15	2.52
Sciaenids	9	24	13.1	5.84
Squids	NA	NA	NA	NA

2014 update

Prey name/group	Minimum size	Maximum size	Size alpha	Size beta
Bay anchovy	1	11	9.78	6.64
Benthic crustacean	1	6	3.76	0.83
Benthic invertebrates	1	5	3.87	3.90
Clupeids	5	35	2.83	2.96
Macrozooplankton	1	3	0.36	1.56
Medium forage fish	5	50	4.03	9.80
Sciaenids	15	45	2.14	2.04
Squids	5	45	2.39	5.60

Table 1B. Note that species membership in some of the prey groups has changed between updates. See table below for a summary of details and the text of the report for more detail.

Prey group membership: 2012 versus 2014 MSVPA updates:

Prey Group	2012 Biomass Taxa	2012 Diet Taxa	2014 Biomass & Diet Taxa
Bay anchovy	Bay Anchovy	All anchovy spp, silversides	Bay Anchovy
Benthic crustaceans	Blue Crab, Jonah Crab, Rock Crab, Lobster	Lobster, All crab spp	Blue Crab, Jonah Crab, Rock Crab, Lobster
Benthic invertebrates	Amphipods, Isopods, Polychaetes	Amphipods, Isopods, Polychaetes, molluscs, bivalves	Isopods, Polychaetes
Clupeids	Atlantic Herring, Atlantic thread herring, Spanish sardines, and Scads	Atlantic Herring, Alewife, Blueback Herring	Atlantic Herring

Macro-zooplankton	Copepods	Copepods, Euphausiids, Mysids, Ctenophores, All Shrimp spp	Copepods, Euphausiids, Mysids, Amphipods
Medium forage fish	Butterfish, Loligo Squid, Ilex Squid	Most finfish not assigned to other groups (e.g., butterfish, squid, flounders, hakes, sea robins, skates, scup, eel, etc)	Butterfish, White Perch, Scup, Sand Lance
Sciaenids	Croaker, Spot	All sciaenids	Croaker Spot
Squid	NA	NA	Loligo Squid

Table 2. Predator size selection parameters used in the 2012 and 2014 MSVPA updates. For the 2014 update, all sizes of each predator were combined when estimating parameters. Note that we were unable to reproduce the parameter estimates used in previous iterations of the MSVPA. In the table below, S = small, M = medium, and L = large. During a review of previous MSVPA assessment reports and archived files we discovered that at some point in the past a data entry error or spontaneous shuffling of the data within the MSVPA GUI occurred that resulted in size selectivity parameters getting applied, in some cases, to incorrect predators or predator age groupings. Highlighted cells illustrate an instance of the shuffling. The second table below provides a record of how the parameters were and should have been applied to the various predator ages for the 2012 MSVPA update.

	Bluefish	2012		2014		SARC 2006	
Ages	Size	alpha	beta	alpha	beta	alpha	beta
0-1	S	8.650	25.000	2.466	9.639	10.1	25.5
2-3	M	8.650	25.000	2.466	9.639	10.1	25.5
4+	L	8.000	25.000	2.466	9.639	10.1	25.5
	Striped Bass	2012		2014		SARC 2006	
		alpha	beta	alpha	beta	alpha	beta
0-6	S (1)	10.100	25.500	1.670	8.228	2.98	11.244
7-11	M	2.980	11.244	1.670	8.228	9.1	35.2
12-13+	L	9.100	35.200	1.670	8.228	13.9	51.2
	Weakfish	2012		2014		SARC 2006	
		alpha	beta	alpha	beta	alpha	beta
0-2	S	9.100	35.200	5.368	23.613	10.1	25.5
3-6+	M & L	13.900	51.200	5.368	23.613	10.1	25.5

Size selectivity age groups		
Predator	Was (2012 MSVPA update)	Should have been (as were used in 2006 SARC)
Bluefish	0-1	No change
	2-3	No change
	4-6+	No change
Striped bass	0-6	0-4
	7-11	5-9
	12-13+	10-13+
Weakfish	0-2	0-6+
	3-6+	

Table 3. Prey preference electivity cutoffs (prey preferences are entered into the MSVPA as ranked electivities). Cells highlighted in black are those affected by the cutoff and whose prey preference was set equal to 0 (table continues onto the next page).

Weakfish							
	A0	A1	A2	A3	A4	A5	A6+
Menhaden	0.0083	0.0083	0.0099	0.0093	0.0240	0.0035	0.0166
Bay anchovy	0.5918	0.5918	0.5972	0.5800	0.5474	0.6314	0.7172
Benthic crustaceans	0.0677	0.0677	0.0708	0.0794	0.0804	0.1052	0.0073
Benthic invertebrates	0.0021	0.0021	0.0017	0.0019	0.0006	0.0007	0.0022
Clupeids	0.0000	0.0000	0.0002	0.0005	0.0011	0.0020	0.0134
Macrozooplankton	0.0389	0.0389	0.0404	0.0550	0.0542	0.0154	0.0034
Medium forage fish	0.0734	0.0734	0.0694	0.0719	0.0913	0.0852	0.1975
Sciaenids	0.0509	0.0509	0.0539	0.0529	0.0511	0.0651	0.0000
Squids	0.1670	0.1670	0.1563	0.1492	0.1499	0.0915	0.0412

Bluefish			
	A0-1	A2-3	A4+
Menhaden	0.0010	0.0094	0.0155
Bay anchovy	0.3404	0.1631	0.0864
Benthic crustaceans	0.0147	0.0438	0.0277
Benthic invertebrates	0.0003	0.0000	0.0001
Clupeids	0.0000	0.0008	0.0011
Macrozooplankton	0.0037	0.0004	0.0005
Medium forage fish	0.0836	0.2476	0.2564
Sciaenids	0.0268	0.1353	0.0712
Squids	0.5295	0.3997	0.5412

Striped bass									
	A0	A1	A2	A3	A4	A5	A6	A7	A8
Menhaden	0.0000	0.0059	0.0290	0.0347	0.0413	0.0483	0.0529	0.0541	0.0588
Bay anchovy	0.3454	0.5966	0.2879	0.2703	0.2494	0.2394	0.2348	0.2496	0.2878
Benthic crustaceans	0.0000	0.2141	0.3953	0.4079	0.4149	0.3924	0.3691	0.3462	0.3123
Benthic invertebrates	0.0443	0.1068	0.0062	0.0094	0.0068	0.0049	0.0034	0.0032	0.0038
Clupeids	0.0000	0.0000	0.0015	0.0022	0.0028	0.0036	0.0108	0.0125	0.0156
Macrozooplankton	0.3685	0.0475	0.0226	0.0106	0.0075	0.0038	0.0031	0.0052	0.0028
Medium forage fish	0.2418	0.0063	0.2222	0.2239	0.2257	0.2436	0.2524	0.2571	0.2451
Sciaenids	0.0000	0.0227	0.0240	0.0247	0.0340	0.0432	0.0520	0.0497	0.0517
Squids	0.0000	0.0000	0.0113	0.0162	0.0176	0.0209	0.0216	0.0224	0.0221

Striped bass (cont'd)					
	A9	A10	A11	A12	A13+
Menhaden	0.0621	0.0599	0.0693	0.0576	0.0677
Bay anchovy	0.2543	0.2756	0.2769	0.2641	0.2333
Benthic crustaceans	0.3316	0.3149	0.3080	0.3071	0.3017
Benthic invertebrates	0.0058	0.0021	0.0020	0.0021	0.0014
Clupeids	0.0204	0.0223	0.0226	0.0202	0.0730
Macrozooplankton	0.0021	0.0338	0.0023	0.0020	0.0013
Medium forage fish	0.2493	0.2152	0.2387	0.2693	0.1892
Sciaenids	0.0541	0.0567	0.0609	0.0596	0.0856
Squids	0.0204	0.0196	0.0191	0.0180	0.0468

Table 4. Weakfish catch-at-age, recreational catch-per-unit-effort, recreational harvest per-unit-effort, and average size-at-age for 2014 MSVPA-X update.

	Final weakfish catch at age (thousands)					
	Age					
Year	1	2	3	4	5	6+
1982	9914.2	12967.0	5473.0	2778.2	721.6	639.5
1983	8004.0	12869.1	5822.7	2780.0	568.2	424.1
1984	10444.2	14736.9	6521.1	3045.3	484.5	254.5
1985	14153.2	11262.3	3246.1	1171.0	212.9	55.1
1986	18610.7	15778.4	4942.4	1823.7	264.1	52.1
1987	16256.3	14343.1	4347.1	1485.2	145.4	11.0
1988	8161.9	16140.8	10545.3	6092.0	1050.5	70.7
1989	3705.0	5304.9	4333.5	2922.3	626.2	84.6
1990	9510.1	4890.1	2093.6	1204.8	591.4	89.1
1991	9795.9	5825.6	2750.0	1373.6	463.4	57.3
1992	5179.5	6046.0	2211.0	1255.0	527.8	65.0
1993	4974.8	6357.0	2179.8	1138.6	401.1	48.2
1994	3761.9	4347.4	3561.0	1563.5	204.1	39.8
1995	4336.3	3727.7	3566.7	1637.8	198.1	54.3
1996	2498.8	2689.5	5033.3	3174.2	1379.3	100.1
1997	1716.4	2394.2	2913.2	5522.0	1523.1	410.2
1998	1270.6	2138.3	3983.1	2019.2	2928.8	909.5
1999	1412.6	1300.4	2256.6	3326.0	725.7	1145.0
2000	1377.0	1727.1	1985.7	1663.7	1528.2	403.0
2001	2420.7	2953.1	1474.1	1219.9	658.7	485.9

Recreational CPUE	
Year	Index
1982	0.7613
1983	0.2021
1984	0.5109
1985	0.3001
1986	0.2777
1987	0.7681
1988	0.5178
1989	0.5738
1990	0.1673
1991	0.1557
1992	0.1778
1993	0.1928
1994	0.1651
1995	0.3849
1996	0.5079
1997	0.6054
1998	0.5177
1999	0.5297
2000	0.4101
2001	0.4585

2002	2591.7	1070.5	2695.7	823.9	388.2	231.5
2003	335.6	949.9	959.7	718.4	209.5	254.2
2004	852.3	1511.9	667.8	115.8	49.7	38.4
2005	334.3	1771.5	1255.2	191.5	10.2	27.1
2006	747.3	637.3	959.2	252.9	15.5	11.9
2007	386.3	725.5	324.5	125.4	23.4	5.8
2008	599.2	670.2	247.2	80.8	6.2	1.7
2009	439.5	498.8	139.2	16.4	3.7	1.8
2010	487.1	508.3	106.3	4.8	2.0	0.4
2011	116.6	244.8	87.6	7.0	0.3	0.0
2012	391.1	421.5	413.4	46.6	0.7	0.0

2002	0.2818
2003	0.2379
2004	0.1162
2005	0.1154
2006	0.2303
2007	0.1926
2008	0.0951
2009	0.1624
2010	0.0179
2011	0.0461
2012	0.0476
2013	0.1166

Recreational HPUE

Year	3	4	5	6+
1982	0.1865	0.2176	0.2131	0.1066
1983	0.0084	0.0588	0.0671	0.0630
1984	0.1771	0.1631	0.1165	0.0326
1985	0.1033	0.0919	0.0632	0.0172
1986	0.0933	0.0758	0.0525	0.0175
1987	0.3885	0.1329	0.0664	0.0102
1988	0.2272	0.1262	0.0707	0.0101
1989	0.1498	0.1915	0.1290	0.0291
1990	0.0527	0.0527	0.0341	0.0093
1991	0.0574	0.0309	0.0177	0.0044

Weakfish ave size at age (inches and lbs)

	0	1	2	3	4	5
2011 Len	7.25408	9.75347	12.4136	14.2297	17.2885	27
2012 Len	6.90959	10.9398	11.6378	14.063	16.2912	27
2011 Wgt	0.16787	0.46297	0.89071	1.25937	2.38915	7.91398
2012 Wgt	0.15615	0.61711	0.74247	1.27598	1.84405	8.6995

1992	0.0530	0.0485	0.0265	0.0088
1993	0.0370	0.0328	0.0287	0.0082
1994	0.0300	0.0258	0.0172	0.0043
1995	0.0355	0.0659	0.0304	0.0000
1996	0.0271	0.0588	0.0407	0.0045
1997	0.0137	0.0504	0.1054	0.0321
1998	0.0151	0.0605	0.0958	0.0302
1999	0.0162	0.0647	0.1024	0.0323
2000	0.0105	0.0264	0.0632	0.0474
2001	0.0109	0.0274	0.0328	0.0711
2002	0.0368	0.0263	0.0158	0.0158
2003	0.0051	0.0462	0.0205	0.0154
2004	0.0094	0.0047	0.0047	0.0047
2005	0.0135	0.0058	0.0021	0.0020
2006	0.0489	0.0384	0.0058	0.0001
2007	0.0084	0.0196	0.0088	0.0009
2008	0.0113	0.0054	0.0026	0.0003
2009	0.0026	0.0159	0.0060	0.0034
2010	0.0003	0.0012	0.0010	0.0002
2011	0.0006	0.0003	0.0000	0.0002
2012	0.0004	0.0000	0.0000	0.0000
2013	0.0053	0.0098	0.0014	0.0000

Table 5. Prey biomass inputs by year and season.

ZOOPLANKTON (mt)				
Year	Season 1	Season 2	Season 3	Season 4
1982	1137998	4278033	4029682	3631289
1983	1137998	4278033	4029682	3631289
1984	1137998	4278033	4029682	3631289
1985	1137998	4278033	4029682	3631289
1986	1137998	4278033	4029682	3631289
1987	1137998	4278033	4029682	3631289
1988	1137998	4278033	4029682	3631289
1989	1137998	4278033	4029682	3631289
1990	1137998	4278033	4029682	3631289
1991	1137998	4278033	4029682	3631289
1992	1137998	4278033	4029682	3631289
1993	1137998	4278033	4029682	3631289
1994	1137998	4278033	4029682	3631289
1995	1137998	4278033	4029682	3631289
1996	1137998	4278033	4029682	3631289
1997	1137998	4278033	4029682	3631289
1998	1137998	4278033	4029682	3631289
1999	1137998	4278033	4029682	3631289
2000	1137998	4278033	4029682	3631289
2001	1137998	4278033	4029682	3631289
2002	1137998	4278033	4029682	3631289
2003	1137998	4278033	4029682	3631289

BUTTERFISH (mt)				
Year	Season 1	Season 2	Season 3	Season 4
1982	1450.3	1450.3	10423.7	10423.7
1983	6967.08	6967.08	16835.9	16835.9
1984	1182.37	1182.37	15441.5	15441.5
1985	592.407	592.407	43139.9	43139.9
1986	357.236	357.236	21142.4	21142.4
1987	328.294	328.294	2718.22	2718.22
1988	450.297	450.297	10781.9	10781.9
1989	205.547	205.547	12579.4	12579.4
1990	144.284	144.284	5281.14	5281.14
1991	4798.72	4798.72	13693.1	13693.1
1992	299.594	299.594	3789.54	3789.54
1993	324.779	324.779	7070.94	7070.94
1994	3380.18	3380.18	15964.3	15964.3
1995	128.984	128.984	8613.96	8613.96
1996	78.9325	78.9325	5508.09	5508.09
1997	666.622	666.622	20074.6	20074.6
1998	383.326	383.326	14918	14918
1999	1123.66	1123.66	10870.1	10870.1
2000	829.591	829.591	13451.8	13451.8
2001	568.863	568.863	11047.2	11047.2
2002	635.818	635.818	17599.5	17599.5
2003	1073.12	1073.12	17433.3	17433.3

2004	1137998	4278033	4029682	3631289
2005	1137998	4278033	4029682	3631289
2006	1137998	4278033	4029682	3631289
2007	1137998	4278033	4029682	3631289
2008	1137998	4278033	4029682	3631289
2009	1137998	4278033	4029682	3631289
2010	1137998	4278033	4029682	3631289
2011	1137998	4278033	4029682	3631289
2012	1137998	4278033	4029682	3631289

BENTHIC INVERTEBRATES (mt)

Year	Season 1	Season 2	Season 3	Season 4
1982	2606155	2606155	2606155	2606155
1983	2606155	2606155	2606155	2606155
1984	2606155	2606155	2606155	2606155
1985	2606155	2606155	2606155	2606155
1986	2606155	2606155	2606155	2606155
1987	2606155	2606155	2606155	2606155
1988	2606155	2606155	2606155	2606155
1989	2606155	2606155	2606155	2606155
1990	2606155	2606155	2606155	2606155
1991	2606155	2606155	2606155	2606155
1992	2606155	2606155	2606155	2606155
1993	2606155	2606155	2606155	2606155
1994	2606155	2606155	2606155	2606155
1995	2606155	2606155	2606155	2606155
1996	2606155	2606155	2606155	2606155

2004	967.901	967.901	25157.5	25157.5
2005	429.169	429.169	5607.36	5607.36
2006	3278.91	3278.91	31482.3	31482.3
2007	17.6575	17.6575	11939.3	11939.3
2008	827.764	827.764	6999.35	6999.35
2009	531.681	531.681	12624.4	12624.4
2010	21216.2	21216.2	13198.5	13198.5
2011	6100.36	6100.36	13007	13007
2012	7838.12	7838.12	17989.6	17989.6

LONGFIN SQUID (mt)

Year	Season 1	Season 2	Season 3	Season 4
1982	1881.74	1881.74	23285.7	23285.7
1983	458.262	458.262	31353.2	31353.2
1984	1114.74	1114.74	18947.8	18947.8
1985	2401.76	2401.76	30047.1	30047.1
1986	2359.03	2359.03	29624.8	29624.8
1987	1373.55	1373.55	10044.8	10044.8
1988	4429.56	4429.56	46665.2	46665.2
1989	5106.46	5106.46	43476.1	43476.1
1990	4383.63	4383.63	23141.6	23141.6
1991	5094.39	5094.39	35034	35034
1992	1396.35	1396.35	18247.5	18247.5
1993	2803.75	2803.75	19305.7	19305.7
1994	1978.69	1978.69	38761.9	38761.9
1995	1515.41	1515.41	10741.1	10741.1
1996	1362.26	1362.26	14792.1	14792.1

1997	2606155	2606155	2606155	2606155
1998	2606155	2606155	2606155	2606155
1999	2606155	2606155	2606155	2606155
2000	2606155	2606155	2606155	2606155
2001	2606155	2606155	2606155	2606155
2002	2606155	2606155	2606155	2606155
2003	2606155	2606155	2606155	2606155
2004	2606155	2606155	2606155	2606155
2005	2606155	2606155	2606155	2606155
2006	2606155	2606155	2606155	2606155
2007	2606155	2606155	2606155	2606155
2008	2606155	2606155	2606155	2606155
2009	2606155	2606155	2606155	2606155
2010	2606155	2606155	2606155	2606155
2011	2606155	2606155	2606155	2606155
2012	2606155	2606155	2606155	2606155
BLUE CRAB (mt)				
Year	Season 1	Season 2	Season 3	Season 4
1982	9062.42	7834.57	3957.23	6563.82
1983	8750.18	7564.63	3820.88	6337.67
1984	7940.42	6864.58	3467.29	5751.16
1985	7501.01	6484.71	3275.41	5432.9
1986	7383.32	6382.96	3224.02	5347.66
1987	7631.71	6597.7	3332.49	5527.57
1988	8276.04	7154.73	3613.84	5994.25
1989	17815.5	15401.7	7779.37	12903.6

1997	2981.65	2981.65	19164.7	19164.7
1998	555.307	555.307	14541.5	14541.5
1999	2926.78	2926.78	48041	48041
2000	1924.57	1924.57	34445.4	34445.4
2001	2097.21	2097.21	21425.5	21425.5
2002	4369.58	4369.58	50559.1	50559.1
2003	979.663	979.663	23912	23912
2004	565.227	565.227	20825.9	20825.9
2005	1268.47	1268.47	19302.8	19302.8
2006	3158.57	3158.57	30484.3	30484.3
2007	1128.05	1128.05	42000.9	42000.9
2008	1446.89	1446.89	32705	32705
2009	6767.79	6767.79	26830.5	26830.5
2010	6470.34	6470.34	56286.6	56286.6
2011	10240.9	10240.9	26940.5	26940.5
2012	9071.48	9071.48	104460	104460
SAND LANCE (mt)				
Year	Season 1	Season 2	Season 3	Season 4
1982	44101.7	44101.7	242188	242188
1983	74864.9	74864.9	12418.7	12418.7
1984	8210.76	8210.76	1632.47	1632.47
1985	39709.1	39709.1	29951	29951
1986	11234.4	11234.4	3927.55	3927.55
1987	13651.2	13651.2	7031.08	7031.08
1988	213806	213806	1222.37	1222.37
1989	144211	144211	4172.08	4172.08

1990	9412.37	8137.11	4110.04	6817.29
1991	14609	12629.6	6379.2	10581.1
1992	6138.37	5306.69	2680.4	4445.96
1993	11474.5	9919.84	5010.49	8310.86
1994	9453.95	8173.06	4128.2	6847.4
1995	6573.7	5683.04	2870.49	4761.26
1996	9621.85	8318.2	4201.51	6969.01
1997	10259.1	8869.1	4479.77	7430.55
1998	6997.88	6049.75	3055.72	5068.49
1999	7524.53	6505.04	3285.69	5449.94
2000	5059.92	4374.36	2209.48	3664.85
2001	4870.73	4210.8	2126.87	3527.82
2002	6247.24	5400.82	2727.94	4524.81
2003	5907.92	5107.47	2579.77	4279.05
2004	4998.95	4321.65	2182.86	3620.69
2005	5305.66	4586.81	2316.79	3842.84
2006	4908.9	4243.8	2143.54	3555.47
2007	3645.65	3151.7	1591.92	2640.51
2008	5030.4	4348.84	2196.59	3643.47
2009	4744.53	4101.7	2071.76	3436.41
2010	7012.12	6062.06	3061.94	5078.81
2011	5739.7	4962.04	2506.32	4157.21
2012	9264.19	8009	4045.33	6709.96

LOBSTER (mt)

Year	Season 1	Season 2	Season 3	Season 4
1982	10344.4	4431.48	8685.32	4600.82

1990	26309.8	26309.8	22641.7	22641.7
1991	2568.12	2568.12	80.2526	80.2526
1992	10933.1	10933.1	160.047	160.047
1993	2242.55	2242.55	2993.47	2993.47
1994	3759.59	3759.59	220.184	220.184
1995	8023.22	8023.22	295.1	295.1
1996	13531.1	13531.1	8940.87	8940.87
1997	4251.23	4251.23	13159.8	13159.8
1998	25193.3	25193.3	581.976	581.976
1999	39081.3	39081.3	3110.09	3110.09
2000	4872.24	4872.24	5577.13	5577.13
2001	18470.1	18470.1	13074.4	13074.4
2002	17977.3	17977.3	344.765	344.765
2003	15307	15307	2293.83	2293.83
2004	16886.7	16886.7	877.687	877.687
2005	31671.7	31671.7	5856.99	5856.99
2006	39502.7	39502.7	15031.3	15031.3
2007	11013.6	11013.6	91920.9	91920.9
2008	157375	157375	4299.57	4299.57
2009	8711.79	8711.79	160.453	160.453
2010	2171.12	2171.12	490.639	490.639
2011	15978.1	15978.1	8.48269	8.48269
2012	8359.95	8359.95	2678.94	2678.94

SCUP (mt)

Year	Season 1	Season 2	Season 3	Season 4
1982	1915.75	1915.75	53382.4	53382.4

1983	5755.56	9596.96	5777.98	9963.67
1984	8277.85	5339.68	7018.47	5543.72
1985	5748.34	7679.73	5542.1	7973.18
1986	11255.6	5332.99	9405.03	5536.77
1987	8345.36	10442.4	7927.83	10841.4
1988	10276.8	7742.36	8963.05	8038.22
1989	9371.02	9534.23	8504.91	9898.54
1990	9129.35	8693.9	8226.42	9026.1
1991	12267.4	8469.7	10664.7	8793.33
1992	11581.9	11381	10551.9	11815.9
1993	10987.7	10745	9878.7	11155.6
1994	12941.1	10193.8	11385.2	10583.3
1995	13850	12006	12399.7	12464.8
1996	12878.6	12849.2	11632.9	13340.2
1997	18270.9	11948	15777.1	12404.6
1998	9269.47	16950.7	9438.78	17598.4
1999	16172.6	8599.7	13536.6	8928.31
2000	10980	15004	10624.9	15577.4
2001	16166.1	10186.6	13789.4	10575.9
2002	13944.4	14998	12898.5	15571.1
2003	16019.3	12936.8	14084	13431.2
2004	11208.1	14861.9	10653.8	15429.8
2005	13396.2	10398.3	11657.7	10795.6
2006	13847.9	12428.3	12491.5	12903.2
2007	18016.3	12847.3	15683.5	13338.2
2008	18016.3	12847.3	15683.5	13338.2

1983	5458.73	5458.73	34326	34326
1984	975.806	975.806	22033.3	22033.3
1985	1066.48	1066.48	14650.3	14650.3
1986	2.44558	2.44558	19885.5	19885.5
1987	26.5251	26.5251	18745	18745
1988	36.3457	36.3457	13816	13816
1989	13.9752	13.9752	17322.9	17322.9
1990	331.451	331.451	17380.4	17380.4
1991	16.0395	16.0395	22999.1	22999.1
1992	53.9567	53.9567	11150.6	11150.6
1993	17.6193	17.6193	7839.97	7839.97
1994	46.3612	46.3612	9093.12	9093.12
1995	12.6434	12.6434	4617.97	4617.97
1996	1.71311	1.71311	4508.62	4508.62
1997	13.8508	13.8508	9002.46	9002.46
1998	3.20717	3.20717	9965.36	9965.36
1999	6.09823	6.09823	15634.4	15634.4
2000	41.9371	41.9371	24586.5	24586.5
2001	8.06265	8.06265	32605.6	32605.6
2002	3.94808	3.94808	42618.5	42618.5
2003	8.6638	8.6638	78087.1	78087.1
2004	98.4142	98.4142	72243.7	72243.7
2005	19.4274	19.4274	53267.1	53267.1
2006	112.207	112.207	80749.3	80749.3
2007	231.687	231.687	118349	118349
2008	36.1117	36.1117	164684	164684

2009	18016.3	12847.3	15683.5	13338.2
2010	18016.3	12847.3	15683.5	13338.2
2011	18016.3	12847.3	15683.5	13338.2
2012	18016.3	12847.3	15683.5	13338.2
JONAH CRAB (mt)				
Year	Season 1	Season 2	Season 3	Season 4
1982	1.4183	1.4183	2.52387	2.52387
1983	0.2881	0.2881	3.17384	3.17384
1984	0.49658	0.49658	0.75821	0.75821
1985	0.17725	0.17725	2.93131	2.93131
1986	0.02669	0.02669	2.67356	2.67356
1987	0.60487	0.60487	2.734	2.734
1988	1.27435	1.27435	0.31248	0.31248
1989	0.00547	0.00547	2.12915	2.12915
1990	0.07294	0.07294	1.11273	1.11273
1991	0.05762	0.05762	0.814	0.814
1992	1.97782	1.97782	0.76602	0.76602
1993	0.04965	0.04965	0.14874	0.14874
1994	0.06877	0.06877	2.65699	2.65699
1995	0.20305	0.20305	1.46256	1.46256
1996	0.29739	0.29739	1.44129	1.44129
1997	0.28993	0.28993	0.34892	0.34892
1998	1.41113	1.41113	2.40699	2.40699
1999	1.22475	1.22475	3.31063	3.31063
2000	6.07962	6.07962	7.73254	7.73254
2001	1.86423	1.86423	6.26435	6.26435

2009	63.4476	63.4476	126040	126040
2010	1214.57	1214.57	74809.3	74809.3
2011	420.544	420.544	136722	136722
2012	89.8349	89.8349	152528	152528
WHITE PERCH (mt)				
Year	Season 1	Season 2	Season 3	Season 4
1982	4064.83	4061.18	4064.56	4057.25
1983	4064.83	4061.18	4064.56	4057.25
1984	4064.83	4061.18	4064.56	4057.25
1985	4064.83	4061.18	4064.56	4057.25
1986	4064.83	4061.18	4064.56	4057.25
1987	4064.83	4061.18	4064.56	4057.25
1988	4064.83	4061.18	4064.56	4057.25
1989	4064.83	4061.18	4064.56	4057.25
1990	4064.83	4061.18	4064.56	4057.25
1991	4064.83	4061.18	4064.56	4057.25
1992	4064.83	4061.18	4064.56	4057.25
1993	4064.83	4061.18	4064.56	4057.25
1994	4064.83	4061.18	4064.56	4057.25
1995	4064.83	4061.18	4064.56	4057.25
1996	4064.83	4061.18	4064.56	4057.25
1997	4064.83	4061.18	4064.56	4057.25
1998	4064.83	4061.18	4064.56	4057.25
1999	4064.83	4061.18	4064.56	4057.25
2000	4064.83	4061.18	4064.56	4057.25
2001	4064.83	4061.18	4064.56	4057.25

2002	1.8192	1.8192	6.24055	6.24055
2003	0.63201	0.63201	8.94271	8.94271
2004	0.38085	0.38085	2.39495	2.39495
2005	0.35832	0.35832	3.9942	3.9942
2006	5.80618	5.80618	2.10436	2.10436
2007	0.63956	0.63956	5.92815	5.92815
2008	0.18587	0.18587	1.46487	1.46487
2009	4.00925	4.00925	2.68901	2.68901
2010	1.41471	1.41471	6.19644	6.19644
2011	0.93995	0.93995	2.15773	2.15773
2012	4.82247	4.82247	7.70913	7.70913

ROCK CRAB (mt)

Year	Season 1	Season 2	Season 3	Season 4
1982	1184.78	1184.34	37.8701	37.8442
1983	38.0129	37.569	7.39049	7.36468
1984	44.9345	44.4906	6.69906	6.67325
1985	38.3053	37.8614	28.0413	28.0155
1986	20.6339	20.19	67.7159	67.6901
1987	12.2856	11.8418	33.6626	33.6368
1988	23.0311	22.5872	22.9536	22.9278
1989	8.53243	8.08855	39.1503	39.1245
1990	4.63247	4.18859	12.5307	12.5049
1991	34.1761	33.7322	12.4197	12.3939
1992	10.516	10.0721	25.5177	25.4919
1993	7.95907	7.51519	10.0844	10.0586
1994	19.4857	19.0419	19.1086	19.0828

2002	4064.83	4061.18	4064.56	4057.25
2003	4064.83	4061.18	4064.56	4057.25
2004	4064.83	4061.18	4064.56	4057.25
2005	4064.83	4061.18	4064.56	4057.25
2006	4064.83	4061.18	4064.56	4057.25
2007	4064.83	4061.18	4064.56	4057.25
2008	4064.83	4061.18	4064.56	4057.25
2009	4064.83	4061.18	4064.56	4057.25
2010	4064.83	4061.18	4064.56	4057.25
2011	4064.83	4061.18	4064.56	4057.25
2012	4064.83	4061.18	4064.56	4057.25

BAY ANCHOVY (mt)

Year	Season 1	Season 2	Season 3	Season 4
1982	72413.1	172898	208979	548030
1983	80739.8	189455	229799	840133
1984	90934	224021	283173	1137574
1985	100645	211363	237810	669342
1986	107234	250386	304238	1101255
1987	78747.9	166768	187949	531027
1988	100124	226995	257914	851905
1989	81484.3	188112	222543	776403
1990	115490	247937	276033	809278
1991	78153.3	167458	189975	563443
1992	33867.8	120305	191258	1048102
1993	49693.5	118569	153479	599462
1994	40181.2	99102.6	127540	506214

1995	69.5375	69.0936	9.20306	9.17725
1996	9.63745	9.19357	11.5579	11.5321
1997	6.13025	5.68637	32.8983	32.8724
1998	79.8694	79.4255	18.5149	18.4891
1999	34.6173	34.1734	53.7879	53.7621
2000	101.439	100.995	60.7861	60.7603
2001	50.1587	49.7148	26.5998	26.574
2002	45.1615	44.7177	15.8038	15.778
2003	36.259	35.8151	11.9599	11.9341
2004	25.4019	24.958	6.11137	6.08557
2005	18.1676	17.7238	10.345	10.3192
2006	10.391	9.94712	5.15321	5.1274
2007	25.8406	25.3967	21.5849	21.5591
2008	68.3628	67.919	42.9798	42.954
2009	85.0463	84.6024	24.0047	23.9789
2010	16.612	16.1681	55.634	55.6082
2011	27.7556	27.3117	23.4978	23.472
2012	49.6185	49.1746	111.897	111.871
ATLANTIC HERRING (mt)				
Year	Season 1	Season 2	Season 3	Season 4
1982	164844	164844	164844	164844
1983	213389	213389	213389	213389
1984	246409	246409	246409	246409
1985	277295	277295	277295	277295
1986	248633	248633	248633	248633
1987	354470	354470	354470	354470

1995	41736.3	127092	182493	913201
1996	40303.5	119529	166700	779825
1997	49282.7	115670	140822	514255
1998	88275	185099	199150	526675
1999	156969	330911	346581	891123
2000	161257	335171	346072	850542
2001	63457.4	139094	151712	441273
2002	46270.1	132132	178616	690028
2003	47660.3	139521	190148	791367
2004	90903	209190	240497	767684
2005	117130	245899	255325	639665
2006	95099.9	197457	208705	521272
2007	63884.6	160016	205276	834633
2008	98385.5	214668	243493	722311
2009	116397	251589	273419	785043
2010	147484	312157	332377	755616
2011	99383.4	221141	245446	627080
2012	164374	324671	324435	634068
SPOT & CROAKER (mt)				
Year	Season 1	Season 2	Season 3	Season 4
1982	182551	185371	185592	183680
1983	182551	185371	185592	183680
1984	182551	185371	185592	183680
1985	182551	185371	185592	183680
1986	182551	185371	185592	183680
1987	182551	185371	185592	183680

1988	502578	502578	502578	502578
1989	746377	746377	746377	746377
1990	755761	755761	755761	755761
1991	470703	470703	470703	470703
1992	676071	676071	676071	676071
1993	805076	805076	805076	805076
1994	409730	409730	409730	409730
1995	947333	947333	947333	947333
1996	544700	544700	544700	544700
1997	1122326	1122326	1122326	1122326
1998	318770	318770	318770	318770
1999	1439700	1439700	1439700	1439700
2000	953981	953981	953981	953981
2001	824478	824478	824478	824478
2002	919705	919705	919705	919705
2003	570784	570784	570784	570784
2004	715409	715409	715409	715409
2005	344093	344093	344093	344093
2006	614364	614364	614364	614364
2007	584827	584827	584827	584827
2008	416954	416954	416954	416954
2009	604043	604043	604043	604043
2010	1159690	1159690	1159690	1159690
2011	806926	806926	806926	806926
2012	1125452	1125452	1125452	1125452

1988	182551	185371	185592	183680
1989	182551	185371	185592	183680
1990	182551	185371	185592	183680
1991	182551	185371	185592	183680
1992	182551	185371	185592	183680
1993	182551	185371	185592	183680
1994	182551	185371	185592	183680
1995	182551	185371	185592	183680
1996	182551	185371	185592	183680
1997	182551	185371	185592	183680
1998	182551	185371	185592	183680
1999	182551	185371	185592	183680
2000	182551	185371	185592	183680
2001	182551	185371	185592	183680
2002	182551	185371	185592	183680
2003	182551	185371	185592	183680
2004	182551	185371	185592	183680
2005	182551	185371	185592	183680
2006	182551	185371	185592	183680
2007	182551	185371	185592	183680
2008	182551	185371	185592	183680
2009	182551	185371	185592	183680
2010	182551	185371	185592	183680
2011	182551	185371	185592	183680
2012	182551	185371	185592	183680

Table 6. Temperature inputs used in the 2014 MSVPA update.

Year	Season 1	Season 2	Season 3	Season 4
1982	12.06	15.60	21.69	13.77
1983	12.06	15.87	21.65	13.73
1984	12.06	15.65	21.78	13.75
1985	12.12	16.13	22.30	14.00
1986	12.14	16.34	22.25	14.36
1987	12.20	15.87	22.59	13.48
1988	12.05	16.19	21.61	13.83
1989	12.39	16.28	22.42	13.67
1990	12.56	16.08	22.56	14.90
1991	12.83	17.53	22.73	14.16
1992	12.47	14.36	21.25	13.65
1993	12.23	16.32	22.24	13.39
1994	12.17	15.62	21.38	14.62
1995	12.45	15.90	22.57	13.66
1996	11.68	15.23	21.64	13.26
1997	12.58	14.53	21.85	13.73
1998	12.91	15.88	22.54	14.73
1999	12.47	15.67	22.63	14.71
2000	12.60	15.57	21.78	13.89
2001	12.20	15.98	22.31	14.82
2002	12.95	16.20	23.19	14.14
2003	11.88	14.11	21.87	14.01
2004	12.25	15.53	22.30	14.50
2005	12.59	15.71	23.33	12.12
2006	12.99	16.54	22.45	13.14
2007	12.55	15.24	22.31	16.55
2008	12.71	15.45	22.29	13.99
2009	12.15	15.21	22.62	14.34
2010	12.10	16.58	23.15	13.79
2011	12.08	16.63	23.10	13.97
2012	12.36	16.92	23.81	14.79

Figure 1. Prey group length frequencies fit to a beta distribution used in the 2014 MSVPA update. Note differences in x- and y-scales among each plot.

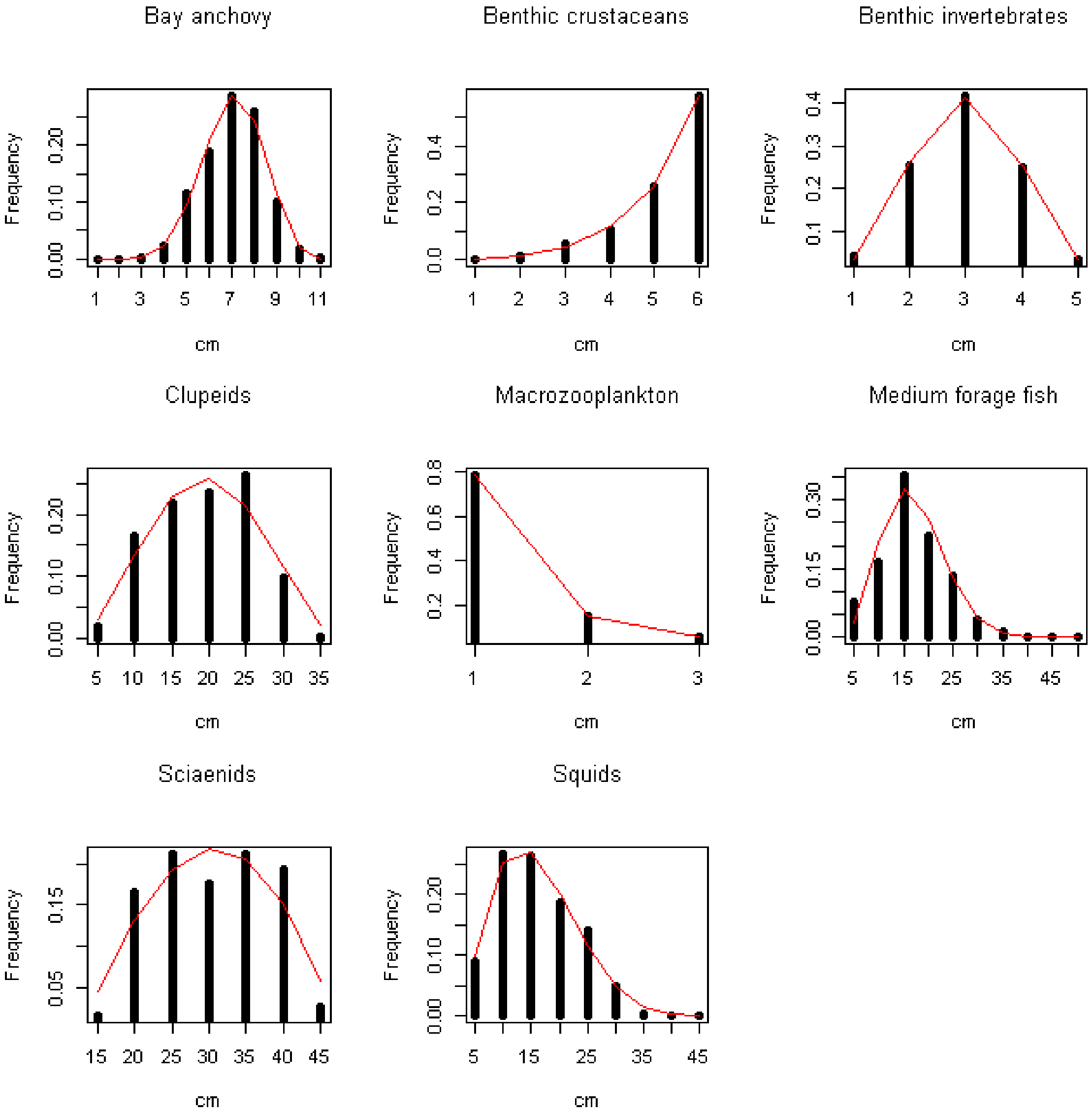


Fig
No
squ
fre
20
me

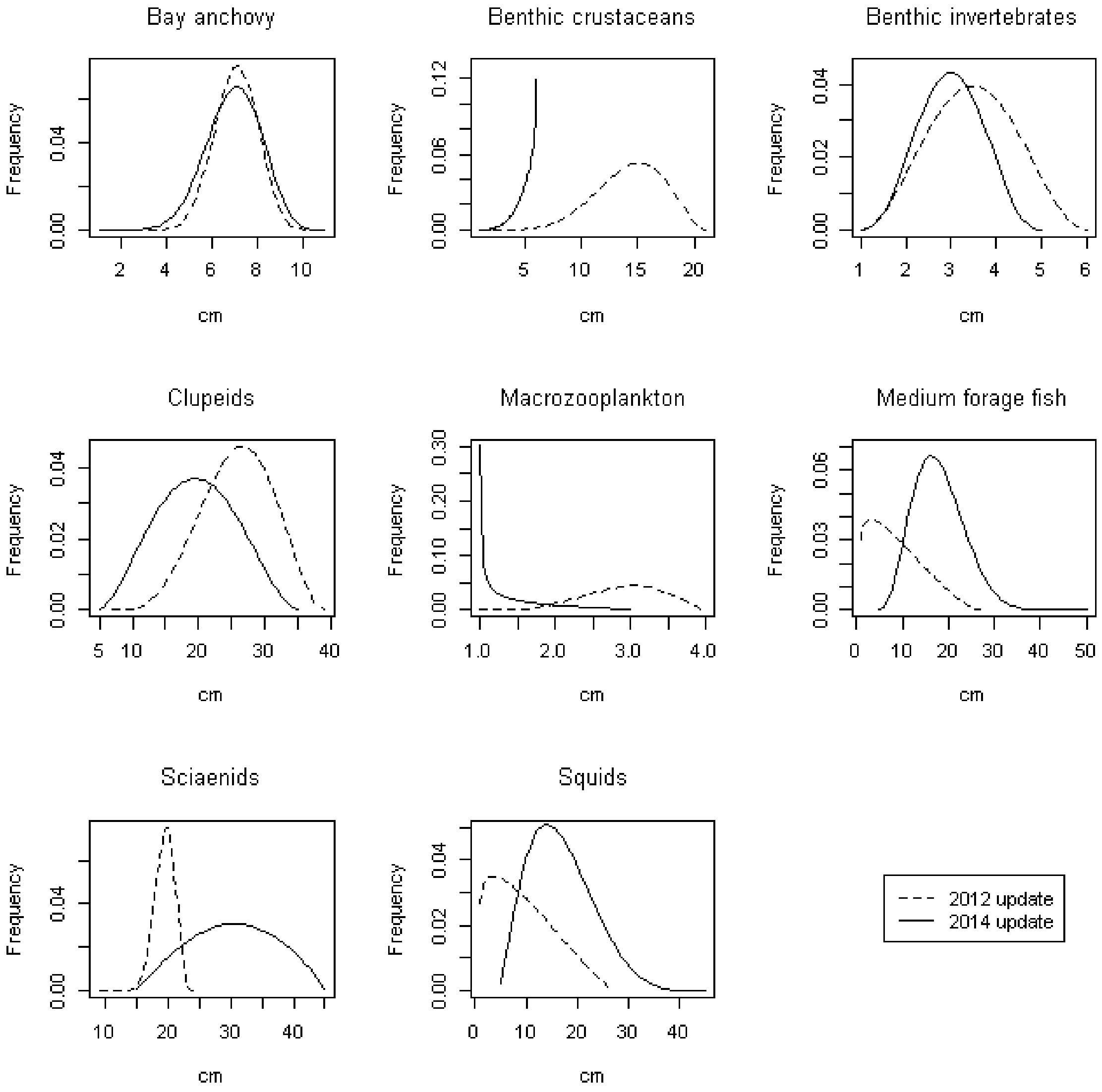

Bay anchovy
Frequency
0.00
0.04
2
4
6
8
10
cm
Benthic crustaceans
Frequency
0.00
0.06
0.12
5
10
15
20
cm
Benthic invertebrates
Frequency
0.00
0.02
0.04
1
2
3
4
5
6
cm
Clupeids
Frequency
0.00
0.02
0.04
5
10
20
30
40
cm
Macrozooplankton
Frequency
0.00
0.10
0.20
0.30
1.0
2.0
3.0
4.0
cm
Medium forage fish
Frequency
0.00
0.03
0.06
0
10
20
30
40
50
cm
Sciaenids
Frequency
0.00
0.04
10
20
30
40
cm
Squids
Frequency
0.00
0.02
0.04
0
10
20
30
40
cm
2012 update
2014 update

Figure 3. Predator size selectivity curves estimated for the 2014 MSVPA update. Each plot depicts observed (open circles) and predicted (red solid line) proportion of predator diets as a function of prey to predator length ratios.

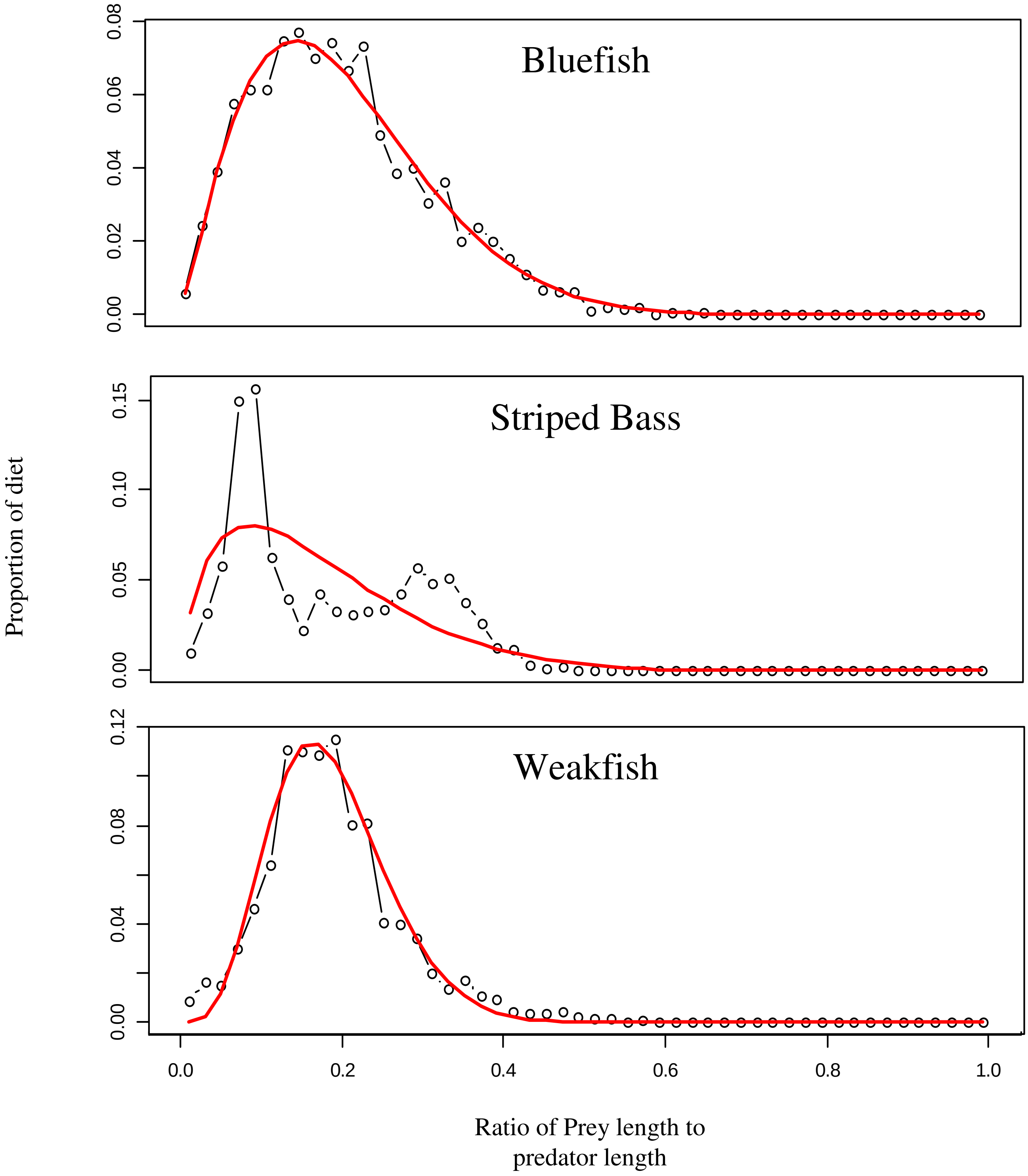


Figure 4. Comparison of 2012 and 2014 MSVPA predator size selectivity configurations. Note that in the 2014 MSVPA configuration predator size selection was based on all sizes of each predator whereas in 2012, size selection was estimated for various size/age categories of predators as follows: small bluefish = ages 0-1, medium bluefish = ages 2-3, large bluefish = ages 4-6+; small striped bass = ages 0-6, medium striped bass = ages 5-9, large striped bass = ages 10-13+; small weakfish = ages 0-2, and medium & large weakfish = ages 3-6+.

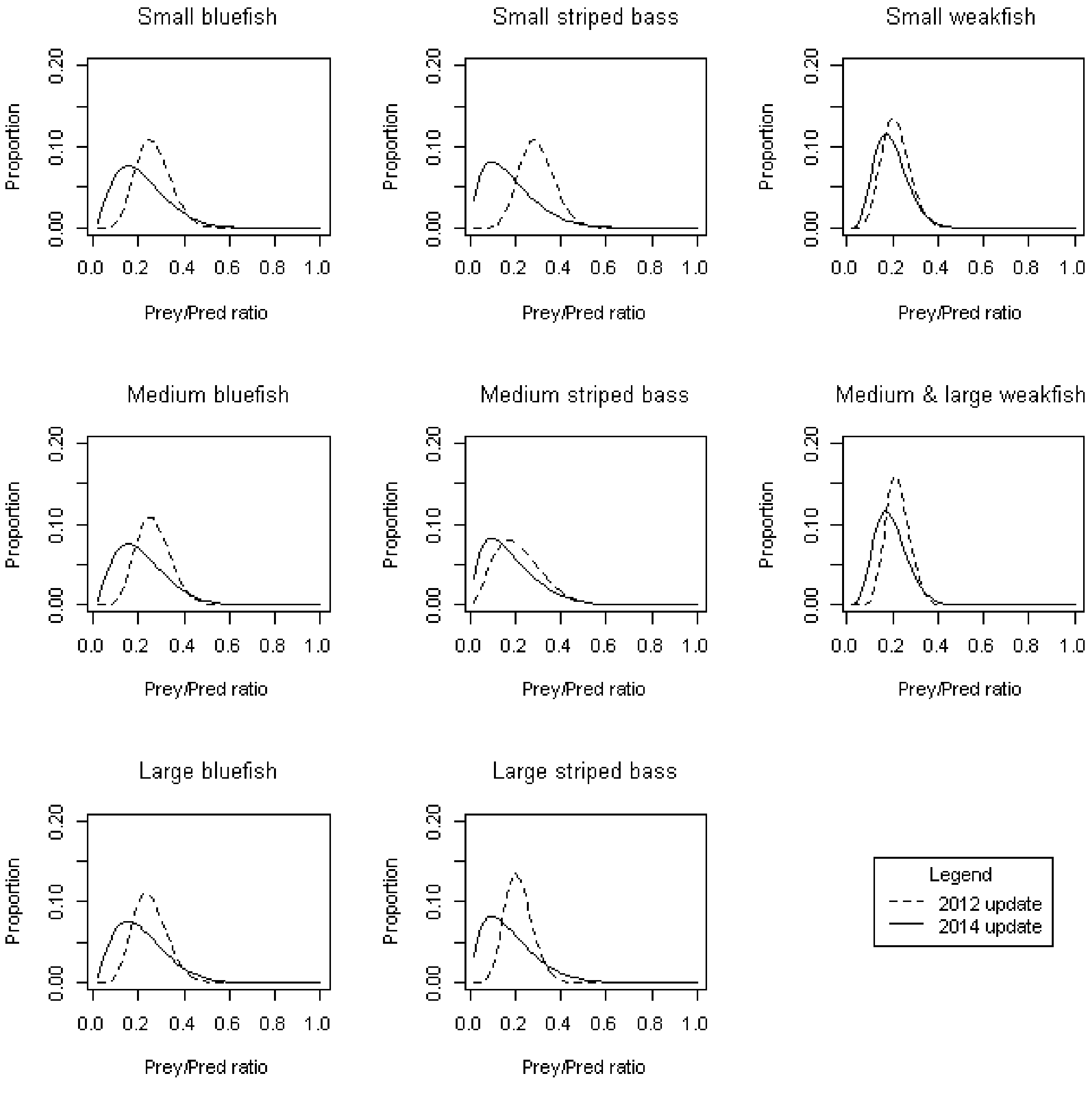


Figure 5.

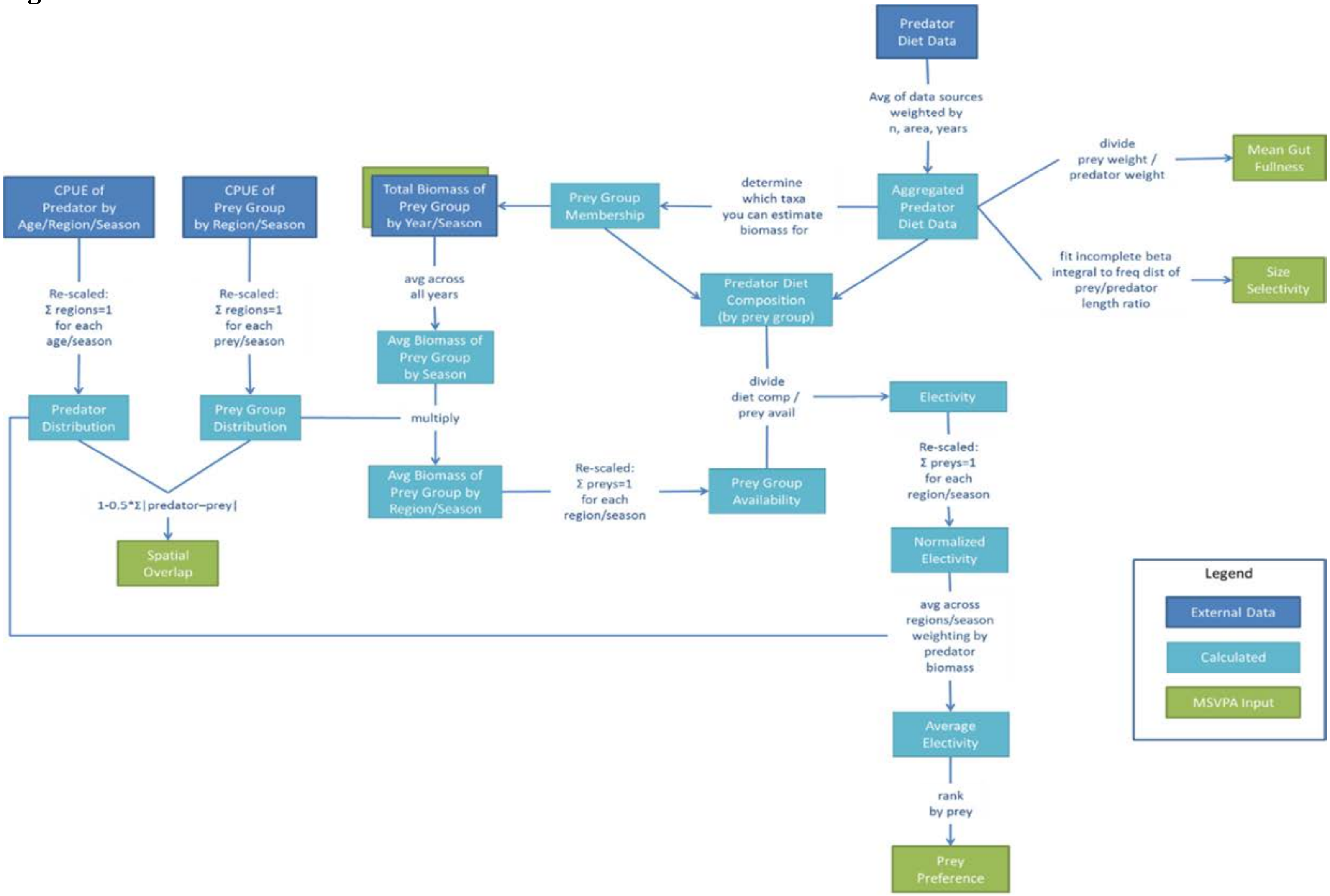

Predator Diet Data
Avg of data sources weighted by n, area, years
Aggregated Predator Diet Data
divide prey weight / predator weight
Mean Gut Fullness
fit incomplete beta integral to freq dist of prey/predator length ratio
Size Selectivity
determine which taxa you can estimate biomass for
Prey Group Membership
Total Biomass of Prey Group by Year/Season
CPUE of Predator by Age/Region/Season
CPUE of Prey Group by Region/Season
Re-scaled: Σ regions=1 for each age/season
Re-scaled: Σ regions=1 for each prey/season
avg across all years
Avg Biomass of Prey Group by Season
Predator Diet Composition (by prey group)
Predator Distribution
Prey Group Distribution
multiply
divide diet comp / prey avail
Electivity
1-0.5*Σ|predator–prey|
Spatial Overlap
Avg Biomass of Prey Group by Region/Season
Re-scaled: Σ preys=1 for each region/season
Prey Group Availability
Re-scaled: Σ preys=1 for each region/season
Normalized Electivity
avg across regions/season weighting by predator biomass
Average Electivity
rank by prey
Prey Preference
Legend
External Data
Calculated
MSVPA Input

Figure 6. Striped bass model output average diet from early 2014 MSVPA model runs where prey preference was estimated following methods outlined in NEFSC (2006) and Dean (2012). Note the dominance of macrozooplankton and benthic invertebrates across most ages of striped bass. Similar patterns were produced for bluefish and weakfish.

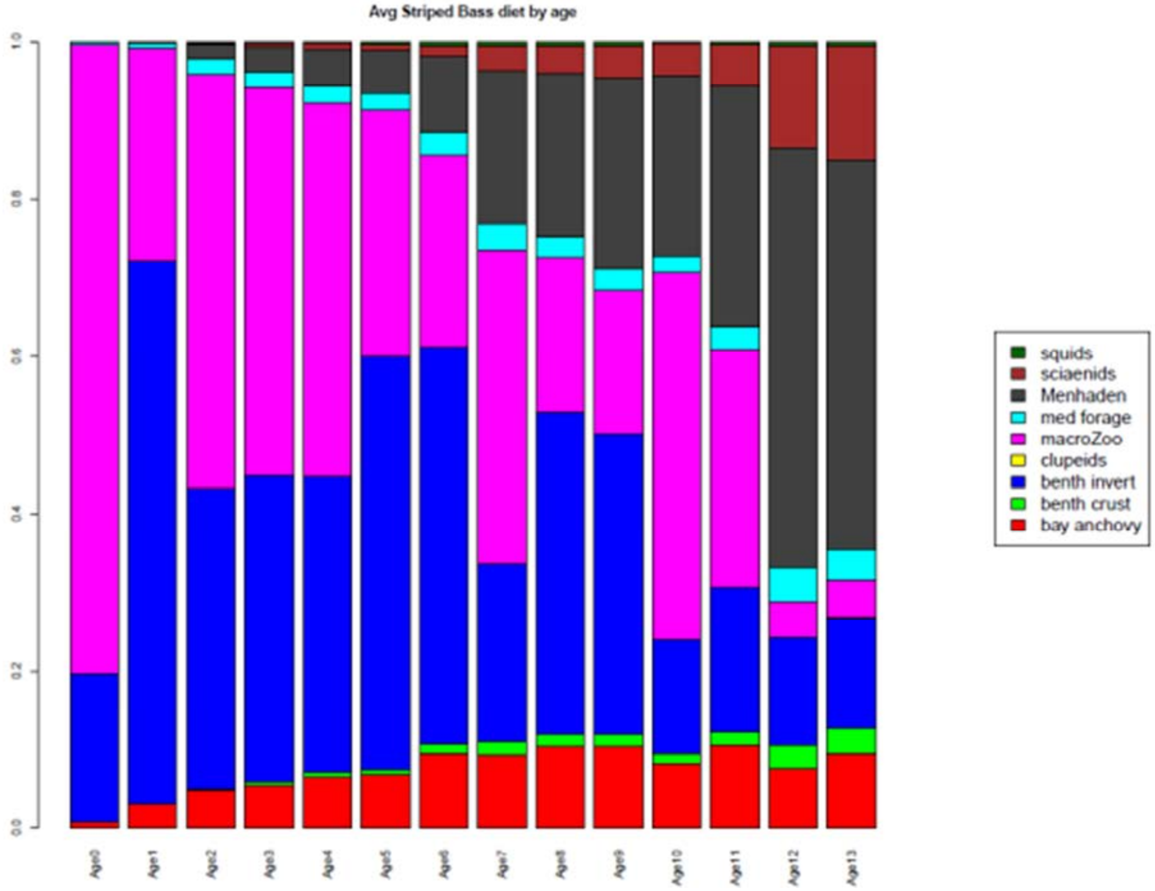


Figure 7. Time series of prey biomass by year, prey type, and season (where S1 = season 1 = January – March, ..., S4 = season 4 = October – December). Legend: SC = sciaenids, MF = medium forage fish, SQ = squid, ZP = macrozooplankton, CL = clupeids, BI = benthic invertebrates, BC = benthic crustaceans, and BA = bay anchovies. For the 2012 MSVPA squid were classified as medium forage fish. Scale of y-axes are identical on all plots & equal to million metric tons.

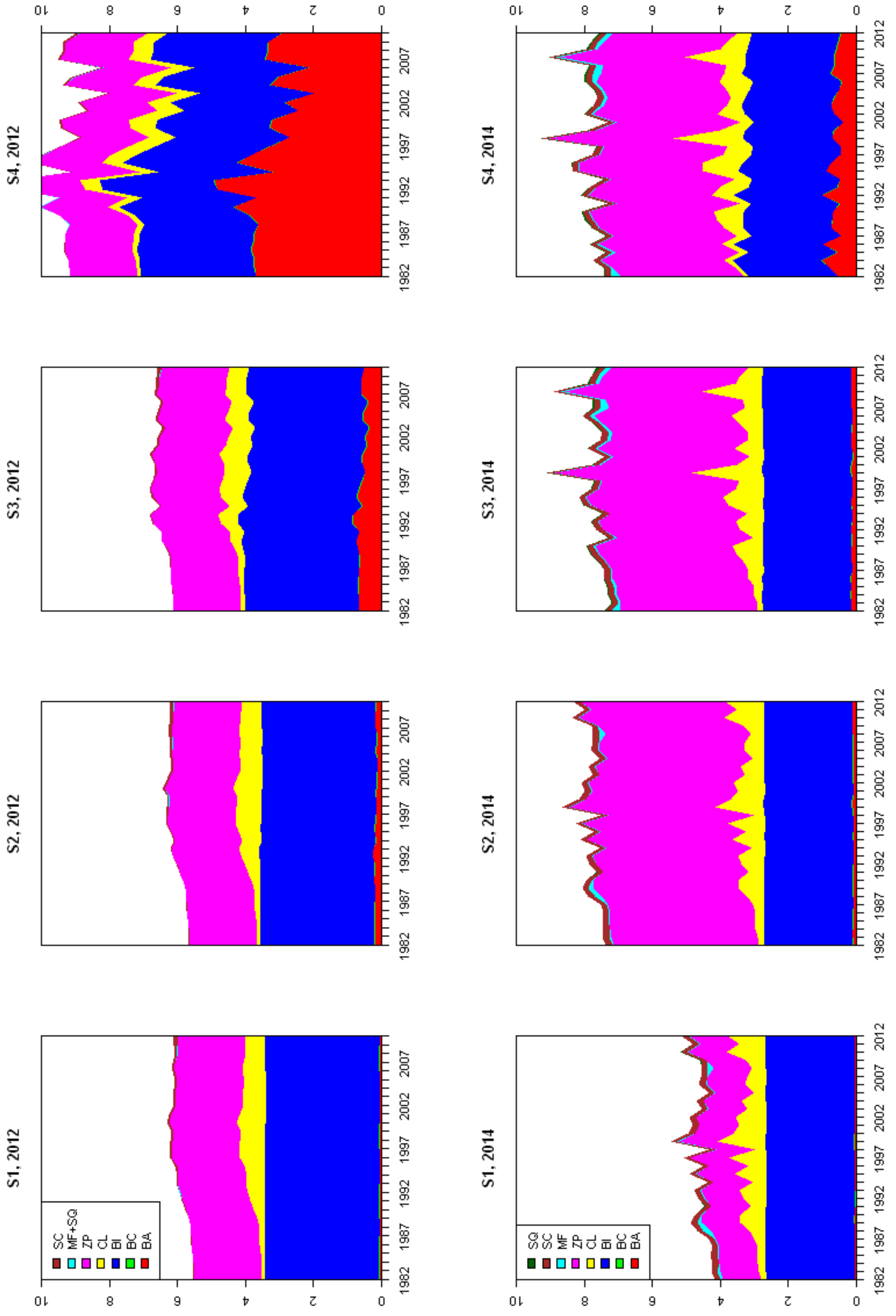


Figure 8. Average proportions of total prey biomass by MSVPA update year, prey type, and season (where S1 = season 1 = January – March, ... , S4 = season 4 = October – December).

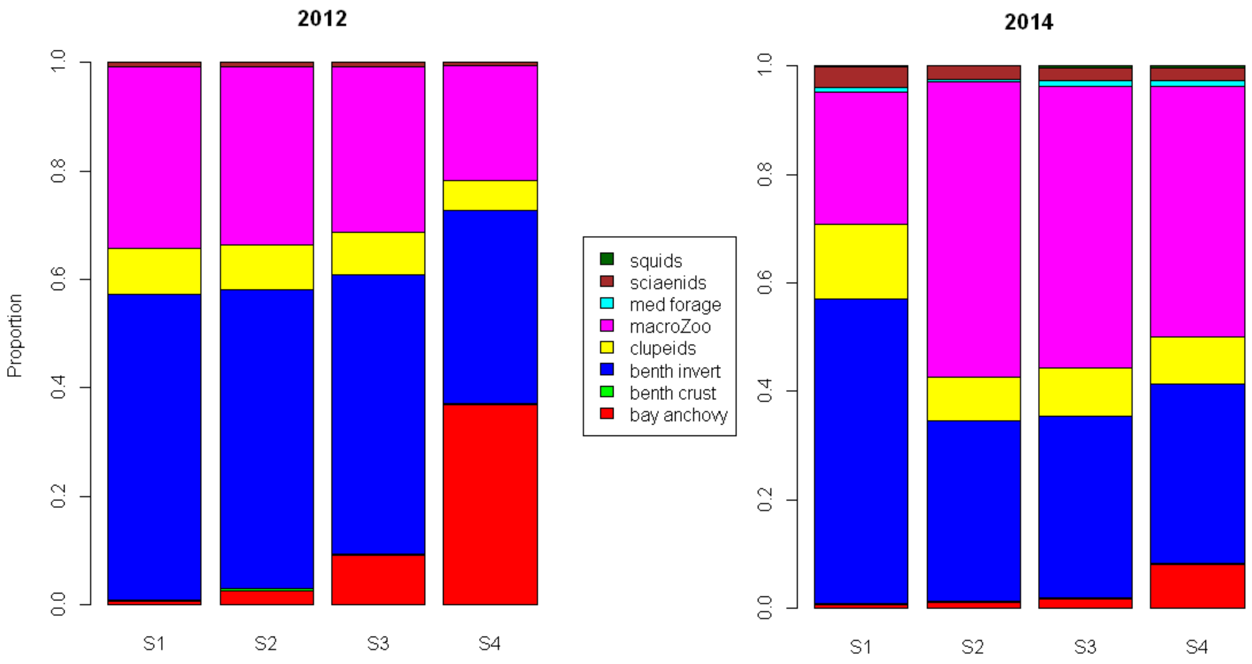
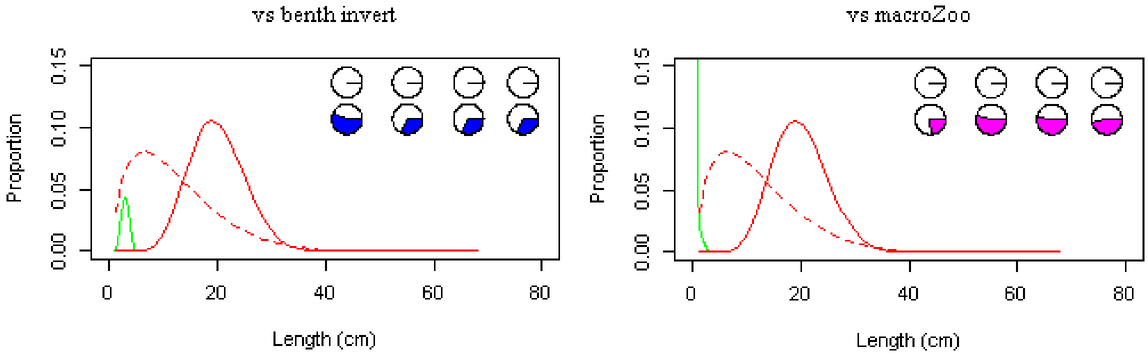


Figure 9. Depictions of benthic invertebrate (BI) and macrozooplankton (ZP) suitable biomass for age 6 and 13+ striped bass (see Appendix 2 for plots of all prey items and all ages of our predators). Green curves represent length frequency of the specified prey item (either BI or ZP) for the 2014 update (note that prey length frequencies differed for the 2012 update); solid red curve represents size selectivity curve used in 2012 MSVPA update; dotted red curve represents size selectivity curve used in 2014 MSVPA update. The top row of pie charts represent the seasonal fraction of prey biomass that is suitable for the predator's age accounting for spatial overlap and type preference (left pie chart = season 1, ... , right pie chart = season 4) for the specified prey. The bottom row of pie charts represent the seasonal fraction of specified prey biomass relative to all prey biomass (left pie chart = season 1, ... , right pie chart = season 4; these are analogous to the bar charts in Figure 8). In 2012's update, since the predator's selectivity curve (solid red line) has no area in common with either BI or ZP (green solid line) (i.e., there is no overlap between the curves) neither BI nor ZP could have been a component of the output diet whereas in 2014, the predator selectivity curves (dotted red lines) overlap entirely with the length frequency of BI and ZP, so that not only can they be part of the modeled output diet, but due to the very large fraction of biomass that is BI and ZP (Figures 7 and 8), the predicted diets of striped bass become dominated by BI and ZP.

Age 6 striped bass



Age 13+ striped bass

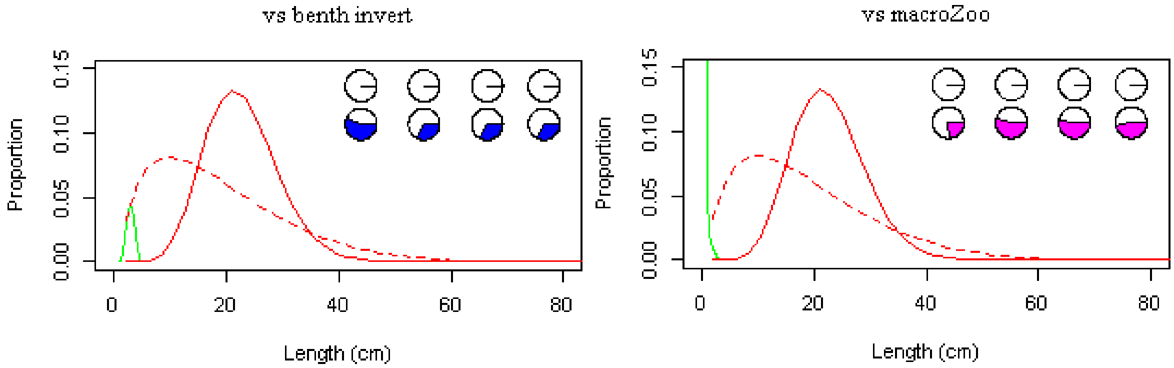
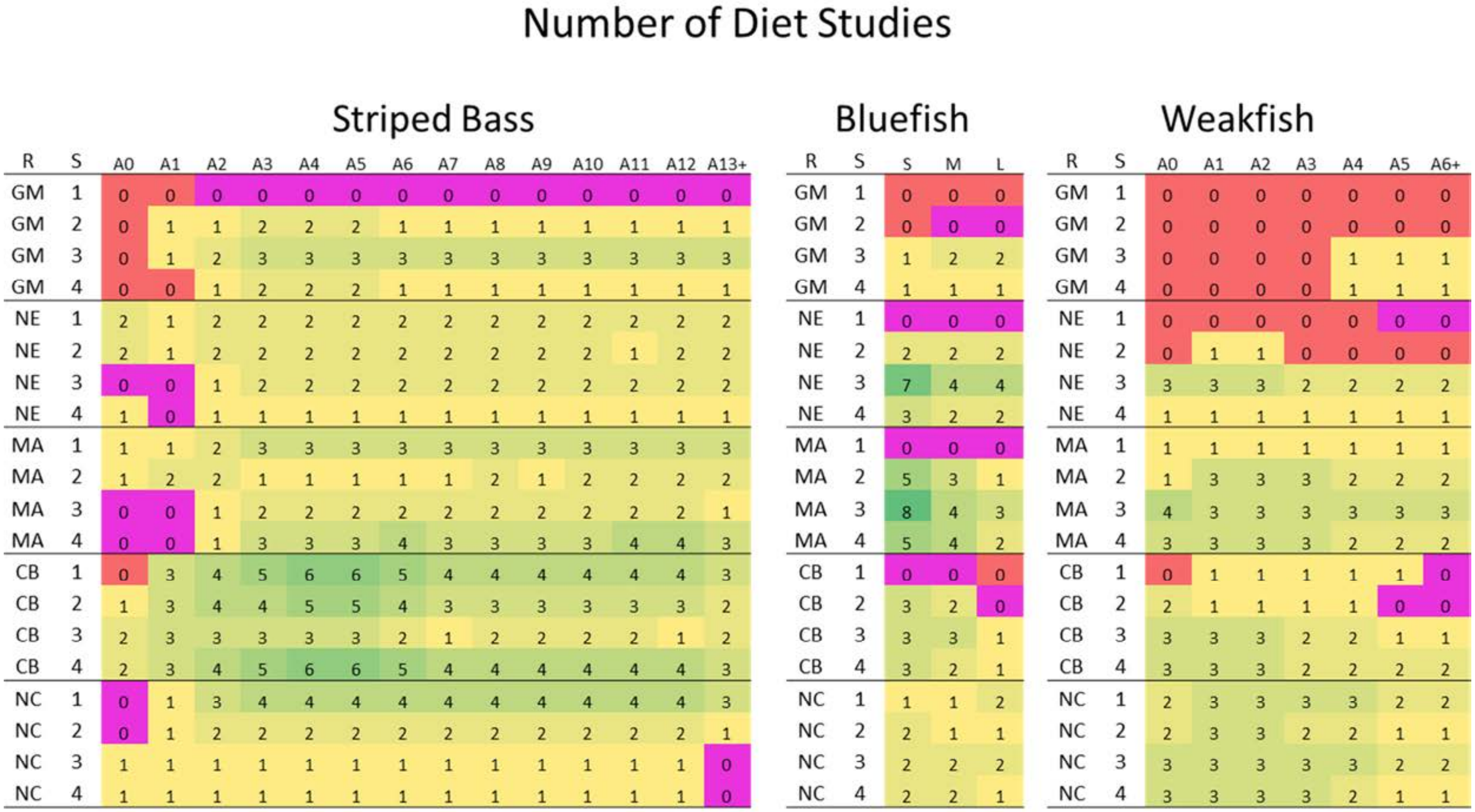


Figure 10. Number of diet studies informing the MSVPA's type preference for each of our predators, by age (A0, ..., A13+), by region (R) (GM = Gulf of Maine, NE = New England, MA = Mid Atlantic, CB = Chesapeake Bay, and NC = North Carolina), and by season (S; 1 = January - March, inclusive, ..., 4 = October - December, inclusive) and number of individual predator stomachs sampled from the diet studies (continued onto next page).



Number of Diet Studies

Striped Bass

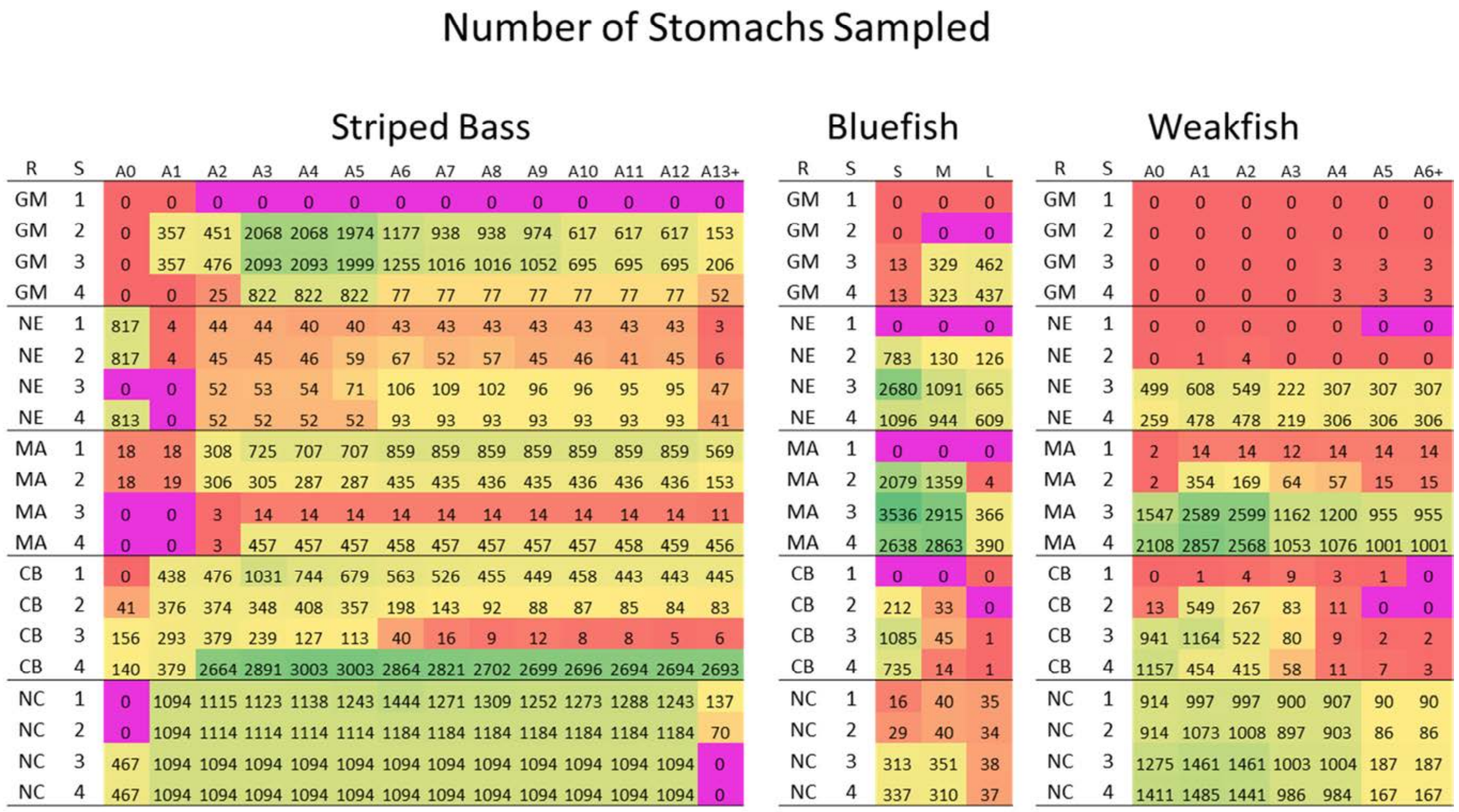
R	S	A0	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13+
GM	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GM	2	0	1	1	2	2	2	1	1	1	1	1	1	1	1
GM	3	0	1	2	3	3	3	3	3	3	3	3	3	3	3
GM	4	0	0	1	2	2	2	1	1	1	1	1	1	1	1
NE	1	2	1	2	2	2	2	2	2	2	2	2	2	2	2
NE	2	2	1	2	2	2	2	2	2	2	2	2	1	2	2
NE	3	0	0	1	2	2	2	2	2	2	2	2	2	2	2
NE	4	1	0	1	1	1	1	1	1	1	1	1	1	1	1
MA	1	1	1	2	3	3	3	3	3	3	3	3	3	3	3
MA	2	1	2	2	1	1	1	1	1	2	1	2	2	2	2
MA	3	0	0	1	2	2	2	2	2	2	2	2	2	2	1
MA	4	0	0	1	3	3	3	4	3	3	3	3	4	4	3
CB	1	0	3	4	5	6	6	5	4	4	4	4	4	4	3
CB	2	1	3	4	4	5	5	4	3	3	3	3	3	3	2
CB	3	2	3	3	3	3	3	2	1	2	2	2	2	1	2
CB	4	2	3	4	5	6	6	5	4	4	4	4	4	4	3
NC	1	0	1	3	4	4	4	4	4	4	4	4	4	4	3
NC	2	0	1	2	2	2	2	2	2	2	2	2	2	2	1
NC	3	1	1	1	1	1	1	1	1	1	1	1	1	1	0
NC	4	1	1	1	1	1	1	1	1	1	1	1	1	1	0

Bluefish

R	S	S	M	L
GM	1	0	0	0
GM	2	0	0	0
GM	3	1	2	2
GM	4	1	1	1
NE	1	0	0	0
NE	2	2	2	2
NE	3	7	4	4
NE	4	3	2	2
MA	1	0	0	0
MA	2	5	3	1
MA	3	8	4	3
MA	4	5	4	2
CB	1	0	0	0
CB	2	3	2	0
CB	3	3	3	1
CB	4	3	2	1
NC	1	1	1	2
NC	2	2	1	1
NC	3	2	2	2
NC	4	2	2	1

Weakfish

R	S	A0	A1	A2	A3	A4	A5	A6+
GM	1	0	0	0	0	0	0	0
GM	2	0	0	0	0	0	0	0
GM	3	0	0	0	0	1	1	1
GM	4	0	0	0	0	1	1	1
NE	1	0	0	0	0	0	0	0
NE	2	0	1	1	0	0	0	0
NE	3	3	3	3	2	2	2	2
NE	4	1	1	1	1	1	1	1
MA	1	1	1	1	1	1	1	1
MA	2	1	3	3	3	2	2	2
MA	3	4	3	3	3	3	3	3
MA	4	3	3	3	3	2	2	2
CB	1	0	1	1	1	1	1	0
CB	2	2	1	1	1	1	0	0
CB	3	3	3	3	2	2	1	1
CB	4	3	3	3	2	2	2	2
NC	1	2	3	3	3	3	2	2
NC	2	2	3	3	2	2	1	1
NC	3	3	3	3	3	3	2	2
NC	4	3	3	3	3	2	1	1



Number of Stomachs Sampled

Striped Bass

R	S	A0	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13+
GM	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GM	2	0	357	451	2068	2068	1974	1177	938	938	974	617	617	617	153
GM	3	0	357	476	2093	2093	1999	1255	1016	1016	1052	695	695	695	206
GM	4	0	0	25	822	822	822	77	77	77	77	77	77	77	52
NE	1	817	4	44	44	40	40	43	43	43	43	43	43	43	3
NE	2	817	4	45	45	46	59	67	52	57	45	46	41	45	6
NE	3	0	0	52	53	54	71	106	109	102	96	96	95	95	47
NE	4	813	0	52	52	52	52	93	93	93	93	93	93	93	41
MA	1	18	18	308	725	707	707	859	859	859	859	859	859	859	569
MA	2	18	19	306	305	287	287	435	435	436	435	436	436	436	153
MA	3	0	0	3	14	14	14	14	14	14	14	14	14	14	11
MA	4	0	0	3	457	457	457	458	457	457	457	457	458	459	456
CB	1	0	438	476	1031	744	679	563	526	455	449	458	443	443	445
CB	2	41	376	374	348	408	357	198	143	92	88	87	85	84	83
CB	3	156	293	379	239	127	113	40	16	9	12	8	8	5	6
CB	4	140	379	2664	2891	3003	3003	2864	2821	2702	2699	2696	2694	2694	2693
NC	1	0	1094	1115	1123	1138	1243	1444	1271	1309	1252	1273	1288	1243	137
NC	2	0	1094	1114	1114	1114	1114	1184	1184	1184	1184	1184	1184	1184	70
NC	3	467	1094	1094	1094	1094	1094	1094	1094	1094	1094	1094	1094	1094	0
NC	4	467	1094	1094	1094	1094	1094	1094	1094	1094	1094	1094	1094	1094	0

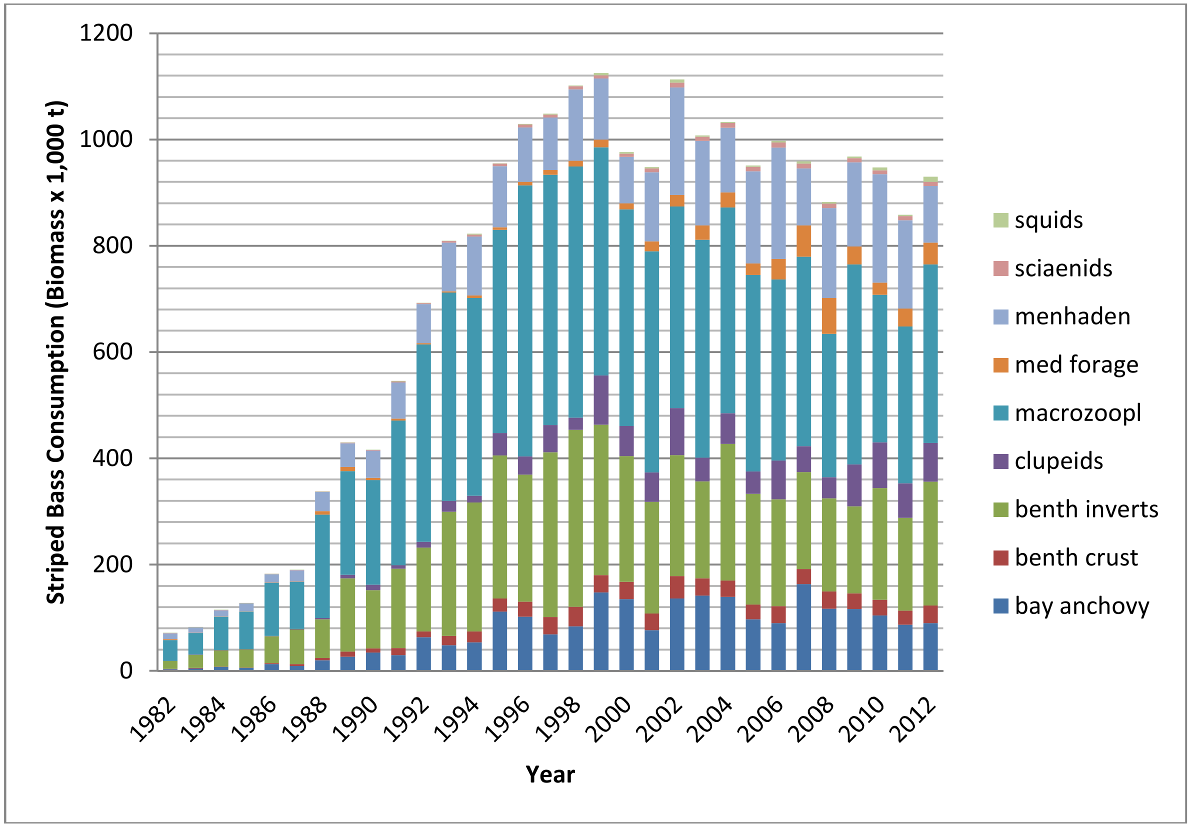
Bluefish

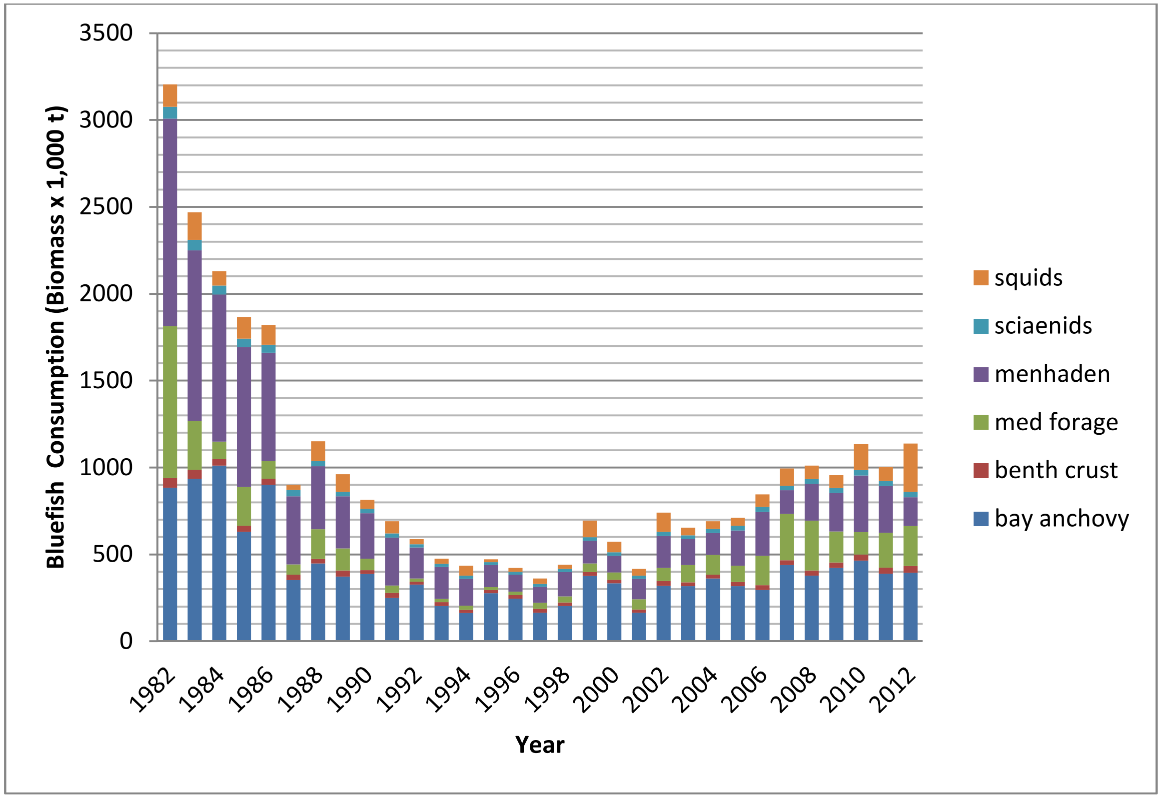
R	S	S	M	L
GM	1	0	0	0
GM	2	0	0	0
GM	3	13	329	462
GM	4	13	323	437
NE	1	0	0	0
NE	2	783	130	126
NE	3	2680	1091	665
NE	4	1096	944	609
MA	1	0	0	0
MA	2	2079	1359	4
MA	3	3536	2915	366
MA	4	2638	2863	390
CB	1	0	0	0
CB	2	212	33	0
CB	3	1085	45	1
CB	4	735	14	1
NC	1	16	40	35
NC	2	29	40	34
NC	3	313	351	38
NC	4	337	310	37

Weakfish

R	S	A0	A1	A2	A3	A4	A5	A6+
GM	1	0	0	0	0	0	0	0
GM	2	0	0	0	0	0	0	0
GM	3	0	0	0	0	3	3	3
GM	4	0	0	0	0	3	3	3
NE	1	0	0	0	0	0	0	0
NE	2	0	1	4	0	0	0	0
NE	3	499	608	549	222	307	307	307
NE	4	259	478	478	219	306	306	306
MA	1	2	14	14	12	14	14	14
MA	2	2	354	169	64	57	15	15
MA	3	1547	2589	2599	1162	1200	955	955
MA	4	2108	2857	2568	1053	1076	1001	1001
CB	1	0	1	4	9	3	1	0
CB	2	13	549	267	83	11	0	0
CB	3	941	1164	522	80	9	2	2
CB	4	1157	454	415	58	11	7	3
NC	1	914	997	997	900	907	90	90
NC	2	914	1073	1008	897	903	86	86
NC	3	1275	1461	1461	1003	1004	187	187
NC	4	1411	1485	1441	986	984	167	167

Figure 11. Biomass of all prey consumed by each predator species in the 2014 MSVPA update (continued onto next two pages).




3500
3000
2500
2000
1500
1000
500
0
Bluefish Consumption (Biomass x 1,000 t)
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Year
squids
sciaenids
menhaden
med forage
benth crust
bay anchovy

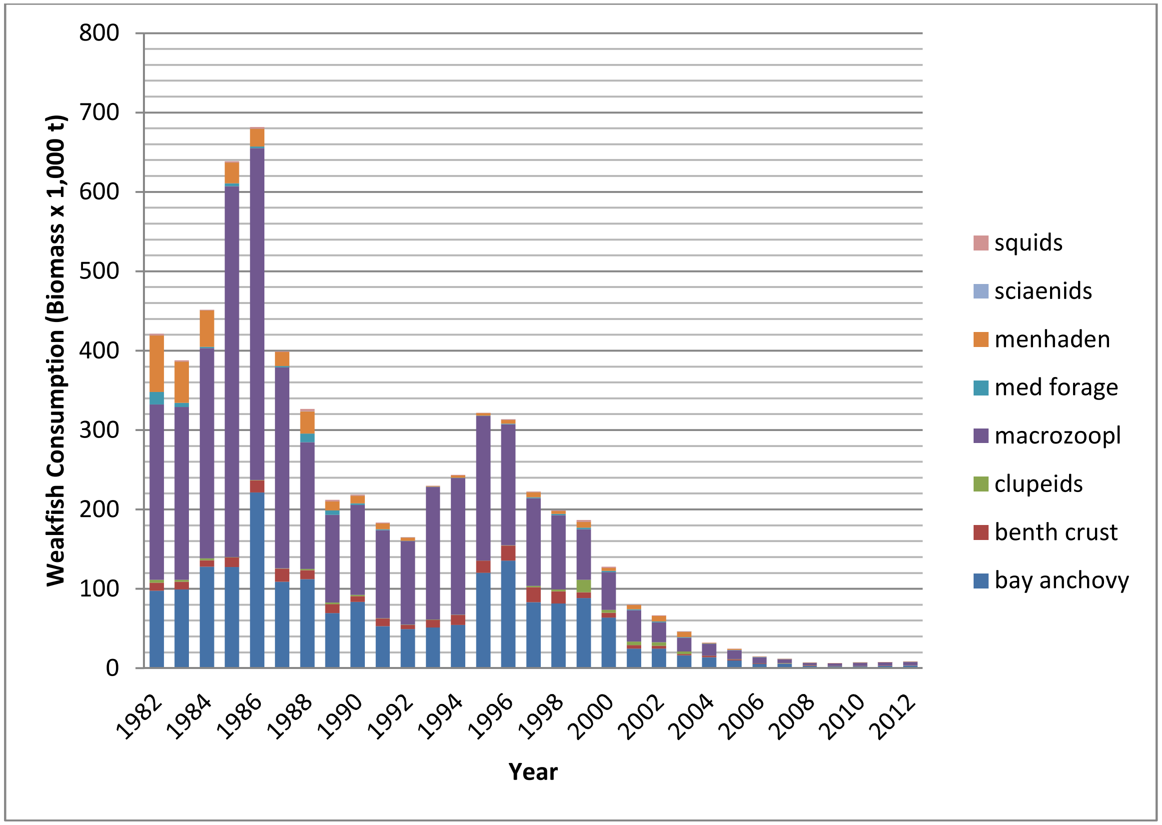
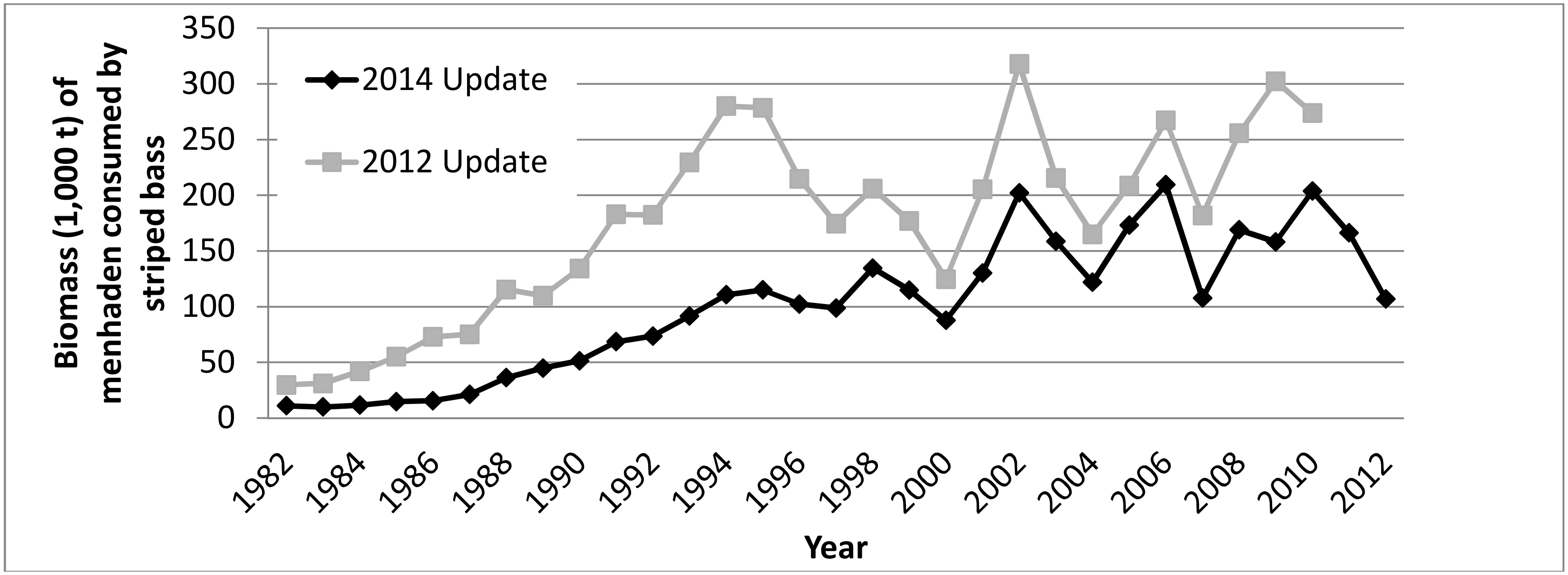
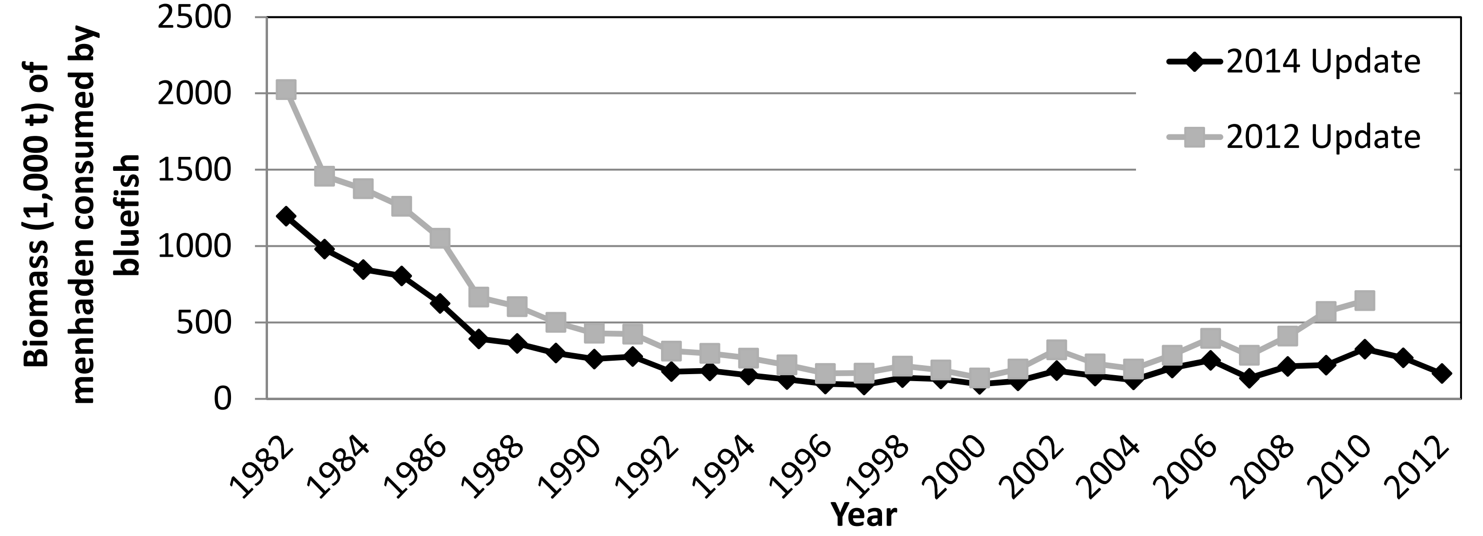

Weakfish Consumption (Biomass x 1,000 t)
800
700
600
500
400
300
200
100
0
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Year
squids
sciaenids
menhaden
med forage
macrozoopl
clupeids
benth crust
bay anchovy

Figure 12. Comparison of Atlantic menhaden consumed by each predator species in the 2012 and 2014 MSVPA updates (continued onto next page).




Biomass (1,000 t) of menhaden consumed by bluefish
2500
2000
1500
1000
500
0
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Year
2014 Update
2012 Update

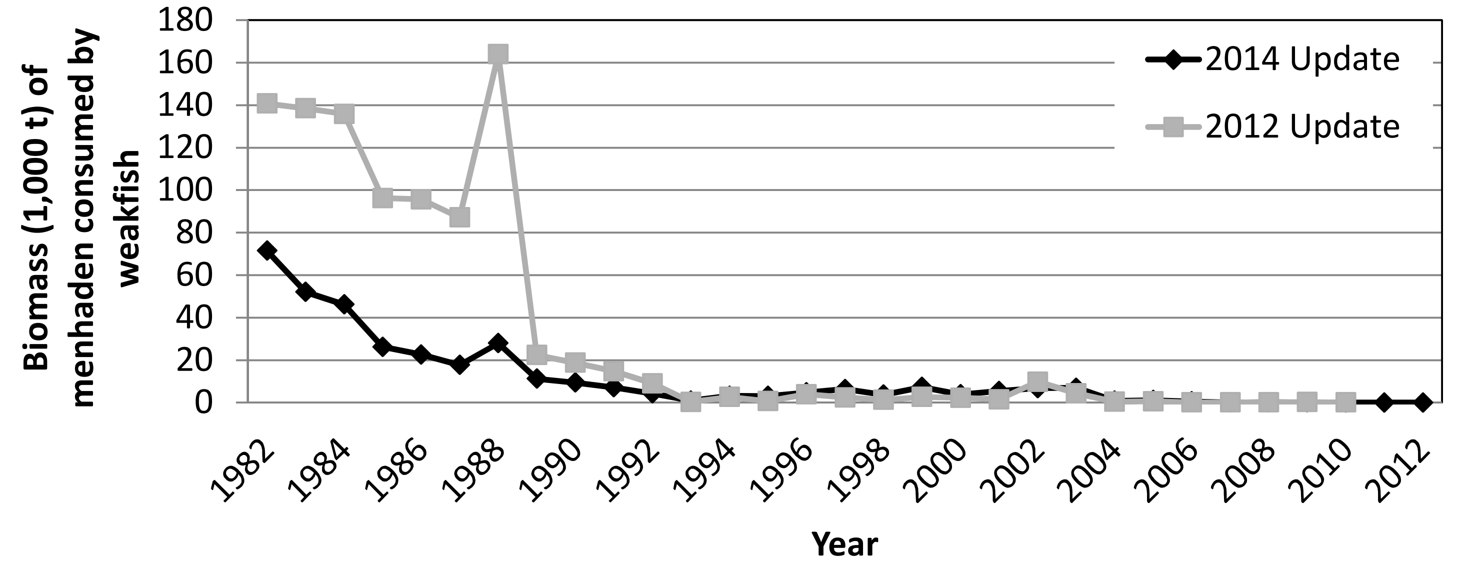
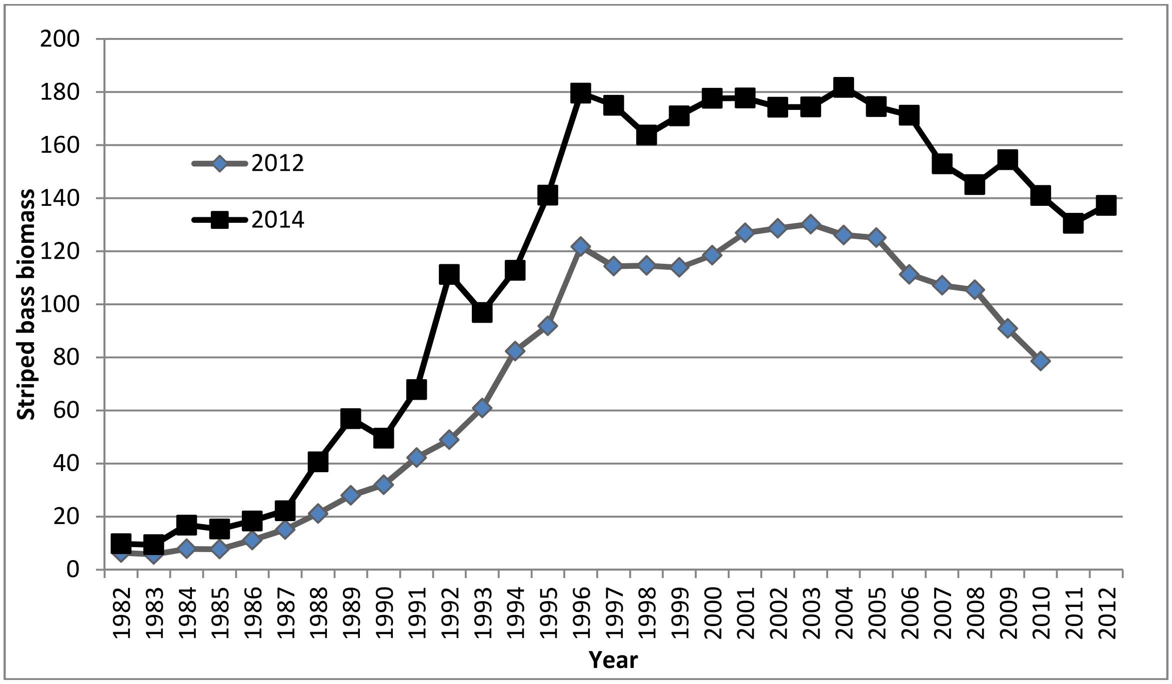
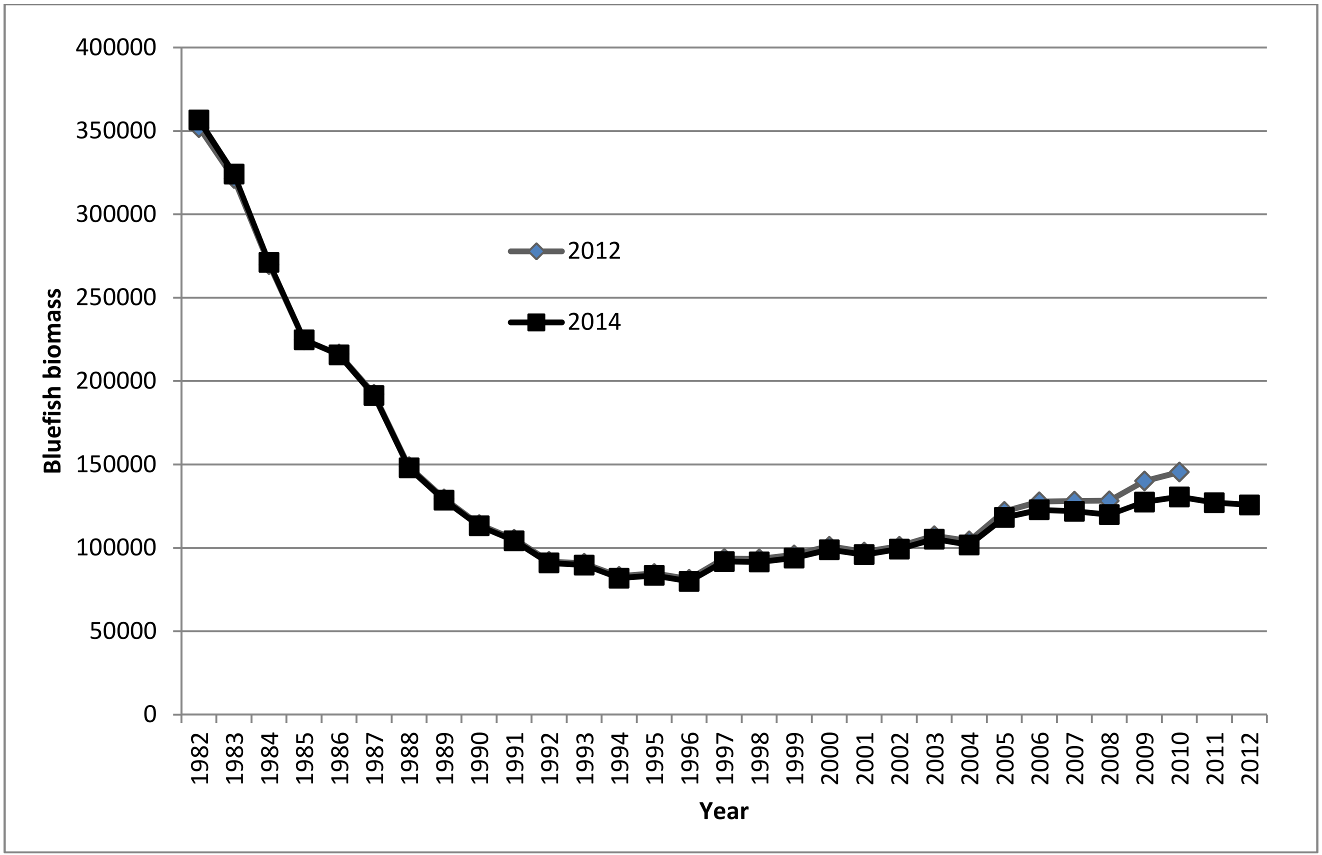

Biomass (1,000 t) of menhaden consumed by weakfish
180
160
140
120
100
80
60
40
20
0
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Year
2014 Update
2012 Update

Figure 13. Comparison of predator biomass used in the 2012 and 2014 MSVPA updates (continued onto next page).




400000
350000
300000
250000
200000
150000
100000
50000
0
Bluefish biomass
2012
2014
1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012
Year

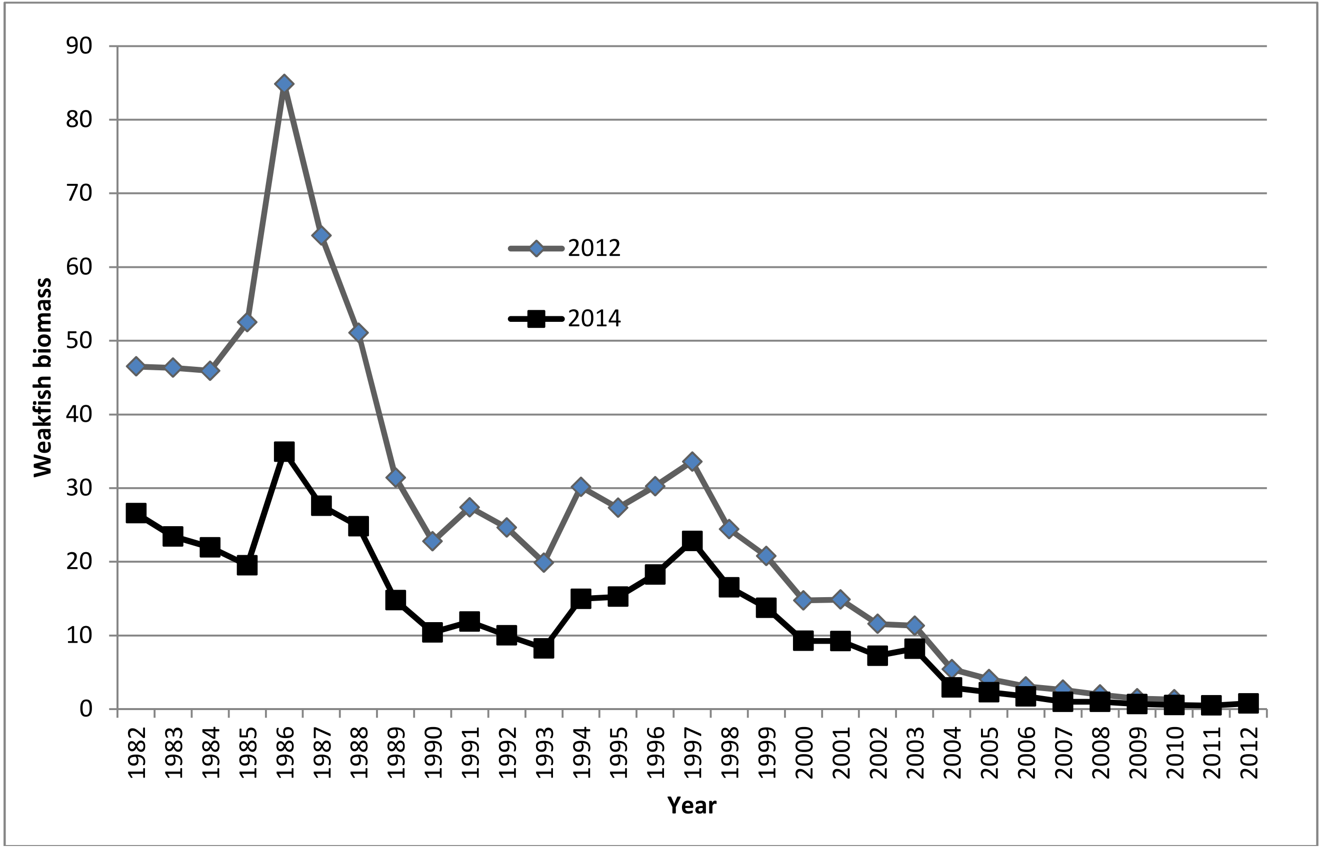
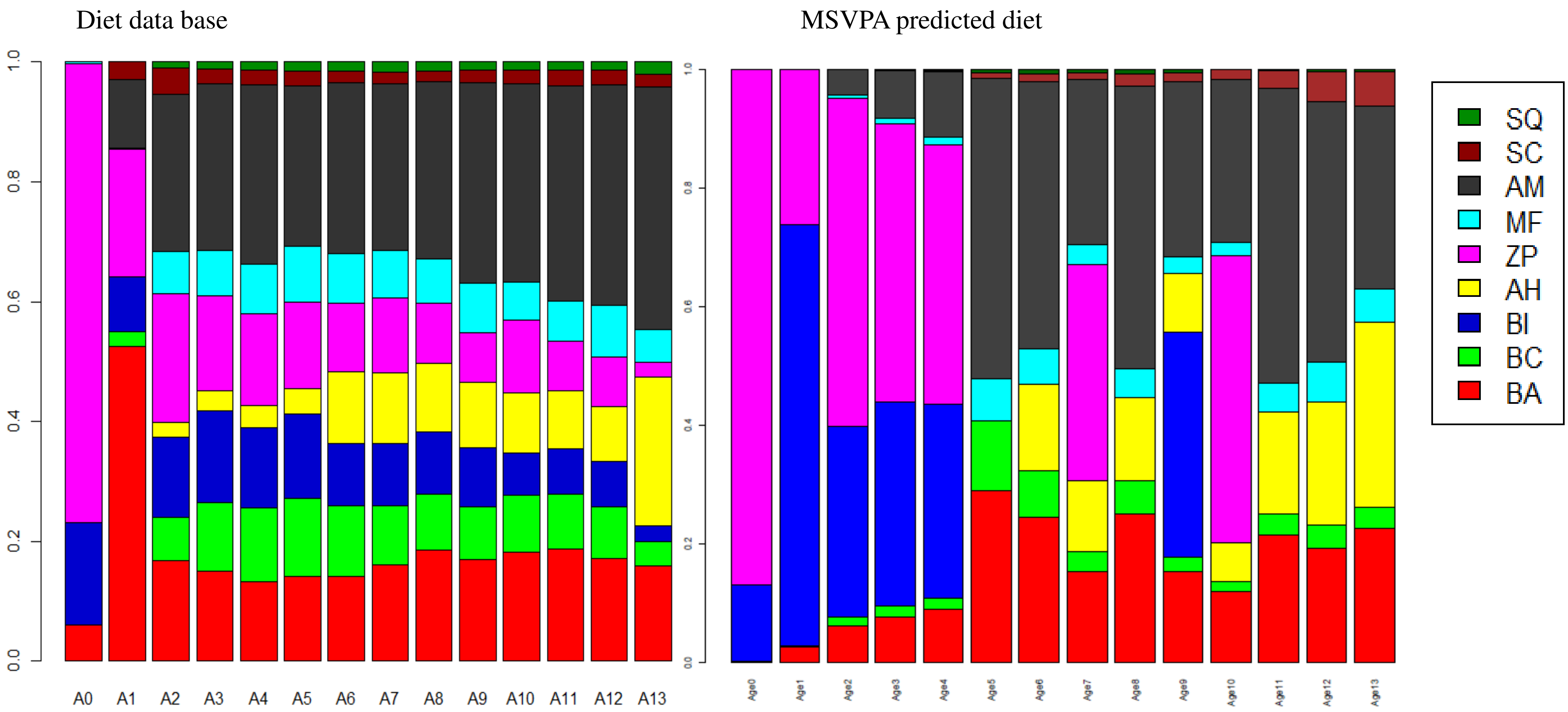

90
80
70
60
50
40
30
20
10
0
Weakfish biomass
2012
2014
1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012
Year

Figure 14. Comparison of striped bass diet (averaged across all seasons and years) predicted by the MSVPA and seen in our diet database. See Figure 6 for definition of prey groups listed in legend.


Diet data base

MSVPA predicted diet

Figure 15. Size selectivity of an age 2 striped bass for benthic invertebrates and macrozooplankton. Red solid line = selectivity from 2012 update; red dotted line = selectivity from 2014 update; green solid line = prey length frequency; see Figure 8 for further explanation. See appendix 2 for the complete set of predator age × prey combinations.

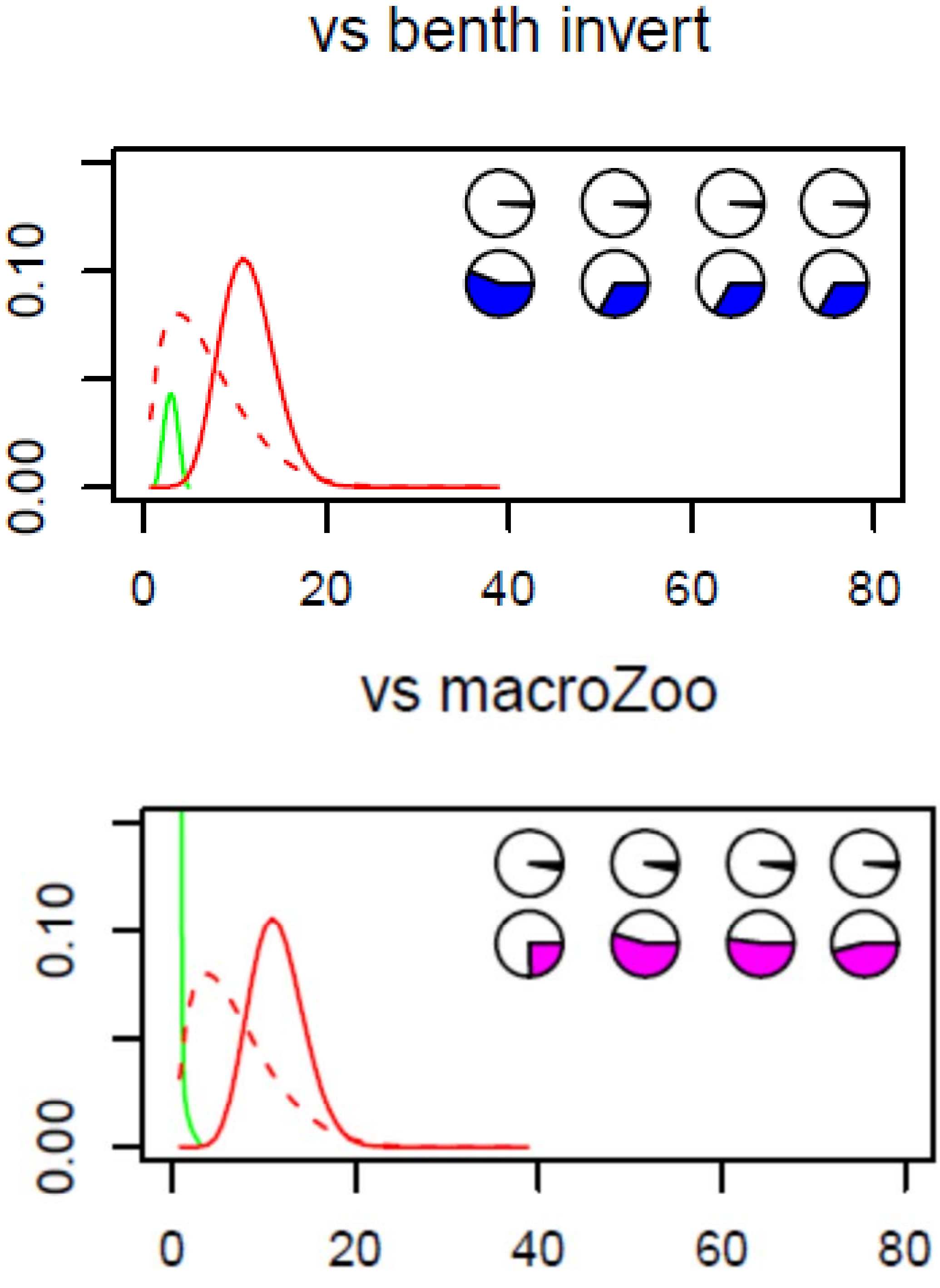


Figure 16. Biomass of menhaden consumed by predator species across all years

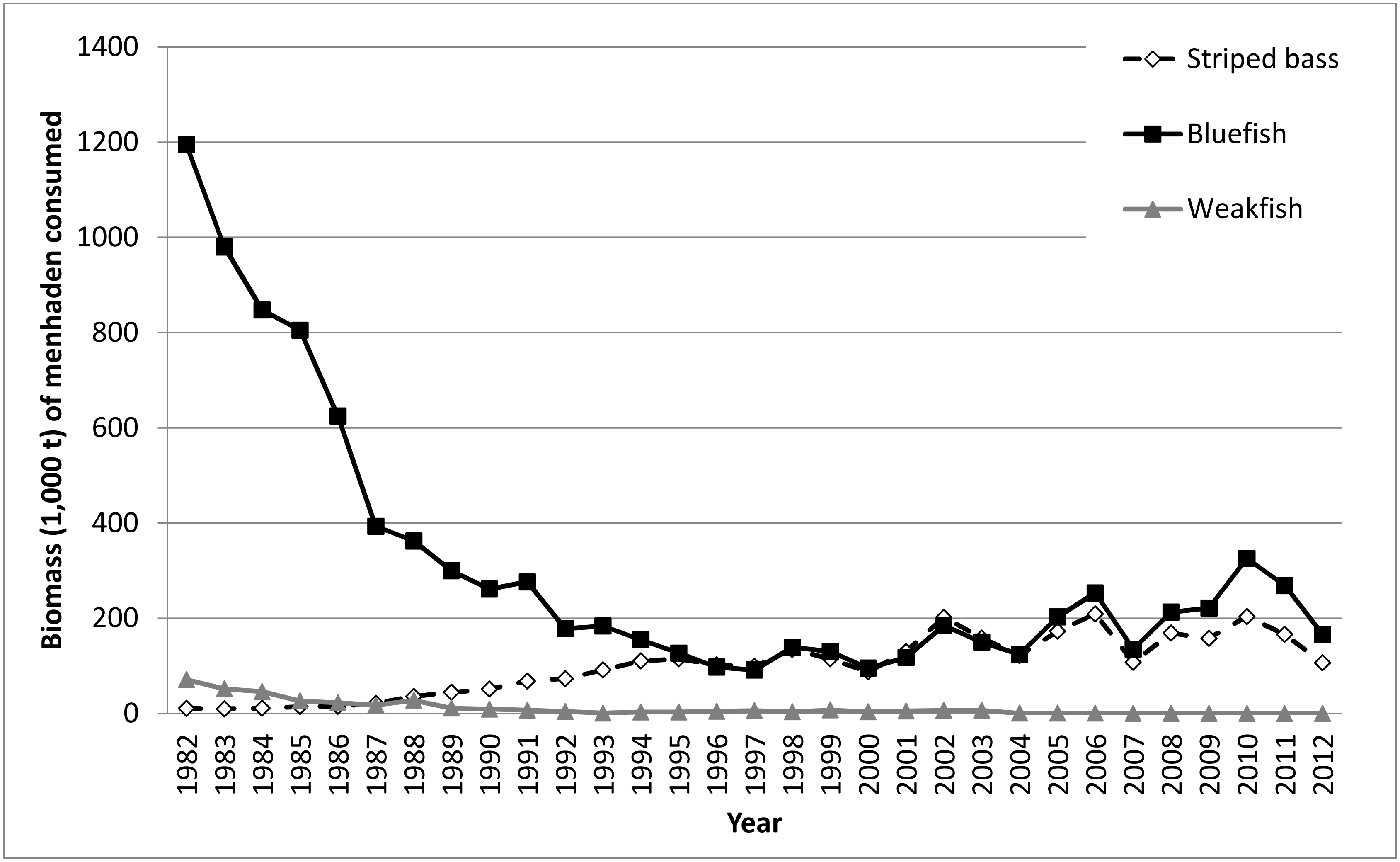


Figure 17. Atlantic menhaden natural mortality by striped bass, bluefish, and weakfish

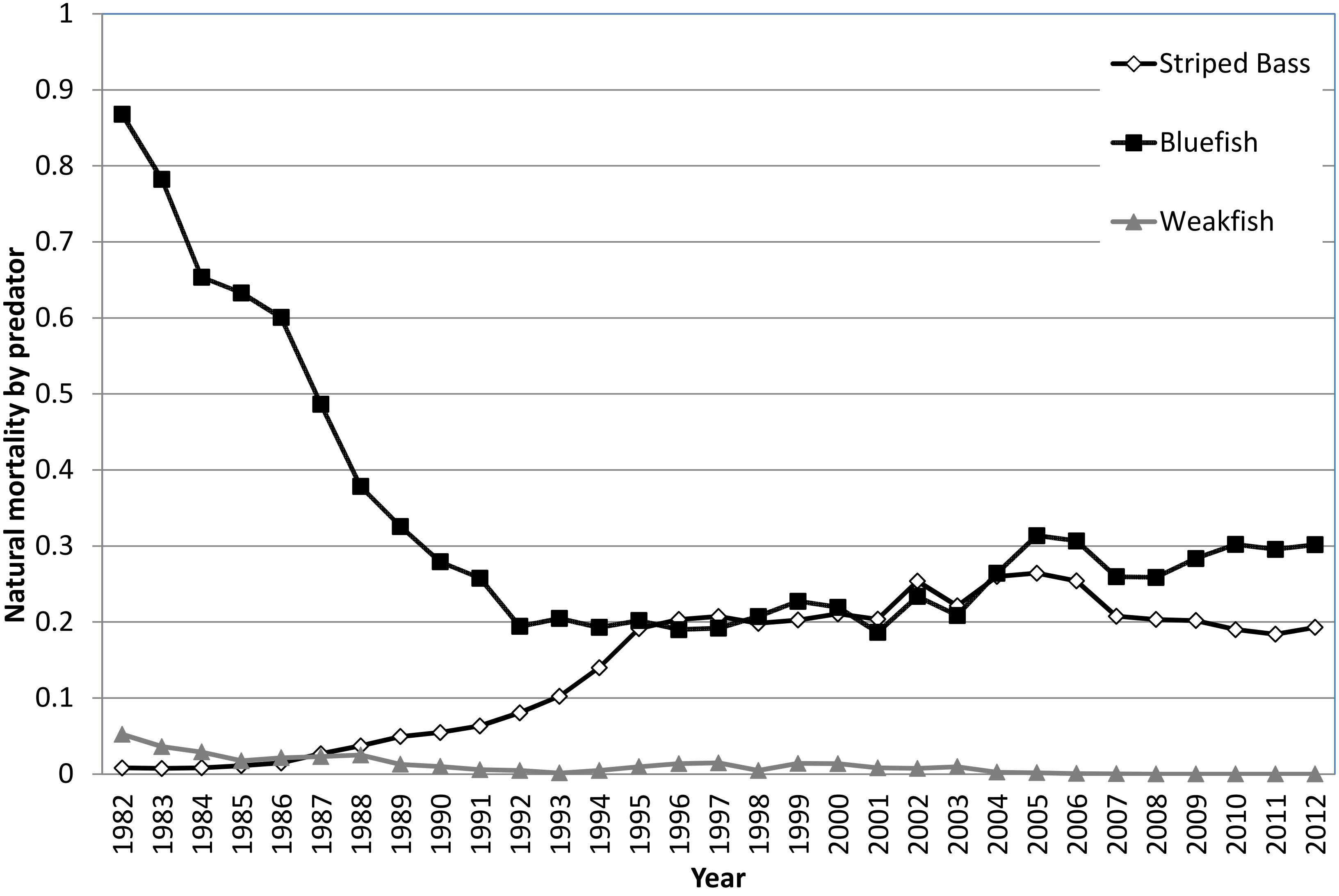
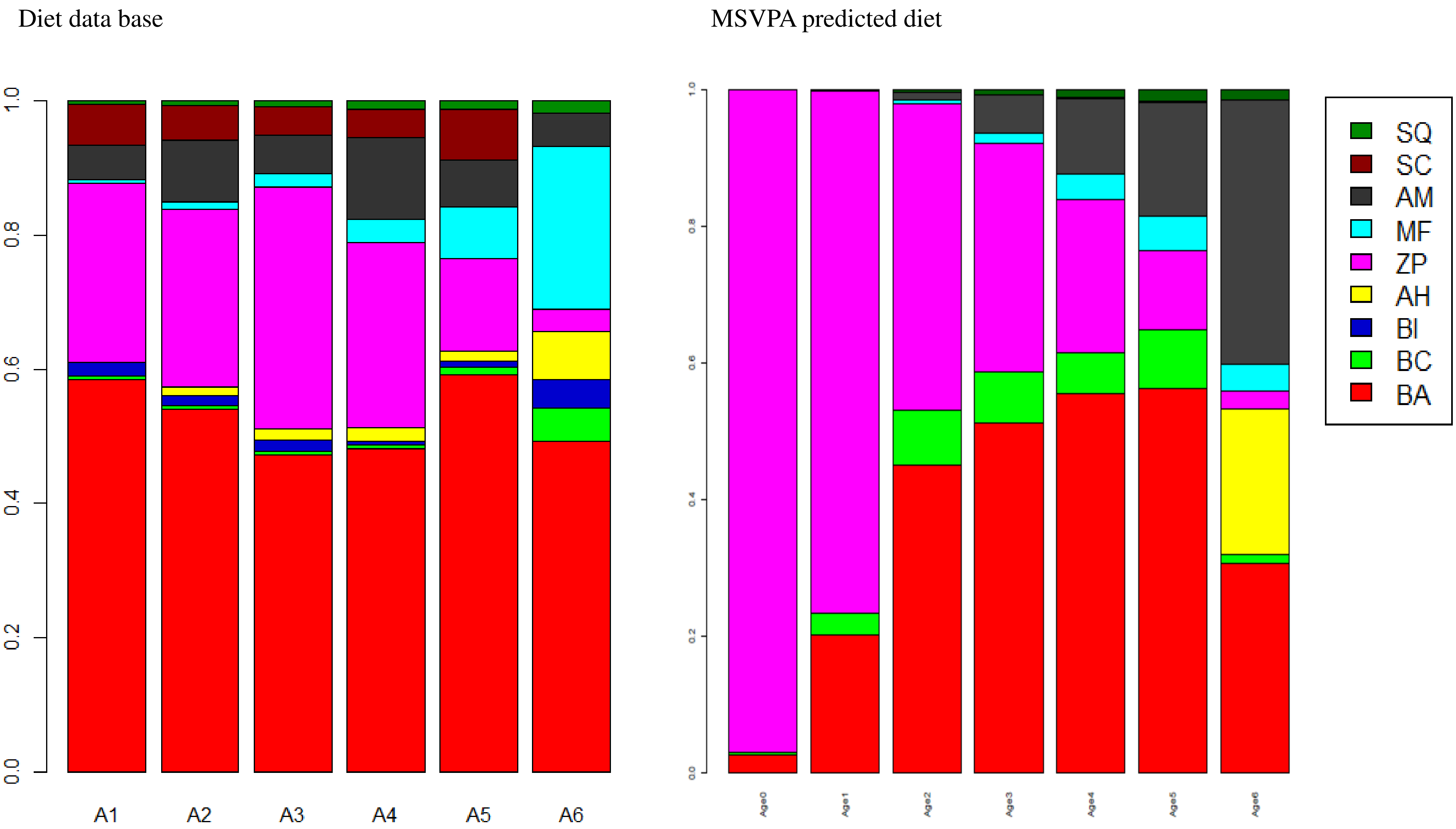


Figure 18. Comparison of weakfish diet (averaged across all seasons and years) predicted by the MSVPA and seen in our diet database. See Figure 6 for definition of prey groups listed in legend.


Diet data base

MSVPA predicted diet

Figure 19. Comparison of bluefish diet (averaged across all seasons and years) predicted by the MSVPA and seen in our diet database. See Figure 6 for definition of prey groups listed in legend.

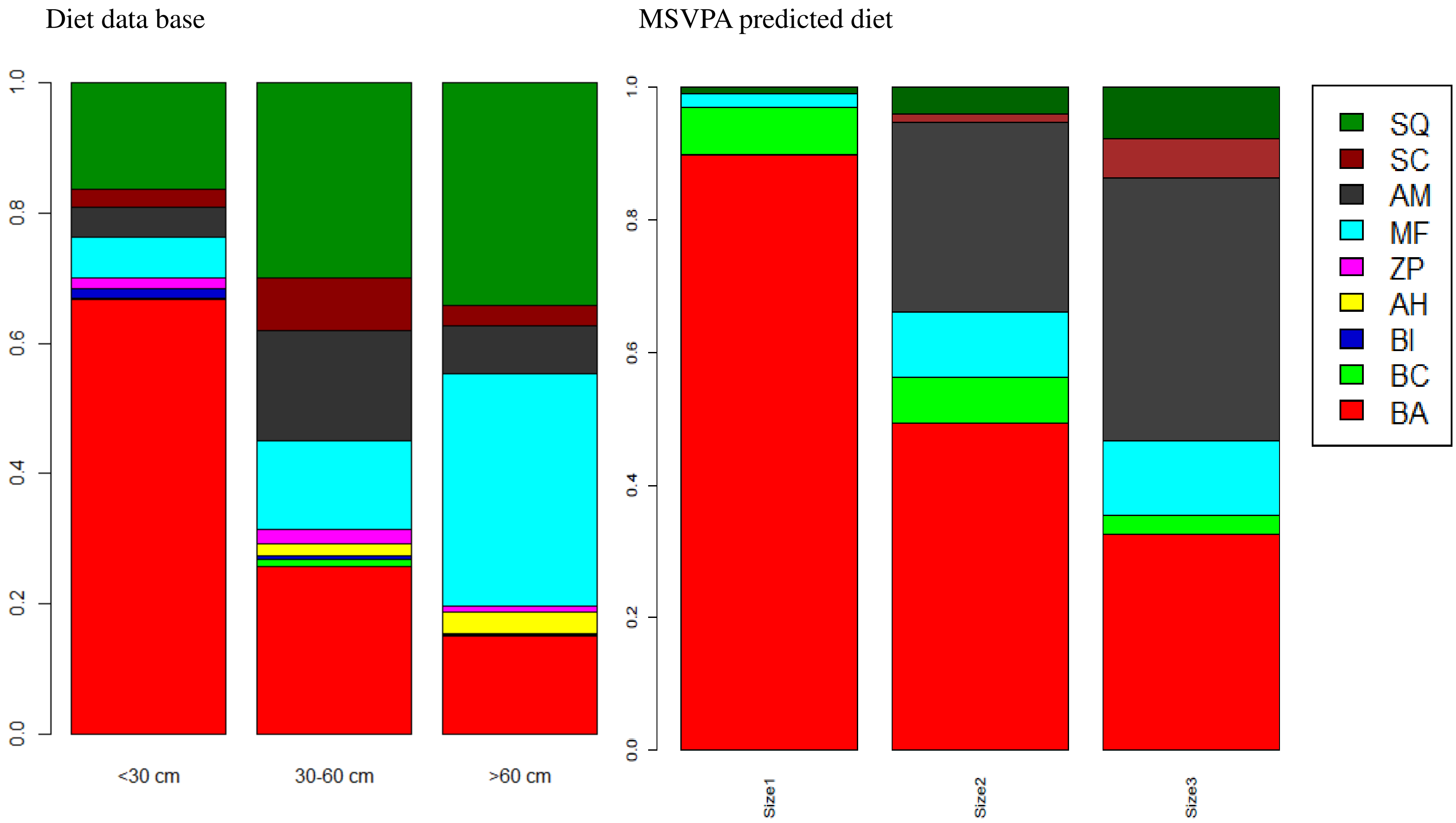
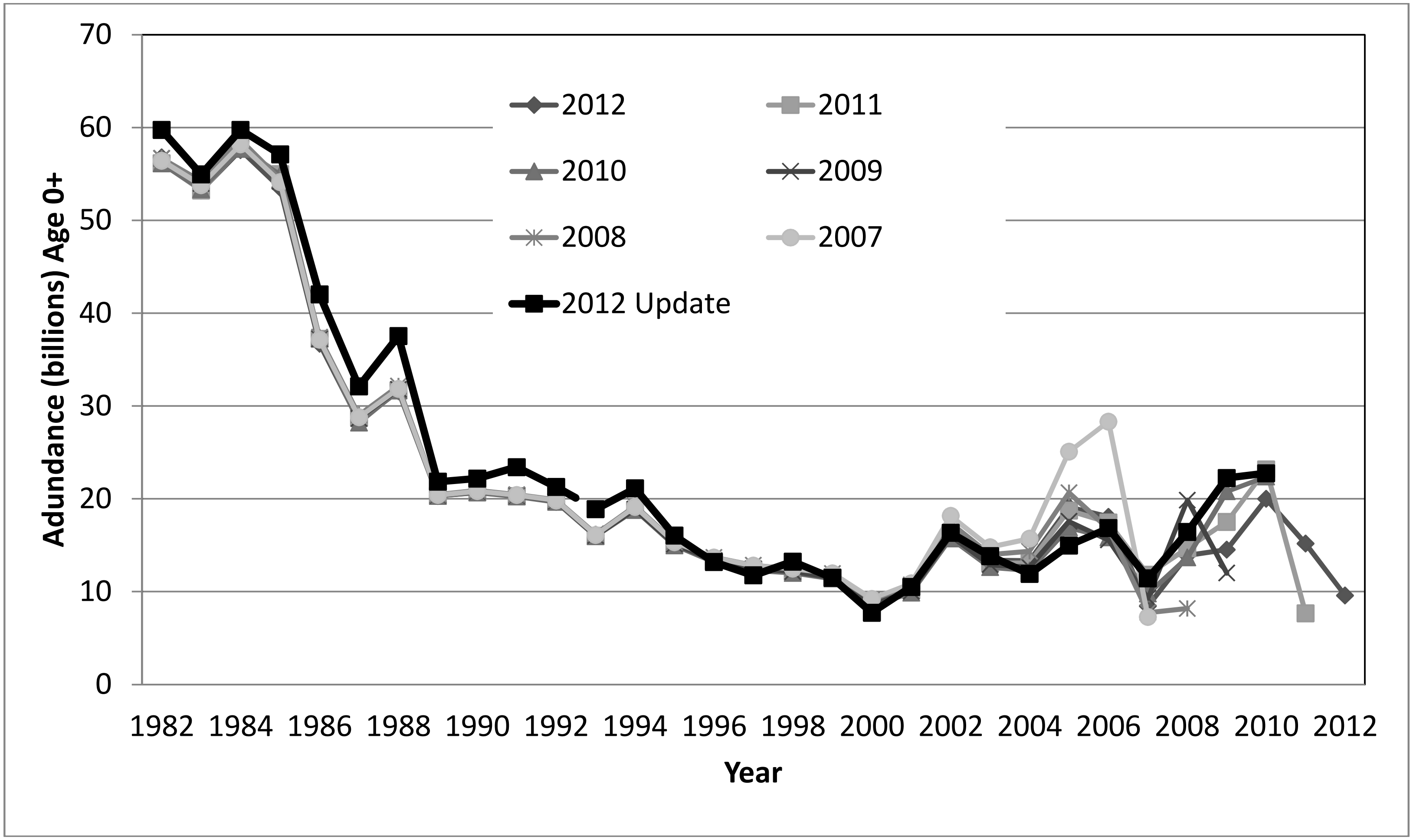


Figure 20. Total population abundance (ages 1+) of Atlantic menhaden



Application of a spatial tag-return model to historic Atlantic menhaden data

Final report to Atlantic States Marine Fisheries Commission

October 7, 2014

William E. Smith

North Carolina Division of Marine Fisheries

3441 Arendell Street, Morehead City, NC

Amy M. Schueller and Joseph W. Smith

National Marine Fisheries Service

101 Pivers Island Road, Beaufort, NC

ABSTRACT

Historic Atlantic menhaden tag-return data collected during 1966–1970 were recently redigitized from raw data sheets. While the dataset had been analyzed previously, it had not been analyzed using a modern tag-return modeling approach. This report presents a preliminary analysis of the Atlantic menhaden tag-return data using a multistate or spatial tag-return model that accounts for important model assumptions, including tag-return efficiencies (or reporting rates) and tag retention. The model is used to quantify instantaneous rates of fishing mortality and age-specific movement probabilities between three spatial strata, New York, New Jersey, and a final stratum including all areas from Chesapeake Bay to Florida. Fishing mortality was greatest in the southern region, and fish movement appeared to vary by season and age, with older fish having a high probability of moving from southern to northern regions in spring and summer and lower probabilities of northward movement in fall and winter.

INTRODUCTION

In the mid-1960s the Menhaden Program at the Beaufort Laboratory embarked on an extensive coastwide tagging project of adult Atlantic menhaden (Kroger and Dryfoos 1972; Dryfoos et al. 1973). Through the 1970s over one million Atlantic menhaden (adults and juveniles) were injected with uniquely labeled ferro-magnetic tags and released. Tag recoveries occurred on magnets strategically located within menhaden processing plants along the East coast of the US. The menhaden factories were also “salted” with plant release tags to estimate recovery efficiencies of wild tags. Several publications ensued reporting on general migratory routes of menhaden and estimates of natural mortality rates (Dryfoos et al. 1973; Nicholson 1978; Ahrenholz et al. 1987).

Menhaden fishery-dependent and -independent data were historically maintained on mainframe computers at NOAA’s Southeast Fisheries Science Center in Miami. In the early 1990s, all data at the Center were to migrate from Miami to servers at the Beaufort Lab. Unfortunately, electronic versions of the adult menhaden tagging data never made the transition and were lost. Personnel at the Beaufort Lab were fortunate to have preserved summary hard copies (= bound print-outs) of adult menhaden tagging data files.

In early 2013 the Atlantic States Marine Fisheries Commission approved funding to key-enter hard copies of the historical adult menhaden tagging data into electronic files. This task was completed in summer 2013. The data files were subsequently loaded into Access data bases (by R. Sysak of NY DEC) and were edited for errors.

MODEL DESCRIPTION

A Bayesian multistate tag-return model was fit to Atlantic menhaden tag-return data collected during 1966–1970 in three areas: New York (NY), New Jersey (NJ), and the South Atlantic (SA;

Chesapeake Bay to Florida) (see Dryfoos et al. 1973 for tag-return study design and field methods). The multistate tag-return model is an extension of the (1) multistate model (Brownie et al. 1993), which estimates survival, observation, and state transition probabilities over time in a population of tagged animals, and (2) an instantaneous rates version of the Brownie et al. (1985) tag-return model (Hoenig et al. 1998), which estimates survival and the instantaneous rate of fishing mortality. The multistate tag-return model is similar to the traditional single state tag-return model, except that parameters are state-specific and transitions between states are modeled (Brownie et al. 1993; Joe and Pollock 2000; Eveson et al. 2009). In this application, states were defined spatially as the state of being in NY, NJ, or SA. The multistate or spatial tag-return model consisted of two coupled equations: (1) a state equation describing how cohorts of fish tagged move, conditional on cohort movement and survival during the previous sampling occasion and (2) an observation equation linking the probability of harvest to spatial states.

A matrix of state transition probabilities, **Ω,** with rows corresponding to current states and columns corresponding to future states, was defined by movement and survival probabilities,

$$\begin{array}{l|ccc} \underline{\text{State at time } t} & & \underline{\text{State at time } t{+}1} & \\ & s = \text{NY} & s = \text{NJ} & s = \text{SA} \end{array}$$

$$\text{Pr(state)} = \begin{array}{c} s = NY \\ s = NJ \\ s = SA \end{array} \begin{bmatrix} \phi_{a-1,NY} * \psi_{a-1,NY,NY} & \phi_{a-1,NY} * \psi_{a-1,NY,NJ} & \phi_{a-1,NY} * \psi_{a-1,NY,SA} \\ \phi_{a-1,NJ} * \psi_{a-1,NJ,NY} & \phi_{a-1,NJ} * \psi_{a-1,NJ,NJ} & \phi_{a-1,NJ} * \psi_{a-1,NJ,SA} \\ \phi_{a-1,SA} * \psi_{a-1,SA,NY} & \phi_{a-1,SA} * \psi_{a-1,SA,NJ} & \phi_{a-1,SA} * \psi_{a-1,SA,SA} \end{bmatrix}.$$

$\phi_{a,s}$ was the discrete probability of surviving at age ***a*** and state ***s***, and $\psi_{a,s,ss}$ was the age-specific probability of transitioning from ***s*** to another state ***ss*** by the subsequent time period (Tables 1 and 2).

$\phi_{a,s}$ was a function of an age-specific rate of instantaneous mortality M_a, selectivity at age, sel_a, and state-specific fishing mortality, F_s,

$$\phi_{a,s} = \mathrm{e}^{-(sel_a * F_s + M_a)}.$$

$\boldsymbol{M_a}$ were set to rates used in the stock assessment (Section 3.6). Most tagging models assume that fish are tagged at the beginning of each time period, but Atlantic menhaden were tagged continuously throughout each time period. ϕ were adjusted during each tagged cohort's initial time period to account for variable time at large by multiplying total mortality ($\boldsymbol{sel_a}$ * $\boldsymbol{F_s}$ + $\boldsymbol{M_a}$) by the average fraction of each time period remaining when each cohort of fish was tagged. $\psi_{\boldsymbol{a,s,ss}}$ were estimated for each time period and age-1 through age-4; age-4 and greater movement patterns were considered equal. $\psi_{\boldsymbol{a,s,ss}}$ were constrained to sum to one for each age and starting location (i.e. probability of staying in a spatial stratum plus the probability of moving elsewhere equaled one).

Tag return rates, or observation probabilities, can be modeled as a function of instantaneous rates of mortality after accounting for tag loss and incomplete reporting of harvested tags (Pollock et al. 1991). Instantaneous rates of fishing mortality are generally the focus of inference in fisheries applications of single state tag-return models (Bacheler et al. 2008; Jiang et al. 2007; Smith et al. 2009). Θ was an observation probability vector with rows corresponding to states where harvest occurred,

$$\text{Pr(observation)} = \begin{array}{cc} & \underline{\text{State at time } t} \\ \left[\begin{array}{c} \rho * \lambda_{NY} * sel_a * F_{NY} * (1-\phi_{a,NY})/(sel_a + F_{NY} + M_a) \\ \rho * \lambda_{NJ} * sel_a * F_{NJ} * (1-\phi_{a,NJ})/(sel_a + F_{NJ} + M_a) \\ \rho * \lambda_{SA} * sel_a * F_{SA} * (1-\phi_{a,SA})/(sel_a + F_{SA} + M_a) \end{array}\right] & \begin{array}{c} s = NY \\ s = NJ \\ s = SA \end{array} \end{array}.$$

Acute tag retention and survival of the tagging process, ρ**,** was estimated by holding 100 tagged fish for 10 weeks in large circular tanks (Kroger and Dryfoos 1972). ρ was set equal to the number surviving with tag intact divided by the total number observed for tag loss and mortality (ρ = 0.83). Magnet efficiency in each area, $\lambda_{\boldsymbol{s}}$, was estimated by "salting" a known quantity of tagged fish into the catch processed at each monitored reduction plant. The total number of tag recoveries, $\boldsymbol{r}$**,** from each trial, $\boldsymbol{tr}$**,** was binomially distributed, with rate $\boldsymbol{\lambda_s}$ and sample size equal to the number of “salted” tags in each trial, $\boldsymbol{n_{tr}}$,

$$r_{tr} \sim binomial(\lambda_s, n_{tr}).$$

Three selectivity-at-age ($\boldsymbol{sel_a}$) functions were tested: age-constant, logistic, and double logistic. Age-3 fish were assumed to be fully recruited to the fishery.

The triangular matrix of tag recoveries by area and time, ***y,*** (Table 3) was multinomially distributed, with a corresponding matrix of multinomial probabilities defined as the product of Θ and **Ω**,

$$y_{i,s,t} \sim multinomial\left(\theta * \Omega, N_{s,t}\right),$$

where ***N*** was a matrix of the total number tagged in each state and time.

A seasonal time step was defined, with April–September representing spring-summer periods and October–March representing fall-winter. The fishery did not operate in northern regions, NY and NJ, from December–March, so the probability of observations in northern regions was zero during the winter, regardless of presence or absence. December–March data were considered incomplete, consisting of SA data alone; thus, all data collected from December–March were censored.

A set of 24 candidate models was developed and tested, including models with age-constant and age-variable ***M*** and ψ, models with and without a seasonal effect on ψ, and three fishery selectivity functions. All possible candidate models were compared using Deviance Information Criteria (DIC; Spiegelhalter et al. 2002), and the model with lowest DIC was identified as the best model to use for inference. JAGS software and the R package rjags were used to sample the posterior distributions of all model parameters (Plummer 2003; R 2010). For each model, a burn-in period of 50,000 was followed by 200,000 samples of the posterior distribution. Model convergence was assessed among two chains by examining trace plots of each model parameter and using Gelman and Rubin’s diagnostic (Gelman and Rubin 1992). Only models that reached convergence were considered in the set of candidate models.

RESULTS

Data from 918,912 tagged Atlantic menhaden and 101,985 tag recoveries were included in the model (Table 3). Based on lengths from a subset of fish aged at tagging and an age-length key developed from fishery catches in the same years as the tagging project, most fish tagged in NY and NJ were age-3 at tagging (61%) and most fish tagged in SA were age-1 at tagging (56%). The best model identified by DIC model selection included age-specific natural mortality, age-specific and seasonal movement probabilities, and domed-shaped selectivity (Table 4; Figure 1). Area-specific magnet efficiencies ranged from 67–82%, and estimates of fishing mortality showed a strong latitudinal gradient, with highest mortality in southern areas (Figure 2). Estimates of movement probabilities indicated a high probability of remaining in NY (Figure 3); however, fish were never tagged in the fall-winter in NY, so fall-winter migrations from NY could not be characterized. Fish tagged in NJ had a high probability of moving northward to NY.

Age- and seasonal-specific movement rates were evident in the SA, where the largest number of fish were tagged and where fish were tagged throughout the year. At age-1, SA-tagged fish had a high probability of remaining in the SA, but at later ages, fish appeared to begin moving northwards to NJ and NY. By age-3 few fish appeared to move from SA to NJ, but appeared instead to move to NY with a very high probability. In general the probability of SA-tagged fish moving northwards was highest in the spring-summer and lowest in the fall-winter.

DISCUSSION

Movement rate estimates generated by the spatial tag-return model represent direct estimates of dispersal rates for adult Atlantic menhaden using tagging data. The distribution of tag recoveries indicated significant mixing of the stock from Florida to NY, and model estimates indicated that movements were seasonal and age-specific. During the spring and summer, older fish had a much higher probability of migrating to northern regions than remaining in southern regions, and the probabilities of northwards movements were lower during cooler months. These model estimates are consistent with the observation that most fish aged in NY and NJ were age-3 or older and that the Atlantic menhaden reduction fishery has a history of contracting to southern regions in the fall, presumably following a seasonal southern migration of the stock.

Early analysis of tag-return data

The modeling approach employed in this analysis represents an improvement over previous analyses of the same dataset (Dryfoos et al. 1973, Nicholson 1978). Earlier analyses did not employ a tag-return model that accounted for reporting rates, tag retention, or continuous tagging throughout each time period; further, movement rates were only qualitatively described in the early analyses. The use of a more quantitatively-based tag-return model in the current analysis enabled fishing mortality estimates to be separated from the effects of assumption violations (incomplete magnet efficiencies and tag loss) and movement estimates to be quantified.

Although the current analysis represented a clear quantitative improvement over early analyses of the Atlantic menhaden tag-return data, the general conclusions drawn from each analysis were similar. Dryfoos et al. (1973) identified generally low survival rates of approximately $\boldsymbol{S}$ = 0.23, and Nicholson (1978) identified age-based stratification in summer northwards movements and winter contraction of the stock to SA waters. Likewise, the tag-return model estimates indicated high levels of mortality (e.g. $\boldsymbol{F}_{\text{age-3}} + \boldsymbol{M}_{\text{age-3}} = 1.67$ in SA) and age-based, seasonal movement patterns with higher probabilities of northwards movement during the spring-summer and in older fish.

Data limitations

Data from northern regions of the stock limited the scope of the tag-return model. The lack of younger fish tagged in northern regions precluded estimation of selectivity and movement for young northern fish, and zero fishery effort during winter months (zero probability of tag recovery) may have confounded estimates of winter movement patterns. The most robust data, in terms of spatial coverage of sampling and sample sizes, was collected during the spring-summer and in southern regions; therefore, results regarding fall-winter movements and movements of northern-tagged fish should be interpreted with greater caution than results regarding spring-summer movements and movements of SA-tagged fish.

The spatial domain of the model did not match the spatial range of the Atlantic menhaden stock. Atlantic menhaden range as far north as Canada (Ahrenholz 1991), yet the most northern reduction plant with magnets installed to recover tags was located in New York. It is possible that fish migrated northwards, beyond New York, where they could not be recovered, resulting in an unaccounted disappearance of tagged fish. The resulting tag-return model might estimate high-biased natural mortality rates or high movement rates into an area with low observation probability (i.e. low fishing mortality). As natural mortality was fixed in the model, the combination of low NY fishing mortality estimates, low NY emigration probabilities, and high immigration probabilities from SA and NJ to NY may have been an artifact of emigration northwards out of the model’s spatial domain. However, lower landings in areas north of NY during 1966–1970 suggest low fishing mortality in that area, which would support the tag-return model estimates of low fishing mortality, and therefore movement probabilities, in the northernmost region.

The domed-shaped fishery selectivity patterns estimated by the tag-return model may also be related to migration northwards beyond NY, representing a decline in availability of older fish to the tag-return dataset and model but not necessarily to the fishery. Testing area-specific selectivity functions in future analyses of the tag-return dataset might help to explore this possibility. Menhaden reduction fishery methods are uniform throughout the US East Coast, so area-specific fishery selectivity could result from changes in availability not in catchability. For example, asymptotic fishery selectivity in northern regions but domed-shaped selectivity in southern regions would be consistent with a decline in availability of older fish in southern regions.

Future directions and use in stock assessment

Corroboration of tag-return model results using population simulation may help to build confidence in results or identify biases in the tag-return estimates. If estimates generated by the tag-return model are accurate, a population simulation using the tag-return estimates should replicate the population structure observed in fishery landings and fishery-independent surveys. Given potential biases in fall-winter estimates of movement from the tag-return model, a parsimonious assumption to make in a simulation may be that all ages move to southern regions in the fall-winter and movement probabilities follow tag-return model estimates during spring-summer.

Fishing mortality and movement estimates presented here may be useful in future assessments of the Atlantic menhaden stock. Tag-return estimates of fishing mortality could be used to corroborate stock assessment estimates of fishing mortality, and tag-return movement rate estimates could be used to fix rates in a spatially-structured assessment model. There is evidence for spatial structure in fishing mortality, and age-specific movement rates are likely to produce some heterogeneity in age structure among different regions. While it remains unclear what combined effect spatial structure in mortality and age distributions may have, the effect represents a potential bias in a non-spatial stock assessment.

REFERENCES

Ahrenholz, D. W. 1991. Population biology and life history of the North American menhadens, ***Brevoortia*** spp. Marine Fisheries Review 53:3–19.

Ahrenholz, D.W., W.R. Nelson and S.P. Epperly. 1987. Populaution and fishery characteristics of Atlantic menhaden, ***Brevoortia tyrannus***. Fishery Bulletin 85(3): 569-600.

Bacheler, N. M., J. E. Hightower, L. M. Paramore, J. A. Buckel, and K. H. Pollock. 2008. An age-dependent tag-return model for estimating mortality and selectivity of an estuarine-dependent fish with high rates of catch and release. Transactions of the American Fisheries Society 137:1422–1432.

Brownie, C., D. R. Anderson, K. P. Burnham, and D. S. Robson. 1985. Statistical Inference from Band-Recovery Data: a Handbook. Second ed. Resource Publication 156. US Department of the Interior, Fish and Wildlife Service, Washington D.C.

Brownie, C., J. E. Hines , J. D. Nichols, K. H. Pollock, and J. B. Hestbeck. 1993. Capture-recapture studies for multiple strata including non-Markovian transitions. Biometrics 49:1173–1187.

Dryfoos, R. L., R. P. Cheek, and R. L. Kroger. 1973. Preliminary analysis of Atlantic menhaden, ***Brevoortia tyrannus***, migrations, population structure, survival, and exploitation rates, and availability as indicated by tag-returns. Fishery Bulletin 71:719–734.

Eveson, J. P., G. M. Laslett, and T. Polacheck. 2009. A spatial model for estimating mortality rates, abundance, and movement from fishery tag-recovery data. ***In*** Thompson, D. L., E. G. Cooch, and M. J. Conroy (editors). ***Modeling Demographic Processes in Marked Populations***. Springer, New York, USA. pp 987–1010.

Gelman, A., and D. B. Rubin. 1992. Inference from iterative simulation using multiple sequences. Statistical Science 7:457–511.

Hoenig, J. M., J. Barrowman, W. S. Hearn, and K. H. Pollock. 1998. Multiyear tagging studies that incorporate fishing effort data. Canadian Journal of Fisheries and Aquatic Sciences 55:1466–1476.

Jiang, H., K. H. Pollock, C. Brownie, J. E. Hightower, J. M. Hoenig, and W. S. Hearn. 2007. Age-dependent tag return models for estimating fishing mortality, natural mortality, and selectivity. Journal of Agricultural, Biological, and Environmental Statistics 12:177–194.

Joe, M. and K. H. Pollock. 2000. Separation of survival and movement rates in multi-state tag-return and capture-recapture models. Journal of Applied Statistics 29:373–384.

Kroger, R. L. and R. L. Dryfoos. 1972. Tagging and tag-recovery experiments with Atlantic menhaden, ***Brevoortia tyrannus***. NOAA Technical Report NMFS SSRF-664. Seattle, WA.

Nicholson, W. R. 1978. Movements and population structure of Atlantic menhaden indicated by tag returns. Estuaries 1:141–150.

Plummer, M. 2003. JAGS: a program for analysis of Bayesian graphical models using Gibbs sampling. Proceedings of the 3rd International Workshop on Distributed Statistical Computing, Vienna, Austria.

Pollock, K. H., J. M. Hoenig, and C. M. Jones. 1991. Estimation of fishing and natural mortality when a tagging study is combined with a creel survey or port sampling. American Fisheries Society Symposium 12:423–434.

R Development Core Team. 2010. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0. URL: http://www.R-project.org.

Smith, W. E., F. S. Scharf, and J. E. Hightower. 2009. Fishing mortality in North Carolina's southern flounder fishery: direct estimates of instantaneous fishing mortality from a tag return experiment. Marine and Coastal Fisheries 1:283–299.

Spiegelhalter, D. J., N. G. Best, B. P. Carlin, and A. van der Linde. 2002. Bayesian measures of model complexity and fit. Journal of the Royal Statistical Society, Series B 64:583–639.

Table 1. Parameters, indices, and data for the multistate tag-return model.

Parameters	
M_a	instantaneous rate of natural mortality at age a
F_s	instantaneous rate of fishing mortality (when sel = 1) in state s
$\psi_{a,s,ss}$	age-specific probability of transitioning from state s to state ss
P	acute probability of tag retention and survival of the tagging process
λ_s	magnet efficiency in state s
sel_a	selectivity at age a
α, β	logistic regression parameters describing sel_a

Indices	
a	age
s	strata at time t (s = NY, NJ, SA)
ss	strata at time t+1 (ss = NY, NJ, SA)
i	time period of tagging (i = 1, …, 10)
t	seasonal sampling period (t = 1, …, 10)

Data	
$y_{i,s,t}$	total number of recoveries at time t of a cohort of fish tagged in strata s, period i
$N_{i,s}$	total number tagged in cohort stratum s period i
$m_{i,s}$	fraction of the initial time period remaining when cohort in stratum s period I was tagged

Table 2. Prior distributions for all multistate tag-return model parameters.

Parameter	Prior
$\boldsymbol{F_s}$	Gamma(0.001,0.001)
$\psi_{\boldsymbol{a,s,ss}}$	Beta(1,1)
A	Uniform(-15,15)
B	Uniform(-5,5)
$\lambda_{\boldsymbol{s}}$	Beta(1,1)

Table 3. Observed tag recovery matrix ***y***.

			Year of recovery	1966	1966	1966	1966	1966	1966	1967	1967	1967	1967	1967	1967
			Area	NY	NJ	SA	NY	NJ	SA	NY	NJ	SA	NY	NJ	SA
Number tagged	Year of tagging	Area	Season	Spring	Spring	Spring	Fall	Fall	Fall	Spring	Spring	Spring	Fall	Fall	Fall
0	1966	NY	Spring	0	0	0	0	0	0	0	0	0	0	0	0
0	1966	NJ	Spring	0	0	0	0	0	0	0	0	0	0	0	0
45862	1966	SA	Spring	0	0	1,831	0	0	797	0	12	191	1	6	25
0	1966	NY	Fall	NA	NA	NA	0	0	0	0	0	0	0	0	0
0	1966	NJ	Fall	NA	NA	NA	0	0	0	0	0	0	0	0	0
29353	1966	SA	Fall	NA	NA	NA	0	0	2,730	0	16	259	6	9	73
2093	1967	NY	Spring	NA	NA	NA	NA	NA	NA	0	158	0	7	0	0
10846	1967	NJ	Spring	NA	NA	NA	NA	NA	NA	0	452	0	10	27	0
216413	1967	SA	Spring	NA	NA	NA	NA	NA	NA	0	51	12,815	53	381	5,922
0	1967	NY	Fall	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	0	0
2814	1967	NJ	Fall	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	6	1
23312	1967	SA	Fall	NA	NA	NA	NA	NA	NA	NA	NA	NA	3	53	1,460

Table 3 continued.

			Year of recovery	1968	1968	1968	1968	1968	1968	1969	1969	1969	1969	1969	1969
			Area	NY	NJ	SA	NY	NJ	SA	NY	NJ	SA	NY	NJ	SA
Number tagged	Year of tagging	Area	Season	Spring	Spring	Spring	Fall	Fall	Fall	Spring	Spring	Spring	Fall	Fall	Fall
0	1966	NY	Spring	0	0	0	0	0	0	0	0	0	0	0	0
0	1966	NJ	Spring	0	0	0	0	0	0	0	0	0	0	0	0
45862	1966	SA	Spring	5	21	42	1	6	9	7	5	4	0	0	1
0	1966	NY	Fall	0	0	0	0	0	0	0	0	0	0	0	0
0	1966	NJ	Fall	0	0	0	0	0	0	0	0	0	0	0	0
29353	1966	SA	Fall	14	57	100	6	9	29	14	4	9	0	0	3
2093	1967	NY	Spring	34	40	2	7	0	0	9	17	0	0	0	0
10846	1967	NJ	Spring	13	147	68	10	27	6	7	16	2	0	2	0
216413	1967	SA	Spring	134	1,515	4,782	53	381	1,041	127	289	510	1	70	176
0	1967	NY	Fall	0	0	0	0	0	0	0	0	0	0	0	0
2814	1967	NJ	Fall	8	32	12	0	6	1	2	6	1	0	0	0
23312	1967	SA	Fall	14	143	1,005	3	53	174	17	34	108	0	13	33
2370	1968	NY	Spring	51	116	0	51	1	0	22	40	1	0	0	1
20678	1968	NJ	Spring	92	2,456	5	6	497	1	32	95	10	0	16	3
303293	1968	SA	Spring	5	49	24,824	1	33	5,261	92	230	3504	4	132	858
0	1968	NY	Fall	NA	NA	NA	0	0	0	0	0	0	0	0	0
1111	1968	NJ	Fall	NA	NA	NA	0	123	0	12	46	7	0	5	3
18859	1968	SA	Fall	NA	NA	NA	0	0	584	5	28	433	0	17	85
8268	1969	NY	Spring	NA	NA	NA	NA	NA	NA	813	203	0	18	7	0
700	1969	NJ	Spring	NA	NA	NA	NA	NA	NA	1	3	0	0	4	0
143679	1969	SA	Spring	NA	NA	NA	NA	NA	NA	0	2	3961	0	43	2028
0	1969	NY	Fall	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	0	0
0	1969	NJ	Fall	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	0	0
52587	1969	SA	Fall	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	0	830

Table 3 continued.

			Year of recovery	1970	1970	1970	1970	1970	1970	
			Area	NY	NJ	SA	NY	NJ	SA	
Number tagged	Year of tagging	Area	Season	Spring	Spring	Spring	Fall	Fall	Fall	never seen again
0	1966	NY	Spring	0	0	0	0	0	0	0
0	1966	NJ	Spring	0	0	0	0	0	0	0
45862	1966	SA	Spring	0	0	2	0	0	0	45860
0	1966	NY	Fall	0	0	0	0	0	0	0
0	1966	NJ	Fall	0	0	0	0	0	0	0
29353	1966	SA	Fall	0	0	3	0	6	1	29343
2093	1967	NY	Spring	0	0	0	0	0	0	2093
10846	1967	NJ	Spring	0	0	0	0	0	0	10846
216413	1967	SA	Spring	0	10	72	0	37	49	216245
0	1967	NY	Fall	0	0	0	0	0	0	0
2814	1967	NJ	Fall	0	0	0	0	0	0	2814
23312	1967	SA	Fall	0	1	12	0	6	11	23282
2370	1968	NY	Spring	0	0	0	0	0	0	2370
20678	1968	NJ	Spring	0	0	0	0	0	0	20678
303293	1968	SA	Spring	0	14	296	0	118	152	302713
0	1968	NY	Fall	0	0	0	0	0	0	0
1111	1968	NJ	Fall	0	0	0	0	0	0	1111
18859	1968	SA	Fall	0	0	32	0	15	26	18786
8268	1969	NY	Spring	0	2	10	0	28	4	8224
700	1969	NJ	Spring	0	0	0	0	0	1	699
143679	1969	SA	Spring	0	28	1755	0	147	432	141317
0	1969	NY	Fall	0	0	0	0	0	0	0
0	1969	NJ	Fall	0	0	0	0	0	0	0
52587	1969	SA	Fall	1	11	2596	0	67	461	49451
0	1970	NY	Spring	0	0	0	0	0	0	0
0	1970	NJ	Spring	0	0	0	0	0	0	0
36674	1970	SA	Spring	0	3	7078	0	39	1857	27697
0	1970	NY	Fall	NA	NA	NA	0	0	0	0
0	1970	NJ	Fall	NA	NA	NA	0	0	0	0
0	1970	SA	Fall	NA	NA	NA	0	0	0	0

Table 4. DIC values for all candidate models. The lowest DIC value, indicating the best model, is bolded and underlined.

Selectivity model	Movement(age)	Natural mortality (age)	Movement(season)	
			seasonal movement	no seasonal movement
age-constant	age-specific movement	age-specific ***M***	62364	62549
age-constant	age-specific movement	age-constant ***M***	62254	62544
age-constant	age-constant movement	age-specific ***M***	63385	62805
age-constant	age-constant movement	age-constant ***M***	63312	62821
logistic	age-specific movement	age-specific ***M***	60138	60561
logistic	age-specific movement	age-constant ***M***	60918	61477
logistic	age-constant movement	age-specific ***M***	62163	61368
logistic	age-constant movement	age-constant ***M***	71087	62182
double logistic	age-specific movement	age-specific ***M***	**<u>58783</u>**	59335
double logistic	age-specific movement	age-constant ***M***	59746	60359
double logistic	age-constant movement	age-specific ***M***	61137	60346
double logistic	age-constant movement	age-constant ***M***	61895	61260

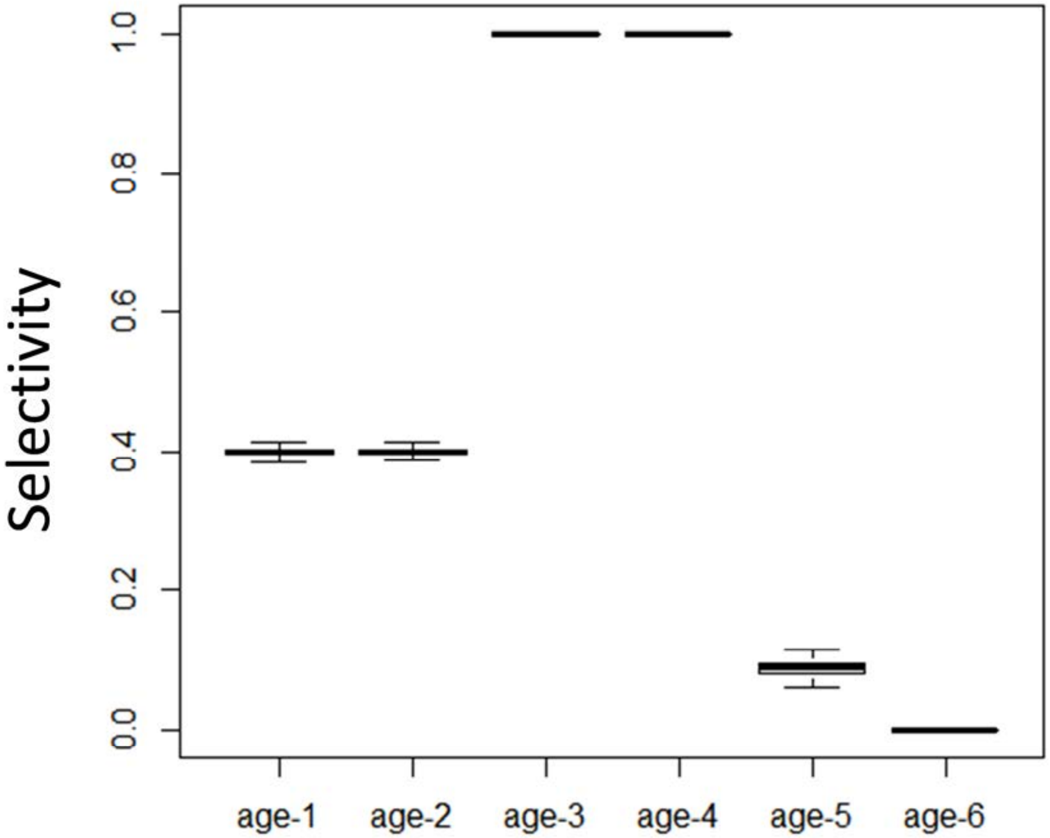


Figure 1. Boxplots of the posterior distributions of age-specific selectivities estimated by the tag-return model.

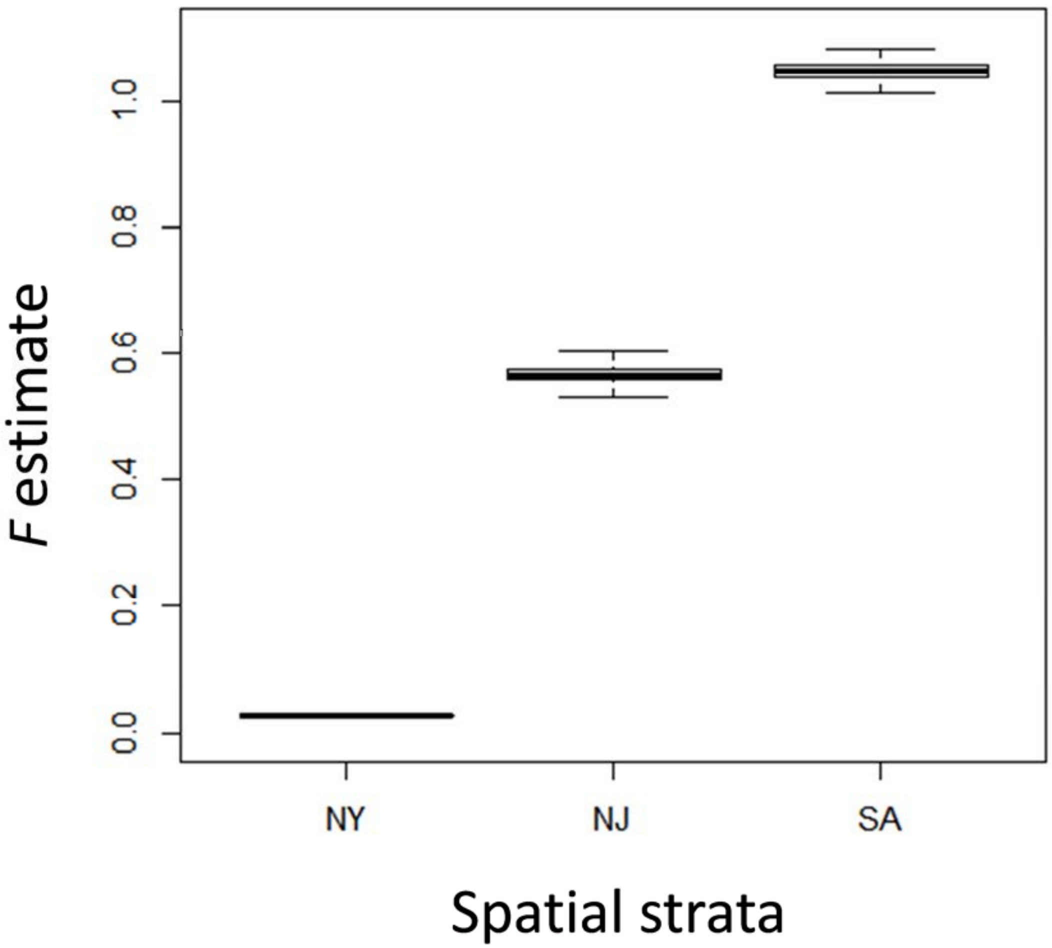


Figure 2. Boxplots of the posterior distributions of area-specific fishing mortalities (***F_s***) estimated by the tag-return model.

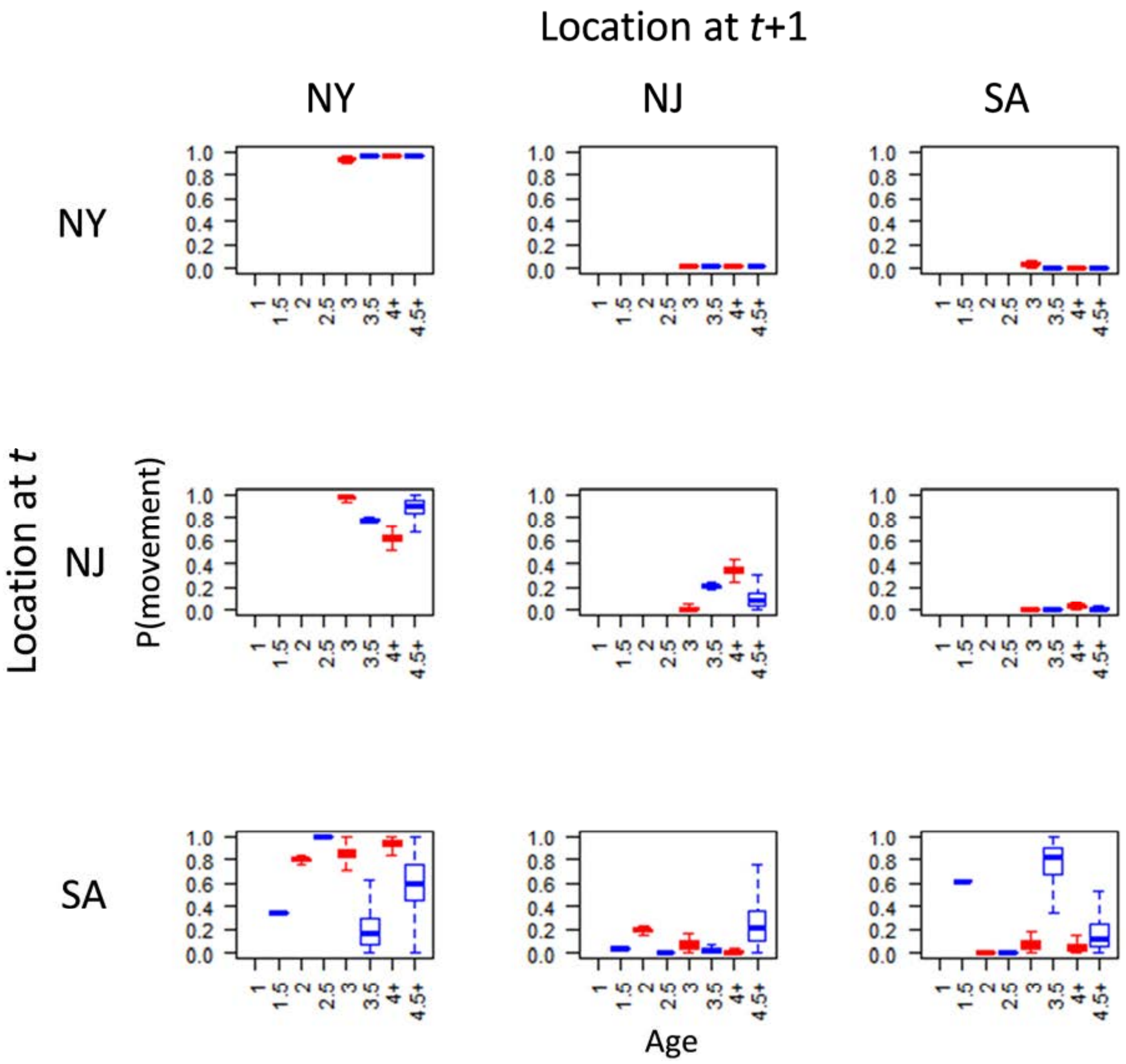


Figure 3. Boxplots of the posterior distributions of age-specific, seasonal movement probabilities estimated by the tag-return model. Rows of the three by three matrix of plots indicate locations at time t and columns indicate locations at time t + 1. Within each cell of the matrix, the y-axis indicates movement probabilities, the x-axis indicates age, red boxplots indicate spring-summer estimates, and blue boxplots indicate fall-winter estimates.

The Beaufort Assessment Model (BAM) with application to Atlantic menhaden: mathematical description, implementation details, and computer code

Sustainable Fisheries Branch

National Marine Fisheries Service

Southeast Fisheries Science Center

NOAA Beaufort Laboratory

101 Pivers Island Road, Beaufort, NC 28516

1 Overview

The primary model in this assessment was the Beaufort assessment model (BAM), which applies a statistical catch-age formulation. The model was implemented with the AD Model Builder software (Fournier et al. 2012), and its structure and equations are detailed herein. In essence, a statistical catch-age model simulates a population forward in time while including fishing processes (Quinn and Deriso 1999; Shertzer et al. 2008). Quantities to be estimated are systematically varied until characteristics of the simulated population match available data on the real population. Statistical catch-age models share many attributes with ADAPT-style tuned and untuned VPAs.

The method of forward projection has a long history in fishery models. It was introduced by Pella and Tomlinson (1969) for fitting production models and has been used by many applications including by Fournier and Archibald (1982), by Deriso et al. (1985) in their CAGEAN model, and by Methot (1989; 2009) in his Stock Synthesis model. The catch-age model of this assessment is similar in structure to the CAGEAN and Stock Synthesis models. Versions of this assessment model have been used in previous SEDAR assessments in the U.S. South Atlantic, such as red porgy, black sea bass, snowy grouper, gag grouper, greater amberjack, vermilion snapper, Spanish mackerel, red grouper, red snapper, tilefish, and Gulf menhaden assessments.

2 Model configuration and equations

Model equations are detailed in Table 2.1, and AD Model Builder code is supplied in Appendix A. A general description of the assessment model follows.

Stock dynamics In the assessment model, new biomass was acquired through growth and recruitment, while abundance of existing cohorts experienced exponential decay from fishing and natural mortality. The population was assumed closed to immigration and emigration. The model included age classes $0 - 6^+$, where the oldest age class 6^+ allowed for the accumulation of fish (i.e., plus group).

Initialization Initial (1955) abundance at age was computed in the model assuming an equilibrium age structure and fishing mortality rate. The equilibrium age structure was computed for ages $1 - 6^+$ based on natural and fishing mortality (F), where F was set equal to the geometric mean fishing mortality from the first three assessment years (1955-1957). In addition, deviations from the equilibrium age structure were estimated for each age 1 through 6+. The deviations were informed by the age composition data available in the first year of the assessment. Finally, initial age-0 abundance was computed in the model using estimated median recruitment plus an estimated annual recruitment deviation.

Natural mortality rate The natural mortality rate (M) was assumed constant over time, but decreasing with age. The form of M as a function of age was based on Lorenzen (1996). The Lorenzen (1996) approach inversely relates the natural mortality at age M_a to mean weight at age W_a by the power function $\mathrm{M}_a = \alpha W_a^{\beta}$, where α is a scale parameter and β is a shape parameter. Lorenzen (1996) provided point estimates of α and β for oceanic fishes, which were used for this assessment. The Lorenzen version of M was scaled to 0.5 at the older ages (ages 4-6+), which is the estimated natural mortality rate based on a tagging study.

Growth Annual mean size at age of the fishery and the population (fork length, FL) were modeled with the von Bertalanffy equation based on the cohort. Annual mean size at age for the fishery was modeled using the fishery data, while annual mean size at age for the population was modeled based on fishery data with a bias correction (Schueller et al. 2014). Annual weight at age of the fishery and the population were modeled as a function of FL. Annual weight at age of the fishery and population were estimated during the data process and were treated as an input to the model. For fitting length composition data, the annual von Bertalanffy growth curves were used to estimate the size at age for the time of sampling for the surveys in the index. The annual length compositions were then fit to those annual input lengths with a constant coefficient of variation (CV) estimated by the assessment model.

Female maturity Maturity was modeled as a function of length through the estimation of a logistic regression function between length and maturity. Mean length-at-age by year was input into the logistic regression in order to obtain maturity at age over time, which was then a model input.

Spawning stock Spawning stock was modeled using total fecundity (mature ova) at the time of peak spawning. For Atlantic menhaden, peak spawning was considered to occur March 1.

Recruitment Expected recruitment of age-0 fish was predicted from spawning stock in fecundity using the median recruitment. Annual variation in recruitment was assumed to occur with lognormal deviations for the years 1955–2013.

Landings The model included four time series of landings from 1955-2013: northern commerical reduction landings, southern commercial reduction landings, northern bait landings, and southern bait landings. Bait and recreational landings for each respective area were pooled outside of the model and were entered as one data stream for the northern region and one data stream for the southern region. Landings consisted of mostly commercial reduction fishery landings, which made up about 75% of the total landings. The landings were modeled with the Baranov catch equation (Baranov 1918) and were fitted in units of weight (1,000s metric tons).

Fishing Mortality For the time series of removals, the assessment model estimated an annual full fishing mortality rate (F). Age-specific rates were then computed as the product of full F and selectivity at age.

Selectivities The selectivity curves for indices and fisheries were estimated using a parametric approach. The parametric approach applies plausible structure on the shape of the curve and achieves greater parsimony than occurs with unique parameters for each age. Selectivity of the northern adult index (NAD) was modeled as flat-topped, using a two parameter logistic function. Selectivity of the southern adult index (SAD) was modeled as dome-shaped, using a four parameter double logistic function. The selectivity for the recruitment index based on the state survey data was fixed with selectivity of age-0 being 1.0, while the selectivity of all the other ages was 0.0. The selectivity for each fishery was estimated as dome-shaped, using a four parameter double logistic function.

Indices of abundance The model was fit to three indices of relative abundance: the northern adult index (1980-2013), the southern adult index (1990-2013), and the recruitment index (1959-2013). Predicted indices were conditional on selectivities and were computed from May 15 abundance for the SAD index, from September 1 abundance for the NAD index, and from June 1 abundance for the recruitment index.

Catchability In the BAM, catchability scales indices of relative abundance to estimated population abundance at large. Several options for time-varying catchability can be implemented in the BAM following recommendations of the 2009 SEDAR procedural workshop on catchability (SEDAR Procedural Guidance 2009). Parameters for each option could be estimated or fixed based on *a priori* considerations. For the base model, the AW assumed time-invariant catchability for both the NAD and SAD indices. Because both of these indices are based on consistent, fishery-independent sampling, a constant catchability value was a reasonable assumption. For the recruitment index, catchability was estimated with two values, one for 1959-1986 and one for 1987-2013. Catchability for the recruitment index was split in this way to accomodate for the change in spatial coverage of the index over time.

Biological reference points Biological reference points (benchmarks) were calculated based on spawner per recruit (SPR) analyses. Specifically, the current reference points for Atlantic menhaden are $F_{15\%}$, $F_{30\%}$, $FEC_{15\%}$, and $FEC_{30\%}$. In this assessment, spawning stock measures total fecundity (FEC) in mature ova. These benchmarks are conditional on the estimated selectivity functions and use the average over the time series 1955-2013 for any time varying components.

Fitting criterion The fitting criterion was a penalized likelihood approach in which observed landings were fit closely, and observed composition data and abundance indices were fit to the degree that they were compatible. Landings and index data were fitted using lognormal likelihoods. Length and age composition data were fitted using robust multinomial likelihoods.

The model includes the capability for each component of the likelihood to be weighted by user-supplied values (for instance, to give more influence to stronger data sources). For data components, these weights were applied by either adjusting CVs (lognormal components) or adjusting effective sample sizes (multinomial components). In this application to Atlantic menhaden, the CV of reduction removals both north and south (in arithmetic space) were assumed equal to 0.03, to achieve a close fit to this time series yet allow some imprecision. For the northern and southern commercial bait fisheries, the CVs were assumed equal to 0.15 for 1955-1984 and 0.05 for 1985-2013. In practice, the small CVs are a matter of computational convenience, as they help achieve the desired result of close fits to the landings, while avoiding having to solve the Baranov equation iteratively. Weights on other data components (indices, age and length compositions) were adjusted iteratively, starting from initial weights as follows. The CVs of indices were set equal to the values estimated by hierarchical modeling as reported in the stock assessment report. Effective sample sizes of the annual length compositions were assumed equal to the annual number of sets sampled. Number of annual trips sampled was the effective sample size for the age composition data. These initial weights were then adjusted until standard deviations of normalized residuals (SDNRs) were near 1.0 (SEDAR24-RW03, SEDAR25-RW05, Francis 2011) for the composition data and near 2.0 for the index data. Computed SDNRs accounted for potential correlations in the composition data (TA1.8 in Table A1 of (Francis 2011)).

The compound objective function included some penalties on the recruitment time series based on Beddington and Cooke (1983) and Mertz and Myers (1996)]. Penalties or priors were applied to maintain parameter estimates near reasonable values, and to prevent the optimization routine from drifting into parameter space with negligible gradient in the likelihood.

Model testing Experiments with a simulation model indicated that parameters estimated from the BAM were unbiased and could be recovered from simulated data. Further, the general model structure has been through multiple SEDAR reviews. As an additional measure of quality control, Atlantic menhaden code and input data were examined for accuracy by multiple analysts. This combination of testing and verification procedures suggest that the assessment model is implemented correctly and can provide an accurate assessment of Atlantic menhaden stock dynamics.

References

Baranov, F. I. 1918. On the question of the biological basis of fisheries. Nauchnye Issledovaniya Ikhtiologicheskii Instituta Izvestiya **1**:81–128.

Beddington, J. R., and J. G. Cooke, 1983. The potential yield of fish stocks. FAO Fish. Tech. Pap. 242, 47 p.

Deriso, R. B., T. J. Quinn, and P. R. Neal. 1985. Catch-age analysis with auxiliary information. Canadian Journal of Fisheries and Aquatic Sciences **42**:815–824.

Fournier, D., and C. P. Archibald. 1982. A general theory for analyzing catch at aage data. Canadian Journal of Fisheries and Aquatic Sciences **39**:1195–1207.

Fournier, D. A., H. J. Skaug, J. Ancheta, J. Ianelli, A. Magnusson, M. N. Maunder, A. Nielsen, and J. Sibert. 2012. AD Model Builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. Optimization Methods and Software **27**:233–249.

Francis, R. 2011. Data weighting in statistical fisheries stock assessment models. Canadian Journal of Fisheries and Aquatic Sciences **68**:1124–1138.

Lorenzen, K. 1996. The relationship between body weight and natural mortality in juvenile and adult fish: a comparison of natural ecosystems and aquaculture. Journal of Fish Biology **49**:627–642.

Mertz, G., and R. Myers. 1996. Influence of fecundity on recruitment variability of marine fish. Canadian Journal of Fisheries and Aquatic Sciences **53**:1618–1625.

Methot, R. D. 1989. Synthetic estimates of historical abundance and mortality for northern anchovy. American Fisheries Society Symposium **6**:66–82.

Methot, R. D., 2009. User Manual for Stock Synthesis, Model Version 3.04. NOAA Fisheries, Seattle, WA.

Pella, J. J., and P. K. Tomlinson. 1969. A generalized stock production model. Bulletin of the Inter-American Tropical Tuna Commission **13**:419–496.

Quinn, T. J., and R. B. Deriso. 1999. Quantitative Fish Dynamics. Oxford University Press, New York, New York.

SEDAR Procedural Guidance, 2009. SEDAR Procedural Guidance Document 2: Addressing Time-Varying Catchability.

Shertzer, K. W., M. H. Prager, D. S. Vaughan, and E. H. Williams, 2008. Fishery models. Pages 1582–1593 *in* S. E. Jorgensen and F. Fath, editors. Population Dynamics. Vol. [2] of Encyclopedia of Ecology, 5 vols. Elsevier, Oxford.

Table 2.1. General definitions, input data, population model, and negative log-likelihood components of the statistical catch-age model applied to Atlantic menhaden. Hat notation ($\widehat{*}$) indicates parameters estimated by the assessment model, and breve notation ($\breve{*}$) indicates estimated quantities whose fit to data forms the objective function.

Quantity	Symbol	Description or definition
General Definitions		
Index of years	y	$y \in \{1955 \ldots 2013\}$
Index of ages	a	$a \in \{0, 1 \ldots A\}$, where $A = 6^+$
Index of length bins	l	$l \in \{1, 2 \ldots 31\}$
Length bins	l'	$l' \in \{95, 105, \ldots, 395\text{mm}\}$, with midpoint of 10 mm bin used to match length compositions. Largest 6 length bins ($FL \geq 345$ mm) treated as a plus group, but retained for weight calculations.
Index of fishery	f	$f \in \{1, 2, 3, 4\}$ is the northern and southern commercial reduction fishery and the northern and southern commercial bait fishery with recreational landings combined with the bait fishery
Index of CPUE	u	$u \in \{1, 2, 3\}$ where 1 = NAD index, 2 = SAD index, 3 = recruitment index
Input Data		
Observed length compositions	$p^{\lambda}_{(u),l,y}$	Proportional contribution of length bin l in year y to index $u \in \{1, 2\}$
Observed age compositions	$p^{\alpha}_{(f),a,y}$	Proportional contribution of age class a in year y to the fishery $f \in \{1, 2, 3, 4\}$
Length composition sample sizes	$n^{\lambda}_{(u),y}$	Effective number of length samples collected in year y from an index u
Age composition sample sizes	$n^{\alpha}_{(f),y}$	Effective number of age samples collected in year y from a fishery f
Observed landings	$L_{f,y}$	Reported landings in year y from a fishery f. Landings are reported in 1000s of metric tons.
CVs of landings	$c^{L}_{f,y}$	Assumed 0.03 in arithmetic space for the northern and southern commercial reduction fisheries. Assumed to be 0.15 for 1955-1984 and 0.05 for 1985-2013 for the northern and southern commercial bait fisheries.
Observed abundance indices	$U_{u,y}$	$u = 1$, NAD index (numbers), $y \in \{1980 \ldots 2013\}$ $u = 2$, SAD index (numbers), $y \in \{1990 \ldots 2013\}$ $u = 3$, recruitment index (numbers), $y \in \{1959 \ldots 2013\}$ Annual values estimated from several indices using hierarchical modeling. Each time series was scaled to its mean.
CVs of abundance indices	$c^{U}_{u,y}$	$u = \{1, 2, 3\}$ as above.
Natural mortality rate	M_a	Function of weight at age (w_a): $M_a = \alpha w_a^{\beta}$, with estimates of α and β from Lorenzen (1996). Lorenzen M_a then rescaled at older ages to M estimated in a tagging study.

Table 2.1. (continued)

Quantity	**Symbol**	**Description or definition**
Population Model		
Proportion female at age	ρ_a	Considered constant (50:50) across years and ages
Proportion females mature at age	$m_{a,y}$	Increasing with age for ages $0-6^+$ and time varying based on mean length at age and a fitted logistic regression.
Spawning date	t_{spawn}	Fraction denoting the proportional time of year when spawning occurs. Set to 0.0 for Atlantic menhaden by assuming peak spawning occurs March 1.
Annual fecundity at age	$\mathcal{F}_{a,y}$	$\mathcal{F}_{a,y} = 2563\ell_{a,y}^{0.015}$ based on equation provided in Lewis and Roithmayr and was a model input
Annual mean length at age for the population	$l_{a,y}$	Fork length (March 1); $l_{a,y} = L_{\infty,y}(1-\exp[-K_y(a-t_{0,y})])$ where K_y, $L_{\infty,y}$, and $t_{0,y}$ were estimated outside the model using cohorts and a bias correction
Annual mean length at age for the population (partial year)	$l^f_{a,y}$	Fork length (partial year); $l_{a,y} = L_{\infty,y}(1-\exp[-K_y(a-t_{0,y}+x)])$ where K_y, $L_{\infty,y}$, and $t_{0,y}$ are parameters estimated outside of the assessment model, x is the portion of the year that has passed (e.g. 0.5 for midyear), and used to fit the length compositions to.
CV of $l_{a,y}$	$\widehat{c}^{\lambda}_{a,y}$	Estimated coefficient of variation of growth, assumed constant across ages and years.
SD of $l_{a,y}$	$\sigma^{\lambda}_{a,y}$	Standard deviation of growth, assumed constant across ages and years.
Age–length conversion of population	$\psi^u_{a,l}$	$\psi^u_{a,l} = \frac{1}{\sqrt{2\pi}(\sigma^{\lambda}_a)} \frac{\exp\left[-\left(l'_l - l_{a,y}\right)^2\right]}{\left(2(\sigma^{\lambda}_a)^2\right)}$, the Gaussian density function. Matrix ψ^u is rescaled to sum to one within ages, with the largest size a plus group. This matrix is constant across years.
Individual weight at age of population	$w_{a,y}$	Computed from length at age by $w_{a,y} = \theta_1 l_{a,y}^{\theta_2}$ where θ_1 and θ_2 are parameters from the DW, and the time varying weight at age of the population is an input into the model.
Individual weight at age of landings	$w^L_{(f),a,y}$	Computed from length at age by $w^L_{(f),a,y} = \theta_1(\xi^L_{(f),a,y})^{\theta_2}$. With weight at age of landings being a model input.
Index selectivity	$s_{(u),a}$	$s_{(u),a} = \frac{1}{1+\exp\left[-\widehat{\eta}_{(u)}\left(a-\widehat{\alpha}_{(u)}\right)\right]}$ where $\widehat{\eta}_{(u)}$ and $\widehat{\alpha}_{(u)}$ are the estimated slope and age at 50% selectivity parameters for u=1. For u=3, the selecitivity was 1.0 for age-0 and 0.0 for all other ages. $s_{(u),a} = \pi[(\frac{1}{1+\exp\left[-\widehat{\eta}_{1(u)}\left(a-\widehat{\alpha}_{1(u)}\right)\right]})(1-\frac{1}{1+\exp\left[-\widehat{\eta}_{2(u)}\left(a-(\widehat{\alpha}_{1(u)}+\widehat{\alpha}_{2(u)})\right)\right]})]$ where $\widehat{\eta}_{1(u)}$ and $\widehat{\eta}_{2(u)}$ are the slope parameters of the ascending and descending limbs, respectively, and $\widehat{\alpha}_{1(u)}$ and $\widehat{\alpha}_{2(u)}$ are the ages at 50% selectivity for the ascending and descending limbs, respectively, for u=2. This selectivity function is estimated and then divided by the maximum value to make the maximum selectivity value equal to 1.0.

Table 2.1. (continued)

Quantity	**Symbol**	**Description or definition**
Fishery selectivity	$s_{(f),a}$	$s_{(f),a} = \pi[(\frac{1}{1+\exp\left[-\widehat{\eta}_{1(f)}\left(a-\widehat{\alpha}_{1(f)}\right)\right]})(1-\frac{1}{1+\exp\left[-\widehat{\eta}_{2(f)}\left(a-(\widehat{\alpha}_{1(f)}+\widehat{\alpha}_{2(f)})\right)\right]})]$ where $\widehat{\eta}_{1(f)}$ and $\widehat{\eta}_{2(f)}$ are the slope parameters of the ascending and descending limbs, respectively, and $\widehat{\alpha}_{1(f)}$ and $\widehat{\alpha}_{2(f)}$ are the ages at 50% selectivity for the ascending and descending limbs, respectively, for all fisheries f. This selectivity function is estimated and then divided by the maximum value to make the maximum selectivity value equal to 1.0.
Fishing mortality rate of landings	$F_{f,a,y}$	$F_{f,a,y} = s_{f,a,y}\widehat{F}_{f,y}$ where $\widehat{F}_{f,y}$ is an estimated fully selected fishing mortality rate by fishery.
Total fishing mortality rate	$F_{a,y}$	$F_{a,y} = \sum_{f} F_{f,a,y}$
Total mortality rate	$Z_{a,y}$	$Z_{a,y} = M_a + F_{a,y}$
Abundance at age	$N_{a,y}$	$N_{0,1955} = \frac{\widehat{R}_0(0.8\varsigma h\phi_{init}-0.2\phi_0(1-h))}{(h-0.2)\phi_{init}}\exp(\widehat{R}_y)$ $\widehat{N}_{1+,1955}$ equilibrium conditions expected given assumptions about initial fishing mortality (described below) and includes an estimated deviation from the equilibrium age structure for each age. $N_{0,y+1} = \frac{0.8\widehat{R}_0 hS_y}{0.2\phi_0\widehat{R}_0(1-h)+(h-0.2)S_y}\exp(\widehat{R}_{y+1})$ $N_{a+1,y+1} = N_{a,y}\exp(-Z_{a,y}) \quad a \in (0\ldots A-1)$ $N_{A,y} = N_{A-1,y-1}\frac{\exp(-Z_{A-1,y-1})}{1-\exp(-Z_{A,y-1})}$ $\widehat{R}_0$ (asymptotic maximum recruitment) is an estimated parameter of the spawner-recruit curve, and $\widehat{R}_y$ are estimated annual recruitment deviations in log space for 1955-2013. The bias correction is $\varsigma = \exp(\sigma_R^2/2)$, where σ_R^2 was fixed at 0.6 and was the variance of recruitment deviations. In the SEDAR-40 base run, h=0.99 was a fixed parameter; thus, median recruitment with deviation was estimated. Quantities ϕ_0, ϕ_{init}, and S_y are described below.
Abundance at age (partial year)	$N'_{a,y}$	Used to match to the NAD, u=1, SAD, u=2, and recruitment, u=3, indices of abundance: $N'_{a,y} = N_{a,y}\exp(-Z_{a,y} * V)$ where V is the portion of the year that has passed. For example, half a year would be 0.50.
Abundance at age at time of spawning	$N''_{a,y}$	Assumed on March 1 to correspond with peak spawning $N''_{a,y} = \exp(-t_{\text{spawn}}Z_{a,y})N_{a,y}$
Unfished abundance at age per recruit at time of spawning	NPR_a	$NPR_1 = 1 \times \exp(-t_{\text{spawn}}M_1)$ $NPR_{a+1} = NPR_a\exp[-(M_a(1-t_{\text{spawn}}) + M_{a+1}t_{\text{spawn}})] \quad a \in (1\ldots A-1)$ $NPR_A = \frac{NPR_{A-1}\exp[-(M_{A-1}(1-t_{\text{spawn}})+M_A t_{\text{spawn}})]}{1-\exp(-M_A)}$
Initial abundance at age per recruit at time of spawning	NPR_a^{init}	Same calculations as for NPR_a, but including fishing mortality (see Z^{init} below).
Unfished spawning biomass per recruit	ϕ_0	$\phi_0 = \sum_{a=0}^{A} NPR_a\rho_a\bar{m}_{a,y}\bar{\mathcal{F}}_{a,y}$ In units of fecundity with maturity and fecundity being the average over 1955-2013.

Table 2.1. (continued)

Quantity	**Symbol**	**Description or definition**
Initial spawning biomass per recruit	ϕ_{init}	$\phi_{init} = \sum_{a=0}^{A} NPR_a^{init} \rho_a \bar{m}_{a,y} \bar{\mathcal{F}}_{a,y}$ In units of fecundity with maturity and fecundity being the average over 1955-2013.
Spawning biomass	S_y	$\sum_{a=1}^{A} N''_{a,y} \rho_a m_{a,y} \mathcal{F}_{a,y}$ Spawning biomass is in units of total fecundity
Initialization mortality at age	Z_a^{init}	$Z_a^{init} = M_a + s_a^{init} F^{init}$ where F^{init} is an initialization F assumed to be the geometric mean of F from the first three assessment years (1955-1957) and s_a^{init} is the commercial selectivity for these three years.
Initial equilibrium abundance at age	N_a^{eq}	Equilibrium age structure given Z_a^{init}
Population biomass	B_y	$B_y = \sum_a N_{a,y} w_{a,y}$
Landings at age in numbers	$L'_{f,a,y}$	$L'_{f,a,y} = \frac{F_{f,a,y}}{Z_{a,y}} N_{a,y} [1 - \exp(-Z_{a,y})]$
Landings at age in weight	$L''_{f,a,y}$	$L''_{f,a,y} = w^L_{f,a,y} L'_{f,a,y}$
Index catchability	$\widehat{q}_u$	estimated constant catchability for indices u=1 and u=2. For u=3, two constant values were estimated, one for the years 1959-1986 and one for the years 1987-2013.
Predicted landings	$\breve{L}_{f,y}$	$\breve{L}_{f,y} = \sum_a L'_{f,a,y}$
Predicted length compositions of fishery independent data	$\breve{p}^{\lambda}_{u,l,y}$	$\breve{p}^{\lambda}_{u,l,y} = \frac{\sum_a \psi_{a,l} s_{u,a,y} N'_{a,y}}{\sum_a s_{u,a,y} N'_{a,y}}$
Predicted age compositions of fishery	$\breve{p}^{\alpha}_{(f),a,y}$	$\breve{p}^{\alpha}_{(f),a,y} = \frac{\mathcal{E} L'_{(f),a,y}}{\sum_a L'_{(f),a,y}}$ this formulation can incorporate ageing uncertainty, but was not included for the base run.
Predicted CPUE	$\breve{U}_{u,y}$	$\breve{U}_{u,y} = \widehat{q}_u \sum_a N'_{a,y} s_{u,a}$ where $s_{u,a}$ is the selectivity of index u in the year corresponding to y and $\widehat{q}_u$ is the catchability of index u in the year corresponding to y.

Table 2.1. (continued)

Quantity	**Symbol**	**Description or definition**
Objective Function		
Robust multinomial length compositions	Λ_1	$\Lambda_1 = \sum_u \sum_y 0.5 \log(E') - \log \left[\exp \left(-\frac{(p^{\lambda}_{(u),l,y} - \breve{p}^{\lambda}_{(u),l,y})^2}{2E' \big/ (n^{\lambda}_{(u),y} \omega^{\lambda}_{(u)})} \right) + x \right]$ where $E' = \left[(1 - p^{\lambda}_{(u),l,y})(p^{\lambda}_{(u),l,y}) + \frac{0.1}{mbin} \right]$, $mbin$ is the number of length bins, $\omega^{\lambda}_{(u)}$ is a preset weight (selected by iterative re-weighting) and x =1e-5 is an arbitrary value to avoid log zero. Bins are 10 mm wide.
Robust multinomial age compositions	Λ_2	$\Lambda_2 = \sum_f \sum_y 0.5 \log(E') - \log \left[\exp \left(-\frac{(p^{\alpha}_{(f),a,y} - \breve{p}^{\alpha}_{(f),a,y})^2}{2E' \big/ (n^{\alpha}_{(f),y} \omega^{\alpha}_{(f)})} \right) + x \right]$ where $E' = \left[(1 - p^{\alpha}_{(f),a,y})(p^{\alpha}_{(f),a,y}) + \frac{0.1}{mbin} \right]$, $mbin$ is the number of age bins, $\omega^{\alpha}_{(f)}$ is a preset weight (selected by iterative re-weighting) and x =1e-5 is an arbitrary value to avoid log zero.
Lognormal landings	Λ_3	$\Lambda_3 = \sum_f \sum_y \frac{\left[\log \left((L_{f,y} + x) \big/ (\breve{L}_{f,y} + x) \right) \right]^2}{2(\sigma^L_{f,y})^2}$ where x =1e-5 is an arbitrary value to avoid log zero or division by zero. Here, $\sigma^L_{f,y} = \sqrt{\log(1 + (c^L_{f,y}/\omega^L_f)^2)}$, with $\omega^L_f = 1$ as a preset weight.
Lognormal CPUE	Λ_4	$\Lambda_4 = \sum_u \sum_y \frac{\left[\log \left((U_{u,y} + x) \big/ (\breve{U}_{u,y} + x) \right) \right]^2}{2(\sigma^U_{u,y})^2}$ where x =1e-5 is an arbitrary value to avoid log zero or division by zero. Here, Here, $\sigma^U_{u,y} = \sqrt{\log(1 + (c^U_{u,y}/\omega^U_u)^2)}$, with ω^U_u as a preset weight.
Lognormal recruitment deviations	Λ_5	$\Lambda_5 = \omega_5 \left[\frac{[R_{1955} + (\widehat{\sigma}^2_R \big/ 2)]^2}{2\widehat{\sigma}^2_R} + \sum_{y>1956}^{2013} \frac{[(R_y - \widehat{\varrho} R_{y-1}) + (\widehat{\sigma}^2_R \big/ 2)]^2}{2\widehat{\sigma}^2_R} + n \log(\widehat{\sigma}_R) \right]$ where R_y are recruitment deviations in log space, n is the number of years, $\omega_5 = 1$ is a preset weight, $\widehat{\varrho}$ is the first-order autocorrelation, and $\widehat{\sigma}^2_R$ is the recruitment variance fixed at 0.6 ($\varrho = 0$ in the SEDAR 40 base run).
Penalty on initial age structure	Λ_6	$\Lambda_6 = \sum_{a=1}^{A} (\widehat{N}_{a,1955} - N^{eq}_a)^2$ where N^{eq}_a is the equilibrium age structure given the initial F, as defined previously.
Prior distributions and penalties	Λ_7	is the sum of penalty terms used to implement prior distributions on several parameters. Normal priors were applied to $\widehat{\alpha}_{2(f=2)}$, $\widehat{\alpha}_{2(u=2)}$, and $\widehat{\eta}_{2(u=2)}$. Normal distributions required a value to describe variance, and each prior had an assumed CV=0.5 (i.e., diffuse priors).
Total objective function	Λ	$\Lambda = \sum_{i=1}^{7} \Lambda_i$ Objective function minimized by the assessment model

Appendix A AD Model Builder code to implement the Beaufort Assessment Model

```
//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//##
//##  SEDAR ## Atlantic menhaden assessment December 2014
//##
//##  NMFS, Beaufort Lab, Sustainable Fisheries Branch
//##
//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
DATA_SECTION

!!cout << "Starting Beaufort Assessment Model" << endl;
!!cout << endl;
!!cout << "                BAM!" << endl;
!!cout << endl;

//--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//-- BAM DATA_SECTION: set-up section
//--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>

// Starting and ending year of the model (year data starts)
init_int styr;
init_int endyr;

//Starting year to estimate recruitment deviation from S-R curve
init_int styr_rec_dev;
//Ending year to estimate recruitment deviation from S-R curve
init_int endyr_rec_dev;
//possible 3 phases of constraints on recruitment deviations
init_int endyr_rec_phase1;
init_int endyr_rec_phase2;

// ending year for first selectivity period
init_int endyr_period1a;
init_int endyr_period1b;
init_int endyr_period1;
init_int endyr_period2;
init_int endyr_period3;

//Total number of ages
init_int nages;

// Vector of ages for age bins
init_vector agebins(1,nages);

//number assessment years
number nyrs;
number nyrs_rec;
//this section MUST BE INDENTED!!!
 LOCAL_CALCS
   nyrs=endyr-styr+1.;
   nyrs_rec=endyr_rec_dev-styr_rec_dev+1.;
 END_CALCS

//Total number of length bins for each matrix and length bins used to compute mass in largest bin (plus group)
init_int nlenbins;       //used to match data
init_int nlenbins_plus;  //used to compute density of largest bin (plus group)

//Vector of lengths for length bins (mm)(midpoint) and bins used in computation of plus group
init_ivector lenbins(1,nlenbins);
init_ivector lenbins_plus(1,nlenbins_plus);

int nlenbins_all;    //largest size class used to compute average lengths and weights
//this section MUST BE INDENTED!!!
 LOCAL_CALCS
   nlenbins_all=nlenbins+nlenbins_plus;
 END_CALCS

//Max F used in spr and msy calcs
init_number max_F_spr_msy;
//Total number of iterations for spr calcs
init_int n_iter_spr;
//Total number of iterations for msy calcs
init_int n_iter_msy;
//Number years at end of time series over which to average sector F's, for weighted selectivities
init_int selpar_n_yrs_wgted;
//bias correction (set to 1.0 for no bias correction or a negative value to compute from rec variance)
init_number set_BiasCor;
//exclude these years from end of time series for computing bias correction
init_number BiasCor_exclude_yrs;

!!cout << "max_F_spr_msy" << max_F_spr_msy  << endl;

//--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//-- BAM DATA_SECTION: observed data section
//--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>

//###################Commercial Reduction fishery #########################

// Landings  (1000 mt)
init_int styr_cR_L;
init_int endyr_cR_L;
init_vector obs_cRn_L(styr_cR_L,endyr_cR_L);   //vector of observed landings by year
init_vector cRn_L_cv(styr_cR_L,endyr_cR_L);    //vector of CV of landings by year
init_vector obs_cRs_L(styr_cR_L,endyr_cR_L);   //vector of observed landings by year
init_vector cRs_L_cv(styr_cR_L,endyr_cR_L);    //vector of CV of landings by year

// Age Compositions
```

```
init_int nyr_cR_agec;
init_ivector yrs_cR_agec(1,nyr_cR_agec);
init_vector nsamp_cRn_agec(1,nyr_cR_agec);
init_vector nfish_cRn_agec(1,nyr_cR_agec);
init_vector nsamp_cRs_agec(1,nyr_cR_agec);
init_vector nfish_cRs_agec(1,nyr_cR_agec);
init_matrix obs_cRn_agec(1,nyr_cR_agec,1,nages);
init_matrix obs_cRs_agec(1,nyr_cR_agec,1,nages);

//###################Commercial Bait fishery #########################

// Landings  (1000 mt)
init_int styr_cB_L;
init_int endyr_cB_L;
init_vector obs_cBn_L(styr_cB_L,endyr_cB_L);   //vector of observed landings by year
init_vector cBn_L_cv(styr_cB_L,endyr_cB_L);    //vector of CV of landings by year
init_vector obs_cBs_L(styr_cB_L,endyr_cB_L);   //vector of observed landings by year
init_vector cBs_L_cv(styr_cB_L,endyr_cB_L);    //vector of CV of landings by year

// Age Compositions
init_int nyr_cB_agec;
init_ivector yrs_cB_agec(1,nyr_cB_agec);
init_vector nsamp_cBn_agec(1,nyr_cB_agec);
init_vector nfish_cBn_agec(1,nyr_cB_agec);
init_vector nsamp_cBs_agec(1,nyr_cB_agec);
init_vector nfish_cBs_agec(1,nyr_cB_agec);
init_matrix obs_cBn_agec(1,nyr_cB_agec,1,nages);
init_matrix obs_cBs_agec(1,nyr_cB_agec,1,nages);

//!!cout << "yrs cB agec" << yrs_cB_agec << endl;
//!!cout << "obs cB agec - south" << obs_cBs_agec  << endl;

//####################### composite trawl index - SEAMAP and GA ###################################

//CPUE
 init_int styr_sgcomp_trawl_cpue;
 init_int endyr_sgcomp_trawl_cpue;
 init_vector obs_sgcomp_trawl_cpue(styr_sgcomp_trawl_cpue,endyr_sgcomp_trawl_cpue);
 init_vector sgcomp_trawl_cpue_cv(styr_sgcomp_trawl_cpue,endyr_sgcomp_trawl_cpue);

// Length Compositions (1 cm bins)
init_int nyr_sgcomp_trawl_lenc;
init_ivector yrs_sgcomp_trawl_lenc(1,nyr_sgcomp_trawl_lenc);
init_vector nsamp_sgcomp_trawl_lenc(1,nyr_sgcomp_trawl_lenc);
init_vector nfish_sgcomp_trawl_lenc(1,nyr_sgcomp_trawl_lenc);
init_matrix obs_sgcomp_trawl_lenc(1,nyr_sgcomp_trawl_lenc,1,nlenbins);

!!cout << "start year SG comp trawl index" << styr_sgcomp_trawl_cpue  << endl;

//####################### composite trawl index ###################################

//CPUE
 init_int styr_comp_trawl_cpue;
 init_int endyr_comp_trawl_cpue;
 init_vector obs_comp_trawl_cpue(styr_comp_trawl_cpue,endyr_comp_trawl_cpue);
 init_vector comp_trawl_cpue_cv(styr_comp_trawl_cpue,endyr_comp_trawl_cpue);

// Length Compositions (1 cm bins)
init_int nyr_comp_trawl_lenc;
init_ivector yrs_comp_trawl_lenc(1,nyr_comp_trawl_lenc);
init_vector nsamp_comp_trawl_lenc(1,nyr_comp_trawl_lenc);
init_vector nfish_comp_trawl_lenc(1,nyr_comp_trawl_lenc);
init_matrix obs_comp_trawl_lenc(1,nyr_comp_trawl_lenc,1,nlenbins);

!!cout << "start year comp trawl index" << styr_comp_trawl_cpue  << endl;

//####################### seine survey index ###############################
//CPUE
 init_int styr_seine_cpue;
 init_int endyr_seine_cpue;
 init_vector obs_seine_cpue(styr_seine_cpue,endyr_seine_cpue);
 init_vector seine_cpue_cv(styr_seine_cpue,endyr_seine_cpue);

//####################### yoy index ###############################
//CPUE:  fishery-dependent
 init_int styr_yoy_cpue;
 init_int endyr_yoy_cpue;
 init_vector obs_yoy_cpue(styr_yoy_cpue,endyr_yoy_cpue);
 init_vector yoy_cpue_cv(styr_yoy_cpue,endyr_yoy_cpue);

!!cout << "start year yoy index" << styr_yoy_cpue  << endl;

//--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//-- BAM DATA_SECTION: parameter section
//--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//##################Single Parameter values and initial guesses #################################
// Von Bert parameters in TL mm all fish
init_vector set_Linf(1,7);
init_vector set_K(1,7);
init_vector set_t0(1,7);
//CV of length at age and its standard error all fish
init_vector set_len_cv(1,7);
//age-independent: used only for MSST and to scale age dependent M, prior if M is estimated
init_vector set_M_constant(1,7);
//Spawner-recruit parameters (Initial guesses or fixed values)
init_vector set_steep(1,7);         //recruitment steepness
init_vector set_log_R0(1,7);        //recruitment R0
init_vector set_R_autocorr(1,7);    //recruitment autocorrelation
init_vector set_rec_sigma(1,7);     //recruitment standard deviation in log space
//Initial guesses or fixed values of estimated selectivity parameters
//reduction fishery
init_vector set_selpar_L50_cRn(1,7);
init_vector set_selpar_slope_cRn(1,7);
init_vector set_selpar_L502_cRn(1,7);
```

```
init_vector set_selpar_slope2_cRn(1,7);

init_vector set_selpar_L50_cRs(1,7);
init_vector set_selpar_slope_cRs(1,7);
init_vector set_selpar_L502_cRs(1,7);
init_vector set_selpar_slope2_cRs(1,7);

init_vector set_selpar_L50_cRn2(1,7);    //for period 2 of cR selectivity-north
init_vector set_selpar_slope_cRn2(1,7);
init_vector set_selpar_L502_cRn2(1,7);
init_vector set_selpar_slope2_cRn2(1,7);

init_vector set_selpar_L50_cRs2(1,7);    //for period 2 of cR selectivity-south
init_vector set_selpar_slope_cRs2(1,7);
init_vector set_selpar_L502_cRs2(1,7);
init_vector set_selpar_slope2_cRs2(1,7);

init_vector set_selpar_L50_cRn3(1,7);    //for period 3 of cR selectivity-north
init_vector set_selpar_slope_cRn3(1,7);
init_vector set_selpar_L502_cRn3(1,7);
init_vector set_selpar_slope2_cRn3(1,7);

init_vector set_selpar_L50_cRs3(1,7);    //for period 3 of cR selectivity-south
init_vector set_selpar_slope_cRs3(1,7);
init_vector set_selpar_L502_cRs3(1,7);
init_vector set_selpar_slope2_cRs3(1,7);

init_vector set_selpar_L50_logexp_cR(1,7);      //selectivity parameters for the modified logistic exponential
init_vector set_selpar_slope_logexp_cR(1,7);
init_vector set_selpar_sigma_logexp_cR(1,7);

init_vector set_sel_age0_cRs(1,7); //input in logit space by age; SOUTH
init_vector set_sel_age1_cRs(1,7);
init_vector set_sel_age2_cRs(1,7);
init_vector set_sel_age3_cRs(1,7);
init_vector set_sel_age4_cRs(1,7);
init_vector set_sel_age5_cRs(1,7);
init_vector set_sel_age6_cRs(1,7);

init_vector set_sel_age0_cRn(1,7); //input in logit space by age; NORTH
init_vector set_sel_age1_cRn(1,7);
init_vector set_sel_age2_cRn(1,7);
init_vector set_sel_age3_cRn(1,7);
init_vector set_sel_age4_cRn(1,7);
init_vector set_sel_age5_cRn(1,7);
init_vector set_sel_age6_cRn(1,7);

init_vector set_sel_age0_cR2(1,7); //input in logit space by age-period 2
init_vector set_sel_age1_cR2(1,7);
init_vector set_sel_age2_cR2(1,7);
init_vector set_sel_age3_cR2(1,7);
init_vector set_sel_age4_cR2(1,7);

//Bait fishery - NORTH-period 1
init_vector set_selpar_L50_cBn(1,7);
init_vector set_selpar_slope_cBn(1,7);
init_vector set_selpar_L502_cBn(1,7);   //for double logistic selectivity
init_vector set_selpar_slope2_cBn(1,7); //for double logistic selectivity

//Bait fishery - NORTH-period 3
init_vector set_selpar_L50_cBn3(1,7);
init_vector set_selpar_slope_cBn3(1,7);
init_vector set_selpar_L502_cBn3(1,7);   //for double logistic selectivity
init_vector set_selpar_slope2_cBn3(1,7); //for double logistic selectivity

//Bait fishery - NORTH, logit
init_vector set_sel_age0_cBn(1,7); //input in logit space by age; NORTH
init_vector set_sel_age1_cBn(1,7);
init_vector set_sel_age2_cBn(1,7);
init_vector set_sel_age3_cBn(1,7);
init_vector set_sel_age4_cBn(1,7);
init_vector set_sel_age5_cBn(1,7);
init_vector set_sel_age6_cBn(1,7);

//Bait fishery - SOUTH
init_vector set_selpar_L50_cBs(1,7);
init_vector set_selpar_slope_cBs(1,7);
init_vector set_selpar_L502_cBs(1,7);   //for double logistic selectivity
init_vector set_selpar_slope2_cBs(1,7); //for double logistic selectivity

//Bait fishery - SOUTH, logit
init_vector set_sel_age0_cBs(1,7); //input in logit space by age; SOUTH
init_vector set_sel_age1_cBs(1,7);
init_vector set_sel_age2_cBs(1,7);
init_vector set_sel_age3_cBs(1,7);
init_vector set_sel_age4_cBs(1,7);
init_vector set_sel_age5_cBs(1,7);
init_vector set_sel_age6_cBs(1,7);

//sg composite trawl survey
init_vector set_selpar_L50_sgcomp_trawl(1,7);
init_vector set_selpar_slope_sgcomp_trawl(1,7);
init_vector set_selpar_L502_sgcomp_trawl(1,7);   //for double logistic selectivity
init_vector set_selpar_slope2_sgcomp_trawl(1,7); //for double logistic selectivity

//composite trawl survey
init_vector set_selpar_L50_comp_trawl(1,7);
init_vector set_selpar_slope_comp_trawl(1,7);
init_vector set_selpar_L502_comp_trawl(1,7);   //for double logistic selectivity
init_vector set_selpar_slope2_comp_trawl(1,7); //for double logistic selectivity

//////--index catchability------------------------------------------------------------------------------------
init_vector set_log_q_sgcomp_trawl(1,7);    //catchability coefficient (log) for sg composite trawl index
init_vector set_log_q_comp_trawl(1,7);    //catchability coefficient (log) for composite trawl index
```

```
init_vector set_log_q_seine(1,7);     //catchability coefficient (log) seine index
init_vector set_log_q1_yoy(1,7);      //catchability coefficient (log) yoy index (1955-1985)
init_vector set_log_q2_yoy(1,7);      //catchability coefficient (log) yoy index (1986-2013)

////--F’s--------------------------------
init_vector set_log_avg_F_cRn(1,7);  //north
init_vector set_log_avg_F_cRs(1,7);  //south
init_vector set_log_avg_F_cBn(1,7);  //north
init_vector set_log_avg_F_cBs(1,7);  //south

//##################Dev Vector Parameter values (vals) and bounds #################################
//--F vectors---------------------------
init_vector set_log_F_dev_cRn(1,3); //north
init_vector set_log_F_dev_cRs(1,3); //south
init_vector set_log_F_dev_cBn(1,3); //north
init_vector set_log_F_dev_cBs(1,3); //south
init_vector set_log_rec_dev(1,3);
init_vector set_M_dev(1,3);
init_vector set_log_N_dev(1,3);

init_vector set_log_F_dev_cRn_vals(styr_cR_L,endyr_cR_L);  //north
init_vector set_log_F_dev_cRs_vals(styr_cR_L,endyr_cR_L);  //south
init_vector set_log_F_dev_cBn_vals(styr_cB_L,endyr_cB_L);  //north
init_vector set_log_F_dev_cBs_vals(styr_cB_L,endyr_cB_L);  //south
init_vector set_log_rec_dev_vals(styr_rec_dev,endyr_rec_dev);
//init_vector set_M_dev_vals(styr_seine_cpue,endyr_seine_cpue);
init_vector set_log_N_dev_vals(2,nages);

!!cout << "set_log_rec_dev" << set_log_rec_dev << endl;
//--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//-- BAM DATA_SECTION: likelihood weights section
//--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>

init_number set_w_L;
init_number set_w_lc_sgcomp_trawl;
init_number set_w_lc_comp_trawl;
init_number set_w_ac_cRn;        //NORTH
init_number set_w_ac_cRs;        //SOUTH
init_number set_w_ac_cBn;        //NORTH
init_number set_w_ac_cBs;        //SOUTH
init_number set_w_I_sgcomp_trawl;        //weight for sg composite trawl index
init_number set_w_I_comp_trawl;        //weight for composite trawl index
init_number set_w_I_seine;           //weight for seine index
init_number set_w_I_yoy;            //weight for yoy index
init_number set_w_M_dev;             //weight on M dev constraint
init_number set_w_rec;               //for fitting S-R curve
init_number set_w_rec_early;         //additional constraint on early years recruitment
init_number set_w_rec_end;           //additional constraint on ending years recruitment
init_number set_w_fullF;             //penalty for any Fapex>3(removed in final phase of optimization)
init_number set_w_Ftune;             //weight applied to tuning F (removed in final phase of optimization)
//init_number set_w_cvlen_dev;       //penalty on cv deviations at age
//init_number set_w_cvlen_diff;      //penalty on first difference of cv deviations at age

!!cout << "set_w_I_seine" << set_w_I_seine  << endl;
//--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//-- BAM DATA_SECTION: miscellaneous stuff section
//--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>

//FL(mm)-weight(whole weight in g) relationship: W=aL^b
init_number wgtpar_a;
init_number wgtpar_b;

//Female maturity and proportion female at age
init_vector maturity_f_obs(1,nages);            //proportion females mature at age
init_matrix tv_maturity_f_obs(styr,endyr,1,nages); //proportion females mature at age over time
init_vector prop_f_obs(1,nages);                //proportion female at age
init_vector fec_at_age(1,nages);                //fecundity at age
init_matrix fec_at_age_tv(styr,endyr,1,nages);  //fecundity at age, time-varying

//weights at start and middle of the year
init_vector wgt_spawn(1,nages);                //weights based on cR fishery, but bias corrected
init_matrix wgt_spawn_tv(styr,endyr,1,nages);  //weights based on cR fishery, but bias corrected, time-varying
init_vector wgt_start(1,nages);                //weights based on cR fishery
init_matrix wgt_start_tv(styr,endyr,1,nages);  //weights based on cR fishery, time-varying

//lengths at start of the year
init_matrix len_may_tv(styr,endyr,1,nages);  //lengths based on cR fishery, but bias corrected, time-varying, May 15
init_matrix len_sept_tv(styr,endyr,1,nages);   //lengths based on cR fishery, but bias corrected, time-varying, September 1

//spawn time fraction - when spawning is occuring
init_number spawn_time_frac; //time of year of peak spawning, as a fraction of the year

// Natural mortality
init_vector set_M(1,nages);     //age-dependent: used in model
init_number max_obs_age;        //max observed age, used to scale M
init_matrix set_M_tv(styr,endyr,1,nages);  //age-dependent, time-varying M

!!cout << "max age" << max_obs_age << endl;

//Spawner-recruit parameters (Initial guesses or fixed values)
init_number SR_switch;

//rate of increase on q
init_int set_q_rate_phase;  //value sets estimation phase of rate increase, negative value turns it off
init_number set_q_rate;

//density dependence on fishery q’s
init_int set_q_DD_phase;      //value sets estimation phase of random walk, negative value turns it off
init_number set_q_DD_beta;    //value of 0.0 is density indepenent
init_number set_q_DD_beta_se;
init_int set_q_DD_stage;      //age to begin counting biomass, should be near full exploitation

//random walk on fishery q’s
init_int set_q_RW_phase;         //value sets estimation phase of random walk, negative value turns it off
```

```
init_number set_q_RW_comp_trawl_var;    //assumed variance of RW q
init_number set_q_RW_sgcomp_trawl_var;    //assumed variance of RW q
init_number set_q_RW_seine_var;    //assumed variance of RW q
init_number set_q_RW_yoy_var;     //assumed variance of RW q

//Tune Fapex (tuning removed in final year of optimization)
init_number set_Ftune;
init_int set_Ftune_yr;

!!cout << "set_Ftune_yr" << set_Ftune_yr << endl;

//threshold sample sizes for length comps
init_number minSS_sgcomp_trawl_lenc;
init_number minSS_comp_trawl_lenc;

//threshold sample sizes for age comps
init_number minSS_cRn_agec;
init_number minSS_cRs_agec;
init_number minSS_cBn_agec;
init_number minSS_cBs_agec;

//ageing error matrix (columns are true ages, rows are ages as read for age comps: columns should sum to one)
init_matrix age_error(1,nages,1,nages);

// #######Indexing integers for year(iyear), age(iage),length(ilen) ###############
int iyear;
int iage;
int ilen;
int ff;
int quant_whole;

number sqrt2pi;
number g2mt;                    //conversion of grams to metric tons
number g2kg;                    //conversion of grams to kg
number g2klb;                   //conversion of grams to 1000 lb
number mt2klb;                  //conversion of metric tons to 1000 lb
number mt2lb;                   //conversion of metric tons to lb
number dzero;                   //small additive constant to prevent division by zero
number huge_number;             //huge number, to avoid irregular parameter space

init_number end_of_data_file;
//this section MUST BE INDENTED!!!
 LOCAL_CALCS
   if(end_of_data_file!=999)
   {
       cout << "*** WARNING: Data File NOT READ CORRECTLY ****" << endl;
       exit(0);
   }
   else
   {
    cout << "Data File read correctly" << endl;
   }
 END_CALCS


PARAMETER_SECTION

 LOCAL_CALCS
  const double Linf_LO=set_Linf(2); const double Linf_HI=set_Linf(3); const double Linf_PH=set_Linf(4);
  const double K_LO=set_K(2); const double K_HI=set_K(3); const double K_PH=set_K(4);
  const double t0_LO=set_t0(2); const double t0_HI=set_t0(3); const double t0_PH=set_t0(4);
  const double len_cv_LO=set_len_cv(2); const double len_cv_HI=set_len_cv(3); const double len_cv_PH=set_len_cv(4);
  const double M_constant_LO=set_M_constant(2); const double M_constant_HI=set_M_constant(3); const double M_constant_PH=set_M_constant(4);
  const double steep_LO=set_steep(2); const double steep_HI=set_steep(3); const double steep_PH=set_steep(4);
  const double log_R0_LO=set_log_R0(2); const double log_R0_HI=set_log_R0(3); const double log_R0_PH=set_log_R0(4);
  const double R_autocorr_LO=set_R_autocorr(2); const double R_autocorr_HI=set_R_autocorr(3); const double R_autocorr_PH=set_R_autocorr(4);
  const double rec_sigma_LO=set_rec_sigma(2); const double rec_sigma_HI=set_rec_sigma(3); const double rec_sigma_PH=set_rec_sigma(4);

  const double selpar_L50_cRn_LO=set_selpar_L50_cRn(2); const double selpar_L50_cRn_HI=set_selpar_L50_cRn(3); const double selpar_L50_cRn_PH=set_selpar_L50_cRn(4);
  const double selpar_slope_cRn_LO=set_selpar_slope_cRn(2); const double selpar_slope_cRn_HI=set_selpar_slope_cRn(3); const double selpar_slope_cRn_PH=set_selpar_slope_cRn(4);
  const double selpar_L502_cRn_LO=set_selpar_L502_cRn(2); const double selpar_L502_cRn_HI=set_selpar_L502_cRn(3); const double selpar_L502_cRn_PH=set_selpar_L502_cRn(4);
  const double selpar_slope2_cRn_LO=set_selpar_slope2_cRn(2); const double selpar_slope2_cRn_HI=set_selpar_slope2_cRn(3); const double selpar_slope2_cRn_PH=set_selpar_slope2_cRn(4);
  const double selpar_L50_cRs_LO=set_selpar_L50_cRs(2); const double selpar_L50_cRs_HI=set_selpar_L50_cRs(3); const double selpar_L50_cRs_PH=set_selpar_L50_cRs(4);
  const double selpar_slope_cRs_LO=set_selpar_slope_cRs(2); const double selpar_slope_cRs_HI=set_selpar_slope_cRs(3); const double selpar_slope_cRs_PH=set_selpar_slope_cRs(4);
  const double selpar_L502_cRs_LO=set_selpar_L502_cRs(2); const double selpar_L502_cRs_HI=set_selpar_L502_cRs(3); const double selpar_L502_cRs_PH=set_selpar_L502_cRs(4);
  const double selpar_slope2_cRs_LO=set_selpar_slope2_cRs(2); const double selpar_slope2_cRs_HI=set_selpar_slope2_cRs(3); const double selpar_slope2_cRs_PH=set_selpar_slope2_cRs(4);

  const double selpar_L50_cRn2_LO=set_selpar_L50_cRn2(2); const double selpar_L50_cRn2_HI=set_selpar_L50_cRn2(3); const double selpar_L50_cRn2_PH=set_selpar_L50_cRn2(4);
  const double selpar_slope_cRn2_LO=set_selpar_slope_cRn2(2); const double selpar_slope_cRn2_HI=set_selpar_slope_cRn2(3); const double selpar_slope_cRn2_PH=set_selpar_slope_cRn2(4);
  const double selpar_L502_cRn2_LO=set_selpar_L502_cRn2(2); const double selpar_L502_cRn2_HI=set_selpar_L502_cRn2(3); const double selpar_L502_cRn2_PH=set_selpar_L502_cRn2(4);
  const double selpar_slope2_cRn2_LO=set_selpar_slope2_cRn2(2); const double selpar_slope2_cRn2_HI=set_selpar_slope2_cRn2(3); const double selpar_slope2_cRn2_PH=set_selpar_slope2_cRn2(4);
  const double selpar_L50_cRs2_LO=set_selpar_L50_cRs2(2); const double selpar_L50_cRs2_HI=set_selpar_L50_cRs2(3); const double selpar_L50_cRs2_PH=set_selpar_L50_cRs2(4);
  const double selpar_slope_cRs2_LO=set_selpar_slope_cRs2(2); const double selpar_slope_cRs2_HI=set_selpar_slope_cRs2(3); const double selpar_slope_cRs2_PH=set_selpar_slope_cRs2(4);
  const double selpar_L502_cRs2_LO=set_selpar_L502_cRs2(2); const double selpar_L502_cRs2_HI=set_selpar_L502_cRs2(3); const double selpar_L502_cRs2_PH=set_selpar_L502_cRs2(4);
  const double selpar_slope2_cRs2_LO=set_selpar_slope2_cRs2(2); const double selpar_slope2_cRs2_HI=set_selpar_slope2_cRs2(3); const double selpar_slope2_cRs2_PH=set_selpar_slope2_cRs2(4);

  const double selpar_L50_cRn3_LO=set_selpar_L50_cRn3(2); const double selpar_L50_cRn3_HI=set_selpar_L50_cRn3(3); const double selpar_L50_cRn3_PH=set_selpar_L50_cRn3(4);
  const double selpar_slope_cRn3_LO=set_selpar_slope_cRn3(2); const double selpar_slope_cRn3_HI=set_selpar_slope_cRn3(3); const double selpar_slope_cRn3_PH=set_selpar_slope_cRn3(4);
  const double selpar_L502_cRn3_LO=set_selpar_L502_cRn3(2); const double selpar_L502_cRn3_HI=set_selpar_L502_cRn3(3); const double selpar_L502_cRn3_PH=set_selpar_L502_cRn3(4);
  const double selpar_slope2_cRn3_LO=set_selpar_slope2_cRn3(2); const double selpar_slope2_cRn3_HI=set_selpar_slope2_cRn3(3); const double selpar_slope2_cRn3_PH=set_selpar_slope2_cRn3(4);
  const double selpar_L50_cRs3_LO=set_selpar_L50_cRs3(2); const double selpar_L50_cRs3_HI=set_selpar_L50_cRs3(3); const double selpar_L50_cRs3_PH=set_selpar_L50_cRs3(4);
  const double selpar_slope_cRs3_LO=set_selpar_slope_cRs3(2); const double selpar_slope_cRs3_HI=set_selpar_slope_cRs3(3); const double selpar_slope_cRs3_PH=set_selpar_slope_cRs3(4);
  const double selpar_L502_cRs3_LO=set_selpar_L502_cRs3(2); const double selpar_L502_cRs3_HI=set_selpar_L502_cRs3(3); const double selpar_L502_cRs3_PH=set_selpar_L502_cRs3(4);
  const double selpar_slope2_cRs3_LO=set_selpar_slope2_cRs3(2); const double selpar_slope2_cRs3_HI=set_selpar_slope2_cRs3(3); const double selpar_slope2_cRs3_PH=set_selpar_slope2_cRs3(4);

  const double selpar_L50_logexp_cR_LO=set_selpar_L50_logexp_cR(2); const double selpar_L50_logexp_cR_HI=set_selpar_L50_logexp_cR(3); const double selpar_L50_logexp_cR_PH=set_selpar_L50_logexp_cR(4);
  const double selpar_slope_logexp_cR_LO=set_selpar_slope_logexp_cR(2); const double selpar_slope_logexp_cR_HI=set_selpar_slope_logexp_cR(3); const double selpar_slope_logexp_cR_PH=set_selpar_slope_logexp_cR(4);
  const double selpar_sigma_logexp_cR_LO=set_selpar_sigma_logexp_cR(2); const double selpar_sigma_logexp_cR_HI=set_selpar_slope_logexp_cR(3); const double selpar_sigma_logexp_cR_PH=set_selpar_sigma_logexp_cR(4);

  const double selpar_age0_cRs_LO=set_sel_age0_cRs(2); const double selpar_age0_cRs_HI=set_sel_age0_cRs(3); const double selpar_age0_cRs_PH=set_sel_age0_cRs(4);
  const double selpar_age1_cRs_LO=set_sel_age1_cRs(2); const double selpar_age1_cRs_HI=set_sel_age1_cRs(3); const double selpar_age1_cRs_PH=set_sel_age1_cRs(4);
  const double selpar_age2_cRs_LO=set_sel_age2_cRs(2); const double selpar_age2_cRs_HI=set_sel_age2_cRs(3); const double selpar_age2_cRs_PH=set_sel_age2_cRs(4);
  const double selpar_age3_cRs_LO=set_sel_age3_cRs(2); const double selpar_age3_cRs_HI=set_sel_age3_cRs(3); const double selpar_age3_cRs_PH=set_sel_age3_cRs(4);
  const double selpar_age4_cRs_LO=set_sel_age4_cRs(2); const double selpar_age4_cRs_HI=set_sel_age4_cRs(3); const double selpar_age4_cRs_PH=set_sel_age4_cRs(4);
```

```
  const double selpar_age5_cRs_LO=set_sel_age5_cRs(2); const double selpar_age5_cRs_HI=set_sel_age5_cRs(3); const double selpar_age5_cRs_PH=set_sel_age5_cRs(4);
  const double selpar_age6_cRs_LO=set_sel_age6_cRs(2); const double selpar_age6_cRs_HI=set_sel_age6_cRs(3); const double selpar_age6_cRs_PH=set_sel_age6_cRs(4);

  const double selpar_age0_cRn_LO=set_sel_age0_cRn(2); const double selpar_age0_cRn_HI=set_sel_age0_cRn(3); const double selpar_age0_cRn_PH=set_sel_age0_cRn(4);
  const double selpar_age1_cRn_LO=set_sel_age1_cRn(2); const double selpar_age1_cRn_HI=set_sel_age1_cRn(3); const double selpar_age1_cRn_PH=set_sel_age1_cRn(4);
  const double selpar_age2_cRn_LO=set_sel_age2_cRn(2); const double selpar_age2_cRn_HI=set_sel_age2_cRn(3); const double selpar_age2_cRn_PH=set_sel_age2_cRn(4);
  const double selpar_age3_cRn_LO=set_sel_age3_cRn(2); const double selpar_age3_cRn_HI=set_sel_age3_cRn(3); const double selpar_age3_cRn_PH=set_sel_age3_cRn(4);
  const double selpar_age4_cRn_LO=set_sel_age4_cRn(2); const double selpar_age4_cRn_HI=set_sel_age4_cRn(3); const double selpar_age4_cRn_PH=set_sel_age4_cRn(4);
  const double selpar_age5_cRn_LO=set_sel_age5_cRn(2); const double selpar_age5_cRn_HI=set_sel_age5_cRn(3); const double selpar_age5_cRn_PH=set_sel_age5_cRn(4);
  const double selpar_age6_cRn_LO=set_sel_age6_cRn(2); const double selpar_age6_cRn_HI=set_sel_age6_cRn(3); const double selpar_age6_cRn_PH=set_sel_age6_cRn(4);

  const double selpar_age0_cR2_LO=set_sel_age0_cR2(2); const double selpar_age0_cR2_HI=set_sel_age0_cR2(3); const double selpar_age0_cR2_PH=set_sel_age0_cR2(4);
  const double selpar_age1_cR2_LO=set_sel_age1_cR2(2); const double selpar_age1_cR2_HI=set_sel_age1_cR2(3); const double selpar_age1_cR2_PH=set_sel_age1_cR2(4);
  const double selpar_age2_cR2_LO=set_sel_age2_cR2(2); const double selpar_age2_cR2_HI=set_sel_age2_cR2(3); const double selpar_age2_cR2_PH=set_sel_age2_cR2(4);
  const double selpar_age3_cR2_LO=set_sel_age3_cR2(2); const double selpar_age3_cR2_HI=set_sel_age3_cR2(3); const double selpar_age3_cR2_PH=set_sel_age3_cR2(4);
  const double selpar_age4_cR2_LO=set_sel_age4_cR2(2); const double selpar_age4_cR2_HI=set_sel_age4_cR2(3); const double selpar_age4_cR2_PH=set_sel_age4_cR2(4);

  const double selpar_L50_cBn_LO=set_selpar_L50_cBn(2); const double selpar_L50_cBn_HI=set_selpar_L50_cBn(3); const double selpar_L50_cBn_PH=set_selpar_L50_cBn(4);
  const double selpar_slope_cBn_LO=set_selpar_slope_cBn(2); const double selpar_slope_cBn_HI=set_selpar_slope_cBn(3); const double selpar_slope_cBn_PH=set_selpar_slope_cBn(4);
  const double selpar_L502_cBn_LO=set_selpar_L502_cBn(2); const double selpar_L502_cBn_HI=set_selpar_L502_cBn(3); const double selpar_L502_cBn_PH=set_selpar_L502_cBn(4);
  const double selpar_slope2_cBn_LO=set_selpar_slope2_cBn(2); const double selpar_slope2_cBn_HI=set_selpar_slope2_cBn(3); const double selpar_slope2_cBn_PH=set_selpar_slope2_cBn(4);
  const double selpar_L50_cBs_LO=set_selpar_L50_cBs(2); const double selpar_L50_cBs_HI=set_selpar_L50_cBs(3); const double selpar_L50_cBs_PH=set_selpar_L50_cBs(4);
  const double selpar_slope_cBs_LO=set_selpar_slope_cBs(2); const double selpar_slope_cBs_HI=set_selpar_slope_cBs(3); const double selpar_slope_cBs_PH=set_selpar_slope_cBs(4);
  const double selpar_L502_cBs_LO=set_selpar_L502_cBs(2); const double selpar_L502_cBs_HI=set_selpar_L502_cBs(3); const double selpar_L502_cBs_PH=set_selpar_L502_cBs(4);
  const double selpar_slope2_cBs_LO=set_selpar_slope2_cBs(2); const double selpar_slope2_cBs_HI=set_selpar_slope2_cBs(3); const double selpar_slope2_cBs_PH=set_selpar_slope2_cBs(4);

  const double selpar_L50_cBn3_LO=set_selpar_L50_cBn3(2); const double selpar_L50_cBn3_HI=set_selpar_L50_cBn3(3); const double selpar_L50_cBn3_PH=set_selpar_L50_cBn3(4);
  const double selpar_slope_cBn3_LO=set_selpar_slope_cBn3(2); const double selpar_slope_cBn3_HI=set_selpar_slope_cBn3(3); const double selpar_slope_cBn3_PH=set_selpar_slope_cBn3(4);
  const double selpar_L502_cBn3_LO=set_selpar_L502_cBn3(2); const double selpar_L502_cBn3_HI=set_selpar_L502_cBn3(3); const double selpar_L502_cBn3_PH=set_selpar_L502_cBn3(4);
  const double selpar_slope2_cBn3_LO=set_selpar_slope2_cBn3(2); const double selpar_slope2_cBn3_HI=set_selpar_slope2_cBn3(3); const double selpar_slope2_cBn3_PH=set_selpar_slope2_cBn3(4);

  const double selpar_age0_cBn_LO=set_sel_age0_cBn(2); const double selpar_age0_cBn_HI=set_sel_age0_cBn(3); const double selpar_age0_cBn_PH=set_sel_age0_cBn(4);
  const double selpar_age1_cBn_LO=set_sel_age1_cBn(2); const double selpar_age1_cBn_HI=set_sel_age1_cBn(3); const double selpar_age1_cBn_PH=set_sel_age1_cBn(4);
  const double selpar_age2_cBn_LO=set_sel_age2_cBn(2); const double selpar_age2_cBn_HI=set_sel_age2_cBn(3); const double selpar_age2_cBn_PH=set_sel_age2_cBn(4);
  const double selpar_age3_cBn_LO=set_sel_age3_cBn(2); const double selpar_age3_cBn_HI=set_sel_age3_cBn(3); const double selpar_age3_cBn_PH=set_sel_age3_cBn(4);
  const double selpar_age4_cBn_LO=set_sel_age4_cBn(2); const double selpar_age4_cBn_HI=set_sel_age4_cBn(3); const double selpar_age4_cBn_PH=set_sel_age4_cBn(4);
  const double selpar_age5_cBn_LO=set_sel_age5_cBn(2); const double selpar_age5_cBn_HI=set_sel_age5_cBn(3); const double selpar_age5_cBn_PH=set_sel_age5_cBn(4);
  const double selpar_age6_cBn_LO=set_sel_age6_cBn(2); const double selpar_age6_cBn_HI=set_sel_age6_cBn(3); const double selpar_age6_cBn_PH=set_sel_age6_cBn(4);

  const double selpar_age0_cBs_LO=set_sel_age0_cBs(2); const double selpar_age0_cBs_HI=set_sel_age0_cBs(3); const double selpar_age0_cBs_PH=set_sel_age0_cBs(4);
  const double selpar_age1_cBs_LO=set_sel_age1_cBs(2); const double selpar_age1_cBs_HI=set_sel_age1_cBs(3); const double selpar_age1_cBs_PH=set_sel_age1_cBs(4);
  const double selpar_age2_cBs_LO=set_sel_age2_cBs(2); const double selpar_age2_cBs_HI=set_sel_age2_cBs(3); const double selpar_age2_cBs_PH=set_sel_age2_cBs(4);
  const double selpar_age3_cBs_LO=set_sel_age3_cBs(2); const double selpar_age3_cBs_HI=set_sel_age3_cBs(3); const double selpar_age3_cBs_PH=set_sel_age3_cBs(4);
  const double selpar_age4_cBs_LO=set_sel_age4_cBs(2); const double selpar_age4_cBs_HI=set_sel_age4_cBs(3); const double selpar_age4_cBs_PH=set_sel_age4_cBs(4);
  const double selpar_age5_cBs_LO=set_sel_age5_cBs(2); const double selpar_age5_cBs_HI=set_sel_age5_cBs(3); const double selpar_age5_cBs_PH=set_sel_age5_cBs(4);
  const double selpar_age6_cBs_LO=set_sel_age6_cBs(2); const double selpar_age6_cBs_HI=set_sel_age6_cBs(3); const double selpar_age6_cBs_PH=set_sel_age6_cBs(4);

  const double selpar_L50_sgcomp_trawl_LO=set_selpar_L50_sgcomp_trawl(2); const double selpar_L50_sgcomp_trawl_HI=set_selpar_L50_sgcomp_trawl(3); const double selpar_L50_sgcomp_trawl_PH=set_selpar_L50_sgcomp_tra
  const double selpar_slope_sgcomp_trawl_LO=set_selpar_slope_sgcomp_trawl(2); const double selpar_slope_sgcomp_trawl_HI=set_selpar_slope_sgcomp_trawl(3); const double selpar_slope_sgcomp_trawl_PH=set_selpar_slop
  const double selpar_L502_sgcomp_trawl_LO=set_selpar_L502_sgcomp_trawl(2); const double selpar_L502_sgcomp_trawl_HI=set_selpar_L502_sgcomp_trawl(3); const double selpar_L502_sgcomp_trawl_PH=set_selpar_L502_sgco
  const double selpar_slope2_sgcomp_trawl_LO=set_selpar_slope2_sgcomp_trawl(2); const double selpar_slope2_sgcomp_trawl_HI=set_selpar_slope2_sgcomp_trawl(3); const double selpar_slope2_sgcomp_trawl_PH=set_selpar
  const double selpar_L50_comp_trawl_LO=set_selpar_L50_comp_trawl(2); const double selpar_L50_comp_trawl_HI=set_selpar_L50_comp_trawl(3); const double selpar_L50_comp_trawl_PH=set_selpar_L50_comp_trawl(4);
  const double selpar_slope_comp_trawl_LO=set_selpar_slope_comp_trawl(2); const double selpar_slope_comp_trawl_HI=set_selpar_slope_comp_trawl(3); const double selpar_slope_comp_trawl_PH=set_selpar_slope_comp_tra
  const double selpar_L502_comp_trawl_LO=set_selpar_L502_comp_trawl(2); const double selpar_L502_comp_trawl_HI=set_selpar_L502_comp_trawl(3); const double selpar_L502_comp_trawl_PH=set_selpar_L502_comp_trawl(4);
  const double selpar_slope2_comp_trawl_LO=set_selpar_slope2_comp_trawl(2); const double selpar_slope2_comp_trawl_HI=set_selpar_slope2_comp_trawl(3); const double selpar_slope2_comp_trawl_PH=set_selpar_slope2_co
  const double log_q_sgcomp_trawl_LO=set_log_q_sgcomp_trawl(2); const double log_q_sgcomp_trawl_HI=set_log_q_sgcomp_trawl(3); const double log_q_sgcomp_trawl_PH=set_log_q_sgcomp_trawl(4);
  const double log_q_comp_trawl_LO=set_log_q_comp_trawl(2); const double log_q_comp_trawl_HI=set_log_q_comp_trawl(3); const double log_q_comp_trawl_PH=set_log_q_comp_trawl(4);
  const double log_q_seine_LO=set_log_q_seine(2); const double log_q_seine_HI=set_log_q_seine(3); const double log_q_seine_PH=set_log_q_seine(4);
  const double log_q1_yoy_LO=set_log_q1_yoy(2); const double log_q1_yoy_HI=set_log_q1_yoy(3); const double log_q1_yoy_PH=set_log_q1_yoy(4);
  const double log_q2_yoy_LO=set_log_q2_yoy(2); const double log_q2_yoy_HI=set_log_q2_yoy(3); const double log_q2_yoy_PH=set_log_q2_yoy(4);
  const double log_avg_F_cRn_LO=set_log_avg_F_cRn(2); const double log_avg_F_cRn_HI=set_log_avg_F_cRn(3); const double log_avg_F_cRn_PH=set_log_avg_F_cRn(4);
  const double log_avg_F_cRs_LO=set_log_avg_F_cRs(2); const double log_avg_F_cRs_HI=set_log_avg_F_cRs(3); const double log_avg_F_cRs_PH=set_log_avg_F_cRs(4);
  const double log_avg_F_cBn_LO=set_log_avg_F_cBn(2); const double log_avg_F_cBn_HI=set_log_avg_F_cBn(3); const double log_avg_F_cBn_PH=set_log_avg_F_cBn(4);
  const double log_avg_F_cBs_LO=set_log_avg_F_cBs(2); const double log_avg_F_cBs_HI=set_log_avg_F_cBs(3); const double log_avg_F_cBs_PH=set_log_avg_F_cBs(4);
  //-dev vectors-------------------------------------------------------------------------------------------------------
  const double log_F_dev_cRn_LO=set_log_F_dev_cRn(1); const double log_F_dev_cRn_HI=set_log_F_dev_cRn(2); const double log_F_dev_cRn_PH=set_log_F_dev_cRn(3);
  const double log_F_dev_cRs_LO=set_log_F_dev_cRs(1); const double log_F_dev_cRs_HI=set_log_F_dev_cRs(2); const double log_F_dev_cRs_PH=set_log_F_dev_cRs(3);
  const double log_F_dev_cBn_LO=set_log_F_dev_cBn(1); const double log_F_dev_cBn_HI=set_log_F_dev_cBn(2); const double log_F_dev_cBn_PH=set_log_F_dev_cBn(3);
  const double log_F_dev_cBs_LO=set_log_F_dev_cBs(1); const double log_F_dev_cBs_HI=set_log_F_dev_cBs(2); const double log_F_dev_cBs_PH=set_log_F_dev_cBs(3);
  const double log_rec_dev_LO=set_log_rec_dev(1); const double log_rec_dev_HI=set_log_rec_dev(2); const double log_rec_dev_PH=set_log_rec_dev(3);
  const double M_dev_LO=set_M_dev(1);const double M_dev_HI=set_M_dev(2);const double M_dev_PH=set_M_dev(3);
  const double N_dev_LO=set_log_N_dev(1);const double N_dev_HI=set_log_N_dev(2);const double N_dev_PH=set_log_N_dev(3);

 END_CALCS

////-------------Growth-----------------------------------------------------------------------
  init_bounded_number Linf(Linf_LO,Linf_HI,Linf_PH);
  init_bounded_number K(K_LO,K_HI,K_PH);
  init_bounded_number t0(t0_LO,t0_HI,t0_PH);
  init_bounded_number len_cv_val(len_cv_LO,len_cv_HI,len_cv_PH);
  vector Linf_out(1,8);
  vector K_out(1,8);
  vector t0_out(1,8);
  vector len_cv_val_out(1,8);

  matrix meanlen_FL_may(styr,endyr,1,nages);   //mean fork length (mm) at age, population, May 15
  matrix meanlen_FL_sept(styr,endyr,1,nages);   //mean fork length (mm) at age, population, September 1
  matrix wgt_fish_mt(styr,endyr,1,nages);  //wgt in mt
  vector wgt_spawn_mt(1,nages);
  matrix wgt_spawn_mt_tv(styr,endyr,1,nages); //wgt in mt

  matrix wholewgt_cR_mt(styr,endyr,1,nages);    //whole wgt of cR landings in mt
  matrix wholewgt_cB_mt(styr,endyr,1,nages);    //whole wgt of cB landings in mt

  vector lbins(1,nlenbins);

  3darray lenprob_may(styr,endyr,1,nages,1,nlenbins);           //distn of size at age (age-length key, 1 cm bins) in population
  3darray lenprob_sept(styr,endyr,1,nages,1,nlenbins);           //distn of size at age (age-length key, 1 cm bins) in population
  3darray lenprob_may_all(styr,endyr,1,nages,1,nlenbins_all);   //extended lenprob
  3darray lenprob_sept_all(styr,endyr,1,nages,1,nlenbins_all);   //extended lenprob
  vector lenbins_all(1,nlenbins_all);

  //matrices below are used to match length comps
  3darray lenprob_sgcomp_trawl(styr,endyr,1,nages,1,nlenbins);     //distn of size at age in sg composite trawl
```

```
  3darray lenprob_comp_trawl(styr,endyr,1,nages,1,nlenbins);     //distn of size at age in composite trawl

  //matrices below pertain to the popn at large, used to compute mean weights
  3darray lenprob_sgcomp_trawl_all(styr,endyr,1,nages,1,nlenbins_all);     //distn of size at age in sg composite trawl
  3darray lenprob_comp_trawl_all(styr,endyr,1,nages,1,nlenbins_all);     //distn of size at age in composite trawl

  //init_bounded_dev_vector log_len_cv_dev(1,nages,-2,2,3)
  //number log_len_cv
  matrix len_sd(styr,endyr,1,nages);
  vector len_cv_may(1,nages);
  vector len_cv_sept(1,nages);
  vector len_cv(1,nages); //for fishgraph

////----Predicted length and age compositions
  matrix pred_sgcomp_trawl_lenc(1,nyr_sgcomp_trawl_lenc,1,nlenbins);
  matrix pred_comp_trawl_lenc(1,nyr_comp_trawl_lenc,1,nlenbins);
  matrix pred_cRn_agec(1,nyr_cR_agec,1,nages);               //NORTH
  matrix ErrorFree_cRn_agec(1,nyr_cR_agec,1,nages);
  matrix pred_cRs_agec(1,nyr_cR_agec,1,nages);               //SOUTH
  matrix ErrorFree_cRs_agec(1,nyr_cR_agec,1,nages);
  matrix pred_cBn_agec(1,nyr_cB_agec,1,nages);               //NORTH
  matrix ErrorFree_cBn_agec(1,nyr_cB_agec,1,nages);
  matrix pred_cBs_agec(1,nyr_cB_agec,1,nages);               //SOUTH
  matrix ErrorFree_cBs_agec(1,nyr_cB_agec,1,nages);

//effective sample size applied in multinomial distributions
  vector nsamp_sgcomp_trawl_lenc_allyr(styr,endyr);
  vector nsamp_comp_trawl_lenc_allyr(styr,endyr);
  vector nsamp_cRn_agec_allyr(styr,endyr);                //NORTH
  vector nsamp_cRs_agec_allyr(styr,endyr);                //SOUTH
  vector nsamp_cBn_agec_allyr(styr,endyr);                //NORTH
  vector nsamp_cBs_agec_allyr(styr,endyr);                //SOUTH

//Nfish used in MCB analysis (not used in fitting)
  vector nfish_sgcomp_trawl_lenc_allyr(styr,endyr);
  vector nfish_comp_trawl_lenc_allyr(styr,endyr);
  vector nfish_cRn_agec_allyr(styr,endyr);                //NORTH
  vector nfish_cRs_agec_allyr(styr,endyr);                //SOUTH
  vector nfish_cBn_agec_allyr(styr,endyr);                //NORTH
  vector nfish_cBs_agec_allyr(styr,endyr);                //SOUTH

//Computed effective sample size for output (not used in fitting)
  vector neff_sgcomp_trawl_lenc_allyr_out(styr,endyr);
  vector neff_comp_trawl_lenc_allyr_out(styr,endyr);
  vector neff_cRn_agec_allyr_out(styr,endyr);             //NORTH
  vector neff_cRs_agec_allyr_out(styr,endyr);             //SOUTH
  vector neff_cBn_agec_allyr_out(styr,endyr);             //NORTH
  vector neff_cBs_agec_allyr_out(styr,endyr);             //SOUTH

//-----Population-----------------------------------------------------------------------------------
  matrix N(styr,endyr+1,1,nages);           //Population numbers by year and age at start of yr
  matrix N_mdyr(styr,endyr,1,nages);        //Population numbers by year and age at mdpt of yr: used for comps and cpue
  matrix N_spawn(styr,endyr,1,nages);       //Population numbers by year and age at peaking spawning: used for SSB
  matrix N_may(styr,endyr,1,nages);
  matrix N_sept(styr,endyr,1,nages);
  init_bounded_dev_vector log_Nage_dev(2,nages,N_dev_LO,N_dev_HI,N_dev_PH);
  vector log_Nage_dev_output(2,nages);      //used in output. equals zero for first age
  matrix B(styr,endyr+1,1,nages);           //Population biomass by year and age at start of yr
  vector totB(styr,endyr+1);                //Total biomass by year
  vector totN(styr,endyr+1);                //Total abundance by year
  vector SSB(styr,endyr+1);                   //Total spawning biomass by year (fecundity in mature ova)
  vector rec(styr,endyr+1);                 //Recruits by year
  vector pred_SPR(styr,endyr);              //spawning biomass-per-recruit (lagged) for Fmed calcs
  vector prop_f(1,nages);                   //Proportion female by age
  vector maturity_f(1,nages);               //Proportion of females mature at age
  matrix tv_maturity_f(styr,endyr,1,nages); //proportion of females mature at age over time
  vector reprod(1,nages);
  matrix reprod_tv(styr,endyr,1,nages);                   //vector used to compute spawning biomass (fecundity)
  matrix SSBatage(styr,endyr,1,nages);

////---Stock-Recruit Function (Beverton-Holt, steepness parameterization)----------
  init_bounded_number log_R0(log_R0_LO,log_R0_HI,log_R0_PH);   //log(virgin Recruitment)
  vector log_R0_out(1,8);
  number R0;                //virgin recruitment

  init_bounded_number steep(steep_LO,steep_HI,steep_PH); //steepness
  vector steep_out(1,8);
  init_bounded_number rec_sigma(rec_sigma_LO,rec_sigma_HI,rec_sigma_PH);  //sd recruitment residuals
  vector rec_sigma_out(1,8);

  number rec_sigma_sq;                        //square of rec_sigma
  number rec_logL_add;                        //additive term in -logL term

  init_bounded_dev_vector log_rec_dev(styr_rec_dev,endyr_rec_dev,log_rec_dev_LO,log_rec_dev_HI,log_rec_dev_PH);  //log recruitment deviations
  vector log_rec_dev_output(styr,endyr+1);           //used in output. equals zero except for yrs in log_rec_dev

  number var_rec_dev;                                //variance of log recruitment deviations, from yrs with unconstrainted S-R
  number sigma_rec_dev;                              //sample SD of log residuals (may not equal rec_sigma)

  number BiasCor;                               //Bias correction in equilibrium recruits
  init_bounded_number R_autocorr(R_autocorr_LO,R_autocorr_HI,R_autocorr_PH);
  vector R_autocorr_out(1,8);

  number S0;                                    //equal to spr_F0*R0 = virgin SSB
  number B0;                                    //equal to bpr_F0*R0 = virgin B
  number R1;                                    //Recruits in styr
  number R_virgin;                              //unfished recruitment with bias correction
  vector SdS0(styr,endyr+1);                      //SSB / virgin SSB


//-----------------------------------------------------------------------------------------------------------------------------------------------
////---Selectivity-------------------------------------------------------------------------

//Commercial Reduction-------------------------------------------------
```

```
  matrix sel_cRn(styr,endyr,1,nages);  //north
  init_bounded_number selpar_L50_cRn(selpar_L50_cRn_LO,selpar_L50_cRn_HI,selpar_L50_cRn_PH);
  init_bounded_number selpar_slope_cRn(selpar_slope_cRn_LO,selpar_slope_cRn_HI,selpar_slope_cRn_PH);
  init_bounded_number selpar_L502_cRn(selpar_L502_cRn_LO,selpar_L502_cRn_HI,selpar_L502_cRn_PH);
  init_bounded_number selpar_slope2_cRn(selpar_slope2_cRn_LO,selpar_slope2_cRn_HI,selpar_slope2_cRn_PH);
  vector selpar_L50_cRn_out(1,8);
  vector selpar_slope_cRn_out(1,8);
  vector selpar_L502_cRn_out(1,8);
  vector selpar_slope2_cRn_out(1,8);
  init_bounded_number selpar_L50_cRn2(selpar_L50_cRn2_LO,selpar_L50_cRn2_HI,selpar_L50_cRn2_PH);
  init_bounded_number selpar_slope_cRn2(selpar_slope_cRn2_LO,selpar_slope_cRn2_HI,selpar_slope_cRn2_PH);
  init_bounded_number selpar_L502_cRn2(selpar_L502_cRn2_LO,selpar_L502_cRn2_HI,selpar_L502_cRn2_PH);
  init_bounded_number selpar_slope2_cRn2(selpar_slope2_cRn2_LO,selpar_slope2_cRn2_HI,selpar_slope2_cRn2_PH);
  vector selpar_L50_cRn2_out(1,8);
  vector selpar_slope_cRn2_out(1,8);
  vector selpar_L502_cRn2_out(1,8);
  vector selpar_slope2_cRn2_out(1,8);
  init_bounded_number selpar_L50_cRn3(selpar_L50_cRn3_LO,selpar_L50_cRn3_HI,selpar_L50_cRn3_PH);
  init_bounded_number selpar_slope_cRn3(selpar_slope_cRn3_LO,selpar_slope_cRn3_HI,selpar_slope_cRn3_PH);
  init_bounded_number selpar_L502_cRn3(selpar_L502_cRn3_LO,selpar_L502_cRn3_HI,selpar_L502_cRn3_PH);
  init_bounded_number selpar_slope2_cRn3(selpar_slope2_cRn3_LO,selpar_slope2_cRn3_HI,selpar_slope2_cRn3_PH);
  vector selpar_L50_cRn3_out(1,8);
  vector selpar_slope_cRn3_out(1,8);
  vector selpar_L502_cRn3_out(1,8);
  vector selpar_slope2_cRn3_out(1,8);

  matrix sel_cRs(styr,endyr,1,nages);  //south
  init_bounded_number selpar_L50_cRs(selpar_L50_cRs_LO,selpar_L50_cRs_HI,selpar_L50_cRs_PH);
  init_bounded_number selpar_slope_cRs(selpar_slope_cRs_LO,selpar_slope_cRs_HI,selpar_slope_cRs_PH);
  init_bounded_number selpar_L502_cRs(selpar_L502_cRs_LO,selpar_L502_cRs_HI,selpar_L502_cRs_PH);
  init_bounded_number selpar_slope2_cRs(selpar_slope2_cRs_LO,selpar_slope2_cRs_HI,selpar_slope2_cRs_PH);
  vector selpar_L50_cRs_out(1,8);
  vector selpar_slope_cRs_out(1,8);
  vector selpar_L502_cRs_out(1,8);
  vector selpar_slope2_cRs_out(1,8);
init_bounded_number selpar_L50_cRs2(selpar_L50_cRs2_LO,selpar_L50_cRs2_HI,selpar_L50_cRs2_PH);
  init_bounded_number selpar_slope_cRs2(selpar_slope_cRs2_LO,selpar_slope_cRs2_HI,selpar_slope_cRs2_PH);
  init_bounded_number selpar_L502_cRs2(selpar_L502_cRs2_LO,selpar_L502_cRs2_HI,selpar_L502_cRs2_PH);
  init_bounded_number selpar_slope2_cRs2(selpar_slope2_cRs2_LO,selpar_slope2_cRs2_HI,selpar_slope2_cRs2_PH);
  vector selpar_L50_cRs2_out(1,8);
  vector selpar_slope_cRs2_out(1,8);
  vector selpar_L502_cRs2_out(1,8);
  vector selpar_slope2_cRs2_out(1,8);
  init_bounded_number selpar_L50_cRs3(selpar_L50_cRs3_LO,selpar_L50_cRs3_HI,selpar_L50_cRs3_PH);
  init_bounded_number selpar_slope_cRs3(selpar_slope_cRs3_LO,selpar_slope_cRs3_HI,selpar_slope_cRs3_PH);
  init_bounded_number selpar_L502_cRs3(selpar_L502_cRs3_LO,selpar_L502_cRs3_HI,selpar_L502_cRs3_PH);
  init_bounded_number selpar_slope2_cRs3(selpar_slope2_cRs3_LO,selpar_slope2_cRs3_HI,selpar_slope2_cRs3_PH);
  vector selpar_L50_cRs3_out(1,8);
  vector selpar_slope_cRs3_out(1,8);
  vector selpar_L502_cRs3_out(1,8);
  vector selpar_slope2_cRs3_out(1,8);

  init_bounded_number sel_age0_cRs_logit(selpar_age0_cRs_LO,selpar_age0_cRs_HI,selpar_age0_cRs_PH);  //cR selectivity at age in logit space
  init_bounded_number sel_age1_cRs_logit(selpar_age1_cRs_LO,selpar_age1_cRs_HI,selpar_age1_cRs_PH);
  init_bounded_number sel_age2_cRs_logit(selpar_age2_cRs_LO,selpar_age2_cRs_HI,selpar_age2_cRs_PH);
  init_bounded_number sel_age3_cRs_logit(selpar_age3_cRs_LO,selpar_age3_cRs_HI,selpar_age3_cRs_PH);
  init_bounded_number sel_age4_cRs_logit(selpar_age4_cRs_LO,selpar_age4_cRs_HI,selpar_age4_cRs_PH);
  init_bounded_number sel_age5_cRs_logit(selpar_age5_cRs_LO,selpar_age5_cRs_HI,selpar_age5_cRs_PH);
  init_bounded_number sel_age6_cRs_logit(selpar_age6_cRs_LO,selpar_age6_cRs_HI,selpar_age6_cRs_PH);
  vector sel_age_cRs_vec(1,nages);
  number selpar_age0_cRs;
  number selpar_age1_cRs;
  number selpar_age2_cRs;
  number selpar_age3_cRs;
  number selpar_age4_cRs;
  number selpar_age5_cRs;
  number selpar_age6_cRs;
  vector selpar_age0_cRs_out(1,8); //reduction, south
  vector selpar_age1_cRs_out(1,8);
  vector selpar_age2_cRs_out(1,8);
  vector selpar_age3_cRs_out(1,8);
  vector selpar_age4_cRs_out(1,8);
  vector selpar_age5_cRs_out(1,8);
  vector selpar_age6_cRs_out(1,8);

  init_bounded_number selpar_L50_logexp_cR(selpar_L50_logexp_cR_LO,selpar_L50_logexp_cR_HI,selpar_L50_logexp_cR_PH);
  init_bounded_number selpar_slope_logexp_cR(selpar_slope_logexp_cR_LO,selpar_slope_logexp_cR_HI,selpar_slope_logexp_cR_PH);
  init_bounded_number selpar_sigma_logexp_cR(selpar_sigma_logexp_cR_LO,selpar_sigma_logexp_cR_HI,selpar_sigma_logexp_cR_PH);
  vector selpar_L50_logexp_cR_out(1,8);
  vector selpar_slope_logexp_cR_out(1,8);
  vector selpar_sigma_logexp_cR_out(1,8);

  init_bounded_number sel_age0_cRn_logit(selpar_age0_cRn_LO,selpar_age0_cRn_HI,selpar_age0_cRn_PH);  //cR selectivity at age in logit space
  init_bounded_number sel_age1_cRn_logit(selpar_age1_cRn_LO,selpar_age1_cRn_HI,selpar_age1_cRn_PH);
  init_bounded_number sel_age2_cRn_logit(selpar_age2_cRn_LO,selpar_age2_cRn_HI,selpar_age2_cRn_PH);
  init_bounded_number sel_age3_cRn_logit(selpar_age3_cRn_LO,selpar_age3_cRn_HI,selpar_age3_cRn_PH);
  init_bounded_number sel_age4_cRn_logit(selpar_age4_cRn_LO,selpar_age4_cRn_HI,selpar_age4_cRn_PH);
  init_bounded_number sel_age5_cRn_logit(selpar_age5_cRn_LO,selpar_age5_cRn_HI,selpar_age5_cRn_PH);
  init_bounded_number sel_age6_cRn_logit(selpar_age6_cRn_LO,selpar_age6_cRn_HI,selpar_age6_cRn_PH);
  vector sel_age_cRn_vec(1,nages);
  number selpar_age0_cRn;
  number selpar_age1_cRn;
  number selpar_age2_cRn;
  number selpar_age3_cRn;
  number selpar_age4_cRn;
  number selpar_age5_cRn;
  number selpar_age6_cRn;
  vector selpar_age0_cRn_out(1,8); //reduction, north
  vector selpar_age1_cRn_out(1,8);
  vector selpar_age2_cRn_out(1,8);
  vector selpar_age3_cRn_out(1,8);
  vector selpar_age4_cRn_out(1,8);
  vector selpar_age5_cRn_out(1,8);
  vector selpar_age6_cRn_out(1,8);
```

```
  init_bounded_number sel_age0_cR2_logit(selpar_age0_cR2_LO,selpar_age0_cR2_HI,selpar_age0_cR2_PH);  //cR selectivity at age in logit space-period 2
  init_bounded_number sel_age1_cR2_logit(selpar_age1_cR2_LO,selpar_age1_cR2_HI,selpar_age1_cR2_PH);
  init_bounded_number sel_age2_cR2_logit(selpar_age2_cR2_LO,selpar_age2_cR2_HI,selpar_age2_cR2_PH);
  init_bounded_number sel_age3_cR2_logit(selpar_age3_cR2_LO,selpar_age3_cR2_HI,selpar_age3_cR2_PH);
  init_bounded_number sel_age4_cR2_logit(selpar_age4_cR2_LO,selpar_age4_cR2_HI,selpar_age4_cR2_PH);
  vector sel_age_cR2_vec(1,nages);
  number selpar_age0_cR2;
  number selpar_age1_cR2;
  number selpar_age2_cR2;
  number selpar_age3_cR2;
  number selpar_age4_cR2;
  vector selpar_age0_cR2_out(1,8);
  vector selpar_age1_cR2_out(1,8);
  vector selpar_age2_cR2_out(1,8);
  vector selpar_age3_cR2_out(1,8);
  vector selpar_age4_cR2_out(1,8);

//commercial bait selectivity
  matrix sel_cBn(styr,endyr,1,nages);  //north
  init_bounded_number selpar_L50_cBn(selpar_L50_cBn_LO,selpar_L50_cBn_HI,selpar_L50_cBn_PH);
  init_bounded_number selpar_slope_cBn(selpar_slope_cBn_LO,selpar_slope_cBn_HI,selpar_slope_cBn_PH);
  init_bounded_number selpar_L502_cBn(selpar_L502_cBn_LO,selpar_L502_cBn_HI,selpar_L502_cBn_PH);
  init_bounded_number selpar_slope2_cBn(selpar_slope2_cBn_LO,selpar_slope2_cBn_HI,selpar_slope2_cBn_PH);
  vector selpar_L50_cBn_out(1,8);
  vector selpar_slope_cBn_out(1,8);
  vector selpar_L502_cBn_out(1,8);
  vector selpar_slope2_cBn_out(1,8);
  init_bounded_number selpar_L50_cBn3(selpar_L50_cBn3_LO,selpar_L50_cBn3_HI,selpar_L50_cBn3_PH);
  init_bounded_number selpar_slope_cBn3(selpar_slope_cBn3_LO,selpar_slope_cBn3_HI,selpar_slope_cBn3_PH);
  init_bounded_number selpar_L502_cBn3(selpar_L502_cBn3_LO,selpar_L502_cBn3_HI,selpar_L502_cBn3_PH);
  init_bounded_number selpar_slope2_cBn3(selpar_slope2_cBn3_LO,selpar_slope2_cBn3_HI,selpar_slope2_cBn3_PH);
  vector selpar_L50_cBn3_out(1,8);
  vector selpar_slope_cBn3_out(1,8);
  vector selpar_L502_cBn3_out(1,8);
  vector selpar_slope2_cBn3_out(1,8);

  init_bounded_number sel_age0_cBn_logit(selpar_age0_cBn_LO,selpar_age0_cBn_HI,selpar_age0_cBn_PH);  //cB selectivity at age in logit space
  init_bounded_number sel_age1_cBn_logit(selpar_age1_cBn_LO,selpar_age1_cBn_HI,selpar_age1_cBn_PH);
  init_bounded_number sel_age2_cBn_logit(selpar_age2_cBn_LO,selpar_age2_cBn_HI,selpar_age2_cBn_PH);
  init_bounded_number sel_age3_cBn_logit(selpar_age3_cBn_LO,selpar_age3_cBn_HI,selpar_age3_cBn_PH);
  init_bounded_number sel_age4_cBn_logit(selpar_age4_cBn_LO,selpar_age4_cBn_HI,selpar_age4_cBn_PH);
  init_bounded_number sel_age5_cBn_logit(selpar_age5_cBn_LO,selpar_age5_cBn_HI,selpar_age5_cBn_PH);
  init_bounded_number sel_age6_cBn_logit(selpar_age6_cBn_LO,selpar_age6_cBn_HI,selpar_age6_cBn_PH);
  vector sel_age_cBn_vec(1,nages);
  number selpar_age0_cBn;
  number selpar_age1_cBn;
  number selpar_age2_cBn;
  number selpar_age3_cBn;
  number selpar_age4_cBn;
  number selpar_age5_cBn;
  number selpar_age6_cBn;
  vector selpar_age0_cBn_out(1,8); //bait, north
  vector selpar_age1_cBn_out(1,8);
  vector selpar_age2_cBn_out(1,8);
  vector selpar_age3_cBn_out(1,8);
  vector selpar_age4_cBn_out(1,8);
  vector selpar_age5_cBn_out(1,8);
  vector selpar_age6_cBn_out(1,8);

  matrix sel_cBs(styr,endyr,1,nages);  //south
  init_bounded_number selpar_L50_cBs(selpar_L50_cBs_LO,selpar_L50_cBs_HI,selpar_L50_cBs_PH);
  init_bounded_number selpar_slope_cBs(selpar_slope_cBs_LO,selpar_slope_cBs_HI,selpar_slope_cBs_PH);
  init_bounded_number selpar_L502_cBs(selpar_L502_cBs_LO,selpar_L502_cBs_HI,selpar_L502_cBs_PH);
  init_bounded_number selpar_slope2_cBs(selpar_slope2_cBs_LO,selpar_slope2_cBs_HI,selpar_slope2_cBs_PH);
  vector selpar_L50_cBs_out(1,8);
  vector selpar_slope_cBs_out(1,8);
  vector selpar_L502_cBs_out(1,8);
  vector selpar_slope2_cBs_out(1,8);

  init_bounded_number sel_age0_cBs_logit(selpar_age0_cBs_LO,selpar_age0_cBs_HI,selpar_age0_cBs_PH);  //cB selectivity at age in logit space
  init_bounded_number sel_age1_cBs_logit(selpar_age1_cBs_LO,selpar_age1_cBs_HI,selpar_age1_cBs_PH);
  init_bounded_number sel_age2_cBs_logit(selpar_age2_cBs_LO,selpar_age2_cBs_HI,selpar_age2_cBs_PH);
  init_bounded_number sel_age3_cBs_logit(selpar_age3_cBs_LO,selpar_age3_cBs_HI,selpar_age3_cBs_PH);
  init_bounded_number sel_age4_cBs_logit(selpar_age4_cBs_LO,selpar_age4_cBs_HI,selpar_age4_cBs_PH);
  init_bounded_number sel_age5_cBs_logit(selpar_age5_cBs_LO,selpar_age5_cBs_HI,selpar_age5_cBs_PH);
  init_bounded_number sel_age6_cBs_logit(selpar_age6_cBs_LO,selpar_age6_cBs_HI,selpar_age6_cBs_PH);
  vector sel_age_cBs_vec(1,nages);
  number selpar_age0_cBs;
  number selpar_age1_cBs;
  number selpar_age2_cBs;
  number selpar_age3_cBs;
  number selpar_age4_cBs;
  number selpar_age5_cBs;
  number selpar_age6_cBs;
  vector selpar_age0_cBs_out(1,8); //bait, south
  vector selpar_age1_cBs_out(1,8);
  vector selpar_age2_cBs_out(1,8);
  vector selpar_age3_cBs_out(1,8);
  vector selpar_age4_cBs_out(1,8);
  vector selpar_age5_cBs_out(1,8);
  vector selpar_age6_cBs_out(1,8);

//sg composite trawl survey selectivity
  matrix sel_sgcomp_trawl(styr_sgcomp_trawl_cpue,endyr_sgcomp_trawl_cpue,1,nages);
  init_bounded_number selpar_L50_sgcomp_trawl(selpar_L50_sgcomp_trawl_LO,selpar_L50_sgcomp_trawl_HI,selpar_L50_sgcomp_trawl_PH);
  init_bounded_number selpar_slope_sgcomp_trawl(selpar_slope_sgcomp_trawl_LO,selpar_slope_sgcomp_trawl_HI,selpar_slope_sgcomp_trawl_PH);
  init_bounded_number selpar_L502_sgcomp_trawl(selpar_L502_sgcomp_trawl_LO,selpar_L502_sgcomp_trawl_HI,selpar_L502_sgcomp_trawl_PH);
  init_bounded_number selpar_slope2_sgcomp_trawl(selpar_slope2_sgcomp_trawl_LO,selpar_slope2_sgcomp_trawl_HI,selpar_slope2_sgcomp_trawl_PH);
  vector selpar_L50_sgcomp_trawl_out(1,8);
  vector selpar_slope_sgcomp_trawl_out(1,8);
  vector selpar_L502_sgcomp_trawl_out(1,8);
  vector selpar_slope2_sgcomp_trawl_out(1,8);
```

```
//composite trawl survey selectivity
  matrix sel_comp_trawl(styr_comp_trawl_cpue,endyr_comp_trawl_cpue,1,nages);
  init_bounded_number selpar_L50_comp_trawl(selpar_L50_comp_trawl_LO,selpar_L50_comp_trawl_HI,selpar_L50_comp_trawl_PH);
  init_bounded_number selpar_slope_comp_trawl(selpar_slope_comp_trawl_LO,selpar_slope_comp_trawl_HI,selpar_slope_comp_trawl_PH);
  init_bounded_number selpar_L502_comp_trawl(selpar_L502_comp_trawl_LO,selpar_L502_comp_trawl_HI,selpar_L502_comp_trawl_PH);
  init_bounded_number selpar_slope2_comp_trawl(selpar_slope2_comp_trawl_LO,selpar_slope2_comp_trawl_HI,selpar_slope2_comp_trawl_PH);
  vector selpar_L50_comp_trawl_out(1,8);
  vector selpar_slope_comp_trawl_out(1,8);
  vector selpar_L502_comp_trawl_out(1,8);
  vector selpar_slope2_comp_trawl_out(1,8);

//Weighted total selectivity--------------------------------------------
  //effort-weighted, recent selectivities
  vector sel_wgted_L(1,nages);  //toward landings
  vector sel_wgted_tot(1,nages);

//------------------------------------------------------------------------------------------------------------------------------------------------
//-------CPUE Predictions--------------------------------
  vector pred_sgcomp_trawl_cpue(styr_sgcomp_trawl_cpue,endyr_sgcomp_trawl_cpue);     //predicted sg composite trawl U
  matrix N_sgcomp_trawl(styr_sgcomp_trawl_cpue,endyr_sgcomp_trawl_cpue,1,nages);     //used to compute sg composite trawl index

  vector pred_comp_trawl_cpue(styr_comp_trawl_cpue,endyr_comp_trawl_cpue);     //predicted composite trawl U
  matrix N_comp_trawl(styr_comp_trawl_cpue,endyr_comp_trawl_cpue,1,nages);     //used to compute composite trawl index

  vector pred_seine_cpue(styr_seine_cpue,endyr_seine_cpue);  //predicted seine index
  vector N_seine(styr_seine_cpue,endyr_seine_cpue);          //used to compute seine index

  vector pred_yoy_cpue(styr_yoy_cpue,endyr_yoy_cpue);     //predicted yoy index
  vector N_yoy(styr_yoy_cpue,endyr_yoy_cpue);             //used to compute yoy index

//---Catchability (CPUE q's)----------------------------------------------------------
  init_bounded_number log_q_sgcomp_trawl(log_q_sgcomp_trawl_LO,log_q_sgcomp_trawl_HI,log_q_sgcomp_trawl_PH);
  init_bounded_number log_q_comp_trawl(log_q_comp_trawl_LO,log_q_comp_trawl_HI,log_q_comp_trawl_PH);
  init_bounded_number log_q_seine(log_q_seine_LO,log_q_seine_HI,log_q_seine_PH);
  init_bounded_number log_q1_yoy(log_q1_yoy_LO,log_q1_yoy_HI,log_q1_yoy_PH);
  init_bounded_number log_q2_yoy(log_q2_yoy_LO,log_q2_yoy_HI,log_q2_yoy_PH);
  vector log_q_sgcomp_trawl_out(1,8);
  vector log_q_comp_trawl_out(1,8);
  vector log_q_seine_out(1,8);
  vector log_q1_yoy_out(1,8);
  vector log_q2_yoy_out(1,8);

  //init_bounded_number q_rate(0.001,0.1,set_q_rate_phase);
  number q_rate;
  vector q_rate_fcn_sgcomp_trawl(styr_sgcomp_trawl_cpue,endyr_sgcomp_trawl_cpue);   //increase due to technology creep
  vector q_rate_fcn_comp_trawl(styr_comp_trawl_cpue,endyr_comp_trawl_cpue);   //increase due to technology creep
  vector q_rate_fcn_seine(styr_seine_cpue,endyr_seine_cpue);      //increase due to technology creep (saturates in 2003)
  vector q_rate_fcn_yoy(styr_yoy_cpue,endyr_yoy_cpue);

  //init_bounded_number q_DD_beta(0.1,0.9,set_q_DD_phase);
  number q_DD_beta;
  vector q_DD_fcn(styr,endyr);    //density dependent function as a multiple of q (scaled a la Katsukawa and Matsuda. 2003)
  number B0_q_DD;                 //B0 of ages q_DD_age plus
  vector B_q_DD(styr,endyr);      //annual biomass of ages q_DD_age plus

  vector q_RW_log_dev_sgcomp_trawl(styr_sgcomp_trawl_cpue,endyr_sgcomp_trawl_cpue-1);
  vector q_RW_log_dev_comp_trawl(styr_comp_trawl_cpue,endyr_comp_trawl_cpue-1);
  vector q_RW_log_dev_seine(styr_seine_cpue,endyr_seine_cpue-1);
  vector q_RW_log_dev_yoy(styr_yoy_cpue,endyr_yoy_cpue-1);

  vector q_sgcomp_trawl(styr_sgcomp_trawl_cpue,endyr_sgcomp_trawl_cpue);
  vector q_comp_trawl(styr_comp_trawl_cpue,endyr_comp_trawl_cpue);
  vector q_seine(styr_seine_cpue,endyr_seine_cpue); //number q_seine;
  vector q1_yoy(styr_yoy_cpue,endyr_yoy_cpue);
  vector q2_yoy(styr_yoy_cpue,endyr_yoy_cpue);

//------------------------------------------------------------------------------------------------------------------------------------------------
//---Landings in numbers (total or 1000 fish) and in wgt (1000s mt)--------------------------------------------------
  matrix L_cRn_num(styr,endyr,1,nages);  //landings (numbers) at age
  matrix L_cRn_mt(styr,endyr,1,nages);   //landings (mt) at age
  vector pred_cRn_L_knum(styr,endyr);    //yearly landings in 1000 fish summed over ages
  vector pred_cRn_L_mt(styr,endyr);     //yearly landings in 1000s mt summed over ages

  matrix L_cRs_num(styr,endyr,1,nages);  //landings (numbers) at age
  matrix L_cRs_mt(styr,endyr,1,nages);   //landings (mt) at age
  vector pred_cRs_L_knum(styr,endyr);    //yearly landings in 1000 fish summed over ages
  vector pred_cRs_L_mt(styr,endyr);     //yearly landings in 1000s mt summed over ages

  matrix L_cBn_num(styr,endyr,1,nages);  //landings (numbers) at age
  matrix L_cBn_mt(styr,endyr,1,nages);   //landings (mt) at age
  vector pred_cBn_L_knum(styr,endyr);    //yearly landings in 1000 fish summed over ages
  vector pred_cBn_L_mt(styr_cB_L,endyr_cB_L);     //yearly landings in 1000s mt summed over ages

  matrix L_cBs_num(styr,endyr,1,nages);  //landings (numbers) at age
  matrix L_cBs_mt(styr,endyr,1,nages);   //landings (mt) at age
  vector pred_cBs_L_knum(styr,endyr);    //yearly landings in 1000 fish summed over ages
  vector pred_cBs_L_mt(styr_cB_L,endyr_cB_L);     //yearly landings in 1000s mt summed over ages

  matrix L_total_num(styr,endyr,1,nages); //total landings in number at age
  matrix L_total_mt(styr,endyr,1,nages);  //landings in mt at age
  vector L_total_knum_yr(styr,endyr);     //total landings in 1000 fish by yr summed over ages
  vector L_total_mt_yr(styr,endyr);      //total landings (1000s mt) by yr summed over ages

////---MSY calcs----------------------------------------------------------------------------
  number F_cRn_prop;       //proportion of F_sum attributable to cR - north
  number F_cRs_prop;       //proportion of F_sum attributable to cR - south
  number F_cBn_prop;       //proportion of F_sum attributable to cB - north
  number F_cBs_prop;       //proportion of F_sum attributable to cB - south
  number F_temp_sum;      //sum of geom mean Fsum's in last X yrs, used to compute F_fishery_prop

  vector F_end(1,nages);
  vector F_end_L(1,nages);
  number F_end_apex;
```

```
  number SSB_msy_out;           //SSB (total fecundity) at msy
  number F_msy_out;             //F at msy
  number msy_mt_out;            //max sustainable yield (1000s mt)
  number msy_knum_out;          //max sustainable yield (1000 fish)
  number B_msy_out;             //total biomass at MSY
  number R_msy_out;             //equilibrium recruitment at F=Fmsy
  number spr_msy_out;           //spr at F=Fmsy

  vector N_age_msy(1,nages);         //numbers at age for MSY calculations: beginning of yr
  vector N_age_msy_mdyr(1,nages);    //numbers at age for MSY calculations: mdpt of yr
  vector L_age_msy(1,nages);         //catch at age for MSY calculations
  vector Z_age_msy(1,nages);         //total mortality at age for MSY calculations
  vector F_L_age_msy(1,nages);       //fishing mortality landings (not discards) at age for MSY calculations
  vector F_msy(1,n_iter_msy);        //values of full F to be used in equilibrium calculations
  vector spr_msy(1,n_iter_msy);      //reproductive capacity-per-recruit values corresponding to F values in F_msy
  vector R_eq(1,n_iter_msy);         //equilibrium recruitment values corresponding to F values in F_msy
  vector L_eq_mt(1,n_iter_msy);      //equilibrium landings(1000s mt) values corresponding to F values in F_msy
  vector L_eq_knum(1,n_iter_msy);    //equilibrium landings(1000 fish) values corresponding to F values in F_msy
  vector SSB_eq(1,n_iter_msy);       //equilibrium reproductive capacity (fecundity) values corresponding to F values in F_msy
  vector B_eq(1,n_iter_msy);         //equilibrium biomass values corresponding to F values in F_msy

  vector FdF_msy(styr,endyr);
  vector SdSSB_msy(styr,endyr+1);
  number SdSSB_msy_end;
  number FdF_msy_end;
  number FdF_msy_end_mean;          //geometric mean of last 3 yrs

  vector wgt_wgted_L_mt(1,nages);  //fishery-weighted average weight at age of landings
  number wgt_wgted_L_denom;         //used in intermediate calculations

  number iter_inc_msy;               //increments used to compute msy, equals 1/(n_iter_msy-1)


////---Fmed calcs---------------------------------------------------------------------------
  number quant_decimal;
  number quant_diff;
  number quant_result;

  number R_med;                                //median recruitment for chosen benchmark years
  vector R_temp(styr,endyr);
  vector R_sort(styr,endyr);
  number SPR_med;                              //median SSB/R (R = SSB year+1) for chosen SSB years
  number SPR_75th;
  vector SPR_temp(styr,endyr);
  vector SPR_sort(styr,endyr);
  number SSB_med;                              //SSB corresponding to SSB/R median and R median
  number SSB_med_thresh;                       //SSB threshold
  vector SPR_diff(1,n_iter_spr);
  number SPR_diff_min;
  number F_med;                                //Fmed benchmark
  number F_med_target;
  number F_med_age2plus;                       //Fmed benchmark
  number F_med_target_age2plus;
  number L_med;
  number L_med_target;


////--------Mortality-----------------------------------------------------------------

  //Stuff immediately below used only if M is estimated
  //init_bounded_number M_constant(0.1,0.2,1);   //age-indpendent: used only for MSST
  //vector Mscale_ages(1,max_obs_age);
  //vector Mscale_len(1,max_obs_age);
  //vector Mscale_wgt_g(1,max_obs_age);
  //vector M_lorenzen(1,max_obs_age);
  //number cum_surv_1plus;

  vector M(1,nages);                  //age-dependent natural mortality
  matrix M_tv(styr,endyr,1,nages);    //age-dependent, time-varying natural mortality
  init_bounded_number M_constant(M_constant_LO,M_constant_HI,M_constant_PH);   //age-indpendent: used only for MSST
  vector M_constant_out(1,8);
//---------------set up for M at age-1 to be estimated
  init_bounded_dev_vector M_dev(styr_seine_cpue,endyr_seine_cpue,M_dev_LO,M_dev_HI,M_dev_PH);  //M devs deviations
  vector M_dev_output(styr_seine_cpue,endyr_seine_cpue);

  matrix F(styr,endyr,1,nages);
  vector Fsum(styr,endyr);                   //Full fishing mortality rate by year
  vector Fapex(styr,endyr);                  //Max across ages, fishing mortality rate by year (may differ from Fsum bc of dome-shaped sel)
  //sdreport_vector fullF_sd(styr,endyr);
  matrix Z(styr,endyr,1,nages);

  init_bounded_number log_avg_F_cRn(log_avg_F_cRn_LO,log_avg_F_cRn_HI,log_avg_F_cRn_PH);
  vector log_avg_F_cRn_out(1,8);
  init_bounded_dev_vector log_F_dev_cRn(styr_cR_L,endyr_cR_L,log_F_dev_cRn_LO,log_F_dev_cRn_HI,log_F_dev_cRn_PH);
  vector log_F_dev_cRn_out(styr_cR_L,endyr_cR_L);
  matrix F_cRn(styr,endyr,1,nages);
  vector F_cRn_out(styr,endyr); //used for intermediate calculations in fcn get_mortality
  number log_F_dev_init_cRn;
  number log_F_dev_end_cRn;

  init_bounded_number log_avg_F_cRs(log_avg_F_cRs_LO,log_avg_F_cRs_HI,log_avg_F_cRs_PH);
  vector log_avg_F_cRs_out(1,8);
  init_bounded_dev_vector log_F_dev_cRs(styr_cR_L,endyr_cR_L,log_F_dev_cRs_LO,log_F_dev_cRs_HI,log_F_dev_cRs_PH);
  vector log_F_dev_cRs_out(styr_cR_L,endyr_cR_L);
  matrix F_cRs(styr,endyr,1,nages);
  vector F_cRs_out(styr,endyr); //used for intermediate calculations in fcn get_mortality
  number log_F_dev_init_cRs;
  number log_F_dev_end_cRs;

  init_bounded_number log_avg_F_cBn(log_avg_F_cBn_LO,log_avg_F_cBn_HI,log_avg_F_cBn_PH);
  vector log_avg_F_cBn_out(1,8);
  init_bounded_dev_vector log_F_dev_cBn(styr_cB_L,endyr_cB_L,log_F_dev_cBn_LO,log_F_dev_cBn_HI,log_F_dev_cBn_PH);
  vector log_F_dev_cBn_out(styr_cB_L,endyr_cB_L);
  matrix F_cBn(styr,endyr,1,nages);
```

```
  vector F_cBn_out(styr,endyr); //used for intermediate calculations in fcn get_mortality
  number log_F_dev_init_cBn;
  number log_F_dev_end_cBn;

  init_bounded_number log_avg_F_cBs(log_avg_F_cBs_LO,log_avg_F_cBs_HI,log_avg_F_cBs_PH);
  vector log_avg_F_cBs_out(1,8);
  init_bounded_dev_vector log_F_dev_cBs(styr_cB_L,endyr_cB_L,log_F_dev_cBs_LO,log_F_dev_cBs_HI,log_F_dev_cBs_PH);
  vector log_F_dev_cBs_out(styr_cB_L,endyr_cB_L);
  matrix F_cBs(styr,endyr,1,nages);
  vector F_cBs_out(styr,endyr); //used for intermediate calculations in fcn get_mortality
  number log_F_dev_init_cBs;
  number log_F_dev_end_cBs;

  vector sel_initial(1,nages);       //initial selectivity (commercial selectivity)

//---Per-recruit stuff----------------------------------------------------------------------------------
  vector N_age_spr(1,nages);         //numbers at age for SPR calculations: beginning of year
  vector N_age_spr_mdyr(1,nages);    //numbers at age for SPR calculations: midyear
  vector L_age_spr(1,nages);         //catch at age for SPR calculations
  vector Z_age_spr(1,nages);         //total mortality at age for SPR calculations
  vector spr_static(styr,endyr);     //vector of static SPR values by year
  vector F_L_age_spr(1,nages);       //fishing mortality of landings (not discards) at age for SPR calculations
  vector F_spr(1,n_iter_spr);        //values of full F to be used in per-recruit calculations
  vector spr_spr(1,n_iter_spr);      //reproductive capacity-per-recruit values corresponding to F values in F_spr
  vector L_spr(1,n_iter_spr);        //landings(mt)-per-recruit (ypr) values corresponding to F values in F_spr

  vector N_spr_F0(1,nages);          //Used to compute spr at F=0: at time of peak spawning
  vector N_bpr_F0(1,nages);          //Used to compute bpr at F=0: at start of year
  vector N_spr_initial(1,nages);     //Initial spawners per recruit at age given initial F
  vector N_initial_eq(1,nages);      //Initial equilibrium abundance at age
  vector F_initial(1,nages);         //initial F at age
  vector Z_initial(1,nages);         //initial Z at age
  number spr_initial;                //initial spawners per recruit
  number spr_F0;                     //Spawning biomass per recruit at F=0
  number bpr_F0;                     //Biomass per recruit at F=0

  number iter_inc_spr;               //increments used to compute msy, equals max_F_spr_msy/(n_iter_spr-1)

////-------SDNR output------------------------------------------------------------------------------

  number sdnr_lc_sgcomp_trawl;
  number sdnr_lc_comp_trawl;

  number sdnr_ac_cRn;      //NORTH
  number sdnr_ac_cRs;      //SOUTH
  number sdnr_ac_cBn;      //NORTH
  number sdnr_ac_cBs;      //SOUTH

  number sdnr_I_sgcomp_trawl;
  number sdnr_I_comp_trawl;
  number sdnr_I_seine;
  number sdnr_I_yoy;

////-------Objective function components-----------------------------------------------------------------------------
  number w_L;

  number w_lc_sgcomp_trawl;
  number w_lc_comp_trawl;

  number w_ac_cRn;      //NORTH
  number w_ac_cRs;      //SOUTH
  number w_ac_cBn;      //NORTH
  number w_ac_cBs;      //SOUTH

  number w_I_sgcomp_trawl;
  number w_I_comp_trawl;
  number w_I_seine;
  number w_I_yoy;

  number w_M_dev;
  number w_rec;
  number w_rec_early;
  number w_rec_end;
  number w_fullF;
  number w_Ftune;
  //number w_cvlen_dev;
  //number w_cvlen_diff;

  number f_sgcomp_trawl_cpue;
  number f_comp_trawl_cpue;
  number f_seine_cpue;
  number f_yoy_cpue;

  number f_cRn_L;
  number f_cRs_L;
  number f_cBn_L;
  number f_cBs_L;

  number f_sgcomp_trawl_lenc;
  number f_comp_trawl_lenc;

  number f_cRn_agec;       //NORTH
  number f_cRs_agec;       //SOUTH
  number f_cBn_agec;       //NORTH
  number f_cBs_agec;       //SOUTH

  number f_sgcomp_trawl_RW_cpue;  //random walk component of indices
  number f_comp_trawl_RW_cpue;  //random walk component of indices
  number f_seine_RW_cpue;   //random walk component of indices
  number f_yoy_RW_cpue;


  //Penalties and constraints. Not all are used.
  number f_M_dev;                  //likelihood component constraint for annual M devs
```

```
  number f_rec_dev;                //weight on recruitment deviations to fit S-R curve
  number f_rec_dev_early;          //extra weight on deviations in first recruitment stanza
  number f_rec_dev_end;            //extra weight on deviations in first recruitment stanza
  number f_rec_historic_dev;       //extra weight on deviations in first recruitment stanza
  number f_Ftune;                  //penalty for tuning F in Ftune yr.  Not applied in final optimization phase.
  number f_fullF_constraint;       //penalty for Fapex>X
  //number f_cvlen_dev_constraint; //deviation penalty on cv's of length at age
  //number f_cvlen_diff_constraint;//first diff penalty on cv's of length at age
  number f_priors;                  //prior information on parameters

  objective_function_value fval;
  number fval_data;

//--Dummy variables ----
  number denom;                   //denominator used in some calculations
  number numer;                   //numerator used in some calculations

//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
INITIALIZATION_SECTION


//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
GLOBALS_SECTION
  #include "admodel.h"          // Include AD class definitions
  #include "admb2r.cpp"    // Include S-compatible output functions (needs preceding)
  #include <time.h>
time_t start,finish;
long hour,minute,second;
double elapsed_time;

//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
RUNTIME_SECTION
 maximum_function_evaluations 1000, 2000,3000, 10000;
 convergence_criteria 1e-2, 1e-2,1e-3, 1e-4;

//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
PRELIMINARY_CALCS_SECTION

// Set values of fixed parameters or set initial guess of estimated parameters
  Linf=set_Linf(1);
  K=set_K(1);
  t0=set_t0(1);
  len_cv_val=set_len_cv(1);

  M=set_M;
  M_tv=set_M_tv;
  M_constant=set_M_constant(1);
  //M_dev=set_M_dev_vals;
  //for (iage=1;iage<=max_obs_age;iage++){Mscale_ages(iage)=iage;}

  log_R0=set_log_R0(1);
  steep=set_steep(1);
  R_autocorr=set_R_autocorr(1);
  rec_sigma=set_rec_sigma(1);

  log_q_sgcomp_trawl=set_log_q_sgcomp_trawl(1);
  log_q_comp_trawl=set_log_q_comp_trawl(1);
  log_q_seine=set_log_q_seine(1);
  log_q1_yoy=set_log_q1_yoy(1);
  log_q2_yoy=set_log_q2_yoy(1);

  q_rate=set_q_rate;
  q_rate_fcn_sgcomp_trawl=1.0;
  q_rate_fcn_comp_trawl=1.0;
  q_rate_fcn_seine=1.0;
  q_rate_fcn_yoy=1.0;
  q_DD_beta=set_q_DD_beta;
  q_DD_fcn=1.0;
  q_RW_log_dev_sgcomp_trawl.initialize();
  q_RW_log_dev_comp_trawl.initialize();
  q_RW_log_dev_seine.initialize();
  q_RW_log_dev_yoy.initialize();


  if (set_q_rate_phase<0 & q_rate!=0.0)
  {

      for (iyear=styr_sgcomp_trawl_cpue; iyear<=endyr_sgcomp_trawl_cpue; iyear++)
      {   if (iyear>styr_sgcomp_trawl_cpue & iyear <=2003)
          {
             q_rate_fcn_sgcomp_trawl(iyear)=(1.0+(iyear-styr_sgcomp_trawl_cpue)*q_rate)*q_rate_fcn_sgcomp_trawl(styr_sgcomp_trawl_cpue);  //linear
          }
          if (iyear>2003) {q_rate_fcn_sgcomp_trawl(iyear)=q_rate_fcn_sgcomp_trawl(iyear-1);}
      }

      for (iyear=styr_comp_trawl_cpue; iyear<=endyr_comp_trawl_cpue; iyear++)
      {   if (iyear>styr_comp_trawl_cpue & iyear <=2003)
          {
             q_rate_fcn_comp_trawl(iyear)=(1.0+(iyear-styr_comp_trawl_cpue)*q_rate)*q_rate_fcn_comp_trawl(styr_comp_trawl_cpue);  //linear
          }
          if (iyear>2003) {q_rate_fcn_comp_trawl(iyear)=q_rate_fcn_comp_trawl(iyear-1);}
      }

      for (iyear=styr_seine_cpue; iyear<=endyr_seine_cpue; iyear++)
      {   if (iyear>styr_seine_cpue & iyear <=2003)
          {//q_rate_fcn_seine(iyear)=(1.0+q_rate)*q_rate_fcn_seine(iyear-1); //compound
             q_rate_fcn_seine(iyear)=(1.0+(iyear-styr_seine_cpue)*q_rate)*q_rate_fcn_seine(styr_seine_cpue);  //linear
          }
          if (iyear>2003) {q_rate_fcn_seine(iyear)=q_rate_fcn_seine(iyear-1);}
      }
```

```
    for (iyear=styr_yoy_cpue; iyear<=endyr_yoy_cpue; iyear++)
    {   if (iyear>styr_yoy_cpue & iyear <=2003)
        {
           q_rate_fcn_yoy(iyear)=(1.0+(iyear-styr_yoy_cpue)*q_rate)*q_rate_fcn_yoy(styr_yoy_cpue);  //linear
        }
        if (iyear>2003) {q_rate_fcn_yoy(iyear)=q_rate_fcn_yoy(iyear-1);}
    }

} //end q_rate conditional


w_L=set_w_L;

w_lc_sgcomp_trawl=set_w_lc_sgcomp_trawl;
w_lc_comp_trawl=set_w_lc_comp_trawl;

w_ac_cRn=set_w_ac_cRn;    //NORTH
w_ac_cRs=set_w_ac_cRs;    //SOUTH
w_ac_cBn=set_w_ac_cBn;    //NORTH
w_ac_cBs=set_w_ac_cBs;    //SOUTH

w_I_sgcomp_trawl=set_w_I_sgcomp_trawl;
w_I_comp_trawl=set_w_I_comp_trawl;
w_I_seine=set_w_I_seine;
w_I_yoy=set_w_I_yoy;

w_M_dev=set_w_M_dev;
w_rec=set_w_rec;
w_fullF=set_w_fullF;
w_rec_early=set_w_rec_early;
w_rec_end=set_w_rec_end;
w_Ftune=set_w_Ftune;
//w_cvlen_dev=set_w_cvlen_dev;
//w_cvlen_diff=set_w_cvlen_diff;

log_avg_F_cRn=set_log_avg_F_cRn(1);
log_F_dev_cRn=set_log_F_dev_cRn_vals;
log_avg_F_cRs=set_log_avg_F_cRs(1);
log_F_dev_cRs=set_log_F_dev_cRs_vals;
log_avg_F_cBn=set_log_avg_F_cBn(1);
log_F_dev_cBn=set_log_F_dev_cBn_vals;
log_avg_F_cBs=set_log_avg_F_cBs(1);
log_F_dev_cBs=set_log_F_dev_cBs_vals;
log_Nage_dev=set_log_N_dev_vals;

selpar_L50_cRs=set_selpar_L50_cRs(1);          //south
selpar_slope_cRs=set_selpar_slope_cRs(1);
selpar_L502_cRs=set_selpar_L502_cRs(1);
selpar_slope2_cRs=set_selpar_slope2_cRs(1);

selpar_L50_cRn=set_selpar_L50_cRn(1);          //north
selpar_slope_cRn=set_selpar_slope_cRn(1);
selpar_L502_cRn=set_selpar_L502_cRn(1);
selpar_slope2_cRn=set_selpar_slope2_cRn(1);

selpar_L50_cRs2=set_selpar_L50_cRs2(1);
selpar_slope_cRs2=set_selpar_slope_cRs2(1);
selpar_L502_cRs2=set_selpar_L502_cRs2(1);
selpar_slope2_cRs2=set_selpar_slope2_cRs2(1);

selpar_L50_cRn2=set_selpar_L50_cRn2(1);
selpar_slope_cRn2=set_selpar_slope_cRn2(1);
selpar_L502_cRn2=set_selpar_L502_cRn2(1);
selpar_slope2_cRn2=set_selpar_slope2_cRn2(1);

selpar_L50_cRs3=set_selpar_L50_cRs3(1);     //south
selpar_slope_cRs3=set_selpar_slope_cRs3(1);
selpar_L502_cRs3=set_selpar_L502_cRs3(1);
selpar_slope2_cRs3=set_selpar_slope2_cRs3(1);

selpar_L50_cRn3=set_selpar_L50_cRn3(1);     //north
selpar_slope_cRn3=set_selpar_slope_cRn3(1);
selpar_L502_cRn3=set_selpar_L502_cRn3(1);
selpar_slope2_cRn3=set_selpar_slope2_cRn3(1);

selpar_L50_logexp_cR=set_selpar_L50_logexp_cR(1);
selpar_slope_logexp_cR=set_selpar_slope_logexp_cR(1);
selpar_sigma_logexp_cR=set_selpar_sigma_logexp_cR(1);

selpar_L50_cBn=set_selpar_L50_cBn(1);      //north-period 1
selpar_slope_cBn=set_selpar_slope_cBn(1);
selpar_L502_cBn=set_selpar_L502_cBn(1);
selpar_slope2_cBn=set_selpar_slope2_cBn(1);

selpar_L50_cBn3=set_selpar_L50_cBn3(1);       //north-period 3
selpar_slope_cBn3=set_selpar_slope_cBn3(1);
selpar_L502_cBn3=set_selpar_L502_cBn3(1);
selpar_slope2_cBn3=set_selpar_slope2_cBn3(1);

selpar_L50_cBs=set_selpar_L50_cBs(1);       //south
selpar_slope_cBs=set_selpar_slope_cBs(1);
selpar_L502_cBs=set_selpar_L502_cBs(1);
selpar_slope2_cBs=set_selpar_slope2_cBs(1);

selpar_L50_sgcomp_trawl=set_selpar_L50_sgcomp_trawl(1);
selpar_slope_sgcomp_trawl=set_selpar_slope_sgcomp_trawl(1);
selpar_L502_sgcomp_trawl=set_selpar_L502_sgcomp_trawl(1);
selpar_slope2_sgcomp_trawl=set_selpar_slope2_sgcomp_trawl(1);

selpar_L50_comp_trawl=set_selpar_L50_comp_trawl(1);
selpar_slope_comp_trawl=set_selpar_slope_comp_trawl(1);
selpar_L502_comp_trawl=set_selpar_L502_comp_trawl(1);
selpar_slope2_comp_trawl=set_selpar_slope2_comp_trawl(1);
```

```
sel_age0_cRn_logit=set_sel_age0_cRn(1);  //setting cR selectivity at age in logit space
sel_age1_cRn_logit=set_sel_age1_cRn(1);  //Reduction, north
sel_age2_cRn_logit=set_sel_age2_cRn(1);
sel_age3_cRn_logit=set_sel_age3_cRn(1);
sel_age4_cRn_logit=set_sel_age4_cRn(1);
sel_age5_cRn_logit=set_sel_age5_cRn(1);
sel_age6_cRn_logit=set_sel_age6_cRn(1);

sel_age0_cR2_logit=set_sel_age0_cR2(1);  //setting cR selectivity at age in logit space
sel_age1_cR2_logit=set_sel_age1_cR2(1);
sel_age2_cR2_logit=set_sel_age2_cR2(1);
sel_age3_cR2_logit=set_sel_age3_cR2(1);
sel_age4_cR2_logit=set_sel_age4_cR2(1);

sel_age0_cRs_logit=set_sel_age0_cRs(1);  //setting cR selectivity at age in logit space
sel_age1_cRs_logit=set_sel_age1_cRs(1);  //Reduction, south
sel_age2_cRs_logit=set_sel_age2_cRs(1);
sel_age3_cRs_logit=set_sel_age3_cRs(1);
sel_age4_cRs_logit=set_sel_age4_cRs(1);
sel_age5_cRs_logit=set_sel_age5_cRs(1);
sel_age6_cRs_logit=set_sel_age6_cRs(1);

sel_age0_cBn_logit=set_sel_age0_cBn(1);  //setting cR selectivity at age in logit space
sel_age1_cBn_logit=set_sel_age1_cBn(1);  //Bait, north
sel_age2_cBn_logit=set_sel_age2_cBn(1);
sel_age3_cBn_logit=set_sel_age3_cBn(1);
sel_age4_cBn_logit=set_sel_age4_cBn(1);
sel_age5_cBn_logit=set_sel_age5_cBn(1);
sel_age6_cBn_logit=set_sel_age6_cBn(1);

sel_age0_cBs_logit=set_sel_age0_cBs(1);  //setting cR selectivity at age in logit space
sel_age1_cBs_logit=set_sel_age1_cBs(1);  //Bait, south
sel_age2_cBs_logit=set_sel_age2_cBs(1);
sel_age3_cBs_logit=set_sel_age3_cBs(1);
sel_age4_cBs_logit=set_sel_age4_cBs(1);
sel_age5_cBs_logit=set_sel_age5_cBs(1);
sel_age6_cBs_logit=set_sel_age6_cBs(1);

sqrt2pi=sqrt(2.*3.14159265);
g2mt=0.000001;         //conversion of grams to metric tons
g2kg=0.001;            //conversion of grams to kg
mt2klb=2.20462;        //conversion of metric tons to 1000 lb
mt2lb=mt2klb*1000.0;   //conversion of metric tons to lb
g2klb=g2mt*mt2klb;     //conversion of grams to 1000 lb
dzero=0.00001;
huge_number=1.0e+10;

SSB_msy_out=0.0;

iter_inc_msy=max_F_spr_msy/(n_iter_msy-1);
iter_inc_spr=max_F_spr_msy/(n_iter_spr-1);

maturity_f=maturity_f_obs;
tv_maturity_f=tv_maturity_f_obs;
prop_f=prop_f_obs;

lbins=lenbins;

lenbins_all(1,nlenbins)=lenbins(1,nlenbins);
for (iyear=1;iyear<=nlenbins_plus; iyear++) {lenbins_all(nlenbins+iyear)=lenbins_plus(iyear);}

//Fill in sample sizes of comps, possibly sampled in nonconsec yrs
//Used primarily for output in R object

    nsamp_sgcomp_trawl_lenc_allyr=missing; //"missing" defined in admb2r.cpp
    nsamp_comp_trawl_lenc_allyr=missing;
    nsamp_cRn_agec_allyr=missing;
    nsamp_cRs_agec_allyr=missing;
    nsamp_cBn_agec_allyr=missing;
    nsamp_cBs_agec_allyr=missing;

    nfish_sgcomp_trawl_lenc_allyr=missing; //"missing" defined in admb2r.cpp
    nfish_comp_trawl_lenc_allyr=missing;
    nfish_cRn_agec_allyr=missing;
    nfish_cRs_agec_allyr=missing;
    nfish_cBn_agec_allyr=missing;
    nfish_cBs_agec_allyr=missing;

    for (iyear=1; iyear<=nyr_sgcomp_trawl_lenc; iyear++)
       {if (nsamp_sgcomp_trawl_lenc(iyear)>=minSS_sgcomp_trawl_lenc)
          {nsamp_sgcomp_trawl_lenc_allyr(yrs_sgcomp_trawl_lenc(iyear))=nsamp_sgcomp_trawl_lenc(iyear);
           nfish_sgcomp_trawl_lenc_allyr(yrs_sgcomp_trawl_lenc(iyear))=nfish_sgcomp_trawl_lenc(iyear);}}

    for (iyear=1; iyear<=nyr_comp_trawl_lenc; iyear++)
       {if (nsamp_comp_trawl_lenc(iyear)>=minSS_comp_trawl_lenc)
          {nsamp_comp_trawl_lenc_allyr(yrs_comp_trawl_lenc(iyear))=nsamp_comp_trawl_lenc(iyear);
           nfish_comp_trawl_lenc_allyr(yrs_comp_trawl_lenc(iyear))=nfish_comp_trawl_lenc(iyear);}}

    for (iyear=1; iyear<=nyr_cR_agec; iyear++)
       {if (nsamp_cRn_agec(iyear)>=minSS_cRn_agec)
         {nsamp_cRn_agec_allyr(yrs_cR_agec(iyear))=nsamp_cRn_agec(iyear);
          nfish_cRn_agec_allyr(yrs_cR_agec(iyear))=nfish_cRn_agec(iyear);}}

    for (iyear=1; iyear<=nyr_cR_agec; iyear++)
       {if (nsamp_cRs_agec(iyear)>=minSS_cRs_agec)
         {nsamp_cRs_agec_allyr(yrs_cR_agec(iyear))=nsamp_cRs_agec(iyear);
          nfish_cRs_agec_allyr(yrs_cR_agec(iyear))=nfish_cRs_agec(iyear);}}

   for (iyear=1; iyear<=nyr_cB_agec; iyear++)
       {if (nsamp_cBn_agec(iyear)>=minSS_cBn_agec)
         {nsamp_cBn_agec_allyr(yrs_cB_agec(iyear))=nsamp_cBn_agec(iyear);
          nfish_cBn_agec_allyr(yrs_cB_agec(iyear))=nfish_cBn_agec(iyear);}}

   for (iyear=1; iyear<=nyr_cB_agec; iyear++)
```

```
         {if (nsamp_cBs_agec(iyear)>=minSS_cBs_agec)
           {nsamp_cBs_agec_allyr(yrs_cB_agec(iyear))=nsamp_cBs_agec(iyear);
            nfish_cBs_agec_allyr(yrs_cB_agec(iyear))=nfish_cBs_agec(iyear);}}



//fill in Fs for msy and per-recruit analyses
  F_msy(1)=0.0;
  for (ff=2;ff<=n_iter_msy;ff++)
  {
    F_msy(ff)=F_msy(ff-1)+iter_inc_msy;
  }
  F_spr(1)=0.0;
  for (ff=2;ff<=n_iter_spr;ff++)
  {
    F_spr(ff)=F_spr(ff-1)+iter_inc_spr;
  }


//fill in F's, Catch matrices, and log rec dev with zero's
  F_cRn.initialize();
  F_cRs.initialize();
  F_cBn.initialize();
  F_cBs.initialize();

  L_cRn_num.initialize();
  L_cRs_num.initialize();
  L_cBn_num.initialize();
  L_cBs_num.initialize();

  F_cRn_out.initialize();
  F_cRs_out.initialize();
  F_cBn_out.initialize();
  F_cBs_out.initialize();

  sel_cRn.initialize();
  sel_cRs.initialize();
  sel_cBn.initialize();
  sel_cBs.initialize();
  sel_sgcomp_trawl.initialize();
  sel_comp_trawl.initialize();

  log_rec_dev_output.initialize();
  log_Nage_dev_output.initialize();
  log_rec_dev=set_log_rec_dev_vals;

  log_Nage_dev.initialize();
  M_dev_output.initialize();


//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
TOP_OF_MAIN_SECTION
  time(&start);
  arrmblsize=20000000;
  gradient_structure::set_MAX_NVAR_OFFSET(1600);
  gradient_structure::set_GRADSTACK_BUFFER_SIZE(2000000);
  gradient_structure::set_CMPDIF_BUFFER_SIZE(2000000);
  gradient_structure::set_NUM_DEPENDENT_VARIABLES(10000);

//>--><>--><>--><>--><>
//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>


PROCEDURE_SECTION

 R0=mfexp(log_R0);

 //cout<<"start"<<endl;

 get_length_weight_at_age();
 //cout << "got length, weight, fecundity transitions" <<endl;
 get_reprod();
 //cout << "got repro stuff" << endl;
 get_length_at_age_dist();
 //cout<< "got predicted length at age distribution"<<endl;
 get_weight_at_age_landings();
 //cout<< "got weight at age of landings"<<endl;
 get_spr_F0();
 //cout << "got F0 spr" << endl;
 get_selectivity();
 //cout << "got selectivity" << endl;
 get_mortality();
 //cout << "got mortalities" << endl;
 get_bias_corr();
 //cout<< "got recruitment bias correction" << endl;
 get_numbers_at_age();
 //cout << "got numbers at age" << endl;
 //exit(0);
 get_landings_numbers();
 //cout << "got catch at age" << endl;
 get_landings_wgt();
 //cout << "got landings" << endl;
 get_catchability_fcns();
 //cout << "got catchability_fcns" << endl;
 get_indices();
 //cout << "got indices" << endl;
 get_length_comps();
 //cout<< "got length comps"<< endl;
 get_age_comps();
 //cout<< "got age comps"<< endl;
 //exit(0);
 evaluate_objective_function();
 //cout << "objective function calculations complete" << endl;
```

```
 //exit(0);


FUNCTION get_length_weight_at_age
  //compute mean length (mm FL) and weight (whole) at age
    //meanlen_FL=Linf*(1.0-mfexp(-K*(agebins-t0+0.5)));    //fork length in mm

  for (iyear=styr; iyear<=endyr; iyear++)
   {
     meanlen_FL_may(iyear)=len_may_tv(iyear);
     meanlen_FL_sept(iyear)=len_sept_tv(iyear);
     wgt_fish_mt(iyear)=g2mt*wgt_start_tv(iyear); //wgt in mt
     wgt_spawn_mt_tv(iyear)=g2mt*wgt_spawn_tv(iyear);   //mt of whole wgt
   }

    wgt_spawn_mt=g2mt*wgt_spawn;   //mt of whole wgt


FUNCTION get_reprod
   //for reproductive capacity calcs
   //product of sex ratio, maturity, and fecundity for atlantic menhaden

  reprod=elem_prod(elem_prod(prop_f,maturity_f),fec_at_age);

  for (iyear=styr; iyear<=endyr; iyear++)
  {
    reprod_tv(iyear)=elem_prod(elem_prod(prop_f,tv_maturity_f(iyear)),fec_at_age_tv(iyear));
  }


FUNCTION get_length_at_age_dist
  //compute matrix of length at age, based on the normal distribution, May 15
  for (iyear=styr; iyear<=endyr; iyear++)
  {
   for (iage=1;iage<=nages;iage++)
   {
    len_cv(iage)=len_cv_val;
    len_sd(iyear,iage)=meanlen_FL_may(iyear,iage)*len_cv(iage);

    for (ilen=1;ilen<=nlenbins_all;ilen++)
     { lenprob_may_all(iyear,iage,ilen)=(mfexp(-(square(lenbins_all(ilen)-meanlen_FL_may(iyear,iage))/
       (2.*square(len_sd(iyear,iage)))))/(sqrt2pi*len_sd(iyear,iage)));
     }

    lenprob_may_all(iyear,iage)/=sum(lenprob_may_all(iyear,iage)); //standardize to approximate integration and to account for truncated normal (i.e., no sizes<smallest)

    for (ilen=1;ilen<=nlenbins;ilen++) {lenprob_may(iyear,iage,ilen)=lenprob_may_all(iyear,iage,ilen);
    }
    for (ilen=nlenbins+1;ilen<=nlenbins_all;ilen++){lenprob_may(iyear,iage)(nlenbins)=lenprob_may(iyear,iage)(nlenbins)+lenprob_may_all(iyear,iage)(ilen);
    } //plus group
   }

   //specific length probs
   lenprob_sgcomp_trawl=lenprob_may;
   lenprob_sgcomp_trawl_all=lenprob_may_all;
  }


  //compute matrix of length at age, based on the normal distribution, September 1
  for (iyear=styr; iyear<=endyr; iyear++)
  {
   for (iage=1;iage<=nages;iage++)
   {
    len_cv(iage)=len_cv_val;
    len_sd(iyear,iage)=meanlen_FL_sept(iyear,iage)*len_cv(iage);

    for (ilen=1;ilen<=nlenbins_all;ilen++)
     { lenprob_sept_all(iyear,iage,ilen)=(mfexp(-(square(lenbins_all(ilen)-meanlen_FL_sept(iyear,iage))/
       (2.*square(len_sd(iyear,iage)))))/(sqrt2pi*len_sd(iyear,iage)));
     }

    lenprob_sept_all(iyear,iage)/=sum(lenprob_sept_all(iyear,iage)); //standardize to approximate integration and to account for truncated normal (i.e., no sizes<smallest)

    for (ilen=1;ilen<=nlenbins;ilen++) {lenprob_sept(iyear,iage,ilen)=lenprob_sept_all(iyear,iage,ilen);
    }
    for (ilen=nlenbins+1;ilen<=nlenbins_all;ilen++){lenprob_sept(iyear,iage)(nlenbins)=lenprob_sept(iyear,iage)(nlenbins)+lenprob_sept_all(iyear,iage)(ilen);
    } //plus group
   }

   //specific length probs
   lenprob_comp_trawl=lenprob_sept;
   lenprob_comp_trawl_all=lenprob_sept_all;
  }


FUNCTION get_weight_at_age_landings

  for (iyear=styr; iyear<=endyr; iyear++)
  {
    wholewgt_cR_mt(iyear)=wgt_fish_mt(iyear);  //whole weight in mt
    wholewgt_cB_mt(iyear)=wgt_fish_mt(iyear);  //whole weight in mt

  }

FUNCTION get_spr_F0
  //at mdyr, apply half this yr's mortality, half next yr's
  N_spr_F0(1)=1.0*mfexp(-1.0*M(1)*spawn_time_frac); //at peak spawning time
  N_bpr_F0(1)=1.0;      //at start of year
  for (iage=2; iage<=nages; iage++)
  {
    N_spr_F0(iage)=N_spr_F0(iage-1)*mfexp(-1.0*(M(iage-1)*(1.0-spawn_time_frac) + M(iage)*spawn_time_frac));
    N_bpr_F0(iage)=N_bpr_F0(iage-1)*mfexp(-1.0*(M(iage-1)));
  }
  N_spr_F0(nages)=N_spr_F0(nages)/(1.0-mfexp(-1.0*M(nages))); //plus group (sum of geometric series)
```

```
  N_bpr_F0(nages)=N_bpr_F0(nages)/(1.0-mfexp(-1.0*M(nages)));

  spr_F0=sum(elem_prod(N_spr_F0,reprod));
  bpr_F0=sum(elem_prod(N_bpr_F0,wgt_spawn_mt));


FUNCTION get_selectivity
  //selpar_age0_cRn=1.0/(1.0+mfexp(-sel_age0_cRn_logit));
  //selpar_age1_cRn=1.0/(1.0+mfexp(-sel_age1_cRn_logit));
  //selpar_age2_cRn=1.0/(1.0+mfexp(-sel_age2_cRn_logit));
  //selpar_age2_cRn=1.0;
  //selpar_age3_cRn=1.0/(1.0+mfexp(-sel_age3_cRn_logit));
  //selpar_age3_cRn=1.0;
  //selpar_age4_cRn=1.0/(1.0+mfexp(-sel_age4_cRn_logit));
  //selpar_age5_cRn=1.0/(1.0+mfexp(-sel_age5_cRn_logit));
  //selpar_age6_cRn=1.0/(1.0+mfexp(-sel_age6_cRn_logit));
  //selpar_age4_cR=0.35;
  //sel_age_cRn_vec(1)=selpar_age0_cRn;
  //sel_age_cRn_vec(2)=selpar_age1_cRn;
  //sel_age_cRn_vec(3)=selpar_age2_cRn;
  //sel_age_cRn_vec(4)=selpar_age3_cRn;
  //sel_age_cRn_vec(5)=selpar_age4_cRn;
  //sel_age_cRn_vec(6)=selpar_age5_cRn;
  //sel_age_cRn_vec(7)=selpar_age6_cRn;

  //selpar_age0_cRs=1.0/(1.0+mfexp(-sel_age0_cRs_logit));
  //selpar_age1_cRs=1.0/(1.0+mfexp(-sel_age1_cRs_logit));
  //selpar_age2_cRs=1.0/(1.0+mfexp(-sel_age2_cRs_logit));
  //selpar_age2_cRs=1.0;
  //selpar_age3_cRs=1.0/(1.0+mfexp(-sel_age3_cRs_logit));
  //selpar_age4_cRs=1.0/(1.0+mfexp(-sel_age4_cRs_logit));
  //selpar_age5_cRs=1.0/(1.0+mfexp(-sel_age5_cRs_logit));
  //selpar_age6_cRs=1.0/(1.0+mfexp(-sel_age6_cRs_logit));
  //sel_age_cRs_vec(1)=selpar_age0_cRs;
  //sel_age_cRs_vec(2)=selpar_age1_cRs;
  //sel_age_cRs_vec(3)=selpar_age2_cRs;
  //sel_age_cRs_vec(4)=selpar_age3_cRs;
  //sel_age_cRs_vec(5)=selpar_age4_cRs;
  //sel_age_cRs_vec(6)=selpar_age5_cRs;
  //sel_age_cRs_vec(7)=selpar_age6_cRs;


  //selpar_age0_cR2=1.0/(1.0+mfexp(-sel_age0_cR2_logit));
  //selpar_age1_cR2=1.0/(1.0+mfexp(-sel_age1_cR2_logit));
  //selpar_age2_cR2=1.0/(1.0+mfexp(-sel_age2_cR2_logit));
  //selpar_age2_cR2=1.0;
  //selpar_age3_cR2=1.0/(1.0+mfexp(-sel_age3_cR_logit));
  //selpar_age3_cR2=0.35;
  //selpar_age4_cR2=1.0/(1.0+mfexp(-sel_age3_cR_logit));
  //selpar_age4_cR2=0.35;
  //sel_age_cR2_vec(1)=selpar_age0_cR2;
  //sel_age_cR2_vec(2)=selpar_age1_cR2;
  //sel_age_cR2_vec(3)=selpar_age2_cR2;
  //sel_age_cR2_vec(4)=selpar_age3_cR2;
  //sel_age_cR2_vec(5)=selpar_age4_cR2;

  //selpar_age0_cBn=1.0/(1.0+mfexp(-sel_age0_cBn_logit));
  //selpar_age1_cBn=1.0/(1.0+mfexp(-sel_age1_cBn_logit));
  //selpar_age2_cBn=1.0/(1.0+mfexp(-sel_age2_cBn_logit));
  //selpar_age3_cBn=1.0;
  //selpar_age3_cBn=1.0/(1.0+mfexp(-sel_age3_cBn_logit));
  //selpar_age4_cBn=1.0/(1.0+mfexp(-sel_age4_cBn_logit));
  //selpar_age5_cBn=1.0/(1.0+mfexp(-sel_age5_cBn_logit));
  //selpar_age6_cBn=1.0/(1.0+mfexp(-sel_age6_cBn_logit));
  //sel_age_cBn_vec(1)=selpar_age0_cBn;
  //sel_age_cBn_vec(2)=selpar_age1_cBn;
  //sel_age_cBn_vec(3)=selpar_age2_cBn;
  //sel_age_cBn_vec(4)=selpar_age3_cBn;
  //sel_age_cBn_vec(5)=selpar_age4_cBn;
  //sel_age_cBn_vec(6)=selpar_age5_cBn;
  //sel_age_cBn_vec(7)=selpar_age6_cBn;

  //selpar_age0_cBs=1.0/(1.0+mfexp(-sel_age0_cBs_logit));
  //selpar_age1_cBs=1.0/(1.0+mfexp(-sel_age1_cBs_logit));
  //selpar_age2_cBs=1.0;
  //selpar_age3_cBs=1.0/(1.0+mfexp(-sel_age3_cBs_logit));
  //selpar_age4_cBs=1.0/(1.0+mfexp(-sel_age4_cBs_logit));
  //selpar_age5_cBs=1.0/(1.0+mfexp(-sel_age5_cBs_logit));
  //selpar_age6_cBs=1.0/(1.0+mfexp(-sel_age6_cBs_logit));
  //sel_age_cBs_vec(1)=selpar_age0_cBs;
  //sel_age_cBs_vec(2)=selpar_age1_cBs;
  //sel_age_cBs_vec(3)=selpar_age2_cBs;
  //sel_age_cBs_vec(4)=selpar_age3_cBs;
  //sel_age_cBs_vec(5)=selpar_age4_cBs;
  //sel_age_cBs_vec(6)=selpar_age5_cBs;
  //sel_age_cBs_vec(7)=selpar_age6_cBs;

  for (iyear=styr; iyear<=endyr_period1a; iyear++)
  {
     //sel_cR(iyear)=logistic(agebins, selpar_L50_cR, selpar_slope_cR);
     sel_cRn(iyear)=logistic_double(agebins, selpar_L50_cRn, selpar_slope_cRn, selpar_L502_cRn, selpar_slope2_cRn);
     //sel_cRn(iyear)=sel_age_cRn_vec;
     //sel_cR(iyear)=logistic_exponential_mod(agebins, selpar_L50_logexp_cR, selpar_slope_logexp_cR, selpar_sigma_logexp_cR);

     sel_cRs(iyear)=logistic_double(agebins, selpar_L50_cRs, selpar_slope_cRs, selpar_L502_cRs, selpar_slope2_cRs);
     //sel_cRs(iyear)=sel_age_cRs_vec;

     //sel_cB(iyear)=logistic(agebins, selpar_L50_cB, selpar_slope_cB);
     sel_cBn(iyear)=logistic_double(agebins, selpar_L50_cBn, selpar_slope_cBn, selpar_L502_cBn, selpar_slope2_cBn);
     //sel_cBn(iyear)=sel_age_cBn_vec;

     sel_cBs(iyear)=logistic_double(agebins, selpar_L50_cBs, selpar_slope_cBs, selpar_L502_cBs, selpar_slope2_cBs);
     //sel_cBs(iyear)=sel_age_cBs_vec;
  }
```

```
  for (iyear=(endyr_period1a+1); iyear<=endyr_period1b; iyear++)
  {
     //sel_cR(iyear)=logistic(agebins, selpar_L50_cR2, selpar_slope_cR2);
     sel_cRn(iyear)=logistic_double(agebins, selpar_L50_cRn2, selpar_slope_cRn2, selpar_L502_cRn2, selpar_slope2_cRn2);
     //sel_cRn(iyear)=sel_cRn(styr);

     sel_cRs(iyear)=sel_cRs(styr);

     sel_cBn(iyear)=sel_cBn(styr);

     sel_cBs(iyear)=sel_cBs(styr);
  }

  for (iyear=(endyr_period1b+1); iyear<=endyr_period1; iyear++)
  {
     //sel_cR(iyear)=logistic(agebins, selpar_L50_cR2, selpar_slope_cR2);
     //sel_cRn(iyear)=logistic_double(agebins, selpar_L50_cRn3, selpar_slope_cRn3, selpar_L502_cRn3, selpar_slope2_cRn3);
     sel_cRn(iyear)=sel_cRn(endyr_period1b);

     //sel_cRs(iyear)=sel_cRs(styr);
     sel_cRs(iyear)=logistic_double(agebins, selpar_L50_cRs2, selpar_slope_cRs2, selpar_L502_cRs2, selpar_slope2_cRs2);

     sel_cBn(iyear)=sel_cBn(styr);

     sel_cBs(iyear)=sel_cBs(styr);
  }


  for (iyear=(endyr_period1+1); iyear<=endyr_period2; iyear++)
  {
     //sel_cR(iyear)=logistic(agebins, selpar_L50_cR2, selpar_slope_cR2);
     sel_cRn(iyear)=logistic_double(agebins, selpar_L50_cRn3, selpar_slope_cRn3, selpar_L502_cRn3, selpar_slope2_cRn3);
     //sel_cRn(iyear)=sel_cRn(styr);

     sel_cRs(iyear)=sel_cRs(endyr_period1);

     sel_cBn(iyear)=sel_cBn(styr);

     sel_cBs(iyear)=sel_cBs(styr);
  }

  for (iyear=(endyr_period2+1); iyear<=endyr_period3; iyear++)
  {
     //sel_cR(iyear)=logistic_double(agebins, selpar_L50_cR3, selpar_slope_cR3, selpar_L502_cR3, selpar_slope2_cR3);
     //sel_cRn(iyear)=sel_cRn(styr);
     sel_cRn(iyear)=sel_cRn(endyr_period2);

     //sel_cRs(iyear)=sel_cRs(styr);
     sel_cRs(iyear)=logistic_double(agebins, selpar_L50_cRs3, selpar_slope_cRs3, selpar_L502_cRs3, selpar_slope2_cRs3);

     sel_cBn(iyear)=sel_cBn(styr);
     //sel_cBn(iyear)=logistic_double(agebins, selpar_L50_cBn3, selpar_slope_cBn3, selpar_L502_cR3, selpar_slope2_cR3);

     sel_cBs(iyear)=sel_cBs(styr);
  }

  for (iyear=styr_sgcomp_trawl_cpue; iyear<=endyr_sgcomp_trawl_cpue; iyear++)
  {
     //sel_sgcomp_trawl(iyear)=logistic(agebins,selpar_L50_sgcomp_trawl,selpar_slope_sgcomp_trawl);
     sel_sgcomp_trawl(iyear)=logistic_double(agebins, selpar_L50_sgcomp_trawl, selpar_slope_sgcomp_trawl, selpar_L502_sgcomp_trawl, selpar_slope2_sgcomp_trawl);
  }

  for (iyear=styr_comp_trawl_cpue; iyear<=endyr_comp_trawl_cpue; iyear++)
  {
     sel_comp_trawl(iyear)=logistic(agebins,selpar_L50_comp_trawl,selpar_slope_comp_trawl);
     //sel_comp_trawl(iyear)=logistic_double(agebins, selpar_L50_comp_trawl, selpar_slope_comp_trawl, selpar_L502_comp_trawl, selpar_slope2_comp_trawl);
  }

  sel_initial=sel_cRs(styr);

FUNCTION get_mortality
  Fsum.initialize();
  Fapex.initialize();
  F.initialize();

  //initialization F is avg from first 3 yrs of observed landings
  log_F_dev_init_cRn=sum(log_F_dev_cRn(styr_cR_L,(styr_cR_L+2)))/3.0;
  log_F_dev_init_cRs=sum(log_F_dev_cRs(styr_cR_L,(styr_cR_L+2)))/3.0;
  log_F_dev_init_cBn=sum(log_F_dev_cBn(styr_cB_L,(styr_cR_L+2)))/3.0;
  log_F_dev_init_cBs=sum(log_F_dev_cBs(styr_cB_L,(styr_cR_L+2)))/3.0;

  for (iyear=styr; iyear<=endyr; iyear++)
  {
    if(iyear>=styr_cR_L & iyear<=endyr_cR_L)
    {  F_cRn_out(iyear)=mfexp(log_avg_F_cRn+log_F_dev_cRn(iyear));
       F_cRn(iyear)=sel_cRn(iyear)*F_cRn_out(iyear);
       Fsum(iyear)+=F_cRn_out(iyear);
    }

   if(iyear>=styr_cR_L & iyear<=endyr_cR_L)
    {  F_cRs_out(iyear)=mfexp(log_avg_F_cRs+log_F_dev_cRs(iyear));
       F_cRs(iyear)=sel_cRs(iyear)*F_cRs_out(iyear);
       Fsum(iyear)+=F_cRs_out(iyear);
    }

    if(iyear>=styr_cB_L & iyear<=endyr_cB_L)
    {  F_cBn_out(iyear)=mfexp(log_avg_F_cBn+log_F_dev_cBn(iyear));
       F_cBn(iyear)=sel_cBn(iyear)*F_cBn_out(iyear);
       Fsum(iyear)+=F_cBn_out(iyear);
    }

    if(iyear>=styr_cB_L & iyear<=endyr_cB_L)
    {  F_cBs_out(iyear)=mfexp(log_avg_F_cBs+log_F_dev_cBs(iyear));
```

```
      F_cBs(iyear)=sel_cBs(iyear)*F_cBs_out(iyear);
      Fsum(iyear)+=F_cBs_out(iyear);
    }

    //Total F at age
    F(iyear)=F_cRn(iyear); //first in additive series (NO +=)
    F(iyear)+=F_cRs(iyear);
    F(iyear)+=F_cBn(iyear);
    F(iyear)+=F_cBs(iyear);

    Fapex(iyear)=max(F(iyear));

    Z(iyear)=M_tv(iyear)+F(iyear);

    //if(iyear>=styr_seine_cpue & iyear<=endyr_seine_cpue)
    //{ Z(iyear,2)=M(2)+M_dev(iyear)+F(iyear,2); //adds deviations in age-1 M
    //}

  }  //end iyear


FUNCTION get_bias_corr
  var_rec_dev=norm2(log_rec_dev(styr_rec_dev,endyr_rec_dev)-
              sum(log_rec_dev(styr_rec_dev,endyr_rec_dev))/nyrs_rec)
              /(nyrs_rec-1.0);

  rec_sigma_sq=square(rec_sigma);
  if (set_BiasCor <= 0.0) {BiasCor=mfexp(rec_sigma_sq/2.0);}   //bias correction
  else {BiasCor=set_BiasCor;}

FUNCTION get_numbers_at_age
//Initialization

  S0=spr_F0*R0;  //virgin SSB

  R_virgin=SR_eq_func(R0, steep, spr_F0, spr_F0, BiasCor, SR_switch);

  B0=bpr_F0*R_virgin*1000000;  //virgin biomass
  //B0_q_DD=R_virgin*sum(elem_prod(N_bpr_F0(set_q_DD_stage,nages),wgt_fish_mt(set_q_DD_stage,nages)));

  //F_initial=sel_cR(styr)*mfexp(log_avg_F_cR+log_F_dev_init_cR);
  F_initial=(sel_cRn(styr)*mfexp(log_avg_F_cRn+log_F_dev_init_cRn))
              +(sel_cRs(styr)*mfexp(log_avg_F_cRs+log_F_dev_init_cRs))
              +(sel_cBn(styr)*mfexp(log_avg_F_cBn+log_F_dev_init_cBn))
              +(sel_cBs(styr)*mfexp(log_avg_F_cBs+log_F_dev_init_cBs));
  Z_initial=M_tv(styr)+F_initial;

//Initial equilibrium age structure
  N_spr_initial(1)=1.0*mfexp(-1.0*Z_initial(1)*spawn_time_frac); //at peak spawning time;
  for (iage=2; iage<=nages; iage++)
    {
      N_spr_initial(iage)=N_spr_initial(iage-1)*
                   mfexp(-1.0*(Z_initial(iage-1)*(1.0-spawn_time_frac) + Z_initial(iage)*spawn_time_frac));
    }
  N_spr_initial(nages)=N_spr_initial(nages)/(1.0-mfexp(-1.0*Z_initial(nages))); //plus group

  spr_initial=sum(elem_prod(N_spr_initial,reprod)); //initial ssb for s-r curve

  R1=SR_eq_func(R0, steep, spr_F0, spr_initial, BiasCor, SR_switch);
  //R1=SR_eq_func(R0, steep, spr_F0, spr_initial, BiasCor, SR_switch);
  if(R1<0.0) {R1=10.0;} //Avoid negative popn sizes during search algorithm



//Compute equilibrium age structure for first year
  N_initial_eq(1)=R1;
  for (iage=2; iage<=nages; iage++)
  {
    N_initial_eq(iage)=N_initial_eq(iage-1)*
        mfexp(-1.0*(Z_initial(iage-1)));
  }
  //plus group calculation
  N_initial_eq(nages)=N_initial_eq(nages)/(1.0-mfexp(-1.0*Z_initial(nages))); //plus group

//Add deviations to initial equilibrium N
  N(styr)(2,nages)=elem_prod(N_initial_eq(2,nages),mfexp(log_Nage_dev));

  //if (styr==styr_rec_dev) {N(styr,1)=N_initial_eq(1)*mfexp(log_rec_dev(styr_rec_dev));}
  //else {N(styr,1)=N_initial_eq(1);}
  N(styr,1)=N_initial_eq(1)*mfexp(log_rec_dev(styr_rec_dev));

  N_mdyr(styr)(1,nages)=elem_prod(N(styr)(1,nages),(mfexp(-1.*(Z_initial(1,nages))*0.5))); //mid year
  N_may(styr)(1,nages)=elem_prod(N(styr)(1,nages),(mfexp(-1.*(Z_initial(1,nages))*0.21))); //May 15
  N_sept(styr)(1,nages)=elem_prod(N(styr)(1,nages),(mfexp(-1.*(Z_initial(1,nages))*0.5))); //September 1
  N_spawn(styr)(1,nages)=elem_prod(N(styr)(1,nages),(mfexp(-1.*(Z_initial(1,nages))*spawn_time_frac))); //peak spawning time

  SSB(styr)=sum(elem_prod(N_spawn(styr),reprod_tv(styr)));
  //B_q_DD(styr)=sum(elem_prod(N(styr)(set_q_DD_stage,nages),wgt_fish_mt(set_q_DD_stage,nages)));


//Rest of years
  for (iyear=styr; iyear<endyr; iyear++)
  {
    if(iyear<(styr_rec_dev-1)||iyear>(endyr_rec_dev-1)) //recruitment follows S-R curve exactly
    {
        //N(iyear+1,1)=BiasCor*SR_func(R0, steep, spr_F0, SSB(iyear),SR_switch);
        N(iyear+1)(2,nages)=++elem_prod(N(iyear)(1,nages-1),(mfexp(-1.*Z(iyear)(1,nages-1))));
        N(iyear+1,nages)+=N(iyear,nages)*mfexp(-1.*Z(iyear,nages));//plus group
        //N_mdyr(iyear+1)(1,nages)=elem_prod(N(iyear+1)(1,nages),(mfexp(-1.*(Z(iyear+1)(1,nages))*0.5)));
        N_spawn(iyear+1)(1,nages)=elem_prod(N(iyear+1)(1,nages),(mfexp(-1.*(Z(iyear+1)(1,nages))*spawn_time_frac))); //peak spawning time
        SSB(iyear+1)=sum(elem_prod(N_spawn(iyear+1),reprod_tv(iyear+1)));
        //B_q_DD(iyear+1)=sum(elem_prod(N(iyear+1)(set_q_DD_stage,nages),wgt_fish_mt(set_q_DD_stage,nages)));

        N(iyear+1,1)=BiasCor*SR_func(R0, steep, spr_F0, SSB(iyear+1),SR_switch);
```

```
        N_mdyr(iyear+1)(1,nages)=elem_prod(N(iyear+1)(1,nages),(mfexp(-1.*(Z(iyear+1)(1,nages))*0.5)));
        N_may(iyear+1)(1,nages)=elem_prod(N(iyear+1)(1,nages),(mfexp(-1.*(Z(iyear+1)(1,nages))*0.21)));
        N_sept(iyear+1)(1,nages)=elem_prod(N(iyear+1)(1,nages),(mfexp(-1.*(Z(iyear+1)(1,nages))*0.5)));

    }
    else   //recruitment follows S-R curve with lognormal deviation
    {
        N(iyear+1)(2,nages)=++elem_prod(N(iyear)(1,nages-1),(mfexp(-1.*Z(iyear)(1,nages-1))));
        N(iyear+1,nages)+=N(iyear,nages)*mfexp(-1.*Z(iyear,nages));//plus group
        N_spawn(iyear+1)(1,nages)=elem_prod(N(iyear+1)(1,nages),(mfexp(-1.*(Z(iyear+1)(1,nages))*spawn_time_frac))); //peak spawning time
        SSB(iyear+1)=sum(elem_prod(N_spawn(iyear+1),reprod_tv(iyear+1)));
        //B_q_DD(iyear+1)=sum(elem_prod(N(iyear+1)(set_q_DD_stage,nages),wgt_fish_mt(set_q_DD_stage,nages)));

        N(iyear+1,1)=BiasCor*SR_func(R0, steep, spr_F0, SSB(iyear+1),SR_switch)*mfexp(log_rec_dev(iyear+1));
        N_mdyr(iyear+1)(1,nages)=elem_prod(N(iyear+1)(1,nages),(mfexp(-1.*(Z(iyear+1)(1,nages))*0.5)));
        N_may(iyear+1)(1,nages)=elem_prod(N(iyear+1)(1,nages),(mfexp(-1.*(Z(iyear+1)(1,nages))*0.21)));
        N_sept(iyear+1)(1,nages)=elem_prod(N(iyear+1)(1,nages),(mfexp(-1.*(Z(iyear+1)(1,nages))*0.5)));

    }
  }

    //values for projections
    N(endyr+1)(2,nages)=++elem_prod(N(endyr)(1,nages-1),(mfexp(-1.*Z(endyr)(1,nages-1))));
    N(endyr+1,nages)+=N(endyr,nages)*mfexp(-1.*Z(endyr,nages));//plus group
    SSB(endyr+1)=sum(elem_prod(N(endyr+1),reprod));
    N(endyr+1,1)=BiasCor*SR_func(R0, steep, spr_F0, SSB(endyr+1),SR_switch);

//Time series of interest
  rec=column(N,1);
  SdS0=SSB/S0;

 for (iyear=styr; iyear<=endyr; iyear++)
  {
    pred_SPR(iyear)=SSB(iyear)/rec(iyear);
  }

FUNCTION get_landings_numbers //Baranov catch eqn
  for (iyear=styr; iyear<=endyr; iyear++)
  {
    for (iage=1; iage<=nages; iage++)
    {
      L_cRn_num(iyear,iage)=N(iyear,iage)*F_cRn(iyear,iage)*
        (1.-mfexp(-1.*Z(iyear,iage)))/Z(iyear,iage);

      L_cRs_num(iyear,iage)=N(iyear,iage)*F_cRs(iyear,iage)*
        (1.-mfexp(-1.*Z(iyear,iage)))/Z(iyear,iage);

      L_cBn_num(iyear,iage)=N(iyear,iage)*F_cBn(iyear,iage)*
        (1.-mfexp(-1.*Z(iyear,iage)))/Z(iyear,iage);

      L_cBs_num(iyear,iage)=N(iyear,iage)*F_cBs(iyear,iage)*
        (1.-mfexp(-1.*Z(iyear,iage)))/Z(iyear,iage);

    }
    pred_cRn_L_knum(iyear)=sum(L_cRn_num(iyear));//landings already being estimated in 1000s
    pred_cRs_L_knum(iyear)=sum(L_cRs_num(iyear));//landings already being estimated in 1000s
    pred_cBn_L_knum(iyear)=sum(L_cBn_num(iyear));//landings already being estimated in 1000s
    pred_cBs_L_knum(iyear)=sum(L_cBs_num(iyear));//landings already being estimated in 1000s
  }


FUNCTION get_landings_wgt

////---Predicted landings------------------------

 for (iyear=styr; iyear<=endyr; iyear++)
  {
    L_cRn_mt(iyear)=elem_prod(L_cRn_num(iyear),wholewgt_cR_mt(iyear))*1000000; //in 1000 mt
    L_cRs_mt(iyear)=elem_prod(L_cRs_num(iyear),wholewgt_cR_mt(iyear))*1000000; //in 1000 mt
    L_cBn_mt(iyear)=elem_prod(L_cBn_num(iyear),wholewgt_cR_mt(iyear))*1000000;
    L_cBs_mt(iyear)=elem_prod(L_cBs_num(iyear),wholewgt_cR_mt(iyear))*1000000;

    pred_cRn_L_mt(iyear)=sum(L_cRn_mt(iyear));
    pred_cRs_L_mt(iyear)=sum(L_cRs_mt(iyear));
    pred_cBn_L_mt(iyear)=sum(L_cBn_mt(iyear));
    pred_cBs_L_mt(iyear)=sum(L_cBs_mt(iyear));
  }



FUNCTION get_catchability_fcns
 //Get rate increase if estimated, otherwise fixed above
  if (set_q_rate_phase>0.0)
  {

      for (iyear=styr_sgcomp_trawl_cpue; iyear<=endyr_sgcomp_trawl_cpue; iyear++)
      {   if (iyear>styr_sgcomp_trawl_cpue & iyear <=2003)
          {
             q_rate_fcn_sgcomp_trawl(iyear)=(1.0+(iyear-styr_sgcomp_trawl_cpue)*q_rate)*q_rate_fcn_sgcomp_trawl(styr_sgcomp_trawl_cpue);  //linear
          }
          if (iyear>2003) {q_rate_fcn_sgcomp_trawl(iyear)=q_rate_fcn_sgcomp_trawl(iyear-1);}
      }

      for (iyear=styr_comp_trawl_cpue; iyear<=endyr_comp_trawl_cpue; iyear++)
      {   if (iyear>styr_comp_trawl_cpue & iyear <=2003)
          {
             q_rate_fcn_comp_trawl(iyear)=(1.0+(iyear-styr_comp_trawl_cpue)*q_rate)*q_rate_fcn_comp_trawl(styr_comp_trawl_cpue);  //linear
          }
          if (iyear>2003) {q_rate_fcn_comp_trawl(iyear)=q_rate_fcn_comp_trawl(iyear-1);}
      }

      for (iyear=styr_seine_cpue; iyear<=endyr_seine_cpue; iyear++)
      {   if (iyear>styr_seine_cpue & iyear <=2003)
          {//q_rate_fcn_seine(iyear)=(1.0+q_rate)*q_rate_fcn_seine(iyear-1); //compound
```

```
             q_rate_fcn_seine(iyear)=(1.0+(iyear-styr_seine_cpue)*q_rate)*q_rate_fcn_seine(styr_seine_cpue);  //linear
          }
          if (iyear>2003) {q_rate_fcn_seine(iyear)=q_rate_fcn_seine(iyear-1);}
      }

      for (iyear=styr_yoy_cpue; iyear<=endyr_yoy_cpue; iyear++)
      {   if (iyear>styr_yoy_cpue & iyear <=2003)
          {
             q_rate_fcn_yoy(iyear)=(1.0+(iyear-styr_yoy_cpue)*q_rate)*q_rate_fcn_yoy(styr_yoy_cpue);  //linear
          }
          if (iyear>2003) {q_rate_fcn_yoy(iyear)=q_rate_fcn_yoy(iyear-1);}
      }


  } //end q_rate conditional


 //Get density dependence scalar (=1.0 if density independent model is used)
  //if (q_DD_beta>0.0)
  //{
  //  B_q_DD+=dzero;
  //  for (iyear=styr;iyear<=endyr;iyear++)
  //      {q_DD_fcn(iyear)=pow(B0_q_DD,q_DD_beta)*pow(B_q_DD(iyear),-q_DD_beta);}
          //{q_DD_fcn(iyear)=1.0+4.0/(1.0+mfexp(0.75*(B_q_DD(iyear)-0.1*B0_q_DD))); }
  //}


FUNCTION get_indices
//---Predicted CPUEs------------------------

  //sg composite trawl index
  q_sgcomp_trawl(styr_sgcomp_trawl_cpue)=mfexp(log_q_sgcomp_trawl);
  for (iyear=styr_sgcomp_trawl_cpue; iyear<=endyr_sgcomp_trawl_cpue; iyear++)
  {   N_sgcomp_trawl(iyear)=elem_prod(N_may(iyear),sel_sgcomp_trawl(iyear));
      pred_sgcomp_trawl_cpue(iyear)=q_sgcomp_trawl(iyear)*q_rate_fcn_sgcomp_trawl(iyear)*q_DD_fcn(iyear)*sum(N_sgcomp_trawl(iyear));
      if (iyear<endyr_sgcomp_trawl_cpue){q_sgcomp_trawl(iyear+1)=q_sgcomp_trawl(iyear)*mfexp(q_RW_log_dev_sgcomp_trawl(iyear));}
  }

  //composite trawl index
  q_comp_trawl(styr_comp_trawl_cpue)=mfexp(log_q_comp_trawl);
  for (iyear=styr_comp_trawl_cpue; iyear<=endyr_comp_trawl_cpue; iyear++)
  {   N_comp_trawl(iyear)=elem_prod(N_sept(iyear),sel_comp_trawl(iyear));
      pred_comp_trawl_cpue(iyear)=q_comp_trawl(iyear)*q_rate_fcn_comp_trawl(iyear)*q_DD_fcn(iyear)*sum(N_comp_trawl(iyear));
      if (iyear<endyr_comp_trawl_cpue){q_comp_trawl(iyear+1)=q_comp_trawl(iyear)*mfexp(q_RW_log_dev_comp_trawl(iyear));}
  }

 //seine index
  q_seine(styr_seine_cpue)=mfexp(log_q_seine);
  for (iyear=styr_seine_cpue; iyear<=endyr_seine_cpue; iyear++)
  {   N_seine(iyear)=N(iyear,1)*mfexp(-1.*(Z(iyear)(1)*0.25));//matching seine index with June 1 (1/4 of the year completed)
      pred_seine_cpue(iyear)=q_seine(iyear)*q_rate_fcn_seine(iyear)*q_DD_fcn(iyear)*N_seine(iyear);
      if (iyear<endyr_seine_cpue){q_seine(iyear+1)=q_seine(iyear)*mfexp(q_RW_log_dev_seine(iyear));}
  }

//yoy index
  q1_yoy(styr_yoy_cpue)=mfexp(log_q1_yoy);
  q2_yoy(styr_yoy_cpue)=mfexp(log_q2_yoy);
  for (iyear=styr_yoy_cpue; iyear<=endyr_yoy_cpue; iyear++)
  {
      N_yoy(iyear)=N(iyear,1)*mfexp(-1.*(Z(iyear)(1)*0.25));//matching yoy index with June 1 (1/4 of the year completed)
      pred_yoy_cpue(iyear)=q1_yoy(iyear)*q_rate_fcn_yoy(iyear)*q_DD_fcn(iyear)*N_yoy(iyear);
  if(iyear>1986)
  {
        pred_yoy_cpue(iyear)=q2_yoy(iyear)*q_rate_fcn_yoy(iyear)*q_DD_fcn(iyear)*N_yoy(iyear);
  }
      if (iyear<endyr_yoy_cpue){q1_yoy(iyear+1)=q1_yoy(iyear)*mfexp(q_RW_log_dev_yoy(iyear));
                            q2_yoy(iyear+1)=q2_yoy(iyear)*mfexp(q_RW_log_dev_yoy(iyear));}
  }


FUNCTION get_length_comps

 //sg composite trawl survey
  for (iyear=1;iyear<=nyr_sgcomp_trawl_lenc;iyear++)
  {
        pred_sgcomp_trawl_lenc(iyear)=(N_sgcomp_trawl(yrs_sgcomp_trawl_lenc(iyear))
                                 *lenprob_sgcomp_trawl(yrs_sgcomp_trawl_lenc(iyear)))
                                 /sum(N_sgcomp_trawl(yrs_sgcomp_trawl_lenc(iyear)));
  }

  //composite trawl survey
  for (iyear=1;iyear<=nyr_comp_trawl_lenc;iyear++)
  {
        pred_comp_trawl_lenc(iyear)=(N_comp_trawl(yrs_comp_trawl_lenc(iyear))
                                 *lenprob_comp_trawl(yrs_comp_trawl_lenc(iyear)))
                                 /sum(N_comp_trawl(yrs_comp_trawl_lenc(iyear)));
  }



FUNCTION get_age_comps

 //Commerical reduction
  for (iyear=1;iyear<=nyr_cR_agec;iyear++)
  {
    ErrorFree_cRn_agec(iyear)=L_cRn_num(yrs_cR_agec(iyear))/sum(L_cRn_num(yrs_cR_agec(iyear)));
    pred_cRn_agec(iyear)=age_error*ErrorFree_cRn_agec(iyear);
  }

  for (iyear=1;iyear<=nyr_cR_agec;iyear++)
  {
    ErrorFree_cRs_agec(iyear)=L_cRs_num(yrs_cR_agec(iyear))/sum(L_cRs_num(yrs_cR_agec(iyear)));
    pred_cRs_agec(iyear)=age_error*ErrorFree_cRs_agec(iyear);
  }
```

```
  for (iyear=1;iyear<=nyr_cB_agec;iyear++)
  {
    ErrorFree_cBn_agec(iyear)=L_cBn_num(yrs_cB_agec(iyear))/sum(L_cBn_num(yrs_cB_agec(iyear)));
    pred_cBn_agec(iyear)=age_error*ErrorFree_cBn_agec(iyear);
  }

   for (iyear=1;iyear<=nyr_cB_agec;iyear++)
  {
    ErrorFree_cBs_agec(iyear)=L_cBs_num(yrs_cB_agec(iyear))/sum(L_cBs_num(yrs_cB_agec(iyear)));
    pred_cBs_agec(iyear)=age_error*ErrorFree_cBs_agec(iyear);
  }


////--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------
FUNCTION get_weighted_current
  F_temp_sum=0.0;
  F_temp_sum+=mfexp((selpar_n_yrs_wgted*log_avg_F_cRn+
        sum(log_F_dev_cRn((endyr-selpar_n_yrs_wgted+1),endyr)))/selpar_n_yrs_wgted);
  F_temp_sum+=mfexp((selpar_n_yrs_wgted*log_avg_F_cRs+
        sum(log_F_dev_cRs((endyr-selpar_n_yrs_wgted+1),endyr)))/selpar_n_yrs_wgted);
  F_temp_sum+=mfexp((selpar_n_yrs_wgted*log_avg_F_cBn+
        sum(log_F_dev_cBn((endyr-selpar_n_yrs_wgted+1),endyr)))/selpar_n_yrs_wgted);
  F_temp_sum+=mfexp((selpar_n_yrs_wgted*log_avg_F_cBs+
        sum(log_F_dev_cBs((endyr-selpar_n_yrs_wgted+1),endyr)))/selpar_n_yrs_wgted);

  F_cRn_prop=mfexp((selpar_n_yrs_wgted*log_avg_F_cRn+
        sum(log_F_dev_cRn((endyr-selpar_n_yrs_wgted+1),endyr)))/selpar_n_yrs_wgted)/F_temp_sum;
  F_cRs_prop=mfexp((selpar_n_yrs_wgted*log_avg_F_cRs+
        sum(log_F_dev_cRs((endyr-selpar_n_yrs_wgted+1),endyr)))/selpar_n_yrs_wgted)/F_temp_sum;
  F_cBn_prop=mfexp((selpar_n_yrs_wgted*log_avg_F_cBn+
        sum(log_F_dev_cBn((endyr-selpar_n_yrs_wgted+1),endyr)))/selpar_n_yrs_wgted)/F_temp_sum;
  F_cBs_prop=mfexp((selpar_n_yrs_wgted*log_avg_F_cBs+
        sum(log_F_dev_cBs((endyr-selpar_n_yrs_wgted+1),endyr)))/selpar_n_yrs_wgted)/F_temp_sum;

  log_F_dev_end_cRn=sum(log_F_dev_cRn((endyr-selpar_n_yrs_wgted+1),endyr))/selpar_n_yrs_wgted;
  log_F_dev_end_cRs=sum(log_F_dev_cRs((endyr-selpar_n_yrs_wgted+1),endyr))/selpar_n_yrs_wgted;
  log_F_dev_end_cBn=sum(log_F_dev_cBn((endyr-selpar_n_yrs_wgted+1),endyr))/selpar_n_yrs_wgted;
  log_F_dev_end_cBs=sum(log_F_dev_cBs((endyr-selpar_n_yrs_wgted+1),endyr))/selpar_n_yrs_wgted;

  //F_end_L=sel_cR(endyr)*mfexp(log_avg_F_cR+log_F_dev_end_cR);

  F_end_L=sel_cRn(endyr)*mfexp(log_avg_F_cRn+log_F_dev_end_cRn)
         +sel_cRs(endyr)*mfexp(log_avg_F_cRs+log_F_dev_end_cRs)
         +sel_cBn(endyr)*mfexp(log_avg_F_cBn+log_F_dev_end_cBn)
         +sel_cBs(endyr)*mfexp(log_avg_F_cBs+log_F_dev_end_cBs);

  F_end=F_end_L;
  F_end_apex=max(F_end);

  sel_wgted_tot=F_end/F_end_apex;
  sel_wgted_L=elem_prod(sel_wgted_tot, elem_div(F_end_L,F_end));

  //wgt_wgted_L_denom=F_cR_prop;
  wgt_wgted_L_denom=F_cRn_prop+F_cRs_prop+F_cBn_prop+F_cBs_prop;
  //wgt_wgted_L_mt=F_cR_prop/wgt_wgted_L_denom*wholewgt_cR_mt(endyr)*1000; //to scale to 1000s mt
  wgt_wgted_L_mt=F_cRn_prop/wgt_wgted_L_denom*wholewgt_cR_mt(endyr)*1000
                +F_cRs_prop/wgt_wgted_L_denom*wholewgt_cR_mt(endyr)*1000
                +F_cBn_prop/wgt_wgted_L_denom*wholewgt_cB_mt(endyr)*1000
                +F_cBs_prop/wgt_wgted_L_denom*wholewgt_cB_mt(endyr)*1000; //to scale to 1000s mt

FUNCTION get_msy

  //compute values as functions of F
  for(ff=1; ff<=n_iter_msy; ff++)
  {
    //uses fishery-weighted F's
    Z_age_msy=0.0;
    F_L_age_msy=0.0;

    F_L_age_msy=F_msy(ff)*sel_wgted_L;
    Z_age_msy=M+F_L_age_msy;

    N_age_msy(1)=1.0;
    for (iage=2; iage<=nages; iage++)
    {
      N_age_msy(iage)=N_age_msy(iage-1)*mfexp(-1.*Z_age_msy(iage-1));
    }
    N_age_msy(nages)=N_age_msy(nages)/(1.0-mfexp(-1.*Z_age_msy(nages)));
    N_age_msy_mdyr(1,(nages-1))=elem_prod(N_age_msy(1,(nages-1)),
                                mfexp((-1.*Z_age_msy(1,(nages-1)))*spawn_time_frac));
    N_age_msy_mdyr(nages)=(N_age_msy_mdyr(nages-1)*
                           (mfexp(-1.*(Z_age_msy(nages-1)*(1.0-spawn_time_frac)+
                            Z_age_msy(nages)*spawn_time_frac)))
                            /(1.0-mfexp(-1.*Z_age_msy(nages)));

    spr_msy(ff)=sum(elem_prod(N_age_msy_mdyr,reprod));


    //Compute equilibrium values of R (including bias correction), SSB and Yield at each F
    R_eq(ff)=SR_eq_func(R0, steep, spr_msy(1), spr_msy(ff), BiasCor, SR_switch);


    if (R_eq(ff)<dzero) {R_eq(ff)=dzero;}
    N_age_msy*=R_eq(ff);
    N_age_msy_mdyr*=R_eq(ff);

    for (iage=1; iage<=nages; iage++)
    {
      L_age_msy(iage)=N_age_msy(iage)*(F_L_age_msy(iage)/Z_age_msy(iage))*
                       (1.-mfexp(-1.*Z_age_msy(iage)));
    }

    SSB_eq(ff)=sum(elem_prod(N_age_msy_mdyr,reprod));
```

```
    B_eq(ff)=sum(elem_prod(N_age_msy,wgt_spawn_mt))*1000000;//to scale to 1000s mt and catch in 1000s
    L_eq_mt(ff)=sum(elem_prod(L_age_msy,wgt_wgted_L_mt))*1000;//to scale to catch in 1000s, wgt_wgted_L_mt is already scaled to 1000s mt
    L_eq_knum(ff)=sum(L_age_msy)/1000.0;
  }

  msy_mt_out=max(L_eq_mt);

  for(ff=1; ff<=n_iter_msy; ff++)
  {
   if(L_eq_mt(ff) == msy_mt_out)
      {
        SSB_msy_out=SSB_eq(ff);
        B_msy_out=B_eq(ff);
        R_msy_out=R_eq(ff);
        msy_knum_out=L_eq_knum(ff);
        F_msy_out=F_msy(ff);
        spr_msy_out=spr_msy(ff);
      }
  }

//----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------
FUNCTION get_miscellaneous_stuff

//switch here if var_rec_dev <=dzero
  if(var_rec_dev>0.0)
   {sigma_rec_dev=sqrt(var_rec_dev);} //pow(var_rec_dev,0.5);  //sample SD of predicted residuals (may not equal rec_sigma)
   else{sigma_rec_dev=0.0;}

  for (iyear=styr; iyear<=endyr; iyear++)
  {
   len_cv_may=mean(elem_div(len_sd(iyear),meanlen_FL_may(iyear)));
   len_cv_sept=mean(elem_div(len_sd(iyear),meanlen_FL_sept(iyear)));
  }
  len_cv=(len_cv_may+len_cv_sept)/2;

  //compute total landings-at-age in 1000 fish and 1000s mt
  L_total_num.initialize();
  L_total_mt.initialize();
  L_total_knum_yr.initialize();
  L_total_mt_yr.initialize();

  for(iyear=styr; iyear<=endyr; iyear++)
  {
        //L_total_mt_yr(iyear)=pred_cR_L_mt(iyear);
        //L_total_knum_yr(iyear)=pred_cR_L_knum(iyear);
        L_total_mt_yr(iyear)=pred_cRn_L_mt(iyear)+pred_cRs_L_mt(iyear)
                            +pred_cBn_L_mt(iyear)+pred_cBs_L_mt(iyear);
        L_total_knum_yr(iyear)=pred_cRn_L_knum(iyear)+pred_cRs_L_knum(iyear)
                              +pred_cBn_L_knum(iyear)+pred_cBs_L_knum(iyear);

        B(iyear)=elem_prod(N(iyear),wgt_spawn_mt_tv(iyear))*1000000;//scale to 1000s mt and 1000s fish landed
        totN(iyear)=sum(N(iyear));  //in 1000s of fish
        totB(iyear)=sum(B(iyear));  //in 1000s of mt
        SSBatage(iyear)=elem_prod(N(iyear),reprod_tv(iyear));
  }

  //L_total_num=L_cR_num;   //landings at age in 1000s fish
  //L_total_mt=L_cR_mt;   //landings at age in 1000s mt whole weight
  L_total_num=L_cRn_num+L_cRs_num+L_cBn_num+L_cBs_num;   //landings at age in 1000s fish
  L_total_mt=L_cRn_mt+L_cRs_mt+L_cBn_mt+L_cBs_mt;   //landings at age in 1000s mt whole weight

  B(endyr+1)=elem_prod(N(endyr+1),wgt_spawn_mt)*1000000;//scale to 1000s mt and 1000s fish
  totN(endyr+1)=sum(N(endyr+1));//in 1000s of fish
  totB(endyr+1)=sum(B(endyr+1));//in 1000s of mt


  if(F_msy_out>0)
    {
      FdF_msy=Fapex/F_msy_out;
      FdF_msy_end=FdF_msy(endyr);
      FdF_msy_end_mean=pow((FdF_msy(endyr)*FdF_msy(endyr-1)*FdF_msy(endyr-2)),(1.0/3.0));
    }
  if(SSB_msy_out>0)
    {
      SdSSB_msy=SSB/SSB_msy_out;
      SdSSB_msy_end=SdSSB_msy(endyr);
    }

   //fill in log recruitment deviations for yrs they are nonzero
   for(iyear=styr_rec_dev; iyear<=endyr_rec_dev; iyear++)
     {log_rec_dev_output(iyear)=log_rec_dev(iyear);}

   //fill in log Nage deviations for ages they are nonzero (ages2+)
   for(iage=2; iage<=nages; iage++)
   {
    log_Nage_dev_output(iage)=log_Nage_dev(iage);
   }


//----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------
FUNCTION get_per_recruit_stuff

  //static per-recruit stuff

  for(iyear=styr; iyear<=endyr; iyear++)
  {
    N_age_spr(1)=1.0;
    for(iage=2; iage<=nages; iage++)
    {
      N_age_spr(iage)=N_age_spr(iage-1)*mfexp(-1.*Z(iyear,iage-1));
    }
    N_age_spr(nages)=N_age_spr(nages)/(1.0-mfexp(-1.*Z(iyear,nages)));
    N_age_spr_mdyr(1,(nages-1))=elem_prod(N_age_spr(1,(nages-1)),
                                mfexp(-1.*Z(iyear)(1,(nages-1))*spawn_time_frac));
```

```
    N_age_spr_mdyr(nages)=(N_age_spr_mdyr(nages-1)*
                          (mfexp(-1.*(Z(iyear)(nages-1)*(1.0-spawn_time_frac)
                          + Z(iyear)(nages)*spawn_time_frac) )))
                          /(1.0-mfexp(-1.*Z(iyear)(nages)));
    spr_static(iyear)=sum(elem_prod(N_age_spr_mdyr,reprod))/spr_F0;
  }


  //compute SSB/R and YPR as functions of F
  for(ff=1; ff<=n_iter_spr; ff++)
  {
    //uses fishery-weighted F's, same as in MSY calculations
    Z_age_spr=0.0;
    F_L_age_spr=0.0;

    F_L_age_spr=F_spr(ff)*sel_wgted_L;

    Z_age_spr=M+F_L_age_spr;

    N_age_spr(1)=1.0;
    for (iage=2; iage<=nages; iage++)
    {
      N_age_spr(iage)=N_age_spr(iage-1)*mfexp(-1.*Z_age_spr(iage-1));
    }
    N_age_spr(nages)=N_age_spr(nages)/(1-mfexp(-1.*Z_age_spr(nages)));
    N_age_spr_mdyr(1,(nages-1))=elem_prod(N_age_spr(1,(nages-1)),
                                   mfexp((-1.*Z_age_spr(1,(nages-1)))*spawn_time_frac));
    N_age_spr_mdyr(nages)=(N_age_spr_mdyr(nages-1)*
                          (mfexp(-1.*(Z_age_spr(nages-1)*(1.0-spawn_time_frac)
                          + Z_age_spr(nages)*spawn_time_frac) )))
                          /(1.0-mfexp(-1.*Z_age_spr(nages)));

    spr_spr(ff)=sum(elem_prod(N_age_spr_mdyr,reprod));
    L_spr(ff)=0.0;
    for (iage=1; iage<=nages; iage++)
    {
      L_age_spr(iage)=N_age_spr(iage)*(F_L_age_spr(iage)/Z_age_spr(iage))*
                      (1.-mfexp(-1.*Z_age_spr(iage)));
      L_spr(ff)+=L_age_spr(iage)*wgt_wgted_L_mt(iage)*1000; //already scaled to 1000s mt, but need to scale to 1000s fish
    }
  }

FUNCTION get_effective_sample_sizes

      neff_sgcomp_trawl_lenc_allyr_out=missing;//"missing" defined in admb2r.cpp
      neff_comp_trawl_lenc_allyr_out=missing;
      neff_cRn_agec_allyr_out=missing;
      neff_cRs_agec_allyr_out=missing;
      neff_cBn_agec_allyr_out=missing;
      neff_cBs_agec_allyr_out=missing;

     for (iyear=1; iyear<=nyr_sgcomp_trawl_lenc; iyear++)
         {if (nsamp_sgcomp_trawl_lenc(iyear)>=minSS_sgcomp_trawl_lenc)
            {neff_sgcomp_trawl_lenc_allyr_out(yrs_sgcomp_trawl_lenc(iyear))=multinom_eff_N(pred_sgcomp_trawl_lenc(iyear),obs_sgcomp_trawl_lenc(iyear));}
          else {neff_sgcomp_trawl_lenc_allyr_out(yrs_sgcomp_trawl_lenc(iyear))=-99;}
         }

     for (iyear=1; iyear<=nyr_comp_trawl_lenc; iyear++)
         {if (nsamp_comp_trawl_lenc(iyear)>=minSS_comp_trawl_lenc)
            {neff_comp_trawl_lenc_allyr_out(yrs_comp_trawl_lenc(iyear))=multinom_eff_N(pred_comp_trawl_lenc(iyear),obs_comp_trawl_lenc(iyear));}
          else {neff_comp_trawl_lenc_allyr_out(yrs_comp_trawl_lenc(iyear))=-99;}
         }

     for (iyear=1; iyear<=nyr_cR_agec; iyear++)
         {if (nsamp_cRn_agec(iyear)>=minSS_cRn_agec)
            {neff_cRn_agec_allyr_out(yrs_cR_agec(iyear))=multinom_eff_N(pred_cRn_agec(iyear),obs_cRn_agec(iyear));}
          else {neff_cRn_agec_allyr_out(yrs_cR_agec(iyear))=-99;}
         }

     for (iyear=1; iyear<=nyr_cR_agec; iyear++)
         {if (nsamp_cRs_agec(iyear)>=minSS_cRs_agec)
            {neff_cRs_agec_allyr_out(yrs_cR_agec(iyear))=multinom_eff_N(pred_cRs_agec(iyear),obs_cRs_agec(iyear));}
          else {neff_cRs_agec_allyr_out(yrs_cR_agec(iyear))=-99;}
         }

     for (iyear=1; iyear<=nyr_cB_agec; iyear++)
         {if (nsamp_cBn_agec(iyear)>=minSS_cBn_agec)
            {neff_cBn_agec_allyr_out(yrs_cB_agec(iyear))=multinom_eff_N(pred_cBn_agec(iyear),obs_cBn_agec(iyear));}
          else {neff_cBn_agec_allyr_out(yrs_cB_agec(iyear))=-99;}
         }

     for (iyear=1; iyear<=nyr_cB_agec; iyear++)
         {if (nsamp_cBs_agec(iyear)>=minSS_cBs_agec)
            {neff_cBs_agec_allyr_out(yrs_cB_agec(iyear))=multinom_eff_N(pred_cBs_agec(iyear),obs_cBs_agec(iyear));}
          else {neff_cBs_agec_allyr_out(yrs_cB_agec(iyear))=-99;}
         }


FUNCTION get_Fmed_benchmarks

  //sorting function for recruitment and SPR values (slow algorithm, but works)
  R_temp=rec(styr,endyr);
  SPR_temp=pred_SPR(styr,endyr);
  for(int jyear=endyr; jyear>=styr; jyear--)
  {
    R_sort(jyear)=max(R_temp);
    SPR_sort(jyear)=max(SPR_temp);
    for(iyear=styr; iyear<=endyr; iyear++)
    {
      if(R_temp(iyear)==R_sort(jyear))
      {
        R_temp(iyear)=0.0;
      }
      if(SPR_temp(iyear)==SPR_sort(jyear))
```

```
      {
        SPR_temp(iyear)=0.0;
      }
    }
  }

  // compute the quantile using quant_whole (declared in the data section)
  // which computes the floor integer of a decimal number
  //median
  quant_decimal=(endyr-styr)*0.5;
  quant_whole=(endyr-styr)*0.5;
  quant_diff=quant_decimal-quant_whole;
  R_med=R_sort(styr+quant_whole)*(1-quant_diff)+R_sort(styr+quant_whole+1)*(quant_diff);
  SPR_med=SPR_sort(styr+quant_whole)*(1-quant_diff)+SPR_sort(styr+quant_whole+1)*(quant_diff);
  //cout << "quant_decimal = " << quant_decimal << endl;
  //cout << "quant_whole = " << quant_whole << endl;
  //cout << "quant_diff = " << quant_diff << endl;
  //cout << "result = " << quant_whole*(1-quant_diff)+(quant_whole+1)*quant_diff << endl;
  //cout << "R_med = " << R_med << endl;
  //cout << "R_sort = " << R_sort << endl;
  //cout << "R = " << R_temp << endl;

  //75th quantile
  quant_decimal=(endyr-styr)*0.75;
  quant_whole=(endyr-styr)*0.75;
  quant_diff=quant_decimal-quant_whole;
  SPR_75th=SPR_sort(styr+quant_whole)*(1-quant_diff)+SPR_sort(styr+quant_whole+1)*(quant_diff);
  //cout << "quant_decimal = " << quant_decimal << endl;
  //cout << "quant_whole = " << quant_whole << endl;
  //cout << "quant_diff = " << quant_diff << endl;
  //cout << "result = " << quant_whole*(1-quant_diff)+(quant_whole+1)*quant_diff << endl;

  //find F that matches SPR_med = F_med
  SPR_diff=square(spr_spr-SPR_med);
  SPR_diff_min=min(SPR_diff);
  for(ff=1; ff<=n_iter_spr; ff++)
  {
    if(SPR_diff(ff)==SPR_diff_min)
    {
      F_med=F_spr(ff);
      //F_med_age2plus=F_spr_age2plus(ff);
      L_med=L_spr(ff)*R_med;
    }
  }
  SSB_med=SPR_med*R_med;
  SSB_med_thresh=SSB_med*0.5;

  //get the target that corresponds to Fmed, based on 75th quantile of SPR scatter
  SPR_diff=square(spr_spr-SPR_75th);
  SPR_diff_min=min(SPR_diff);
  for(ff=1; ff<=n_iter_spr; ff++)
  {
    if(SPR_diff(ff)==SPR_diff_min)
    {
      F_med_target=F_spr(ff);
      //F_med_target_age2plus=F_spr_age2plus(ff);
      L_med_target=L_spr(ff)*R_med;
    }
  }


//-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------


FUNCTION evaluate_objective_function
  fval=0.0;
  fval_data=0.0;
//---likelihoods---------------------------

//---Indices-------------------------------

  f_sgcomp_trawl_cpue=0.0;
  f_sgcomp_trawl_cpue=lk_lognormal(pred_sgcomp_trawl_cpue, obs_sgcomp_trawl_cpue, sgcomp_trawl_cpue_cv, w_I_sgcomp_trawl);
  fval+=f_sgcomp_trawl_cpue;
  fval_data+=f_sgcomp_trawl_cpue;

  f_comp_trawl_cpue=0.0;
  f_comp_trawl_cpue=lk_lognormal(pred_comp_trawl_cpue, obs_comp_trawl_cpue, comp_trawl_cpue_cv, w_I_comp_trawl);
  fval+=f_comp_trawl_cpue;
  fval_data+=f_comp_trawl_cpue;

  //f_seine_cpue=0.0;
  //f_seine_cpue=lk_lognormal(pred_seine_cpue, obs_seine_cpue, seine_cpue_cv, w_I_seine);
  //fval+=f_seine_cpue;
  //fval_data+=f_seine_cpue;

  f_yoy_cpue=0.0;
  f_yoy_cpue=lk_lognormal(pred_yoy_cpue, obs_yoy_cpue, yoy_cpue_cv, w_I_yoy);
  fval+=f_yoy_cpue;
  fval_data+=f_yoy_cpue;

 ////---Landings-------------------------------

  //f_cR_L in 1000s mt
  f_cRn_L=lk_lognormal(pred_cRn_L_mt, obs_cRn_L, cRn_L_cv, w_L);
  f_cRs_L=lk_lognormal(pred_cRs_L_mt, obs_cRs_L, cRs_L_cv, w_L);
  f_cBn_L=lk_lognormal(pred_cBn_L_mt, obs_cBn_L, cBn_L_cv, w_L);
  f_cBs_L=lk_lognormal(pred_cBs_L_mt, obs_cBs_L, cBs_L_cv, w_L);

  fval+=f_cRn_L;
  fval+=f_cRs_L;
  fval+=f_cBn_L;
  fval+=f_cBs_L;
```

```
  fval_data+=f_cRn_L;
  fval_data+=f_cRs_L;
  fval_data+=f_cBn_L;
  fval_data+=f_cBs_L;

//---Length comps-------------------------------

  f_sgcomp_trawl_lenc=lk_robust_multinomial(nsamp_sgcomp_trawl_lenc, pred_sgcomp_trawl_lenc, obs_sgcomp_trawl_lenc, nyr_sgcomp_trawl_lenc, double(nlenbins), minSS_sgcomp_trawl_lenc, w_lc_sgcomp_trawl);
  fval+=f_sgcomp_trawl_lenc;
  fval_data+=f_sgcomp_trawl_lenc;

  f_comp_trawl_lenc=lk_robust_multinomial(nsamp_comp_trawl_lenc, pred_comp_trawl_lenc, obs_comp_trawl_lenc, nyr_comp_trawl_lenc, double(nlenbins), minSS_comp_trawl_lenc, w_lc_comp_trawl);
  fval+=f_comp_trawl_lenc;
  fval_data+=f_comp_trawl_lenc;


//////---Age comps-------------------------------

  f_cRn_agec=lk_robust_multinomial(nsamp_cRn_agec, pred_cRn_agec, obs_cRn_agec, nyr_cR_agec, double(nages), minSS_cRn_agec, w_ac_cRn);

  f_cRs_agec=lk_robust_multinomial(nsamp_cRs_agec, pred_cRs_agec, obs_cRs_agec, nyr_cR_agec, double(nages), minSS_cRs_agec, w_ac_cRs);

  f_cBn_agec=lk_robust_multinomial(nsamp_cBn_agec, pred_cBn_agec, obs_cBn_agec, nyr_cB_agec, double(nages), minSS_cBn_agec, w_ac_cBn);

  f_cBs_agec=lk_robust_multinomial(nsamp_cBs_agec, pred_cBs_agec, obs_cBs_agec, nyr_cB_agec, double(nages), minSS_cBs_agec, w_ac_cBs);

  fval+=f_cRn_agec;
  fval+=f_cRs_agec;
  fval+=f_cBn_agec;
  fval+=f_cBs_agec;
  fval_data+=f_cRn_agec;
  fval_data+=f_cRs_agec;
  fval_data+=f_cBn_agec;
  fval_data+=f_cBs_agec;

////-----------Constraints and penalties--------------------------------
  //f_M_dev=0.0;
  //f_M_dev=norm2(M_dev);
  //fval+=w_M_dev*f_M_dev;

  f_rec_dev=0.0;
  //rec_sigma_sq=square(rec_sigma);
  rec_logL_add=nyrs_rec*log(rec_sigma);
  f_rec_dev=(square(log_rec_dev(styr_rec_dev) + rec_sigma_sq/2.0)/(2.0*rec_sigma_sq));
  for(iyear=(styr_rec_dev+1); iyear<=endyr_rec_dev; iyear++)
    {f_rec_dev+=(square(log_rec_dev(iyear)-R_autocorr*log_rec_dev(iyear-1) + rec_sigma_sq/2.0)/
               (2.0*rec_sigma_sq));}
  f_rec_dev+=rec_logL_add;
  fval+=w_rec*f_rec_dev;

  f_rec_dev_early=0.0; //possible extra constraint on early rec deviations
  if (w_rec_early>0.0)
    { if (styr_rec_dev<endyr_rec_phase1)
        {
          for(iyear=styr_rec_dev; iyear<=endyr_rec_phase1; iyear++)
          //{f_rec_dev_early+=(square(log_rec_dev(iyear)-R_autocorr*log_rec_dev(iyear-1) + rec_sigma_sq/2.0)/
          //                  (2.0*rec_sigma_sq)) + rec_logL_add;}
          {f_rec_dev_early+=square(log_rec_dev(iyear));}
        }
  fval+=w_rec_early*f_rec_dev_early;
  }

  f_rec_dev_end=0.0; //possible extra constraint on ending rec deviations
  if (w_rec_end>0.0)
  { if (endyr_rec_phase2<endyr_rec_dev)
        {
          for(iyear=(endyr_rec_phase2+1); iyear<=endyr; iyear++)
          //{f_rec_dev_end+=(square(log_rec_dev(iyear)-R_autocorr*log_rec_dev(iyear-1) + rec_sigma_sq/2.0)/
          //                 (2.0*rec_sigma_sq)) + rec_logL_add;}
          {f_rec_dev_end+=square(log_rec_dev(iyear));}
        }
      fval+=w_rec_end*f_rec_dev_end;
   }


  fval+=norm2(log_Nage_dev); //applies if initial age structure is estimated


  //Random walk components of fishery dependent indices

  //f_gill_RW_cpue=0.0;
  //for (iyear=styr_gill_cpue; iyear<endyr_gill_cpue; iyear++)
  //    {f_gill_RW_cpue+=square(q_RW_log_dev_gill(iyear))/(2.0*set_q_RW_gill_var);}
  //fval+=f_gill_RW_cpue;

  //f_seine_RW_cpue=0.0;
  //for (iyear=styr_seine_cpue; iyear<endyr_seine_cpue; iyear++)
  //    {f_seine_RW_cpue+=square(q_RW_log_dev_seine(iyear))/(2.0*set_q_RW_seine_var);}
  //fval+=f_seine_RW_cpue;


//---Priors---------------------------------------------------
//neg_log_prior arguments: estimate, prior mean, prior var/-CV, pdf type
//Variance input as a negative value is considered to be CV in arithmetic space (CV=-1 implies loose prior)
//pdf type 1=none, 2=lognormal, 3=normal, 4=beta
  f_priors=0.0;
  //f_priors+=neg_log_prior(Linf,set_Linf(5),set_Linf(6),set_Linf(7));
  //f_priors+=neg_log_prior(K,set_K(5),set_K(6),set_K(7));
  //f_priors+=neg_log_prior(t0,set_t0(5),set_t0(6),set_t0(7));
  //f_priors+=neg_log_prior(len_cv_val,set_len_cv(5),set_len_cv(6),set_len_cv(7));
  //f_priors+=neg_log_prior(M_constant,set_M_constant(5),set_M_constant(6),set_M_constant(7));

  //f_priors+=neg_log_prior(steep,set_steep(5),set_log_R0(6),set_log_R0(7));
  //f_priors+=neg_log_prior(log_R0,set_log_R0(5),set_log_R0(6),set_log_R0(7));
```

```
  //f_priors+=neg_log_prior(R_autocorr,set_R_autocorr(5),set_R_autocorr(6),set_R_autocorr(7));
  //f_priors+=neg_log_prior(rec_sigma,set_rec_sigma(5),set_rec_sigma(6),set_rec_sigma(7));

  //f_priors+=neg_log_prior(selpar_L50_cRn,set_selpar_L50_cRn(5),set_selpar_L50_cRn(6), set_selpar_L50_cRn(7));
  //f_priors+=neg_log_prior(selpar_slope_cRn,set_selpar_slope_cRn(5),set_selpar_slope_cRn(6), set_selpar_slope_cRn(7));
  //f_priors+=neg_log_prior(selpar_L502_cRn,set_selpar_L502_cRn(5),set_selpar_L502_cRn(6), set_selpar_L502_cRn(7));
 // f_priors+=neg_log_prior(selpar_slope2_cRn,set_selpar_slope2_cRn(5),set_selpar_slope2_cRn(6), set_selpar_slope2_cRn(7));
  f_priors+=neg_log_prior(selpar_L502_cRs,set_selpar_L502_cRs(5),set_selpar_L502_cRs(6), set_selpar_L502_cRs(7));
  //f_priors+=neg_log_prior(selpar_L502_cR2,set_selpar_L502_cR2(5),set_selpar_L502_cR2(6), set_selpar_L502_cR2(7));
  //f_priors+=neg_log_prior(selpar_slope2_cR2,set_selpar_slope2_cR2(5),set_selpar_slope2_cR2(6), set_selpar_slope2_cR2(7));
  //f_priors+=neg_log_prior(sel_age1_cR_logit,set_sel_age1_cR(5),set_sel_age1_cR(6), set_sel_age1_cR(7));
  //f_priors+=neg_log_prior(sel_age3_cR_logit,set_sel_age3_cR(5),set_sel_age3_cR(6), set_sel_age3_cR(7));
  //f_priors+=neg_log_prior(sel_age4_cR_logit,set_sel_age4_cR(5),set_sel_age4_cR(6), set_sel_age4_cR(7));
  //f_priors+=neg_log_prior(selpar_L50_cB,set_selpar_L50_cB(5),set_selpar_L50_cB(6), set_selpar_L50_cB(7));
  //f_priors+=neg_log_prior(selpar_slope_cBn,set_selpar_slope_cBn(5),set_selpar_slope_cBn(6), set_selpar_slope_cBn(7));
  //f_priors+=neg_log_prior(selpar_L502_cB,set_selpar_L502_cB(5),set_selpar_L502_cB(6), set_selpar_L502_cB(7));
  //f_priors+=neg_log_prior(selpar_slope2_cBn,set_selpar_slope2_cBn(5),set_selpar_slope2_cBn(6), set_selpar_slope2_cBn(7));

  //f_priors+=neg_log_prior(selpar_slope_cBn3,set_selpar_slope_cBn3(5),set_selpar_slope_cBn3(6), set_selpar_slope_cBn3(7));
  //f_priors+=neg_log_prior(selpar_slope2_cBn3,set_selpar_slope2_cBn3(5),set_selpar_slope2_cBn3(6), set_selpar_slope2_cBn3(7));

  //f_priors+=neg_log_prior(selpar_slope_comp_trawl,set_selpar_slope_comp_trawl(5),set_selpar_slope_comp_trawl(6), set_selpar_slope_comp_trawl(7));
  //f_priors+=neg_log_prior(selpar_slope2_comp_trawl,set_selpar_slope2_comp_trawl(5),set_selpar_slope2_comp_trawl(6), set_selpar_slope2_comp_trawl(7));

  //f_priors+=neg_log_prior(selpar_slope_sgcomp_trawl,set_selpar_slope_sgcomp_trawl(5),set_selpar_slope_sgcomp_trawl(6), set_selpar_slope_sgcomp_trawl(7));
  //f_priors+=neg_log_prior(selpar_L50_sgcomp_trawl,set_selpar_L50_sgcomp_trawl(5),set_selpar_L50_sgcomp_trawl(6), set_selpar_L50_sgcomp_trawl(7));
  f_priors+=neg_log_prior(selpar_slope2_sgcomp_trawl,set_selpar_slope2_sgcomp_trawl(5),set_selpar_slope2_sgcomp_trawl(6), set_selpar_slope2_sgcomp_trawl(7));
  f_priors+=neg_log_prior(selpar_L502_sgcomp_trawl,set_selpar_L502_sgcomp_trawl(5),set_selpar_L502_sgcomp_trawl(6), set_selpar_L502_sgcomp_trawl(7));



  //f_priors+=neg_log_prior(log_q_gill,set_log_q_gill(5),set_log_q_gill(6),set_log_q_gill(7));
  //f_priors+=neg_log_prior(log_q_seine,set_log_q_seine(5),set_log_q_seine(6),set_log_q_seine(7));

  //f_priors+=neg_log_prior(log_avg_F_cR,set_log_avg_F_cR(5),set_log_avg_F_cR(6),set_log_avg_F_cR(7));


  fval+=f_priors;

  //cout << "fval = " << fval << "  fval_data = " << fval_data << endl;


//----------------------------------------------------------------------------------
//Logistic function: 2 parameters
FUNCTION dvar_vector logistic(const dvar_vector& ages, const dvariable& L50, const dvariable& slope)
  //ages=vector of ages, L50=age at 50% selectivity, slope=rate of increase
  RETURN_ARRAYS_INCREMENT();
  dvar_vector Sel_Tmp(ages.indexmin(),ages.indexmax());
  Sel_Tmp=1./(1.+mfexp(-1.*slope*(ages-L50))); //logistic;
  RETURN_ARRAYS_DECREMENT();
  return Sel_Tmp;

//-----------------------------------------------------------------------------------
//Logistic function: 4 parameters
FUNCTION dvar_vector logistic_double(const dvar_vector& ages, const dvariable& L501, const dvariable& slope1, const dvariable& L502, const dvariable& slope2)
  //ages=vector of ages, L50=age at 50% selectivity, slope=rate of increase, L502=age at 50% decrease additive to L501, slope2=slope of decrease
  RETURN_ARRAYS_INCREMENT();
  dvar_vector Sel_Tmp(ages.indexmin(),ages.indexmax());
  Sel_Tmp=elem_prod( (1./(1.+mfexp(-1.*slope1*(ages-L501)))),(1.-(1./(1.+mfexp(-1.*slope2*(ages-(L501+L502)))))) );
  Sel_Tmp=Sel_Tmp/max(Sel_Tmp);
  RETURN_ARRAYS_DECREMENT();
  return Sel_Tmp;

//-----------------------------------------------------------------------------------
//Jointed logistic function: 6 parameters (increasing and decreasing logistics joined at peak selectivity)
FUNCTION dvar_vector logistic_joint(const dvar_vector& ages, const dvariable& L501, const dvariable& slope1, const dvariable& L502, const dvariable& slope2, const dvariable& satval, const dvariable& joint)
  //ages=vector of ages, L501=age at 50% sel (ascending limb), slope1=rate of increase,L502=age at 50% sel (descending), slope1=rate of increase (ascending),
  //satval=saturation value of descending limb, joint=location in age vector to join curves (may equal age or age + 1 if age-0 is included)
  RETURN_ARRAYS_INCREMENT();
  dvar_vector Sel_Tmp(ages.indexmin(),ages.indexmax());
  Sel_Tmp=1.0;
  for (iage=1; iage<=nages; iage++)
  {
   if (double(iage)<joint) {Sel_Tmp(iage)=1./(1.+mfexp(-1.*slope1*(ages(iage)-L501)));}
   if (double(iage)>joint){Sel_Tmp(iage)=1.0-(1.0-satval)/(1.+mfexp(-1.*slope2*(ages(iage)-L502)));}
  }
  Sel_Tmp=Sel_Tmp/max(Sel_Tmp);
  RETURN_ARRAYS_DECREMENT();
  return Sel_Tmp;

//-----------------------------------------------------------------------------------
//Double Gaussian function: 6 parameters (as in SS3)
FUNCTION dvar_vector gaussian_double(const dvar_vector& ages, const dvariable& peak, const dvariable& top, const dvariable& ascwid, const dvariable& deswid, const dvariable& init, const dvariable& final)
  //ages=vector of ages, peak=ascending inflection location (as logistic), top=width of plateau, ascwid=ascent width (as log(width))
  //deswid=descent width (as log(width))
  RETURN_ARRAYS_INCREMENT();
  dvar_vector Sel_Tmp(ages.indexmin(),ages.indexmax());
  dvar_vector sel_step1(ages.indexmin(),ages.indexmax());
  dvar_vector sel_step2(ages.indexmin(),ages.indexmax());
  dvar_vector sel_step3(ages.indexmin(),ages.indexmax());
  dvar_vector sel_step4(ages.indexmin(),ages.indexmax());
  dvar_vector sel_step5(ages.indexmin(),ages.indexmax());
  dvar_vector sel_step6(ages.indexmin(),ages.indexmax());
  dvar_vector pars_tmp(1,6); dvar_vector sel_tmp_iq(1,2);

  pars_tmp(1)=peak;
  pars_tmp(2)=peak+1.0+(0.99*ages(nages)-peak-1.0)/(1.0+mfexp(-top));
  pars_tmp(3)=mfexp(ascwid);
  pars_tmp(4)=mfexp(deswid);
  pars_tmp(5)=1.0/(1.0+mfexp(-init));
  pars_tmp(6)=1.0/(1.0+mfexp(-final));

  sel_tmp_iq(1)=mfexp(-(square(ages(1)-pars_tmp(1))/pars_tmp(3)));
  sel_tmp_iq(2)=mfexp(-(square(ages(nages)-pars_tmp(2))/pars_tmp(4)));
```

```
  sel_step1=mfexp(-(square(ages-pars_tmp(1))/pars_tmp(3)));
  sel_step2=pars_tmp(5)+(1.0-pars_tmp(5))*(sel_step1-sel_tmp_iq(1))/(1.0-sel_tmp_iq(1));
  sel_step3=mfexp(-(square(ages-pars_tmp(2))/pars_tmp(4)));
  sel_step4=1.0+(pars_tmp(6)-1.0)*(sel_step3-1.0)/(sel_tmp_iq(2)-1.0);
  sel_step5=1.0/ (1.0+mfexp(-(20.0* elem_div((ages-pars_tmp(1)), (1.0+sfabs(ages-pars_tmp(1)))) )));
  sel_step6=1.0/(1.0+mfexp(-(20.0*elem_div((ages-pars_tmp(2)),(1.0+sfabs(ages-pars_tmp(2)))) )));

  Sel_Tmp=elem_prod(sel_step2,(1.0-sel_step5))+
          elem_prod(sel_step5,((1.0-sel_step6)+ elem_prod(sel_step4,sel_step6)) );

  Sel_Tmp=Sel_Tmp/max(Sel_Tmp);
  RETURN_ARRAYS_DECREMENT();
  return Sel_Tmp;

//-----------------------------------------------------------------------------------
 //Logistic-exponential: 3 parameters
FUNCTION dvar_vector logistic_exponential_mod(const dvar_vector& ages, const dvariable& L50, const dvariable& slope, const dvariable& sigma)
   //ages=vector of ages, L50=age at 50% sel (ascending limb), slope=rate of increase, sigma=controls rate of ascent/descent of right half of curve
   RETURN_ARRAYS_INCREMENT();
   dvar_vector Sel_Tmp(ages.indexmin(),ages.indexmax());
   Sel_Tmp=1.0;
   for (iage=1; iage<=nages; iage++)
   {
    Sel_Tmp(iage)=mfexp(slope*sigma*(L50-ages(iage)))/((1-sigma)+mfexp(slope*(L50-ages(iage))));
   }
   Sel_Tmp=Sel_Tmp/max(Sel_Tmp);
   RETURN_ARRAYS_DECREMENT();
   return Sel_Tmp;

//-----------------------------------------------------------------------------------
//Spawner-recruit function (Beverton-Holt or Ricker)
FUNCTION dvariable SR_func(const dvariable& R0, const dvariable& h, const dvariable& spr_F0, const dvariable& SSB, int func)
  //R0=virgin recruitment, h=steepness, spr_F0=spawners per recruit @ F=0, SSB=spawning biomass
  //func=1 for Beverton-Holt, 2 for Ricker
  RETURN_ARRAYS_INCREMENT();
  dvariable Recruits_Tmp;
  switch(func) {
    case 1: //Beverton-Holt
      Recruits_Tmp=((0.8*R0*h*SSB)/(0.2*R0*spr_F0*(1.0-h)+(h-0.2)*SSB));
    break;
    case 2: //Ricker
      Recruits_Tmp=((SSB/spr_F0)*mfexp(h*(1-SSB/(R0*spr_F0))));
    break;
  }
  RETURN_ARRAYS_DECREMENT();
  return Recruits_Tmp;

//-----------------------------------------------------------------------------------
//Spawner-recruit equilibrium function (Beverton-Holt or Ricker)
FUNCTION dvariable SR_eq_func(const dvariable& R0, const dvariable& h, const dvariable& spr_F0, const dvariable& spr_F, const dvariable& BC, int func)
  //R0=virgin recruitment, h=steepness, spr_F0=spawners per recruit @ F=0, spr_F=spawners per recruit @ F, BC=bias correction
  //func=1 for Beverton-Holt, 2 for Ricker
  RETURN_ARRAYS_INCREMENT();
  dvariable Recruits_Tmp;
  switch(func) {
    case 1: //Beverton-Holt
      Recruits_Tmp=(R0/((5.0*h-1.0)*spr_F))*(BC*4.0*h*spr_F-spr_F0*(1.0-h));
    break;
    case 2: //Ricker
      Recruits_Tmp=R0/(spr_F/spr_F0)*(1.0+log(BC*spr_F/spr_F0)/h);
    break;
  }
  RETURN_ARRAYS_DECREMENT();
  return Recruits_Tmp;


//-----------------------------------------------------------------------------------
//compute multinomial effective sample size for a single yr
FUNCTION dvariable multinom_eff_N(const dvar_vector& pred_comp, const dvar_vector& obs_comp)
  //pred_comp=vector of predicted comps, obscomp=vector of observed comps
  dvariable EffN_Tmp; dvariable numer; dvariable denom;
  RETURN_ARRAYS_INCREMENT();
  numer=sum( elem_prod(pred_comp,(1.0-pred_comp)) );
  denom=sum( square(obs_comp-pred_comp) );
  if (denom>0.0) {EffN_Tmp=numer/denom;}
  else {EffN_Tmp=-missing;}
  RETURN_ARRAYS_DECREMENT();
  return EffN_Tmp;

//-----------------------------------------------------------------------------------
//Likelihood contribution: lognormal
FUNCTION dvariable lk_lognormal(const dvar_vector& pred, const dvar_vector& obs, const dvar_vector& cv, const dvariable& wgt_dat)
  //pred=vector of predicted vals, obs=vector of observed vals, cv=vector of CVs in arithmetic space, wgt_dat=constant scaling of CVs
  //small_number is small value to avoid log(0) during search
  RETURN_ARRAYS_INCREMENT();
  dvariable LkvalTmp;
  dvariable small_number=0.00001;
  dvar_vector var(cv.indexmin(),cv.indexmax()); //variance in log space
  var=log(1.0+square(cv/wgt_dat));   // convert cv in arithmetic space to variance in log space
  LkvalTmp=sum(0.5*elem_div(square(log(elem_div((pred+small_number),(obs+small_number)))),var) );
  RETURN_ARRAYS_DECREMENT();
  return LkvalTmp;

//-----------------------------------------------------------------------------------
//Likelihood contribution: multinomial
FUNCTION dvariable lk_multinomial(const dvar_vector& nsamp, const dvar_matrix& pred_comp, const dvar_matrix& obs_comp, const double& ncomp, const double& minSS, const dvariable& wgt_dat)
  //nsamp=vector of N's, pred_comp=matrix of predicted comps, obs_comp=matrix of observed comps, ncomp = number of yrs in matrix, minSS=min N threshold, wgt_dat=scaling of N's
  RETURN_ARRAYS_INCREMENT();
  dvariable LkvalTmp;
  dvariable small_number=0.00001;
  LkvalTmp=0.0;
  for (int ii=1; ii<=ncomp; ii++)
  {if (nsamp(ii)>=minSS)
```

```
    {LkvalTmp-=wgt_dat*nsamp(ii)*sum(elem_prod((obs_comp(ii)+small_number),
               log(elem_div((pred_comp(ii)+small_number), (obs_comp(ii)+small_number)))));
    }
  }
  RETURN_ARRAYS_DECREMENT();
  return LkvalTmp;


//-----------------------------------------------------------------------------------
//Likelihood contribution: multinomial
FUNCTION dvariable lk_robust_multinomial(const dvar_vector& nsamp, const dvar_matrix& pred_comp, const dvar_matrix& obs_comp, const double& ncomp, const dvariable& mbin, const double& minSS, const dvariable& wgt
  //nsamp=vector of N's, pred_comp=matrix of predicted comps, obs_comp=matrix of observed comps, ncomp = number of yrs in matrix, mbin=number of bins, minSS=min N threshold, wgt_dat=scaling of N's
  RETURN_ARRAYS_INCREMENT();
  dvariable LkvalTmp;
  dvariable small_number=0.00001;
  LkvalTmp=0.0;
  dvar_matrix Eprime=elem_prod((1.0-obs_comp), obs_comp)+0.1/mbin; //E' of Francis 2011, p.1131
  dvar_vector nsamp_wgt=nsamp*wgt_dat;
  //cout<<nsamp_wgt<<endl;
  for (int ii=1; ii<=ncomp; ii++)
  {if (nsamp(ii)>=minSS)
    {LkvalTmp+= sum(0.5*log(Eprime(ii))-log(small_number+mfexp(elem_div((-square(obs_comp(ii)-pred_comp(ii))) , (Eprime(ii)*2.0/nsamp_wgt(ii)) ))) );
    }
  }
  RETURN_ARRAYS_DECREMENT();
  return LkvalTmp;


//-----------------------------------------------------------------------------------
//-----------------------------------------------------------------------------------
//Likelihood contribution: priors
FUNCTION  dvariable neg_log_prior(dvariable pred, const double& prior, dvariable var, int pdf)
  //prior=prior point estimate, var=variance (if negative, treated as CV in arithmetic space), pred=predicted value, pdf=prior type (1=none, 2=lognormal, 3=normal, 4=beta)
    dvariable LkvalTmp;
    dvariable alpha, beta, ab_iq;
    dvariable big_number=1e10;
    LkvalTmp=0.0;
    // compute generic pdf's
    switch(pdf) {
        case 1: //option to turn off prior
          LkvalTmp=0.0;
          break;
        case 2: // lognormal
          if(prior<=0.0) cout << "YIKES: Don't use a lognormal distn for a negative prior" << endl;
          else if(pred<=0) LkvalTmp=big_number=1e10;
          else {
            if(var<0.0) var=log(1.0+var*var) ;      // convert cv to variance on log scale
            LkvalTmp= 0.5*( square(log(pred/prior))/var + log(var) );
          }
        break;
        case 3: // normal
          if(var<0.0 && prior!=0.0) var=square(var*prior);       // convert cv to variance on observation scale
          else if(var<0.0 && prior==0.0) var=-var;              // cv not really appropriate if prior value equals zero
          LkvalTmp= 0.5*( square(pred-prior)/var + log(var) );
          break;
        case 4: // beta
          if(var<0.0) var=square(var*prior);          // convert cv to variance on observation scale
          if(prior<=0.0 || prior>=1.0) cout << "YIKES: Don't use a beta distn for a prior outside (0,1)" << endl;
          ab_iq=prior*(1.0-prior)/var - 1.0; alpha=prior*ab_iq; beta=(1.0-prior)*ab_iq;
          if(pred>=0 && pred<=1) LkvalTmp= (1.0-alpha)*log(pred)+(1.0-beta)*log(1.0-pred)-gammln(alpha+beta)+gammln(alpha)+gammln(beta);
          else LkvalTmp=big_number;
          break;
        default: // no such prior pdf currently available
          cout << "The prior must be either 1(lognormal), 2(normal), or 3(beta)." << endl;
          cout << "Presently it is " << pdf << endl;
          exit(0);
    }
    return LkvalTmp;

//-----------------------------------------------------------------------------------
//SDNR: age comp likelihood (assumes fits are done with the robust multinomial function)
FUNCTION dvariable sdnr_multinomial(const double& ncomp, const dvar_vector& ages, const dvar_vector& nsamp,
                                    const dvar_matrix& pred_comp, const dvar_matrix& obs_comp, const dvariable& wgt_dat)
  //ncomp=number of years of data, ages=vector of ages, nsamp=vector of N's,
  //pred_comp=matrix of predicted comps, obs_comp=matrix of observed comps, wgt_dat=likelihood weight for data source
  RETURN_ARRAYS_INCREMENT();
  dvariable SdnrTmp;
  dvar_vector o(1,ncomp);
  dvar_vector p(1,ncomp);
  dvar_vector ose(1,ncomp);
  dvar_vector res(1,ncomp);
  SdnrTmp=0.0;
  for (int ii=1; ii<=ncomp; ii++)
  {
    o(ii)=sum(elem_prod(ages,obs_comp(ii)));
    p(ii)=sum(elem_prod(ages,pred_comp(ii)));
    if(square(p(ii))<sum(elem_prod(square(ages),pred_comp(ii))))
{
       ose(ii)=sqrt((sum(elem_prod(square(ages),pred_comp(ii)))-square(p(ii)))/(nsamp(ii)*wgt_dat));
      }else
      {
       ose(ii)=0.001;
      }
   //cout << "ii=" << ii << "  o=" << o(ii) << "  p=" << p(ii) << " sq(p)=" << square(p(ii)) << "  p2=" << sum(elem_prod(square(ages),pred_comp(ii))) <<"  ose=" << ose(ii) << endl;
  }
  res=elem_div((o-p),ose);
  SdnrTmp=sqrt(sum(square(res-(sum(res)/ncomp))/(ncomp-1.0)));
  RETURN_ARRAYS_DECREMENT();
  return SdnrTmp;

//-----------------------------------------------------------------------------------
//SDNR: lognormal likelihood
FUNCTION dvariable sdnr_lognormal(const dvar_vector& pred, const dvar_vector& obs, const dvar_vector& cv, const dvariable& wgt_dat)
  //nyr=number of years of data, pred=vector of predicted data, obs=vector of observed data, cv=vector of cv's, wgt_dat=likelihood weight for data source
```

```
  RETURN_ARRAYS_INCREMENT();
  dvariable SdnrTmp;
  dvariable small_number=0.00001;
  dvariable n;
  dvar_vector res(cv.indexmin(),cv.indexmax());
  SdnrTmp=0.0;
  res=elem_div(log(elem_div(obs+small_number,pred+small_number)),sqrt(log(1+square(cv/wgt_dat))));
  n=cv.indexmax()-cv.indexmin()+1;
  SdnrTmp=sqrt(sum(square(res-(sum(res)/n))/(n-1.0)));
  RETURN_ARRAYS_DECREMENT();
  return SdnrTmp;

//-----------------------------------------------------------------------------------
REPORT_SECTION

  if (last_phase())
  {
      cout<<"start report"<<endl;
      get_weighted_current();
      cout<<"got weighted"<<endl;
      get_msy();
      cout<<"got msy"<<endl;
      get_miscellaneous_stuff();
      cout<<"got misc stuff"<<endl;
      get_per_recruit_stuff();
      cout<<"got per recruit"<<endl;
      get_effective_sample_sizes();
      //get_Fmed_benchmarks();
      //cout << "got Fmed benchmarks" << endl;

      time(&finish);
  elapsed_time=difftime(finish,start);
  hour=long(elapsed_time)/3600;
  minute=long(elapsed_time)%3600/60;
  second=(long(elapsed_time)%3600)%60;
  cout<<endl<<endl<<"*******************************************"<<endl;
  cout<<"--Start time: "<<ctime(&start)<<endl;
  cout<<"--Finish time: "<<ctime(&finish)<<endl;
  cout<<"--Runtime: ";
  cout<<hour<<" hours, "<<minute<<" minutes, "<<second<<" seconds"<<endl;
  cout<<"*******************************************"<<endl;

      cout <<endl;
      cout << "><>--><>--><>--><>--><>--><>--><>--><>--><>--><>"  <<endl;
      cout << "BC Fmsy=" << F_msy_out<< "   BC SSBmsy=" << SSB_msy_out <<endl;
      cout <<"F status="<<FdF_msy_end<<endl;
      cout <<"Pop status="<<SdSSB_msy_end<<endl;
      cout << "h="<<steep<<"   R0="<<R0<<endl;
      cout << "><>--><>--><>--><>--><>--><>--><>--><>--><>--><>"  <<endl;


      report << "TotalLikelihood " << fval << endl;
      report << "N" << endl;
      report << N<<endl;
      report << "F" << endl;
      report << F <<endl;

      sdnr_lc_sgcomp_trawl=sdnr_multinomial(nyr_sgcomp_trawl_lenc, lbins, nsamp_sgcomp_trawl_lenc, pred_sgcomp_trawl_lenc, obs_sgcomp_trawl_lenc, w_lc_sgcomp_trawl);
      sdnr_lc_comp_trawl=sdnr_multinomial(nyr_comp_trawl_lenc, lbins, nsamp_comp_trawl_lenc, pred_comp_trawl_lenc, obs_comp_trawl_lenc, w_lc_comp_trawl);

      sdnr_ac_cRn=sdnr_multinomial(nyr_cR_agec, agebins, nsamp_cRn_agec, pred_cRn_agec, obs_cRn_agec, w_ac_cRn);
      sdnr_ac_cRs=sdnr_multinomial(nyr_cR_agec, agebins, nsamp_cRs_agec, pred_cRs_agec, obs_cRs_agec, w_ac_cRs);
      sdnr_ac_cBn=sdnr_multinomial(nyr_cB_agec, agebins, nsamp_cBn_agec, pred_cBn_agec, obs_cBn_agec, w_ac_cBn);
      sdnr_ac_cBs=sdnr_multinomial(nyr_cB_agec, agebins, nsamp_cBs_agec, pred_cBs_agec, obs_cBs_agec, w_ac_cBs);

      sdnr_I_sgcomp_trawl=sdnr_lognormal(pred_sgcomp_trawl_cpue, obs_sgcomp_trawl_cpue, sgcomp_trawl_cpue_cv, w_I_sgcomp_trawl);
      sdnr_I_comp_trawl=sdnr_lognormal(pred_comp_trawl_cpue, obs_comp_trawl_cpue, comp_trawl_cpue_cv, w_I_comp_trawl);
      //sdnr_I_seine=sdnr_lognormal(pred_seine_cpue, obs_seine_cpue, seine_cpue_cv, w_I_seine);
      sdnr_I_yoy=sdnr_lognormal(pred_yoy_cpue, obs_yoy_cpue, yoy_cpue_cv, w_I_yoy);

      cout << "sdnr.cRn" << sdnr_ac_cRn << endl;
      cout << "sdnr.cBn" << sdnr_ac_cBn << endl;
      //#################################################################################################
      //##  Passing parameters to vector for bounds check plotting
      //#################################################################################################
       Linf_out(8)=Linf; Linf_out(1,7)=set_Linf;
       K_out(8)=K; K_out(1,7)=set_K;
       t0_out(8)=t0; t0_out(1,7)=set_t0;
       len_cv_val_out(8)=len_cv_val; len_cv_val_out(1,7)=set_len_cv;
       log_R0_out(8)=log_R0; log_R0_out(1,7)=set_log_R0;
       steep_out(8)=steep; steep_out(1,7)=set_steep;
       rec_sigma_out(8)=rec_sigma; rec_sigma_out(1,7)=set_rec_sigma;
       R_autocorr_out(8)=R_autocorr; R_autocorr_out(1,7)=set_R_autocorr;

       selpar_L50_cRn_out(8)=selpar_L50_cRn; selpar_L50_cRn_out(1,7)=set_selpar_L50_cRn;
       selpar_slope_cRn_out(8)=selpar_slope_cRn; selpar_slope_cRn_out(1,7)=set_selpar_slope_cRn;
       selpar_L502_cRn_out(8)=selpar_L502_cRn; selpar_L502_cRn_out(1,7)=set_selpar_L502_cRn;
       selpar_slope2_cRn_out(8)=selpar_slope2_cRn; selpar_slope2_cRn_out(1,7)=set_selpar_slope2_cRn;

       selpar_L50_cRs_out(8)=selpar_L50_cRs; selpar_L50_cRs_out(1,7)=set_selpar_L50_cRs;
       selpar_slope_cRs_out(8)=selpar_slope_cRs; selpar_slope_cRs_out(1,7)=set_selpar_slope_cRs;
       selpar_L502_cRs_out(8)=selpar_L502_cRs; selpar_L502_cRs_out(1,7)=set_selpar_L502_cRs;
       selpar_slope2_cRs_out(8)=selpar_slope2_cRs; selpar_slope2_cRs_out(1,7)=set_selpar_slope2_cRs;

       selpar_L50_cRn2_out(8)=selpar_L50_cRn2; selpar_L50_cRn2_out(1,7)=set_selpar_L50_cRn2;
       selpar_slope_cRn2_out(8)=selpar_slope_cRn2; selpar_slope_cRn2_out(1,7)=set_selpar_slope_cRn2;
       selpar_L502_cRn2_out(8)=selpar_L502_cRn2; selpar_L502_cRn2_out(1,7)=set_selpar_L502_cRn2;
       selpar_slope2_cRn2_out(8)=selpar_slope2_cRn2; selpar_slope2_cRn2_out(1,7)=set_selpar_slope2_cRn2;

       selpar_L50_cRs2_out(8)=selpar_L50_cRs2; selpar_L50_cRs2_out(1,7)=set_selpar_L50_cRs2;
       selpar_slope_cRs2_out(8)=selpar_slope_cRs2; selpar_slope_cRs2_out(1,7)=set_selpar_slope_cRs2;
       selpar_L502_cRs2_out(8)=selpar_L502_cRs2; selpar_L502_cRs2_out(1,7)=set_selpar_L502_cRs2;
       selpar_slope2_cRs2_out(8)=selpar_slope2_cRs2; selpar_slope2_cRs2_out(1,7)=set_selpar_slope2_cRs2;
```

```
     selpar_L50_cRn3_out(8)=selpar_L50_cRn3; selpar_L50_cRn3_out(1,7)=set_selpar_L50_cRn3;
     selpar_slope_cRn3_out(8)=selpar_slope_cRn3; selpar_slope_cRn3_out(1,7)=set_selpar_slope_cRn3;
     selpar_L502_cRn3_out(8)=selpar_L502_cRn3; selpar_L502_cRn3_out(1,7)=set_selpar_L502_cRn3;
     selpar_slope2_cRn3_out(8)=selpar_slope2_cRn3; selpar_slope2_cRn3_out(1,7)=set_selpar_slope2_cRn3;

     selpar_L50_cRs3_out(8)=selpar_L50_cRs3; selpar_L50_cRs3_out(1,7)=set_selpar_L50_cRs3;
     selpar_slope_cRs3_out(8)=selpar_slope_cRs3; selpar_slope_cRs3_out(1,7)=set_selpar_slope_cRs3;
     selpar_L502_cRs3_out(8)=selpar_L502_cRs3; selpar_L502_cRs3_out(1,7)=set_selpar_L502_cRs3;
     selpar_slope2_cRs3_out(8)=selpar_slope2_cRs3; selpar_slope2_cRs3_out(1,7)=set_selpar_slope2_cRs3;

     selpar_L50_logexp_cR_out(8)=selpar_L50_logexp_cR; selpar_L50_logexp_cR_out(1,7)=set_selpar_L50_logexp_cR;
     selpar_slope_logexp_cR_out(8)=selpar_slope_logexp_cR; selpar_slope_logexp_cR_out(1,7)=set_selpar_slope_logexp_cR;
     selpar_sigma_logexp_cR_out(8)=selpar_sigma_logexp_cR; selpar_sigma_logexp_cR_out(1,7)=set_selpar_sigma_logexp_cR;

     selpar_age0_cRn_out(8)=sel_age0_cRn_logit; selpar_age0_cRn_out(1,7)=set_sel_age0_cRn;
     selpar_age1_cRn_out(8)=sel_age1_cRn_logit; selpar_age1_cRn_out(1,7)=set_sel_age1_cRn;
     selpar_age2_cRn_out(8)=sel_age2_cRn_logit; selpar_age2_cRn_out(1,7)=set_sel_age2_cRn;
     selpar_age3_cRn_out(8)=sel_age3_cRn_logit; selpar_age3_cRn_out(1,7)=set_sel_age3_cRn;
     selpar_age4_cRn_out(8)=sel_age4_cRn_logit; selpar_age4_cRn_out(1,7)=set_sel_age4_cRn;
     selpar_age5_cRn_out(8)=sel_age5_cRn_logit; selpar_age5_cRn_out(1,7)=set_sel_age5_cRn;
     selpar_age6_cRn_out(8)=sel_age6_cRn_logit; selpar_age6_cRn_out(1,7)=set_sel_age6_cRn;

     selpar_age0_cRs_out(8)=sel_age0_cRs_logit; selpar_age0_cRs_out(1,7)=set_sel_age0_cRs;
     selpar_age1_cRs_out(8)=sel_age1_cRs_logit; selpar_age1_cRs_out(1,7)=set_sel_age1_cRs;
     selpar_age2_cRs_out(8)=sel_age2_cRs_logit; selpar_age2_cRs_out(1,7)=set_sel_age2_cRs;
     selpar_age3_cRs_out(8)=sel_age3_cRs_logit; selpar_age3_cRs_out(1,7)=set_sel_age3_cRs;
     selpar_age4_cRs_out(8)=sel_age4_cRs_logit; selpar_age4_cRs_out(1,7)=set_sel_age4_cRs;
     selpar_age5_cRs_out(8)=sel_age5_cRs_logit; selpar_age5_cRs_out(1,7)=set_sel_age5_cRs;
     selpar_age6_cRs_out(8)=sel_age6_cRs_logit; selpar_age6_cRs_out(1,7)=set_sel_age6_cRs;

     selpar_age0_cR2_out(8)=sel_age0_cR2_logit; selpar_age0_cR2_out(1,7)=set_sel_age0_cR2;
     selpar_age1_cR2_out(8)=sel_age1_cR2_logit; selpar_age1_cR2_out(1,7)=set_sel_age1_cR2;
     selpar_age2_cR2_out(8)=sel_age2_cR2_logit; selpar_age2_cR2_out(1,7)=set_sel_age2_cR2;
     selpar_age3_cR2_out(8)=sel_age3_cR2_logit; selpar_age3_cR2_out(1,7)=set_sel_age3_cR2;
     selpar_age4_cR2_out(8)=sel_age4_cR2_logit; selpar_age4_cR2_out(1,7)=set_sel_age4_cR2;

     selpar_L50_cBn_out(8)=selpar_L50_cBn; selpar_L50_cBn_out(1,7)=set_selpar_L50_cBn;
     selpar_slope_cBn_out(8)=selpar_slope_cBn; selpar_slope_cBn_out(1,7)=set_selpar_slope_cBn;
     selpar_L502_cBn_out(8)=selpar_L502_cBn; selpar_L502_cBn_out(1,7)=set_selpar_L502_cBn;
     selpar_slope2_cBn_out(8)=selpar_slope2_cBn; selpar_slope2_cBn_out(1,7)=set_selpar_slope2_cBn;
     selpar_L50_cBs_out(8)=selpar_L50_cBs; selpar_L50_cBs_out(1,7)=set_selpar_L50_cBs;
     selpar_slope_cBs_out(8)=selpar_slope_cBs; selpar_slope_cBs_out(1,7)=set_selpar_slope_cBs;
     selpar_L502_cBs_out(8)=selpar_L502_cBs; selpar_L502_cBs_out(1,7)=set_selpar_L502_cBs;
     selpar_slope2_cBs_out(8)=selpar_slope2_cBs; selpar_slope2_cBs_out(1,7)=set_selpar_slope2_cBs;

     selpar_L50_cBn3_out(8)=selpar_L50_cBn3; selpar_L50_cBn3_out(1,7)=set_selpar_L50_cBn3;
     selpar_slope_cBn3_out(8)=selpar_slope_cBn3; selpar_slope_cBn3_out(1,7)=set_selpar_slope_cBn3;
     selpar_L502_cBn3_out(8)=selpar_L502_cBn3; selpar_L502_cBn3_out(1,7)=set_selpar_L502_cBn3;
     selpar_slope2_cBn3_out(8)=selpar_slope2_cBn3; selpar_slope2_cBn3_out(1,7)=set_selpar_slope2_cBn3;

     selpar_age0_cBn_out(8)=sel_age0_cBn_logit; selpar_age0_cBn_out(1,7)=set_sel_age0_cBn;
     selpar_age1_cBn_out(8)=sel_age1_cBn_logit; selpar_age1_cBn_out(1,7)=set_sel_age1_cBn;
     selpar_age2_cBn_out(8)=sel_age2_cBn_logit; selpar_age2_cBn_out(1,7)=set_sel_age2_cBn;
     selpar_age3_cBn_out(8)=sel_age3_cBn_logit; selpar_age3_cBn_out(1,7)=set_sel_age3_cBn;
     selpar_age4_cBn_out(8)=sel_age4_cBn_logit; selpar_age4_cBn_out(1,7)=set_sel_age4_cBn;
     selpar_age5_cBn_out(8)=sel_age5_cBn_logit; selpar_age5_cBn_out(1,7)=set_sel_age5_cBn;
     selpar_age6_cBn_out(8)=sel_age6_cBn_logit; selpar_age6_cBn_out(1,7)=set_sel_age6_cBn;

     selpar_age0_cBs_out(8)=sel_age0_cBs_logit; selpar_age0_cBs_out(1,7)=set_sel_age0_cBs;
     selpar_age1_cBs_out(8)=sel_age1_cBs_logit; selpar_age1_cBs_out(1,7)=set_sel_age1_cBs;
     selpar_age2_cBs_out(8)=sel_age2_cBs_logit; selpar_age2_cBs_out(1,7)=set_sel_age2_cBs;
     selpar_age3_cBs_out(8)=sel_age3_cBs_logit; selpar_age3_cBs_out(1,7)=set_sel_age3_cBs;
     selpar_age4_cBs_out(8)=sel_age4_cBs_logit; selpar_age4_cBs_out(1,7)=set_sel_age4_cBs;
     selpar_age5_cBs_out(8)=sel_age5_cBs_logit; selpar_age5_cBs_out(1,7)=set_sel_age5_cBs;
     selpar_age6_cBs_out(8)=sel_age6_cBs_logit; selpar_age6_cBs_out(1,7)=set_sel_age6_cBs;

     selpar_L50_sgcomp_trawl_out(8)=selpar_L50_sgcomp_trawl; selpar_L50_sgcomp_trawl_out(1,7)=set_selpar_L50_sgcomp_trawl;
     selpar_slope_sgcomp_trawl_out(8)=selpar_slope_sgcomp_trawl; selpar_slope_sgcomp_trawl_out(1,7)=set_selpar_slope_sgcomp_trawl;
     selpar_L502_sgcomp_trawl_out(8)=selpar_L502_sgcomp_trawl; selpar_L502_sgcomp_trawl_out(1,7)=set_selpar_L502_sgcomp_trawl;
     selpar_slope2_sgcomp_trawl_out(8)=selpar_slope2_sgcomp_trawl; selpar_slope2_sgcomp_trawl_out(1,7)=set_selpar_slope2_sgcomp_trawl;
     selpar_L50_comp_trawl_out(8)=selpar_L50_comp_trawl; selpar_L50_comp_trawl_out(1,7)=set_selpar_L50_comp_trawl;
     selpar_slope_comp_trawl_out(8)=selpar_slope_comp_trawl; selpar_slope_comp_trawl_out(1,7)=set_selpar_slope_comp_trawl;
     selpar_L502_comp_trawl_out(8)=selpar_L502_comp_trawl; selpar_L502_comp_trawl_out(1,7)=set_selpar_L502_comp_trawl;
     selpar_slope2_comp_trawl_out(8)=selpar_slope2_comp_trawl; selpar_slope2_comp_trawl_out(1,7)=set_selpar_slope2_comp_trawl;
     log_q_comp_trawl_out(8)=log_q_comp_trawl; log_q_comp_trawl_out(1,7)=set_log_q_comp_trawl;
     log_q_sgcomp_trawl_out(8)=log_q_sgcomp_trawl; log_q_sgcomp_trawl_out(1,7)=set_log_q_sgcomp_trawl;
     log_q_seine_out(8)=log_q_seine; log_q_seine_out(1,7)=set_log_q_seine;
     log_q1_yoy_out(8)=log_q1_yoy; log_q1_yoy_out(1,7)=set_log_q1_yoy;
 log_q2_yoy_out(8)=log_q2_yoy; log_q2_yoy_out(1,7)=set_log_q2_yoy;
     M_constant_out(8)=M_constant; M_constant_out(1,7)=set_M_constant;
     log_avg_F_cRn_out(8)=log_avg_F_cRn; log_avg_F_cRn_out(1,7)=set_log_avg_F_cRn;
     log_avg_F_cRs_out(8)=log_avg_F_cRs; log_avg_F_cRs_out(1,7)=set_log_avg_F_cRs;
     log_avg_F_cBn_out(8)=log_avg_F_cBn; log_avg_F_cBn_out(1,7)=set_log_avg_F_cBn;
     log_avg_F_cBs_out(8)=log_avg_F_cBs; log_avg_F_cBs_out(1,7)=set_log_avg_F_cBs;

     log_rec_dev_output(styr_rec_dev,endyr_rec_dev)=log_rec_dev;
     log_F_dev_cRn_out(styr_cR_L,endyr_cR_L)=log_F_dev_cRn;
     log_F_dev_cRs_out(styr_cR_L,endyr_cR_L)=log_F_dev_cRs;
     log_F_dev_cBn_out(styr_cB_L,endyr_cB_L)=log_F_dev_cBn;
     log_F_dev_cBs_out(styr_cB_L,endyr_cB_L)=log_F_dev_cBs;
     M_dev_output(styr_seine_cpue,endyr_seine_cpue)=M_dev;
     log_Nage_dev_output(2,nages)=log_Nage_dev;

  #include "am_make_Robject-016-ehw04.cxx"   // write the S-compatible report

} //endl last phase loop
```

Appendix B Data inputs for the Beaufort Assessment Model

```
##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
##
##  Data Input File
##  SEDAR ## Atlantic menhaden assessment December 2014
##
##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>

##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
##-- BAM DATA SECTION: set-up section
##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>

#Starting and ending year of model
1955
2013

#Starting year to estimate recruitment deviation from S-R curve
1955

#Ending year to estimate recruitment deviation from S-R curve
2013

#3 phases of constraints on recruitment deviations:
#allows possible heavier constraint (weights defined later) in early and late period, with lighter constraint in the middle
#ending years of recruitment constraint phases
1956
2009

#Ending year for first and second selectivity period
1969
1971
1993
2004
2013

#Number of ages (7 classes is 0,...,6+)
7
#Vector of agebins, last is a plus group
0.0 1.0 2.0 3.0 4.0 5.0 6.0

#Number length bins used to match length comps and number used to compute plus group
25
6

#Vector of length bins (mm)(midpoint of bin) used to match length comps and bins used to compute plus group
95 105 115 125 135 145 155 165 175 185 195 205 215      225    235     245     255     265    275    285    295    305    315    325    335
345 355 365 375 385     395


#Max value of F used in spr and msy calculations
7.0
#Number of iterations in spr calculations
10001
#Number of iterations in msy calculations
10001
#Number years at end of time series over which to average sector Fs, for weighted selectivities
3
#Multiplicative bias correction of recruitment (may set to 1.0 for none or negative to compute from recruitment variance)
-1.0
#Number yrs to exclude at end of time series for computing bias correction (end rec devs may have extra constraint)
0



##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
##-- BAM DATA SECTION: observed data section
##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>

######################Commercial Reduction Landings##################################################################
#Landings (includes reduction landings)
#Starting and ending years of landings time series, respectively
1955
2013
#Observed Total removals (1000s of mt) and assumed CVs-NORTH
402.7 478.9 389.8 248.3 318.4 323.9 334.8 321.4 147.5 50.6 58.0 7.9 17.2 33.1 15.4 15.8 33.4 69.1 90.7 77.9 48.4 86.8 53.3 63.5 70.2 83.0 68.1 35.1 39.4 35.0 111.3 42.6 83.0 73.6 98.8 144.1 104.6
99.1 58.4 33.4 96.3 61.6 25.2 12.3 8.4 43.2 39.6 27.2 4.1 25.9 15.4 60.1 36.6 39.3 18.7 28.7 29.6 23.9 32.7
0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03  0.03  0.03    0.03 0.03   0.03    0.03    0.03
#Observed Total removals (1000s of mt) and assumed CVs-SOUTH
241.7 236.4 215.8 264.0 343.7 208.4 243.9 219.3 200.9 219.8 216.6 212.8 177.2 202.8 146.9 243.6 216.9 296.8 256.2 214.3 201.8 253.7 287.8 280.5 305.6 318.5 313.2 347.4 379.3 291.3 195.4 195.4
243.9 235.6 223.2 257.1 276.9 198.5 262.2 226.6 243.6 231.4 234.0 233.6 162.8 124.1 193.9 146.9 162.0 152.6 137.5 97.2 137.8 101.8 125.1 154.4 144.5 136.7 98.3
0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03  0.03  0.03    0.03 0.03   0.03    0.03    0.03
#Number and vector of years of age compositions for commercial reduction fishery
59
1955 1956 1957 1958 1959 1960 1961 1962 1963 1964 1965 1966 1967 1968 1969 1970 1971 1972 1973 1974 1975 1976 1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993
1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008    2009    2010    2011    2012    2013
###sample sizes of age comps by year (first row observed Nfish, second row number of 10 fish samples)
  ##NORTH
8408 11050 11247 8777 10470 9346 8059 9598 6058 4619 6564 1859 1840 5701 3621 700 760 759 729 1280 1850 2010 2200 1861 1688 1744 2220 840 840 3110 1490 530 940 1650 1360 1660 1460 1180 640 300
710 500 130 100 120 490 380 290 90 290 240 1040 520 550 240 380 410 330 370
422 560 564 450 531 475 403 481 303 232 330 93 92 285 181 35 38 76 73 128 185 201 220 190 169 175 222 84 84 311 149 53 94 165 136 166 146 118 64 30 71 50 13 10 12 49 38 29 9 29 24 104 52 55 24
38 41 33 37
  ##SOUTH
7742 8831 8467 7008 7490 4167 5158 6197 6977 5824 13017 13848 13648 21168 11511 7761 7510 5800 5640 4330 5450 4720 5080 5250 4680 5548 7000 8230 4340 8580 6230 4880 6460 5708 5530 5180 6230 4430
4680 4410 3900 3720 3970 3740 3500 2550 3540 3310 3400 3880 3290 2530 3270 2220 2590 2890 2820 2300 1760
384 442 424 377 386 215 258 310 349 293 651 692 690 1061 576 390 379 580 564 433 545 472 508 525 469 556 700 823 434 858 623 488 646 572 553 518 623 443 468 441 390 372 397 374 350 255 354 331
340 387 329 253 327 222 259 289 282 230 176
#age composition samples (year,age) from recreational fishery--combined across gear and unweighted--last age is a plus group (0 to 8+)
```

```
     ##NORTH
0.000 0.015 0.471 0.217 0.253 0.032 0.012
0.000 0.133 0.555 0.195 0.025 0.072 0.020
0.000 0.270 0.610 0.051 0.033 0.017 0.020
0.000 0.025 0.908 0.042 0.010 0.008 0.009
0.000 0.531 0.291 0.159 0.009 0.004 0.007
0.000 0.009 0.892 0.037 0.049 0.009 0.004
0.000 0.003 0.160 0.803 0.012 0.018 0.003
0.000 0.015 0.245 0.218 0.457 0.033 0.032
0.000 0.296 0.438 0.095 0.068 0.080 0.023
0.000 0.034 0.357 0.345 0.128 0.065 0.072
0.000 0.160 0.370 0.373 0.071 0.013 0.014
0.000 0.201 0.467 0.212 0.100 0.009 0.012
0.000 0.055 0.296 0.567 0.072 0.009 0.000
0.000 0.007 0.479 0.388 0.116 0.009 0.001
0.000 0.001 0.251 0.594 0.149 0.005 0.000
0.000 0.150 0.793 0.050 0.007 0.000 0.000
0.000 0.126 0.288 0.433 0.137 0.017 0.000
0.000 0.169 0.286 0.452 0.085 0.008 0.000
0.000 0.021 0.821 0.133 0.024 0.001 0.000
0.000 0.028 0.844 0.117 0.006 0.004 0.000
0.000 0.000 0.798 0.175 0.025 0.001 0.000
0.000 0.092 0.823 0.071 0.013 0.000 0.000
0.000 0.022 0.567 0.326 0.079 0.006 0.001
0.000 0.000 0.298 0.567 0.120 0.015 0.000
0.000 0.007 0.579 0.332 0.076 0.006 0.000
0.000 0.002 0.237 0.462 0.243 0.051 0.004
0.000 0.001 0.357 0.357 0.210 0.070 0.006
0.000 0.042 0.393 0.473 0.063 0.025 0.004
0.000 0.012 0.826 0.120 0.037 0.005 0.000
0.000 0.024 0.343 0.506 0.097 0.029 0.001
0.000 0.020 0.760 0.089 0.111 0.017 0.003
0.000 0.010 0.795 0.107 0.050 0.031 0.006
0.000 0.005 0.652 0.277 0.058 0.006 0.002
0.000 0.000 0.225 0.486 0.260 0.026 0.003
0.000 0.081 0.623 0.173 0.097 0.025 0.000
0.000 0.011 0.788 0.134 0.049 0.018 0.001
0.000 0.085 0.430 0.385 0.072 0.023 0.005
0.000 0.058 0.687 0.107 0.118 0.026 0.004
0.000 0.045 0.675 0.226 0.036 0.017 0.002
0.000 0.017 0.420 0.333 0.183 0.047 0.000
0.000 0.020 0.567 0.329 0.079 0.006 0.000
0.000 0.000 0.579 0.320 0.092 0.008 0.000
0.000 0.000 0.495 0.293 0.158 0.055 0.000
0.000 0.000 0.657 0.281 0.062 0.000 0.000
0.000 0.000 0.389 0.428 0.168 0.015 0.000
0.000 0.005 0.559 0.406 0.019 0.011 0.000
0.000 0.000 0.150 0.796 0.055 0.000 0.000
0.000 0.040 0.347 0.491 0.120 0.002 0.000
0.000 0.000 0.474 0.378 0.139 0.010 0.000
0.000 0.004 0.615 0.320 0.061 0.000 0.000
0.000 0.000 0.219 0.605 0.174 0.002 0.000
0.000 0.022 0.456 0.422 0.099 0.001 0.000
0.000 0.022 0.761 0.174 0.041 0.002 0.000
0.000 0.002 0.216 0.668 0.106 0.008 0.000
0.000 0.123 0.299 0.463 0.102 0.013 0.000
0.000 0.000 0.456 0.348 0.193 0.003 0.000
0.000 0.058 0.726 0.190 0.023 0.003 0.000
0.000 0.001 0.778 0.192 0.029 0.000 0.000
0.000 0.028 0.724 0.233 0.015 0.000 0.000

     ##SOUTH
0.374 0.323 0.269 0.016 0.016 0.002 0.000
0.017 0.885 0.049 0.018 0.004 0.022 0.004
0.151 0.598 0.217 0.010 0.011 0.007 0.006
0.059 0.466 0.443 0.018 0.005 0.005 0.004
0.003 0.855 0.099 0.034 0.005 0.002 0.002
0.052 0.192 0.701 0.018 0.025 0.008 0.004
0.000 0.538 0.217 0.234 0.004 0.007 0.000
0.040 0.387 0.491 0.033 0.044 0.003 0.002
0.079 0.460 0.386 0.059 0.007 0.008 0.002
0.187 0.433 0.349 0.028 0.002 0.000 0.000
0.184 0.528 0.269 0.018 0.001 0.000 0.000
0.265 0.414 0.299 0.020 0.001 0.000 0.000
0.007 0.663 0.269 0.057 0.003 0.000 0.000
0.143 0.349 0.468 0.037 0.003 0.000 0.000
0.188 0.442 0.330 0.038 0.002 0.000 0.000
0.016 0.650 0.309 0.022 0.003 0.000 0.000
0.083 0.288 0.569 0.054 0.005 0.001 0.000
0.033 0.618 0.285 0.061 0.003 0.000 0.000
0.036 0.372 0.591 0.001 0.000 0.000 0.000
0.196 0.388 0.413 0.003 0.000 0.000 0.000
0.154 0.371 0.469 0.006 0.001 0.000 0.000
0.101 0.572 0.324 0.003 0.000 0.000 0.000
0.140 0.289 0.567 0.003 0.000 0.000 0.000
0.158 0.230 0.558 0.050 0.003 0.000 0.000
0.413 0.172 0.403 0.012 0.001 0.000 0.000
0.028 0.476 0.452 0.038 0.004 0.001 0.000
0.316 0.186 0.460 0.038 0.000 0.000 0.000
0.038 0.306 0.558 0.096 0.001 0.000 0.000
0.279 0.148 0.547 0.016 0.008 0.001 0.000
0.396 0.311 0.244 0.040 0.007 0.002 0.000
0.235 0.394 0.364 0.006 0.000 0.000 0.000
0.056 0.126 0.797 0.019 0.002 0.001 0.000
0.022 0.253 0.691 0.031 0.003 0.000 0.000
0.175 0.146 0.573 0.099 0.006 0.001 0.000
0.069 0.514 0.402 0.014 0.001 0.000 0.000
0.190 0.078 0.697 0.023 0.010 0.002 0.000
0.317 0.360 0.281 0.038 0.004 0.001 0.000
0.243 0.428 0.313 0.014 0.002 0.000 0.000
0.049 0.266 0.608 0.074 0.003 0.000 0.000
0.064 0.197 0.609 0.094 0.035 0.002 0.000
0.044 0.408 0.366 0.150 0.031 0.002 0.000
0.036 0.226 0.630 0.092 0.015 0.001 0.000
```

```
0.027 0.260 0.423 0.236 0.047 0.007 0.001
0.073 0.187 0.535 0.123 0.073 0.009 0.001
0.188 0.292 0.428 0.069 0.020 0.003 0.000
0.140 0.205 0.510 0.127 0.016 0.002 0.000
0.039 0.073 0.604 0.265 0.018 0.001 0.000
0.242 0.284 0.321 0.140 0.012 0.000 0.000
0.088 0.185 0.643 0.073 0.010 0.001 0.000
0.020 0.234 0.670 0.060 0.015 0.001 0.000
0.020 0.131 0.618 0.210 0.018 0.003 0.000
0.016 0.525 0.378 0.072 0.008 0.000 0.000
0.001 0.306 0.631 0.054 0.008 0.000 0.000
0.017 0.115 0.812 0.053 0.003 0.000 0.000
0.007 0.515 0.311 0.147 0.019 0.001 0.000
0.017 0.447 0.494 0.034 0.008 0.000 0.000
0.000 0.477 0.467 0.048 0.007 0.002 0.000
0.007 0.183 0.789 0.020 0.001 0.000 0.000
0.043 0.457 0.388 0.095 0.016 0.000 0.000


######################Commercial Bait Landings#################################################################
#Landings (includes bait and recreational landings)
#Starting and ending years of landings time series, respectively
1955
2013
##Observed landings (1000 mt) and assumed CVs (includes MRFSS landings) - NORTH
10.1 17.5 10.6 3.5 8.0 7.6 8.4 10.6 6.1 4.3 3.3 1.8 1.4 0.8 1.1 1.4 1.9 2.1 2.6 2.1 1.9 2.0 1.4 1.1 1.2 1.1 1.1 1.4 1.5 1.7 8.2 18.2 16.7 21.3 11.3 15.9 24.0 27.7 26.0 18.1 21.4 17.5 19.1 16.4
12.9 14.6 12.7 12.8 8.2 10.1 9.3 11.7 20.1 26.6 18.9 25.6 34.2 40.3 21.1
0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05
0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05    0.05    0.05    0.05    0.05    0.05
##Observed landings (1000 mt) and assumed CVs (includes MRFSS landings) - SOUTH
4.5 5.7 14.1 11.2 12.6 11.8 16.6 16.0 18.3 16.0 20.3 12.0 10.2 8.7 9.5 20.2 11.6 8.2 12.2 12.4 19.8 17.7 21.7 24.8 11.8 25.0 21.4 18.6 17.7 12.8 22.0 17.1 18.0 16.6 20.5 14.5 13.3 13.3 13.9 16.6
18.4 18.8 21.9 23.0 21.7 18.8 22.8 24.0 25.0 24.9 28.8 15.6 22.4 21.9 20.1 18.5 17.3 23.6 17.3
0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.15 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05
0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05    0.05    0.05    0.05    0.05    0.05
##Number and vector of years of age compositions for bait fishery
29
1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008    2009    2010    2011   2012   2013
##sample sizes of age comps by year (first row observed Nfish, second row Nsets or 10-fish samples) - NORTH
#600 40 0 0 20 0 0 0 30 430 210 250 120 280 239 319 749 160 120 30 10 349 780 1008 470 550 510 590 270
#60 4 0 0 2 0 0 0 3 43 21 25 12 28 24 32 75 16 12 3 1 35 78 101 47 55 51 59 67
600 40 10 10 20 10 10 10 30 430 210 250 120 280 239 319 749 160 120 30 10 349 780 1008 470 550 510 590 270
60 4 1 1 2 1 1 1 3 43 21 25 12 28 24 32 75 16 12 3 1 35 78 101 47 55 51 59 67
##sample sizes of age comps by year (first row observed Nfish, second row Nsets or 10-fish samples) - SOUTH
170 340 220 10 10 10 80 70 140 140 180 160 220 460 420 310 340 630 410 400 410 260 470 370 570 360 370 310 340
17 34 22 1 1 1 8 7 14 14 18 16 22 46 42 31 34 63 41 40 41 26 47 37 57 36 37 31 34
#age composition samples (year,age)
        ##NORTH
0.000 0.000 0.660 0.189 0.119 0.025 0.006
0.000 0.000 0.072 0.619 0.281 0.026 0.003
0.000 0.000 0.073 0.619 0.280 0.026 0.003
0.000 0.000 0.069 0.621 0.282 0.026 0.003
0.000 0.000 0.085 0.612 0.275 0.025 0.003
0.000 0.000 0.113 0.597 0.262 0.025 0.003
0.000 0.000 0.125 0.591 0.256 0.025 0.003
0.000 0.000 0.152 0.576 0.244 0.025 0.003
0.000 0.000 0.160 0.571 0.240 0.025 0.003
0.000 0.000 0.111 0.495 0.341 0.049 0.003
0.000 0.000 0.088 0.476 0.435 0.001 0.000
0.000 0.000 0.411 0.452 0.130 0.007 0.000
0.000 0.000 0.146 0.345 0.382 0.110 0.017
0.004 0.000 0.106 0.413 0.390 0.075 0.012
0.005 0.000 0.149 0.482 0.312 0.041 0.010
0.000 0.004 0.414 0.318 0.228 0.029 0.007
0.000 0.000 0.113 0.732 0.137 0.014 0.004
0.000 0.000 0.058 0.570 0.318 0.054 0.000
0.000 0.000 0.126 0.665 0.198 0.010 0.000
0.000 0.000 0.260 0.517 0.195 0.025 0.003
0.000 0.000 0.238 0.529 0.205 0.025 0.003
0.000 0.004 0.279 0.570 0.140 0.007 0.000
0.000 0.000 0.391 0.492 0.108 0.007 0.002
0.000 0.000 0.248 0.607 0.131 0.014 0.000
0.000 0.000 0.182 0.614 0.186 0.017 0.000
0.000 0.000 0.367 0.389 0.217 0.024 0.002
0.000 0.000 0.143 0.487 0.326 0.045 0.000
0.000 0.000 0.393 0.472 0.125 0.008 0.002
0.000 0.000 0.259 0.560 0.155 0.026 0.000

        ##SOUTH
0.003 0.172 0.654 0.141 0.027 0.003 0.000
0.002 0.123 0.704 0.147 0.021 0.002 0.000
0.003 0.124 0.698 0.143 0.028 0.003 0.000
0.003 0.147 0.654 0.163 0.030 0.003 0.000
0.003 0.148 0.653 0.163 0.030 0.003 0.000
0.005 0.327 0.530 0.114 0.021 0.002 0.000
0.002 0.243 0.606 0.123 0.023 0.002 0.000
0.005 0.317 0.532 0.120 0.023 0.002 0.000
0.010 0.400 0.415 0.143 0.029 0.003 0.000
0.003 0.199 0.623 0.147 0.027 0.003 0.000
0.000 0.391 0.373 0.219 0.017 0.000 0.000
0.001 0.049 0.739 0.179 0.033 0.000 0.000
0.000 0.083 0.521 0.303 0.074 0.012 0.006
0.038 0.069 0.538 0.234 0.106 0.012 0.003
0.000 0.053 0.722 0.169 0.050 0.006 0.000
0.008 0.234 0.640 0.118 0.001 0.000 0.000
0.003 0.062 0.685 0.233 0.014 0.003 0.000
0.000 0.043 0.259 0.500 0.176 0.020 0.002
0.006 0.101 0.751 0.129 0.013 0.000 0.000
0.000 0.070 0.735 0.162 0.030 0.003 0.000
0.000 0.018 0.532 0.423 0.024 0.003 0.000
0.000 0.286 0.494 0.196 0.023 0.000 0.000
0.000 0.272 0.689 0.029 0.011 0.000 0.000
0.000 0.045 0.860 0.080 0.012 0.003 0.000
0.004 0.266 0.409 0.292 0.030 0.000 0.000
0.000 0.348 0.564 0.067 0.021 0.000 0.000
```

```
0.000 0.406 0.500 0.080 0.015 0.000 0.000
0.000 0.090 0.892 0.018 0.000 0.000 0.000
0.009 0.609 0.287 0.091 0.003 0.000 0.000


########################################Composite adult trawl index - SEAMAP and GA ##########################################################
#Starting and ending years of VA shad survey index
1990
2013
#Observed index and assumed CVs
2.73 1.06 0.53 0.41 0.63 0.13 0.81 0.34 0.69 0.70 0.77 0.62 0.57 0.70 0.27 0.77 3.78 0.28 0.36 2.49 0.70 3.00 0.88 0.78
0.49 0.44 0.51 0.53 0.57 0.44 0.38 0.45 0.50 0.53 0.79 0.52 0.51 0.40 0.46 0.39 0.39 0.39 0.41 0.41 0.44 0.34 0.33 0.35
#Number and vector of years of length compositions for gill net survey
24
1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013
#sample size of gill net survey length comp data by year (first row observed Ntrips, second row Nfish)
41 46 32 38 29 24 53 78 53 40 17 57 35 105 48 100 118 45 64 109 82 162 100 104
3904 1332 1032 496 322 110 407 238 975 359 477 1017 901 1206 642 4129 6736 353 599 19418 694 3228 1186 2450
#gill net length composition samples (year,lengthbin 1 cm)
0.0000 0.0000 0.0000 0.0835 0.3635 0.2907 0.1642 0.0551 0.0241 0.0085 0.0044 0.0023 0.0023 0.0003 0.0003 0.0010 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
0.0000 0.0000 0.0105 0.0526 0.3078 0.2575 0.0931 0.0563 0.0413 0.0788 0.0736 0.0210 0.0060 0.0008 0.0008 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
0.0000 0.0000 0.1560 0.2083 0.2529 0.1705 0.0678 0.0378 0.0397 0.0339 0.0165 0.0136 0.0010 0.0000 0.0000 0.0000 0.0000 0.0010 0.0010 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
0.0000 0.0000 0.0746 0.2157 0.2661 0.1250 0.0484 0.0524 0.1431 0.0504 0.0141 0.0101 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
0.0000 0.0000 0.0497 0.0839 0.0466 0.1056 0.1211 0.3137 0.1366 0.0807 0.0280 0.0311 0.0031 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
0.0000 0.0000 0.0091 0.1000 0.0545 0.0455 0.0273 0.1091 0.1909 0.3364 0.1182 0.0091 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
0.0000 0.0000 0.1548 0.1081 0.0467 0.0860 0.0811 0.0663 0.0934 0.1032 0.1057 0.0393 0.0074 0.0025 0.0172 0.0197 0.0221 0.0270 0.0074 0.0074 0.0025 0.0025 0.0000 0.0000 0.0000
0.0000 0.0000 0.0588 0.1303 0.0840 0.1050 0.1345 0.1008 0.0882 0.2059 0.0504 0.0168 0.0084 0.0000 0.0042 0.0042 0.0000 0.0042 0.0000 0.0000 0.0000 0.0042 0.0000 0.0000 0.0000
0.0000 0.0000 0.0821 0.2646 0.1867 0.1446 0.0862 0.0821 0.0472 0.0544 0.0390 0.0113 0.0000 0.0010 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0010 0.0000 0.0000
0.0000 0.0000 0.0000 0.0084 0.0279 0.0891 0.0919 0.1142 0.1616 0.2117 0.1476 0.1281 0.0111 0.0028 0.0028 0.0000 0.0000 0.0000 0.0028 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
0.0000 0.0000 0.0063 0.0252 0.0734 0.1321 0.1195 0.1551 0.1782 0.2683 0.0356 0.0063 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
0.0000 0.0000 0.0265 0.3117 0.2163 0.1573 0.1131 0.0452 0.0433 0.0482 0.0256 0.0118 0.0000 0.0000 0.0000 0.0000 0.0000 0.0010 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
0.0000 0.0000 0.0011 0.0622 0.3607 0.2941 0.1332 0.0666 0.0333 0.0277 0.0166 0.0044 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
0.0000 0.0008 0.0796 0.1418 0.1766 0.2886 0.1501 0.0489 0.0307 0.0572 0.0182 0.0058 0.0000 0.0000 0.0008 0.0000 0.0000 0.0000 0.0000 0.0008 0.0000 0.0000 0.0000 0.0000 0.0000
0.0000 0.0016 0.0950 0.0125 0.1480 0.2212 0.0670 0.2181 0.1106 0.0841 0.0312 0.0093 0.0000 0.0016 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
0.0000 0.0017 0.2659 0.4163 0.0969 0.0533 0.0559 0.0322 0.0378 0.0148 0.0075 0.0131 0.0044 0.0002 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
0.0000 0.0000 0.0509 0.4336 0.1871 0.1700 0.0768 0.0300 0.0056 0.0111 0.0122 0.0189 0.0010 0.0028 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
0.0000 0.0000 0.0142 0.0057 0.1331 0.3201 0.3683 0.0963 0.0340 0.0227 0.0028 0.0000 0.0000 0.0000 0.0000 0.0028 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
0.0000 0.0000 0.0033 0.1135 0.4073 0.1653 0.0467 0.1352 0.0351 0.0417 0.0451 0.0067 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
0.0000 0.0003 0.0781 0.4674 0.2996 0.1276 0.0105 0.0070 0.0039 0.0036 0.0008 0.0011 0.0002 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
0.0000 0.0000 0.1441 0.2017 0.0879 0.0965 0.0922 0.1542 0.1138 0.0850 0.0101 0.0058 0.0014 0.0000 0.0000 0.0000 0.0029 0.0000 0.0000 0.0029 0.0014 0.0000 0.0000 0.0000 0.0000
0.0000 0.0028 0.0499 0.1493 0.0616 0.1413 0.2141 0.1908 0.0849 0.0604 0.0285 0.0149 0.0015 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
0.0000 0.0000 0.0000 0.0801 0.1088 0.0987 0.0691 0.1585 0.1906 0.1939 0.0295 0.0531 0.0135 0.0042 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000
0.0000 0.0016 0.0020 0.0669 0.1469 0.2184 0.1976 0.1947 0.1041 0.0510 0.0082 0.0073 0.0008 0.0004 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000


########################################Composite adult trawl index - all other trawls besides GA and SEAMAP############################################################
#Starting and ending years of Composite adult trawl index (Conn 2010)
1980
2013
#Observed index and assumed CVs
0.76 0.50 2.37 0.77 0.39 0.77 4.78 3.51 1.86 1.17 0.56 0.70 0.69 0.62 0.30 0.53 0.23 0.21 0.14 0.37 0.26 0.30 0.50 0.22 0.38 0.77 1.08 1.14 1.16 1.28 1.05 1.67 1.97 0.98
0.74 0.79 0.76 0.69 0.85 0.77 0.64 0.68 0.38 0.38 0.35 0.35 0.33 0.40 0.39 0.36 0.40 0.35 0.36 0.33 0.33 0.39 0.35 0.31 0.31 0.30 0.28 0.27 0.34 0.30 0.28 0.31 0.30 0.29
#Number and vector of years of length compositions for trawl  survey
26
1988    1989    1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013
#sample size of trawl survey length comp data by year (first row observed Ntrips, second row Nfish)
169 178 284 151 175 102 211 156 123 140 166 265 234 132 492 260 348 337 322 525 409 293 296 355 338 200
107 103 154 104 247 272 144 589 487 185 184 699 168 511 806 871 1044 877 768 1049 845 709 1706 1355 1063 1074
#trawl length composition samples (year,lengthbin 1 cm)
0.0000 0.0000 0.0000 0.0093 0.0187 0.0280 0.1028 0.1121 0.1215 0.0374 0.0467 0.0654 0.0374 0.0654 0.0935 0.0561 0.0935 0.0654 0.0374 0.0000 0.0093 0.0000 0.0000 0.0000 0.0000
0.0000 0.0291 0.0388 0.0194 0.0583 0.0971 0.1165 0.1165 0.0291 0.0583 0.0388 0.0583 0.0291 0.0388 0.0291 0.0388 0.0971 0.0583 0.0097 0.0097 0.0097 0.0097 0.0000 0.0000 0.0097
0.0000 0.0000 0.0000 0.0000 0.0000 0.0390 0.0584 0.0584 0.0649 0.0519 0.0260 0.0519 0.0519 0.0779 0.0974 0.1364 0.1169 0.0714 0.0260 0.0260 0.0260 0.0130 0.0000 0.0000 0.0065
0.0000 0.0096 0.0096 0.0385 0.0385 0.0577 0.0385 0.0481 0.0769 0.0865 0.1154 0.1250 0.0769 0.0673 0.0096 0.0192 0.0481 0.0481 0.0481 0.0288 0.0096 0.0000 0.0000 0.0000 0.0000
0.0000 0.0000 0.0000 0.0000 0.0040 0.0121 0.0526 0.0364 0.0405 0.0526 0.0607 0.0688 0.0972 0.1053 0.0850 0.0810 0.0769 0.0729 0.0729 0.0526 0.0202 0.0040 0.0000 0.0000 0.0040
0.0000 0.0000 0.0000 0.0074 0.0000 0.0000 0.0110 0.0147 0.0000 0.0368 0.0368 0.0294 0.0441 0.0735 0.0846 0.1691 0.1507 0.1654 0.1140 0.0404 0.0147 0.0074 0.0000 0.0000 0.0000
0.0000 0.0000 0.0069 0.0000 0.0069 0.0208 0.0694 0.0278 0.0486 0.0625 0.0000 0.0208 0.0625 0.0417 0.0417 0.0833 0.1181 0.1806 0.1111 0.0556 0.0208 0.0208 0.0000 0.0000 0.0000
0.0000 0.0000 0.0017 0.0000 0.0017 0.0000 0.0170 0.0119 0.0187 0.0272 0.0340 0.0424 0.0306 0.0611 0.1087 0.0866 0.1154 0.1460 0.1104 0.0798 0.0458 0.0153 0.0204 0.0136 0.0119
0.0000 0.0000 0.0000 0.0000 0.0000 0.0041 0.0185 0.0062 0.0021 0.0082 0.0000 0.0062 0.0082 0.0021 0.0062 0.0472 0.0739 0.1047 0.1417 0.2074 0.1889 0.1253 0.0370 0.0082 0.0041
0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.1081 0.0378 0.0649 0.0324 0.0000 0.0000 0.0162 0.0054 0.0054 0.0216 0.0108 0.0108 0.0324 0.0757 0.1946 0.1892 0.1351 0.0432 0.0162
0.0000 0.0000 0.0000 0.0054 0.0109 0.0761 0.1250 0.1033 0.1141 0.0326 0.0489 0.0163 0.0217 0.0217 0.0217 0.0272 0.0163 0.0326 0.0380 0.0272 0.0489 0.0761 0.0707 0.0380 0.0272
0.0000 0.0000 0.0014 0.0000 0.0000 0.0072 0.0243 0.0200 0.0129 0.0172 0.0100 0.0100 0.0129 0.0129 0.0215 0.0372 0.0329 0.0286 0.0329 0.0887 0.1788 0.1774 0.1559 0.0687 0.0486
0.0000 0.0000 0.0060 0.0000 0.0000 0.0060 0.0655 0.0417 0.0714 0.0417 0.0238 0.0179 0.0357 0.0179 0.0417 0.0476 0.0357 0.0417 0.0833 0.0298 0.0536 0.0476 0.0774 0.1131 0.1012
0.0000 0.0000 0.0000 0.0000 0.0000 0.0059 0.0587 0.0411 0.0196 0.0157 0.0078 0.0039 0.0098 0.0039 0.0117 0.0372 0.0528 0.0607 0.0607 0.1194 0.1468 0.1057 0.0920 0.0763 0.0705
0.0000 0.0000 0.0174 0.0136 0.0074 0.0062 0.0819 0.0509 0.0434 0.0397 0.0273 0.0236 0.0236 0.0360 0.0459 0.0484 0.0471 0.0521 0.0546 0.0620 0.0769 0.0707 0.0682 0.0447 0.0583
0.0000 0.0000 0.0000 0.0000 0.0000 0.0023 0.0264 0.0057 0.0069 0.0115 0.0000 0.0023 0.0011 0.0069 0.0046 0.0069 0.0057 0.0034 0.0138 0.0356 0.1079 0.2698 0.2503 0.1435 0.0953
0.0000 0.0000 0.0010 0.0029 0.0000 0.0019 0.0489 0.0412 0.0594 0.0402 0.0115 0.0096 0.0163 0.0144 0.0086 0.0163 0.0125 0.0182 0.0517 0.1092 0.1466 0.1322 0.1274 0.0862 0.0441
0.0000 0.0000 0.0011 0.0000 0.0000 0.0011 0.0410 0.0103 0.0057 0.0046 0.0068 0.0091 0.0137 0.0114 0.0228 0.0399 0.0559 0.0992 0.1254 0.1163 0.1300 0.1311 0.0992 0.0468 0.0285
0.0000 0.0000 0.0013 0.0078 0.0091 0.0078 0.0365 0.0313 0.0326 0.0195 0.0195 0.0260 0.0352 0.0404 0.0430 0.0495 0.0755 0.1133 0.1081 0.1211 0.0742 0.0768 0.0391 0.0182 0.0143
0.0000 0.0000 0.0010 0.0019 0.0048 0.0114 0.0439 0.0353 0.0181 0.0210 0.0191 0.0296 0.0172 0.0400 0.0667 0.0677 0.0906 0.0629 0.1096 0.1182 0.1258 0.0705 0.0286 0.0076 0.0086
0.0000 0.0000 0.0024 0.0024 0.0059 0.0130 0.0485 0.0355 0.0379 0.0213 0.0189 0.0237 0.0426 0.0497 0.0473 0.0781 0.0888 0.0899 0.1053 0.1183 0.0923 0.0521 0.0213 0.0036 0.0012
0.0000 0.0000 0.0014 0.0085 0.0197 0.0508 0.0592 0.0339 0.0141 0.0254 0.0226 0.0254 0.0296 0.0649 0.0508 0.0677 0.0973 0.0889 0.1001 0.0931 0.0719 0.0564 0.0155 0.0028 0.0000
0.0000 0.0000 0.0000 0.0012 0.0012 0.0035 0.3429 0.2392 0.1295 0.0281 0.0094 0.0117 0.0158 0.0205 0.0317 0.0334 0.0199 0.0275 0.0311 0.0281 0.0117 0.0076 0.0018 0.0012 0.0029
0.0000 0.0000 0.0000 0.0007 0.0074 0.0133 0.0893 0.0804 0.0686 0.0583 0.0280 0.0399 0.0303 0.0509 0.0590 0.0399 0.0413 0.0435 0.0627 0.1041 0.1004 0.0664 0.0111 0.0022 0.0022
0.0000 0.0000 0.0038 0.0151 0.0075 0.0056 0.0621 0.0583 0.0452 0.0329 0.0273 0.0263 0.0141 0.0235 0.0339 0.0480 0.0724 0.0668 0.0856 0.1364 0.1421 0.0668 0.0245 0.0009 0.0009
0.0000 0.0000 0.0000 0.0037 0.0065 0.0084 0.0596 0.0298 0.0177 0.0084 0.0121 0.0251 0.0428 0.0680 0.0456 0.0791 0.1182 0.1034 0.1099 0.0912 0.0959 0.0503 0.0205 0.0028 0.0000


########################################Seine survey index - MD seine###########################################################
#Starting and ending years of the seine survey index
1959
1986
#Observed CPUE and assumed CVs
0.12 0.02 0.01 0.92 0.18 0.00 0.05 0.07 0.10 0.04 0.11 0.03 0.79 0.64 0.76 1.66 3.03 3.98 2.88 0.86 2.12 1.36 1.84 0.98 1.00 1.03 1.77 1.66
0.70 0.64 0.85 0.72 1.34 0.50 0.40 0.95 1.55 1.14 0.61 1.59 0.61 0.37 0.79 0.40 0.39 0.40 0.41 0.43 0.43 0.36 0.40 0.68 0.46 0.40 0.54 0.31


########################################YOY index - all gears using area composite##########################################################
#Starting and ending years of VA shad survey index
1959
2013
#Observed index and assumed CVs
0.70 0.35 0.33 1.60 0.93 0.21 0.48 0.63 0.79 0.56 0.61 0.41 1.59 2.03 1.48 2.10 2.79 3.15 2.71 1.59 2.36 1.70 2.46 2.05 1.25 0.94 1.88 1.05 0.46 0.87 1.32 1.59 1.13 0.70 0.13 0.52 0.31 0.24 0.53
0.50 0.83 0.79 0.37 1.04 0.50 0.69 0.73 0.39 0.56 0.38 0.32 0.60 0.28 0.23 0.23
0.96 0.98 1.02 0.92 0.98 1.01 0.94 1.00 1.01 0.82 0.80 0.89 0.77 0.73 0.93 0.86 0.85 0.86 0.86 0.88 0.86 0.67 0.75 0.70 0.74 0.76 0.58 0.63 0.58 0.52 0.46 0.45 0.45 0.45 0.49 0.45 0.44 0.44 0.42
```

```
0.44 0.47 0.43 0.42 0.43 0.42 0.42 0.40 0.40 0.41 0.41 0.41 0.42 0.40 0.41 0.43


##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
##-- BAM DATA SECTION: parameter section
##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
##################Parameter values and initial guesses#################################################################################
#####################################################
##prior PDF (1=none, 2=lognormal, 3=normal, 4=beta)
###############################################################
#initial # lower # upper #       #  prior  # prior   # prior #
# guess  # bound # bound # phase #  mean   # var/-CV #  PDF  #
#--------#-------#-------#-------#---------#---------#-------#
                                                              ###### Biological input ####################################
 450.0      350     650      -3     500.0    0.087      1     # VonBert Linf (units in mm FL)
 0.32       0.05    0.8      -3    0.40     -0.27       1      # VonBert K (units in mm FL)
 -0.83    -2.0     0.0       -3     -1.013   -0.28      1      # VonBert t0 (units in mm FL)
 0.3        0.01    0.5       3     0.08     0.235      1    # CV of length at age
 0.26       0.05    0.65     -3     0.26     0.092      1    # constant M (used only to compute MSST=(1-M)SSBmsy)
                                                              ###### SR parameters ######################################
 0.99       0.21    0.99      -4     0.75     0.0196    1     # SR steepness parameter
 3.3       2.0      7.5       1     5.3     -0.25       1     # SR log_R0 parameter
 0.0       -1.0     1.0      -3     0.0      -0.5       1    # SR recruitment autocorrelation (lag 1)
 0.6        0.2     1.2      -4     0.6      -0.25      1    # s.d. of recruitment in log space
                                                              ###### Selectivity parameters ##############################
                                                             #PERIOD 1 (north and south)
 1.76       0.75    10.0     3    1.50     -0.5       1    # reduction age at 50% selectivity
 3.01       0.5     12.0     3     4.08     -0.5      1    # reduction slope of ascending limb
 0.0017       -1.0   10.0    4     5.75     -0.5      1    # reduction age at 50% selectivity for descending limb
 3.16       0.05     25.0    4     4.08     -0.5      1    # reduction slope of descending limb

 2.07       0.75    10.0     3    1.50     -0.5       1    # reduction age at 50% selectivity
 2.94       0.5     12.0     3     4.08     -0.5      1    # reduction slope of ascending limb
 1.60       -1.0     10.0    4     3.75     -0.5      3    # reduction age at 50% selectivity for descending limb
 1.00       0.005     25.0   4     4.08     -0.5      1    # reduction slope of descending limb

                                                             #PERIOD 2 (north and south)
 2.07       0.75     10.0    3    1.25     -0.5       1    # reduction age at 50% selectivity
 2.94       0.5     12.0     3     4.08     -0.5      1    # reduction slope of ascending limb
 1.60       -1.0     10.0    4     5.75     -0.5      1    # reduction age at 50% selectivity for descending limb
 0.996       0.05     25.0   4     4.08     -0.5      1    # reduction slope of descending limb

 2.07       0.75     10.0    3    1.25     -0.5       1    # reduction age at 50% selectivity
 2.94       0.5     12.0     3     4.08     -0.5      1    # reduction slope of ascending limb
 1.60       -1.0     10.0    4     5.75     -0.5      1    # reduction age at 50% selectivity for descending limb
 0.996       0.05     25.0   4     4.08     -0.5      1    # reduction slope of descending limb

                                                             #PERIOD 3 (north and south)
 1.50       0.75    10.0     3     1.50     -0.5      1    # reduction age at 50% selectivity
 7.08       0.5     12.0     3     4.08     -0.5      1    # reduction slope of ascending limb
 4.75       2.5     10.0     4     4.75     -0.5      1    # reduction age at 50% selectivity for descending limb
 4.08       0.5     25.0     4     4.08     -0.5      1    # reduction slope of descending limb

 1.50       0.75    10.0     3     1.50     -0.5      1    # reduction age at 50% selectivity
 7.08       0.5     12.0     3     4.08     -0.5      1    # reduction slope of ascending limb
 4.75       2.5     10.0     4     4.75     -0.5      1    # reduction age at 50% selectivity for descending limb
 4.08       0.5     25.0     4     4.08     -0.5      1    # reduction slope of descending limb


 2.0       0.05    15.0     -1    0.5      -0.1       1    #L50 for the modified logistic exponential
 2.5      -1.0     25.0     -1    20       -0.5       1    #slope for the modified logistic exponential
 0.075      0.05    0.45    -2    0.25     -0.5       1    #sigma for the modified logistic exponential

 -9.0    -10.0     10.0      -3     -5.0     -0.5      1     #age-0 cR selectivity in logit space - cR south!
 0.0       -10.0     10.0     -3      0.0     -0.5      1    #age-1 cR selectivity in logit space
 9.0     -10.0     10.0     -1      5.0     -0.5      1    #age-2 cR selectivity in logit space
 0.0       -15.0     10.0     -3      0.0     -0.5      1    #age-3 cR selectivity in logit space
 -3.5       -10.0     10.0   -3      0.0     -0.5      1  #age-4 cR selectivity in logit space
 -9.0      -10.0     10.0    -3      0.0     -0.5      1  #age-5 cR selectivity in logit space
 -9.0      -10.0     10.0    -3      0.0     -0.5      1  #age-6+ cR selectivity in logit space

 -9.0    -15.0     10.0     -3     -5.0     -0.5      1    #age-0 cR selectivity in logit space - cR north!
 0.0      -10.0     10.0    -3      0.0     -0.5      1   #age-1 cR selectivity in logit space
 9.0     -10.0     10.0     -3      5.0     -0.5      1    #age-2 cR selectivity in logit space
 9.0      -15.0     10.0    -1      0.0     -0.5      1   #age-3 cR selectivity in logit space
 -3.0     -10.0     10.0    -3      0.0     -0.5      1  #age-4 cR selectivity in logit space
 -3.0     -10.0     10.0    -3      0.0     -0.5      1  #age-5 cR selectivity in logit space
 -3.0     -10.0     10.0    -3      0.0     -0.5      1  #age-6+ cR selectivity in logit space

 -9.0    -10.0     10.0     -1     -5.0     -0.5      1    #age-0 cR selectivity in logit space-period 2
 0.0      -10.0     10.0    -1      0.0     -0.5      1    #age-1 cR selectivity in logit space-period 2
 9.0     -10.0     10.0     -1      5.0     -0.5      1    #age-2 cR selectivity in logit space-period 2
 0.0      -15.0     10.0    -1      0.0     -0.5      1   #age-3 cR selectivity in logit space-period 2
 0.0      -10.0     10.0    -1      0.0     -0.5      1   #age-4+ cR selectivity in logit space-period 2

                                                              #NORTH     Period 1
 2.25       0.75     10.0    3    2.25     -0.3       1     # bait age at 50% selectivity
 5.08       0.5     20.0     3     5.08     -0.3      1     # bait slope of ascending limb
 3.75       -1.0     10.0    4     3.75     -0.5      1    # bait age at 50% selectivity for descending limb
 4.08       0.05     20.0    4     4.08     -0.5      1    # bait slope of descending limb
                                                                    #Period 3
 1.80       0.25     10.0   -2    2.25     -0.3       1     # bait age at 50% selectivity
 2.69       0.5     20.0    -2     5.08     -0.3      1     # bait slope of ascending limb
 3.85       -1.0     10.0   -4     3.75     -0.5      1    # bait age at 50% selectivity for descending limb
 4.38       0.05     20.0   -4     4.08     -0.5      1    # bait slope of descending limb

 -9.0    -15.0     10.0     -3     -5.0     -0.5      1    #age-0 cB selectivity in logit space - cB north!
 0.0      -10.0     10.0     -3      0.0     -0.5      1    #age-1 cB selectivity in logit space
 5.0     -10.0     10.0      -3      5.0     -0.5      1     #age-2 cB selectivity in logit space
 9.0       -15.0     10.0   -1      0.0     -0.5      1   #age-3 cB selectivity in logit space
 -9.0      -10.0     40.0    -3      0.0     -0.5      1   #age-4 cB selectivity in logit space
 -9.0      -10.0     10.0    -3      0.0     -0.5      1   #age-5 cB selectivity in logit space
 -9.0      -10.0     10.0    -3      0.0     -0.5      1   #age-6+ cB selectivity in logit space
```

```
                                                              #SOUTH
 2.25       0.75     10.0    3    2.25     -0.3       1     # bait age at 50% selectivity
 5.08       0.5      45.0    3     5.08     -0.3      1     # bait slope of ascending limb
 3.75       -1.0     10.0    4     3.75     -0.5      1    # bait age at 50% selectivity for descending limb
 4.08       0.05     25.0    4     4.08     -0.5      1    # bait slope of descending limb

 -9.0    -10.0     10.0      -3     -5.0     -0.5      1     #age-0 cB selectivity in logit space - cB south!
 0.0      -10.0     10.0     -3      0.0     -0.5      1    #age-1 cB selectivity in logit space
 9.0     -10.0     10.0      -1      5.0     -0.5      1     #age-2 cB selectivity in logit space
 0.0      -15.0     10.0     -3      0.0     -0.5      1    #age-3 cB selectivity in logit space
 0.0      -10.0     10.0     -3      0.0     -0.5      1   #age-4 cB selectivity in logit space
 -9.0      -10.0     10.0    -3      0.0     -0.5      1   #age-5 cB selectivity in logit space
 -9.0      -10.0     10.0    -3      0.0     -0.5      1   #age-6+ cB selectivity in logit space

 2.25       0.025     10.0     2     1.25     -0.5      1    # sg composite trawl index age at 50% selectivity
 10.08       2.5      35.0     2     4.08     -0.5      1   # sg composite trawl index slope of ascending limb
 3.75       0.025     10.0      3     2.75     -0.5     3    # sg composite trawl index age at 50% selectivity for descending limb
 4.08       0.5     55.0      3     4.08     -0.5      3    # sg composite trawl index slope of descending limb

 2.50       0.25      10.0     4     3.25     -0.5      1    # Composite trawl index age at 50% selectivity
 13.08       2.5      25.0     4    10.08     -0.5      1    # Composite trawl index slope of ascending limb
 13.75       -1.0     20.0    -3     5.75     -0.5      1    # Composite trawl index age at 50% selectivity for descending limb
 4.08       0.05      25.0    -3     4.08     -0.5      1    # Composite trawl index slope of descending limb


                                                               ###### Index catchability parameters ########################
 -10.0      -15   10.0        1     -10.0    -0.5      1     # sg composite trawl index (log q)
 -10.0      -15   25.0        1     -10.0    -0.5      1     # composite trawl index (log q)
 -10.0      -15   10.0       -1     -10.0    -0.5      1     # seine index (log q)
 -10.0      -15   10.0        1     -10.0    -0.5      1     # yoy all gears index (log q)
 -10.0      -15   10.0        1     -10.0    -0.5      1     # yoy all gears index (log q)

                                                               ###### Fishing mortality parameters #########################
 -1.0       -10.0   1.00      1     -1.0     -0.5      1     #cR average log mean F - north
 -1.0       -10.0   1.00      1     -1.0     -0.5      1     #cR average log mean F - south
 -3.0       -10.0   0.50      1     -1.0     -0.5      1     #cB average log mean F - north
 -3.0       -10.0   0.50      1     -1.0     -0.5      1     #cB average log mean F - south

##### Dev vectors #######################################################################################
#########################
# lower # upper #       #
# bound # bound # phase #
#-------#-------#-------#
   -5      5       2       # cR F devs - north
   -5      5       2       # cR F devs - south
   -5      5       2       # cB F devs - north
   -5      5       2       # cB F devs - south
   -3      3       4       # rec devs
   -1.25   2.0    -2       # M devs for age-1
   -15     15       3      #devs for initial N or age structure


# cR F dev initial guesses - north
#0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

# cR F dev initial guesses - south
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0    0    0

# cB F dev initial guesses - north
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0    0    0
# cB F dev initial guesses - south
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0    0    0

# rec devs
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0    0    0

# M devs for age-1
#0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

#N devs
0 0 0 0 0 0


##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
##-- BAM DATA SECTION: likelihood weights section
##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>

###################Likelihood Component Weighting#################################################################################
##Weights in objective fcn  (commented wgts are those after correcting M vector--did not use)
1.0         #landings
0.054#1.0         #sg composite trawl index length comps
0.019#1.0  #composite trawl index length comps
0.0024#1.0  #commercial reduction age comps-north
0.0023      #commercial reduction age comps-south
0.040#1.0   #commercial bait age comps-north
0.017       #commercial bait age comps-south
1.22#1.0         #sg composite trawl index
1.85#1.0    #composite trawl index
1.0    #seine index
2.38#1.0         #yoy all gears index
0.0         #M_devs
1.0     #S-R residuals
0.0     #constraint on early recruitment deviations
0.0     #constraint on ending recruitment deviations
0.0         #penalty if F exceeds 3.0 (reduced by factor of 10 each phase, not applied in final phase of optimization) fULL F summed over fisheries
0.0     #weight on tuning F (penalty not applied in final phase of optimization)



##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
##-- BAM DATA SECTION: miscellaneous stuff section
##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
```

```
#length-weight (FL-whole wgt) coefficients a and b, W=aL^b, (W in g, FL in mm)--sexes combined
7.28E-6
3.16

#time-invariant vector of % maturity-at-age for females (ages 0-6+)
0.00   0.13   0.53   0.83   0.98   1.00   1.00

#time-varying maturity-at-age for females (ages 0-6+)
0.00 0.07 0.70 0.93 0.97 0.99 1.00
0.00 0.06 0.66 0.95 0.98 0.99 0.99
0.00 0.05 0.49 0.95 0.99 0.99 0.99
0.00 0.08 0.49 0.90 0.99 0.99 1.00
0.00 0.03 0.49 0.89 0.98 1.00 1.00
0.00 0.14 0.35 0.88 0.98 1.00 1.00
0.00 0.08 0.65 0.83 0.98 0.99 1.00
0.00 0.11 0.61 0.93 0.97 0.99 1.00
0.00 0.13 0.63 0.93 0.99 0.99 1.00
0.00 0.15 0.66 0.91 0.98 1.00 1.00
0.00 0.14 0.69 0.92 0.97 0.99 1.00
0.00 0.10 0.75 0.94 0.98 0.99 1.00
0.00 0.17 0.66 0.97 0.98 0.99 0.99
0.00 0.13 0.83 0.96 0.99 0.99 0.99
0.00 0.16 0.67 0.98 1.00 1.00 1.00
0.00 0.24 0.73 0.96 1.00 1.00 1.00
0.00 0.20 0.90 0.96 0.99 1.00 1.00
0.00 0.10 0.91 0.99 1.00 1.00 1.00
0.00 0.05 0.57 0.99 1.00 1.00 1.00
0.00 0.06 0.66 0.92 1.00 1.00 1.00
0.00 0.04 0.52 0.94 0.99 1.00 1.00
0.00 0.03 0.30 0.90 0.98 1.00 1.00
0.00 0.02 0.23 0.78 0.98 0.99 1.00
0.00 0.02 0.19 0.69 0.96 0.99 0.99
0.00 0.03 0.22 0.66 0.92 0.99 1.00
0.00 0.02 0.20 0.72 0.93 0.98 1.00
0.00 0.02 0.15 0.62 0.95 0.98 0.99
0.00 0.03 0.23 0.52 0.89 0.99 1.00
0.00 0.03 0.26 0.68 0.85 0.97 1.00
0.00 0.03 0.29 0.73 0.91 0.96 0.99
0.00 0.02 0.22 0.79 0.94 0.97 0.99
0.00 0.02 0.22 0.68 0.96 0.99 0.99
0.00 0.03 0.19 0.67 0.92 0.99 1.00
0.00 0.02 0.24 0.65 0.91 0.98 1.00
0.00 0.04 0.25 0.69 0.92 0.98 1.00
0.00 0.07 0.41 0.73 0.92 0.98 0.99
0.00 0.05 0.56 0.86 0.94 0.98 1.00
0.00 0.11 0.45 0.89 0.97 0.98 0.99
0.00 0.04 0.59 0.87 0.97 0.99 0.99
0.00 0.10 0.42 0.92 0.97 0.99 1.00
0.00 0.04 0.66 0.89 0.98 0.99 0.99
0.00 0.03 0.63 0.95 0.99 1.00 1.00
0.00 0.03 0.57 0.96 0.99 1.00 1.00
0.00 0.04 0.39 0.95 0.99 1.00 1.00
0.00 0.14 0.50 0.89 0.99 1.00 1.00
0.00 0.08 0.69 0.91 0.98 1.00 1.00
0.00 0.06 0.80 0.95 0.98 1.00 1.00
0.00 0.14 0.75 0.98 0.99 1.00 1.00
0.00 0.08 0.70 0.96 1.00 1.00 1.00
0.00 0.08 0.60 0.91 0.99 1.00 1.00
0.00 0.03 0.57 0.92 0.96 0.99 1.00
0.00 0.06 0.46 0.91 0.98 0.97 0.99
0.00 0.09 0.60 0.90 0.98 0.99 0.98
0.00 0.11 0.64 0.89 0.98 0.99 1.00
0.00 0.11 0.65 0.90 0.95 0.99 1.00
0.00 0.12 0.53 0.90 0.96 0.97 1.00
0.00 0.13 0.65 0.87 0.95 0.98 0.98
0.00 0.12 0.63 0.89 0.96 0.97 0.98
0.00 0.12 0.60 0.88 0.95 0.99 0.98


#time-invariant vector of proportion female (ages 0-6+)--assume 50:50 sex ratio
0.5 0.5 0.5 0.5 0.5 0.5     0.5

#time-invariant fecundity at age (number of maturing ova per individual)
18415 31215 69046 112949 166207 178345 207843

#time-varying fecundity at age (number of maturing ova per individual)
15567 26267 76356 134072 171499 225574 314702
13431 24883 72366 143502 198473 238833 279006
17813 23368 57467 144117 219979 262471 296958
12581 27254 57476 117858 230192 293759 320304
20803 20527 57823 113474 218295 316474 357302
14827 32777 47911 109417 189742 370470 392930
17456 26775 71349 96300 187906 279836 583275
19250 30235 67500 134037 171141 297215 375348
20150 32403 68920 131049 223455 274818 438442
19543 33692 72330 120396 210941 338151 405941
17700 33326 75794 127224 175648 296815 473099
19187 29143 82221 136478 189256 226831 379233
20535 35572 71658 169108 209101 250238 269709
22194 32194 96373 156906 300776 284953 304553
21693 35028 73488 203311 310553 476360 356683
16872 40785 80098 153362 355629 562879 687690
18546 37767 116588 165349 295467 540609 944933
10120 28938 120135 264616 312075 530105 739806
14006 23352 64090 251253 501646 544506 892560
14086 24271 71970 126973 402194 826354 886857
11982 21245 59625 138682 228571 542898 1219898
11440 18604 44895 118252 203248 378919 657341
11555 17400 39935 86830 199236 253960 585202
13208 17768 37208 75112 155318 296465 289161
12347 19244 39023 72427 126644 259346 401304
11574 17524 37913 78409 129836 195075 407546
12951 18298 33502 68360 145595 216542 278839
11150 19817 39834 60076 114123 252076 339017
```

```
13069 18579 42124 74366 101690 178182 410168
11965 19306 44310 79989 122730 163410 262470
11895 18410 39323 89194 137999 183470 250572
12195 17838 39010 73718 156641 219434 253334
11140 19072 37306 72816 128431 246471 325540
12005 18035 40898 71494 122319 209725 354998
14451 21041 41123 75715 126859 188243 323439
14039 26177 52198 80213 124490 210324 269352
18883 23564 63325 103370 137864 185986 328444
13539 29834 55250 114350 172802 213846 257181
16786 21955 65819 106374 169801 254310 305240
10353 29190 52835 126214 176012 221209 340065
8849 21827 72214 114326 215661 259222 264026
10149 19204 69223 144185 225319 335133 349075
11492 18541 64206 156512 244434 409063 481664
19958 21465 51057 151852 278590 365730 690935
12353 32798 58256 113812 280572 418758 497451
9393 27487 75179 121790 214629 434711 558555
17576 24369 89659 144090 209972 354575 594044
14983 33274 82031 196498 240004 313961 527521
16233 26878 76273 157805 330756 358097 422592
9555 27465 66446 120859 224531 467296 490110
11655 19130 63834 126059 156028 271539 587754
14563 24912 55360 119383 198305 179784 300837
15875 28460 66301 116016 190006 273240 194493
20487 30382 69774 113395 194201 268277 342797
16557 30670 71500 117175 152188 277993 346570
18411 31077 61013 116070 158122 178830 356863
18415 31910 70991 106252 152698 188034 195368
18415 31215 69046 112949 166207 178345 207843
18415 31215 66874 111211 146641 238433 194730


#time-invariant weight (in grams) at age at spawning with bias correction
37.0 78.4 182.0 287.9 360.1 515.7 446.2

#time-varying weight (in grams) at age at spawning with bias correction
27.9 62.5 206.5 335.5 406.1 496.0 622.3
21.3 58.1 196.3 354.1 452.5 516.3 574.4
35.1 53.1 156.6 355.3 487.2 551.0 598.9
18.8 65.7 156.6 302.1 503.1 594.6 629.6
44.8 43.9 157.5 292.8 484.6 624.6 675.8
25.6 83.4 129.4 284.0 437.8 691.6 717.8
34.0 64.2 193.7 254.5 434.7 575.5 911.7
39.7 75.3 183.7 335.4 405.5 599.2 697.4
42.7 82.2 187.4 329.4 492.7 568.5 768.5
40.7 86.3 196.2 307.5 472.8 652.2 732.6
34.7 85.1 205.0 321.6 413.5 598.7 805.0
39.5 71.8 221.0 340.3 437.0 497.9 701.9
43.9 92.2 194.5 401.8 469.9 533.2 561.3
49.3 81.5 254.7 379.5 604.0 582.6 609.0
47.7 90.5 199.2 460.4 616.9 808.4 675.0
32.1 108.2 215.8 372.9 673.8 892.9 1002.1
37.5 99.0 299.4 395.1 596.9 871.9 1193.6
11.8 71.2 306.9 554.1 618.9 861.9 1044.1
23.1 53.1 174.6 534.7 834.0 875.6 1157.6
23.3 56.1 195.3 321.1 728.4 1110.0 1153.6
17.0 46.2 162.5 344.7 500.6 874.1 1364.6
15.5 37.6 120.5 303.0 460.3 701.6 976.8
15.8 33.8 105.6 232.2 453.7 538.7 913.5
20.7 35.0 97.2 203.3 376.6 598.2 588.3
18.1 39.7 102.8 196.5 320.5 546.5 727.4
15.8 34.2 99.4 211.6 327.0 446.8 734.4
19.9 36.7 85.7 185.9 358.1 481.8 574.1
14.6 41.6 105.3 163.7 294.2 535.9 653.3
20.2 37.6 112.2 201.4 266.8 417.9 737.4
17.0 39.9 118.8 215.5 312.4 391.5 551.0
16.8 37.0 103.7 237.9 343.3 427.1 533.7
17.6 35.2 102.8 199.8 379.1 486.4 537.8
14.6 39.2 97.5 197.5 324.1 527.7 636.3
17.1 35.8 108.5 194.1 311.5 470.9 673.0
24.5 45.6 109.2 204.8 320.9 435.3 633.6
23.2 62.3 141.7 216.1 316.0 471.8 560.8
38.5 53.8 172.5 270.6 343.1 431.4 640.0
21.7 74.0 150.4 294.7 408.4 477.5 543.4
31.8 48.5 179.2 277.3 403.1 539.2 609.9
12.4 72.0 143.6 319.6 414.1 489.1 654.6
8.5 48.1 195.9 294.6 480.4 546.3 553.2
11.9 39.6 188.2 355.4 495.6 648.4 665.8
15.6 37.4 174.9 378.8 524.7 736.1 813.8
42.0 46.9 138.5 370.1 573.8 685.9 1004.8
18.1 83.4 158.7 293.5 576.5 746.9 829.8
9.9 66.5 203.5 310.4 478.7 764.4 888.9
34.3 56.4 239.0 355.2 471.3 672.5 921.5
26.1 84.9 220.6 449.2 518.0 621.4 859.4
30.0 64.5 206.3 381.2 642.9 676.8 751.2
10.3 66.4 180.9 308.5 494.3 799.0 822.4
16.1 39.3 173.9 319.3 377.9 563.9 915.8
24.8 58.1 150.7 305.4 452.2 420.7 604.1
28.9 69.6 180.5 298.2 438.3 566.3 445.8
43.8 75.8 189.6 292.6 445.3 559.3 658.0
31.1 76.7 194.1 300.7 370.7 573.0 662.7
37.0 78.0 166.3 298.3 381.8 419.0 675.3
37.0 80.6 192.8 277.0 371.7 434.9 447.3
37.0 78.4 187.7 291.6 396.6 418.2 467.8
37.0 78.4 182.0 287.9 360.1 515.7 446.2

#time-invariant weight (in grams) at age at middle of fishing year
56.9 128.1 231.7 328.5 371.1 537.1 448.1

#time-varying weight (in grams) at age at middle of fishing year
36.7 126.2 279.1 397.5 459.9 533.3 622.6
25.3 105.8 269.1 431.5 502.2 563.4 606.7
43.2 94.0 232.5 410.6 545.5 586.4 634.6
```

```
24.0 110.2 227.0 368.9 530.1 622.7 651.3
62.8 77.5 230.6 367.0 494.1 622.4 672.2
35.3 132.3 189.8 363.2 488.8 599.3 690.3
51.6 118.9 254.9 328.0 489.7 585.0 683.1
57.5 128.0 265.9 396.4 471.3 600.8 656.5
62.0 140.9 248.2 407.2 542.2 606.4 693.4
63.7 142.7 266.4 360.2 520.9 682.4 726.0
52.8 143.7 270.0 377.5 450.9 604.4 810.9
65.6 121.0 280.1 392.7 462.8 518.8 662.5
63.8 158.4 251.0 426.5 496.4 523.7 567.4
73.0 124.8 307.7 411.7 565.3 577.8 565.3
75.6 138.4 243.6 452.7 587.6 687.3 638.9
55.7 177.6 258.8 404.1 575.4 766.0 789.5
48.4 167.4 344.6 411.4 603.0 671.5 937.8
24.8 125.4 339.9 511.8 588.8 834.8 743.4
40.5 118.0 263.8 486.2 658.5 783.1 1093.6
28.6 104.0 266.0 414.5 591.5 777.6 986.9
27.1 84.2 213.8 377.5 556.6 661.3 870.0
18.0 67.4 186.2 328.0 445.9 679.7 705.5
21.2 64.2 145.2 294.9 430.8 484.3 781.1
28.9 68.1 157.4 240.2 393.5 516.1 504.9
25.3 67.8 161.4 262.4 341.6 475.4 583.3
22.1 55.7 141.2 269.1 361.0 441.2 539.7
20.8 69.0 117.5 230.4 373.8 444.8 534.0
24.9 71.9 159.3 202.1 325.7 466.2 511.8
30.6 69.9 171.6 260.0 306.0 420.0 543.2
23.8 67.7 157.8 279.9 354.8 425.0 508.6
21.9 67.5 138.9 262.0 378.1 436.1 554.5
25.5 65.9 150.3 228.9 367.8 458.8 502.1
25.9 73.7 149.9 243.7 330.5 466.1 521.5
27.3 69.0 160.6 243.7 333.8 437.1 552.5
41.2 93.2 150.8 252.2 332.5 413.4 543.4
37.5 114.7 207.7 246.0 334.3 409.3 479.9
52.5 94.0 228.2 315.9 341.6 401.8 472.1
30.1 128.3 192.9 327.1 401.2 429.6 454.3
51.0 95.3 247.2 298.8 400.7 462.7 506.4
25.2 122.8 218.5 358.6 397.3 451.5 504.8
23.5 118.6 243.0 351.9 449.3 481.7 484.8
18.2 98.5 286.6 366.4 473.6 517.7 550.5
29.7 88.3 243.1 435.1 477.0 574.9 567.0
61.1 94.7 227.0 388.4 541.6 568.5 654.4
40.3 134.7 219.5 363.3 507.8 610.8 640.7
28.2 136.2 261.3 357.0 471.4 596.4 653.6
55.4 128.0 291.6 400.2 484.6 548.7 658.6
37.8 145.9 289.3 426.1 535.1 592.5 600.9
48.1 116.9 262.8 414.7 523.7 656.8 678.6
24.8 114.4 242.1 345.9 494.5 588.5 761.4
35.3 88.3 224.0 350.8 397.0 540.9 629.6
43.6 114.2 199.2 334.7 430.7 426.2 566.7
53.7 129.6 233.0 303.1 432.7 484.5 442.5
59.7 134.8 252.5 328.1 384.1 512.8 519.3
53.4 117.6 245.6 347.3 392.2 441.6 575.2
57.7 134.6 215.1 331.7 409.4 432.1 480.5
56.9 132.7 241.5 324.0 389.7 447.2 455.8
56.9 128.1 239.1 320.4 433.7 426.1 469.2
56.9 128.1 231.7 328.5 371.1 537.1 448.1

#time-varying length at age for the population - May 15 = 76/365d - SEAMAP and GA composite trawl
101.0 171.6 236.5 270.1 285.7 302.0 321.0
86.5 164.0 233.9 275.3 294.4 305.9 315.0
111.7 161.4 218.0 276.2 301.5 311.8 319.2
85.6 168.8 217.9 264.4 305.0 319.3 324.1
120.5 151.5 217.3 260.7 304.2 324.6 331.3
91.0 181.7 205.7 258.3 293.0 338.3 337.9
103.1 171.1 231.3 250.4 293.2 317.4 367.6
111.3 177.9 228.6 271.6 287.2 322.7 335.9
114.9 182.0 228.5 269.9 304.2 317.5 347.7
112.9 184.6 231.7 262.8 299.5 330.6 342.5
108.5 184.8 235.1 266.7 286.0 320.7 352.0
107.5 175.4 242.2 271.8 291.3 301.7 335.9
120.5 190.9 233.6 288.1 298.3 308.6 312.3
125.3 180.8 253.5 284.4 324.7 317.6 320.7
115.5 186.5 234.5 300.3 328.6 353.9 331.6
88.5 200.7 240.2 282.4 335.4 367.1 377.3
113.7 198.5 267.1 287.2 325.1 361.7 400.7
51.6 173.4 268.7 319.0 328.3 363.1 381.4
89.6 166.6 224.8 313.5 359.5 364.4 397.0
96.9 163.8 233.6 268.9 342.0 391.1 396.1
84.5 152.0 220.4 272.6 306.9 360.2 415.7
82.6 143.7 200.6 263.6 295.4 339.5 371.8
83.0 138.9 192.6 243.4 296.4 308.6 367.6
93.9 140.6 188.2 233.1 281.2 321.4 316.3
90.7 144.4 191.8 231.4 266.5 314.4 340.5
81.2 137.6 188.3 237.1 269.2 294.2 343.8
90.5 142.9 179.9 226.5 277.4 302.4 317.1
76.5 147.6 192.4 218.0 259.7 313.0 331.4
92.8 145.3 196.2 232.2 252.3 288.5 344.7
84.8 145.1 200.7 237.5 264.0 283.2 313.6
85.9 142.7 191.3 245.2 272.7 289.6 311.1
85.2 140.2 190.9 232.1 281.1 302.5 310.2
77.7 145.4 188.1 230.9 268.2 310.0 328.0
78.7 142.6 194.0 230.3 264.2 300.0 333.2
88.4 154.5 195.2 233.3 267.6 291.8 328.1
91.2 169.3 211.6 237.8 265.0 300.4 314.8
114.0 161.1 223.4 254.5 272.3 290.6 329.3
91.3 175.6 214.9 259.7 286.8 300.3 311.2
101.5 156.1 226.2 256.2 283.9 311.0 323.0
60.0 176.2 213.1 267.9 288.0 300.1 329.3
48.4 161.2 233.3 263.2 302.2 312.4 310.9
66.2 153.5 232.8 276.9 307.2 330.4 331.2
72.8 147.4 228.4 283.3 310.1 345.9 353.6
115.7 157.4 211.7 281.9 319.1 335.5 379.9
68.5 182.7 219.8 262.6 320.0 344.3 354.9
39.7 177.5 235.2 266.0 302.9 347.2 362.2
```

```
97.3 171.5 249.8 276.5 300.0 334.7 366.6
91.8 185.4 242.6 297.8 308.8 325.2 360.0
100.2 171.1 234.2 280.9 329.7 334.1 343.8
56.8 171.4 227.2 261.3 301.5 350.8 354.0
63.8 151.1 224.2 266.9 276.4 312.7 364.8
83.7 168.7 216.7 263.4 295.0 284.7 318.7
90.2 175.9 226.3 262.4 292.5 314.9 289.4
121.6 179.7 229.2 257.8 294.3 314.1 329.0
93.9 175.9 230.3 260.0 275.1 316.4 330.1
105.8 180.7 219.8 258.9 277.8 284.6 331.9
107.1 181.1 229.5 255.1 275.2 288.1 289.8
107.1 179.2 227.6 256.9 283.6 284.4 294.0
107.1 179.2 225.6 256.3 272.3 306.6 289.6

#time-varying length at age for the population - September 1 = 185/365d
120.3 192.2 249.4 278.0 292.4 306.3 321.4
110.4 180.5 247.9 284.0 300.1 310.3 317.9
129.2 179.4 232.2 285.7 307.4 315.8 322.1
106.1 183.7 231.6 276.6 311.5 323.3 327.0
139.6 168.3 229.9 271.0 314.6 329.0 334.0
117.0 197.2 219.6 269.0 300.8 347.3 340.9
127.9 189.8 243.9 261.8 302.2 323.3 375.3
134.4 194.7 242.0 281.7 296.6 330.4 340.4
137.5 198.3 239.9 279.5 312.4 325.3 354.2
135.4 200.9 243.1 270.5 306.4 337.3 348.9
128.8 202.8 247.0 274.7 291.2 325.6 357.4
134.2 193.1 256.6 280.4 296.9 305.2 339.5
138.7 211.0 249.1 299.6 304.6 312.5 314.7
143.9 197.0 268.5 297.8 333.9 322.2 323.5
142.4 202.8 249.0 311.6 340.3 361.3 334.9
125.6 221.7 254.4 295.3 343.8 377.3 383.1
131.9 222.2 283.5 299.7 336.5 368.0 409.6
91.6 189.1 283.8 331.8 339.3 373.3 386.1
113.2 189.9 238.3 323.1 369.4 374.0 406.1
113.6 181.9 247.1 280.5 348.2 398.8 404.5
102.8 166.7 234.2 280.5 316.9 364.1 421.8
99.7 158.8 213.6 274.0 300.0 348.1 374.3
100.4 153.9 205.1 254.8 304.4 311.3 375.0
109.3 156.1 201.3 243.4 291.2 327.5 317.9
104.8 157.8 205.5 242.9 275.1 323.3 345.1
100.5 150.3 199.9 249.3 279.3 301.3 351.6
108.0 158.4 191.3 236.6 288.2 311.2 322.9
98.0 162.5 204.9 228.3 268.4 322.6 339.2
108.6 162.6 208.9 242.1 261.6 296.1 353.2
102.7 159.1 214.6 248.3 272.1 291.6 320.2
102.3 157.6 203.6 256.4 281.8 296.1 318.7
104.0 154.7 203.3 243.0 290.1 310.3 315.3
98.0 160.6 200.9 241.2 277.8 317.2 334.6
102.9 159.0 206.3 241.6 272.7 308.5 339.0
115.3 172.8 208.5 243.2 277.5 298.9 335.7
113.4 187.3 225.3 248.6 273.0 309.2 320.7
133.1 178.2 235.5 264.8 281.1 297.0 337.1
111.0 191.3 228.0 267.7 294.5 307.4 316.4
125.3 173.4 239.1 266.3 289.3 316.9 328.8
93.1 194.4 228.3 278.5 295.7 303.7 333.7
82.6 184.6 247.2 276.5 310.9 318.3 313.3
91.7 177.9 249.3 287.4 318.9 337.6 335.7
100.0 167.7 245.8 295.0 318.2 356.2 359.5
136.8 177.5 227.7 294.3 327.3 341.7 389.0
104.8 199.3 234.7 275.3 328.9 350.2 359.6
86.6 201.6 248.2 276.9 312.9 353.5 366.3
128.4 196.8 265.8 286.7 308.1 342.7 371.1
117.7 202.6 256.2 308.4 316.8 331.2 366.2
123.1 189.4 243.8 288.2 336.7 340.4 348.2
87.7 188.3 240.2 266.7 305.5 355.5 358.9
101.0 172.6 236.8 276.1 279.3 314.8 367.9
115.8 189.1 231.7 272.7 301.5 286.4 319.8
121.6 194.5 237.4 272.9 299.4 319.5 290.3
138.6 197.4 239.9 263.9 301.6 319.2 332.2
124.4 189.6 240.3 266.2 278.4 321.5 333.9
131.5 197.8 230.8 264.6 281.4 286.4 335.4
131.5 196.9 239.1 264.0 278.4 290.2 290.8
131.5 194.8 237.4 262.3 290.8 286.2 295.2
131.5 194.8 235.8 262.3 275.4 312.4 290.6

#time of year (as fraction) for spawning: Mar 1 = 0d/365d
0.0

#age-dependent natural mortality at age (ages 0-6+)
1.12 0.82 0.65 0.57 0.52 0.50 0.48

#Max observed age
12

#age-dependent, time-varying natural mortality at age (ages 0-6+)
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
```

```
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48
1.12 0.82 0.65 0.57 0.52 0.50 0.48


#Spawner-recruit parameters
# SR function switch (integer 1=Beverton-Holt, 2=Ricker)
1

#rate increase switch: Integer value (choose estimation phase, negative value turns it off)
-1
##annual positive rate of increase on all fishery dependent q's due to technology creep
0.0
# DD q switch: Integer value (choose estimation phase, negative value turns it off)
-1
##density dependent catchability exponent, value of zero is density independent, est range is (0.1,0.9)
0.0
##SE of density dependent catchability exponent (0.128 provides 95% CI in range 0.5)
0.128
#Age to begin counting D-D q (should be age near full exploitation)
2
#Random walk switch:Integer value (choose estimation phase, negative value turns it off)
-3
#Variance (sd^2) of fishery dependent random walk catchabilities (0.03 is near the sd=0.17 of Wilberg and Bence
0.03
0.03
0.03
0.03

#Tuning F (not applied in last phase of optimization)
1.5
#Year for tuning F
2013

##threshold sample sizes for length comps (set to 99999.0 if sel is fixed)
10.0 #SG composite trawl
10.0 #Composite Trawl

#threshold sample sizes (greater than or equal to) for age comps
10.0 #commerical reduction - NORTH
10.0 #commercial reduction - SOUTH
10.0 #commercial bait - NORTH
10.0 #commercial bait - SOUTH

#Ageing error matrix (columns are true age 0-6+, rows are ages as read for age comps: columns should sum to one)
#0.98 0.02 0.00 0.00 0.00 0.00 0.00
#0.02 0.97 0.02 0.00 0.00 0.00 0.00
#0.00 0.03 0.93 0.03 0.00 0.00 0.00
#0.00 0.00 0.09 0.82 0.09 0.00 0.00
#0.00 0.00 0.00 0.19 0.62 0.19 0.00
#0.00 0.00 0.01 0.06 0.24 0.39 0.31
#0.00 0.01 0.02 0.06 0.12 0.18 0.60

1.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 1.00 0.00 0.00 0.00 0.00 0.00
0.00 0.00 1.00 0.00 0.00 0.00 0.00
0.00 0.00 0.00 1.00 0.00 0.00 0.00
0.00 0.00 0.00 0.00 1.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 1.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 1.00

999 #end of data file flag
```

PROJECTIONS OF CONSTANT LANDINGS OF ATLANTIC MENHADEN

The following results were computed based on fixed constant landings scenarios with constant landings being 32,700 mt for the northern reduction fishery, 98,300 mt for the southern reduction fishery, 21,100 mt for the northern bait fishery, and 17,300 mt for the southern bait fishery. Thus, total landings are 169,400 mt. These constant landings values were based on the 2013 landings, which is the first year of the currently implemented quotas.

Methods

Data into and output from the Monte Carlo bootstrap (MCB) runs of the base run of the Beaufort Assessment Model (BAM) were used as the basis for the projections within this document (see stock assessment report for details on base run and MCB runs). Projections were run for a total of 9 years with constant landings (2014-2022). The starting conditions of the projection analysis include initial numbers at age, which were the estimated numbers at age, N_a, for year 2014 from the BAM for each MCB run.

Numbers at age after the initial year were calculated as:

$$N_{a+1,y+1} = N_{a,y} e^{-Z_{a,y}}$$

where Z was age and year specific mortality and equals natural mortality for each age for that year plus the fishing mortality rate times the selectivity at age. The vector for natural mortality for each projection was the vector from each MCB run. Selectivity was a vector from each MCB run for each fishery with the northern and southern commercial reduction fishery selectivities being the values in the last time period. Fishing mortality was estimated using the optimize function in R in order to match the annual landings (level of landings denoted above). Annual landings were calculated using the Baranov catch equation and weight of landings.

Recruitment was projected without an underlying stock-recruitment function and was based on the median recruitment observed in each MCB run. Recruitment variability was included whereby for each year a deviation in recruitment was selected randomly with replacement from the deviations estimated in each MCB run.

The number of projections was the same as the number of filtered MCB runs. Outputs included the median and 5th and 95th percentiles for fecundity (ova) over time, fishing mortality over time, recruitment over time, and landings over time. Fecundity for each year was the number of fish in each age times the reproductive vector at age. Specifically, maturity from the final year of each MCB run, a 50:50 sex ratio, and a mean fecundity at age were used to produce the reproductive vector at age.

Notes of interest:

This projection is an example based on the 2013 landings.

The fishing mortality rate associated with constant landings is variable given the uncertainty included in the system. However, using these specified landings, the fishing mortality rate does not go above the fishing mortality threshold or target. In addition, the fecundity does not go below the fecundity threshold or target.

As usual, projections should be interpreted in light of the model assumptions and key aspects of the data. Some major considerations are the following:

- In general, projections of fish stocks are highly uncertain, particularly in the long term (e.g., beyond 5 years).
- Although projections included many major sources of uncertainty, they did not include structural (model) uncertainty. That is, projection results are conditional on one set of functional forms used to describe population dynamics, selectivity, recruitment, etc.
- Fisheries were assumed to continue fishing at their estimated current proportions of total effort, using the estimated current selectivity patterns. New management regulations that alter those proportions or selectivities would likely affect projection results.
- If future recruitment is characterized by runs of large or small year classes, possibly due to environmental or ecological conditions, stock trajectories may be affected.
- Projections apply the Baranov catch equation to relate F and landings using a one-year time step, as in the assessment. The catch equation implicitly assumes that mortality occurs throughout the year. This assumption is violated when seasonal closures are in effect, introducing additional and unquantified uncertainty into the projection results.

Table 1. Median, 5th, and 95th percentiles for fishing mortality (F) over time based on constant landings and a median recruitment with variability based on estimated recruitment deviations for each MCB run.

Year	Median	5th	95th
2014	0.40	0.24	0.67
2015	0.53	0.31	0.91
2016	0.44	0.29	0.61
2017	0.37	0.27	0.49
2018	0.35	0.26	0.45
2019	0.34	0.26	0.43
2020	0.34	0.26	0.43
2021	0.34	0.26	0.42
2022	0.34	0.25	0.42

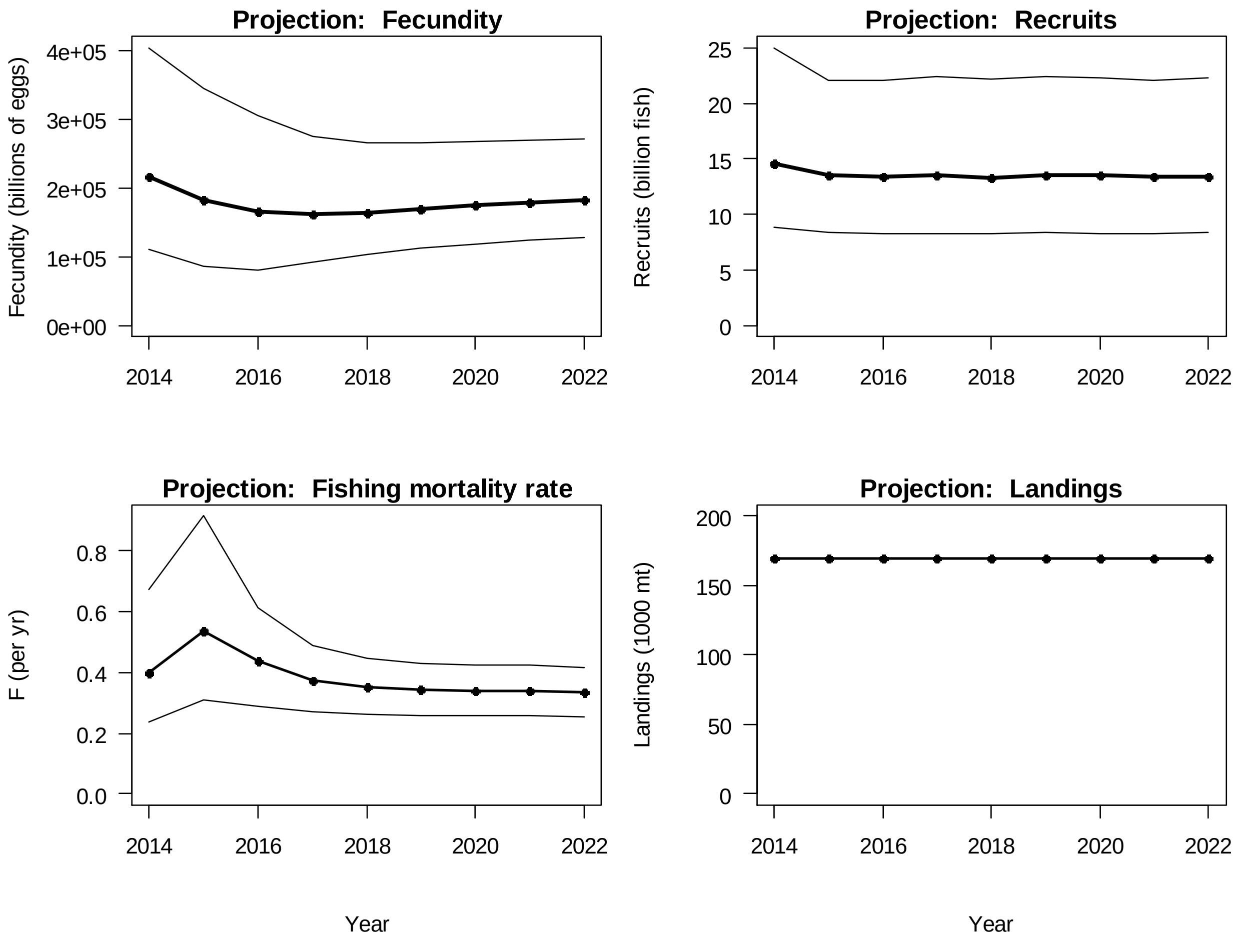


Figure 1. Fecundity, recruits, fishing mortality (*F*), and landings over time based on constant landings and median recruitment with variability based on estimated deviations for each MCB run. The solid flat line in the landings panel is the constant landings specified in the model.

1. Background

This report was drafted in response to the Stock Assessment Term of Reference #7 for the 2014 Atlantic menhaden benchmark assessment:

> "Identify potential ecological reference points that account for Atlantic menhaden's role as a forage fish. Provide proposed methodology, a model development plan, and example results using preliminary model configurations, if time allows. *Note: finalized ERPs will not be developed in time for the 2014 Atlantic menhaden peer review or 2015 Management Board meetings. Additional technical work and peer review will be necessary before ERPs will be available for management use.*"

A subcommittee composed of members of the Atlantic Menhaden Technical Committee and the Multispecies Technical Committee was formed to draft an ERP plan. The subcommittee's plan was vetted and approved by the Atlantic Menhaden Technical Committee (AMTC) prior to inclusion in the 2014 benchmark stock assessment report.

The intent of this report is to describe the ERP options for Atlantic menhaden identified by the AMTC as most likely to address the needs and interests of the Atlantic Menhaden Management Board (AMMB, or Board). In addition, ecosystem monitoring and modeling approaches that would support multispecies management issues faced by the ASMFC as a whole are presented with the hope that the process of managing menhaden for forage services be incorporated into a broader Ecosystem-Based Fisheries Management framework.

2. Overview of approaches considered

The AMMB has expressed an interest in potentially managing menhaden to maintain both sustainable fisheries and forage services. The task generated by the Board was to "identify potential ecological reference points that account for Atlantic menhaden's role as a forage fish". As this task was extremely broad and specific with goals ill-defined, a suite of ERP and ecosystem monitoring approaches are presented in this report. Each approach described addresses different aspects of forage fish management within either a single species or ecosystem-based fisheries management framework.

Some ideas presented in this report could be ready for management use by spring 2015. Others would require more time (ranging from months to years) to fully develop. A summary of the general type of deliverables and the estimated timeline for development of each approach are provided in Table 1. Possible management objectives or goals are outlined in Table 2, as well as which of these approaches may address these goals. The details of each approach are presented in order of increasing complexity in Sections 2.1-2.7 below. Conclusions and recommendations are presented in Section 3.

APPROACH	BRIEF SUMMARY OF ERP/EBFM PRODUCTS	TIME REQUIRED TO DEVELOP
Ecosystem indicators	EBFM monitoring tool	1-2 months, annual updates
Nutrition Ref Points	ERPs for prey and predators, EBFM monitoring tool	1-2 months. **Additional data collection program required.**
Production models		
Steele-Henderson	MSY-based ERPs for menhaden, consumption estimates	6 months-1 year
Time-varying *r*	MSY-based ERPs for menhaden	6 months-1 year
Single-species models		
BAM-based forage services ERPs	SPR-based ERPs for menhaden	Completed. Associated harvest calcs deliverable by early 2015.
BAM or SS-based time-varying M tuned to consumption index	SPR-based ERPs for menhaden	1 year
BAM-based MSE	MSE platform for testing performance of single-species ERPs	Planned for 2015
Multi-species models		
MSVPA or MSSCAA + BAM projections	Estimate of minimum forage needs for major predators	Near completion. Could be available early 2015.
MSSCAA	Forage services ERPs for menhaden, consumption estimates, platform for MS-MSE	1 year to finalize model, 3-4 years for MS-MSE
Ecopath with Ecosim	Forage services ERPs for menhaden, consumption estimates, platform for MS-MSE	2 years for model development, 3-4 years for MS-MSE

Table 1. Summary of approaches pursued in developing ERPs and ecosystem monitoring tools to support menhaden management for forage services. The estimates of time required to complete each approach assume dedicated time from multiple AMTC and ERP subcommittee members. Note: MSE stands for Management Strategy Evaluation; EBFM stands for Ecosystem Based Fisheries Management; SPR stands for Spawning Potential Ratio; BAM stands for Beaufort Assessment Model; SS stands for Stock Synthesis; MSVPA stands for Multi Species Virtual Population Analysis; and MSSCA stands for Multi Species Statistical Catch at Age Model.

	POTENTIAL MANAGEMENT GOALS/OBJECTIVES							
APPROACH	Low disease prevalence	Adequate nutrition levels	Enough prey to support key predator species @ preferred biomass levels	Sustainable AM fishery in light of forage pressure	Better AM recruitment and/or high AM abundance at younger ages	Determine if AM are more economically valuable in the fishery or as forage	Sustainable AM commercial reduction and/or bait fisheries	Manage for a broader-age structure (may lead to re-expansion of historic range)
Ecosystem indicators	x[1]				x			
Nutrition Ref Points	x[1]	x[2]						
Production models								
Steele-Henderson			x	x			x	
Time-varying r				x			x	
Single-species models								
BAM-based forage services ERPs				x	x		x	x
BAM or SS-based time-varying M tuned to consumption index				x	x		x	x
BAM-based MSE				x[3]	x		x	x
Multi-species models								
MSVPA or MSSCAA + BAM projections			x	x	x		x	x
MSSCAA			x	x	x		x	x
Ecopath with Ecosim			x	x	x		x	x

[1] Would require data on disease prevalence be collected.
[2] Would require collection of condition data at a broader spatial scale than at present.
[3] If M is treated in a way that accounts for consumption.

Table 2. Potential management objectives and the approaches suggested to achieve each objective.

2.1 Ecosystem indicators

Development of ERPs is a complex and time intensive process, but a number of methods exist that could provide more timely indicators of ecosystem health. These methods do not provide quantitative single or multi-species reference points; however, qualitative reference points are developed which can provide information on the status of the system as a whole and may be used to guide management decisions in the absence of quantitative reference points. In addition, lack of quantitative reference points is offset by the short time frame in which qualitative indicators can be developed, which allows for annual updates of system status. Development of ecosystem indicators could therefore be used as an interim, or even complementary, step in the development of ecosystem reference points. A number of potential indicators are discussed below, along with examples of their development and implementation.

Deliverables for management include (but would not necessarily be limited to):

- Environmental indicators such as
    - spatial and temporal measures of chlorophyll-a
    - sea surface temperature
    - indices of the Atlantic Multidecadal Oscillation (AMO) and the North Atlantic Oscillation (NAO)
- Indices of forage abundance for a suite of forage species identified by scientists and managers as important for monitoring ASMFC management interests and goals
- Prey: predator ratios
    - prey:predator biomass ratios for species such as Atlantic menhaden relative to bluefish, striped bass, and weakfish
    - ratios based on fishery independent measures of prey and predator abundance
    - ratios of multiple prey items and predators
    - ratios incorporating a feeding model to account for such things as prey and predator temporal and spatial overlap.

Note that these last two items, depending on specific manager requests, would require additional time for development. Additional details on each proposed indicator are provided below.

Environmental indicators

Population size of a given species in an ecosystem is dependent on production at the base of the food web and trophic transfer efficiencies up the food web to the focal species. In the marine environment, phytoplankton are responsible for a large portion of this base production. Thus an estimate of coastal and marine phytoplankton biomass would be a useful indicator for understanding the variability in population sizes of coastal and marine fish stocks.

In addition to providing general utility of estimating system or species productivity, finer temporal and spatial scale information on phytoplankton can be used to identify plankton blooms. In the ocean, plankton blooms can indicate the transfer of energy from pelagic to benthic portions of an ecosystem. As plankton die and settle to the bottom, they become food for benthic invertebrates. Conversely, when phytoplankton blooms occur in shallower and warmer waters of an estuary, the result is often a decrease in the oxygen content in the water, hypoxia and anoxia. Phytoplankton, via photosynthesis, will raise oxygen concentration during daylight hours; however, at night, the plankton will reduce oxygen concentration as respiration occurs. Additionally, when phytoplankton die and sink to bottom, they are decomposed by bacteria. This process also reduces oxygen concentrations. Drastically reduced oxygen concentration often result in fish kills and can kill benthic invertebrates, and generate “dead zones” in estuarine and coastal environments.

Besides the influence of phytoplankton blooms on benthic productivity, the timing of phytoplankton blooms can influence pelagic productivity. Variability in the configurations of annual spring bloom events occur due to fluctuations in environmental conditions, like temperature and light attenuation. As a result, the timing of spring bloom patterns is probably driven by climate patterns.

Many studies have demonstrated the connection between environmental conditions and the patterns of spring blooms. As an example, in Narragansett Bay the start date of the spring bloom was shown to be influenced by temperature and light (Smayda 1988). In addition, Smayda (1988) discussed that in Long Island Sound and the Gulf of Maine, during cooler years, phytoplankton blooms began later in the year, lasted longer, and were more productive. Conversely in warmer years, blooms began sooner and were shorter and more intense. In Chesapeake Bay, Miller and Harding (2007) demonstrated that changes in winter weather patterns and freshwater flows, resulting from climate patterns, caused shifts in spring bloom patterns in Chesapeake Bay. In warm, wet years, the spatial extent of blooms was larger and was located closer to the mouth of the Bay. Phytoplankton concentrations were higher and the peak occurred later in spring.

Temperature shifts also influence the zooplankton that graze on the phytoplankton. Durbin and Durbin (1992) showed that a 2°C increase in water temperature resulted in a three-week shift in the maturation of the zooplankton grazers. The timing and availability of plankton can influence the availability of food for planktivorous fish. In turn, this can influence the availability of prey for piscivore predators. The location and timing of phytoplankton blooms can result in increased or decreased ecosystem productivity.

The importance of phytoplankton to marine and coastal ecosystem productivity suggests that plankton abundance is a useful ecosystem indicator; as such an indicator would provide valuable insights on the bottom-up drivers of the ecosystem. As environmental and climate factors influence the timing, intensity and duration of phytoplankton blooms, environmental and climate indicators will additionally be useful for interpreting how phytoplankton influences ecosystem productivity. In addition, spatial information on environmental parameters will be useful for understanding where fish may be distributed based in their preferences for the levels of these environmental factors.

In the future, additional ecosystem indicators could be added (e.g., zooplankton, jellies, and other benthic organisms) as coastwide data and methods for processing them quickly for this report become available.

Methods

Satellite data: A commonly-used proxy for phytoplankton biomass is the concentration of chlorophyll-a (chl), a pigment used for photosynthesis in phytoplankton. Pigment concentrations can be measured remotely via satellites by observing the ocean color. Satellite-based ocean color remote sensors are often used to estimate chl to assess the productivity of an ocean region. Currently NOAA's Coastwatch program has satellite images for subregions of the Atlantic Coast (Figure 1).

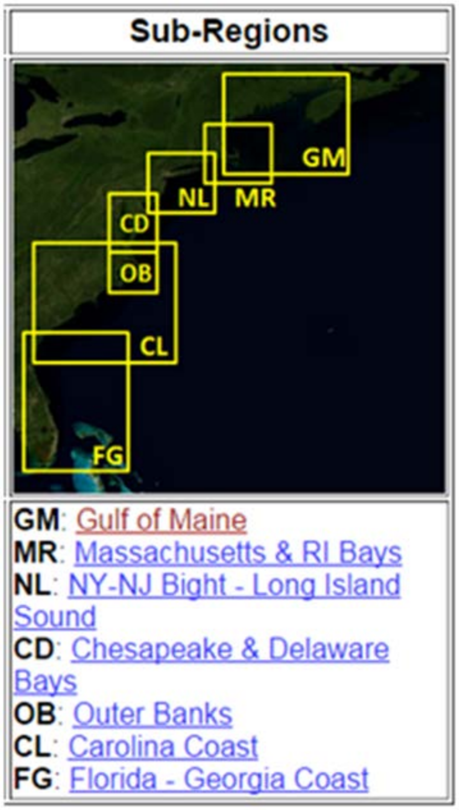


Figure 1. NOAA Coastwatch satellite data regions. (http://eastcoast.coastwatch.noaa.gov/cw_regions.php#ec)

Within each of these subregions, composite images can be created for chl (Figure 2) and sea surface temperature, SST (Figure 3).

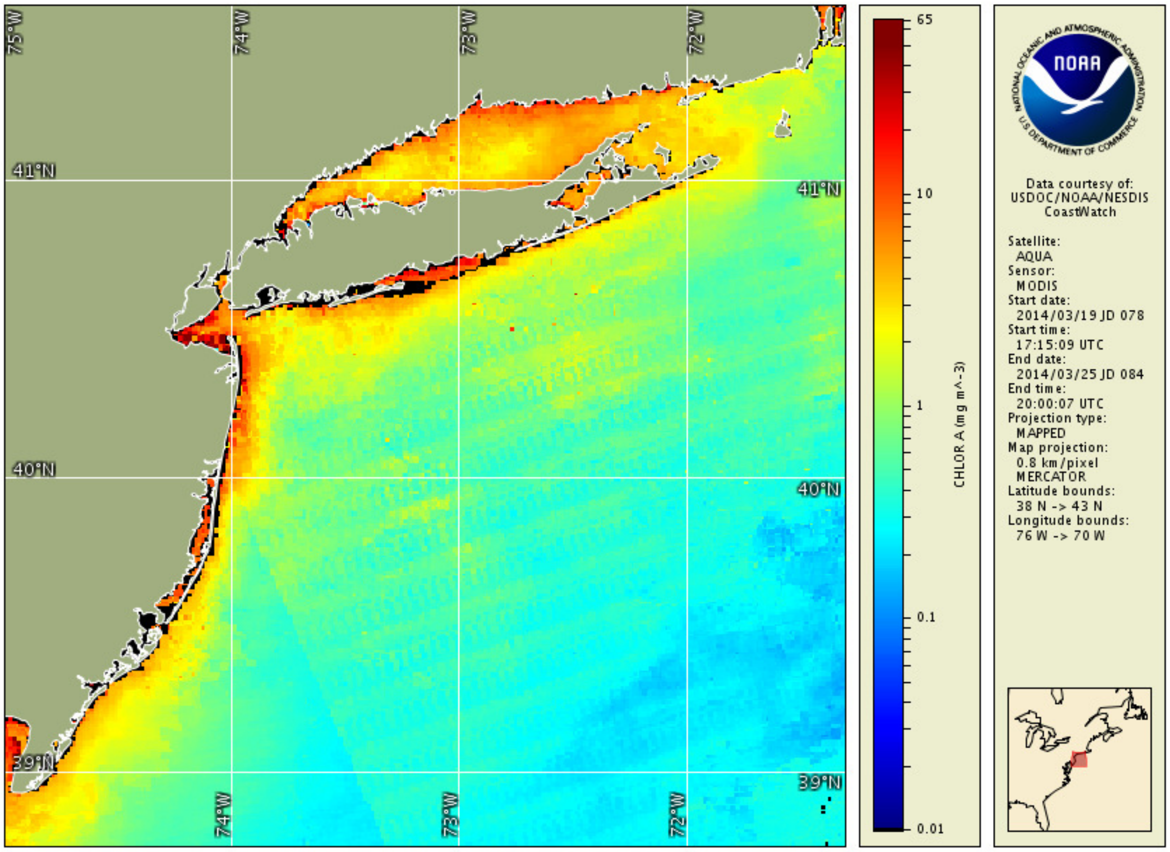


Figure 2. Example satellite image showing spring chl in the NY-NJ Bight and Long Island Sound.

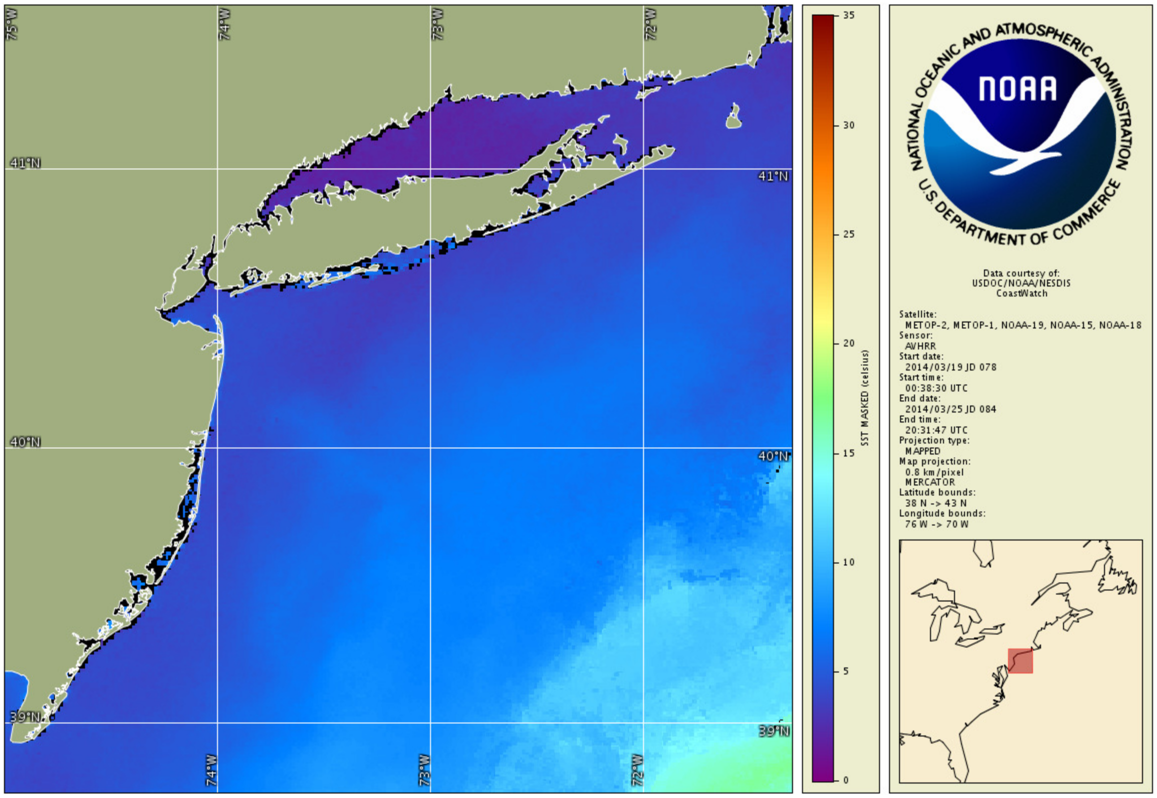


Figure 3. Example satellite image showing spring SST in the NY-NJ Bight and Long Island Sound.

In addition to these maps, staff from NOAA's satellite division (NESDIS) and NASA are converting these images into regional average values and are preparing climatologies (i.e., time series of SST and chl) for the regions/subregions (personal communication, Ron Vogel – NOAA/NESDIS/Coastwatch). Graphs of the time series of SST and chl along with seasonal maps of each of the subregions will be used as ecosystem indicators for ASMFC in a qualitative ecosystem report. Each year a report is produced the time series data will be updated and seasonal maps for that year will be included.

Note that if desired, Coastwatch staff can reconfigure the maps so that the subregions are re-defined or aggregated according to the BERP workgroups specifications (personal communication, Ron Vogel). Currently satellite SST data are available from the 1990s to present and chl data are available for 2002 to present. Suspended solids and light attenuation maps are also available in some parts of the Atlantic Coast and can be incorporated into a report if desired.

Climatology

North Atlantic climate drives SST and chl production. Satellite data are only available for the past couple of decades, whereas information on over a century's data on climate patterns are available. Climate information may be useful for understanding long-term trends in ecosystem productivity and patterns in forage fish production. To provide a useful set of ecosystem indicators for ASMFC, climate indicators should be included. The two indicators of climate to be included in this report are the Atlantic Multidecadal Oscillation (AMO) Index and the North Atlantic Oscillation (NAO) Index.

In the Atlantic, long-term patterns in sea surface temperature (SST) in North Atlantic are represented by the AMO index. The AMO index is based on SST variability. SST data in the AMO index are detrended to remove the anthropogenic forcing on temperature, thus it reveals the natural, long term cycles in SST. The cool and warm phases of the AMO result in below and above average water temperature over most of the North Atlantic.

The NAO index is correlated with key oceanographic and ecological processes in the North Atlantic. The weather and climate of the North Atlantic are largely driven by the relative strengths of two large-scale atmospheric pressure systems. The pattern of these pressure systems oscillates such that when the NAO is high, temperatures of the US coast are high. When the NAO is low, temperatures off the US Coast are low.

Examples climate indicators are shown in Figure 4. Data to reproduce and update these indicators are available from NOAA's Earth Systems Research Laboratory (http://www.esrl.noaa.gov/psd/data/climateindices/list/).

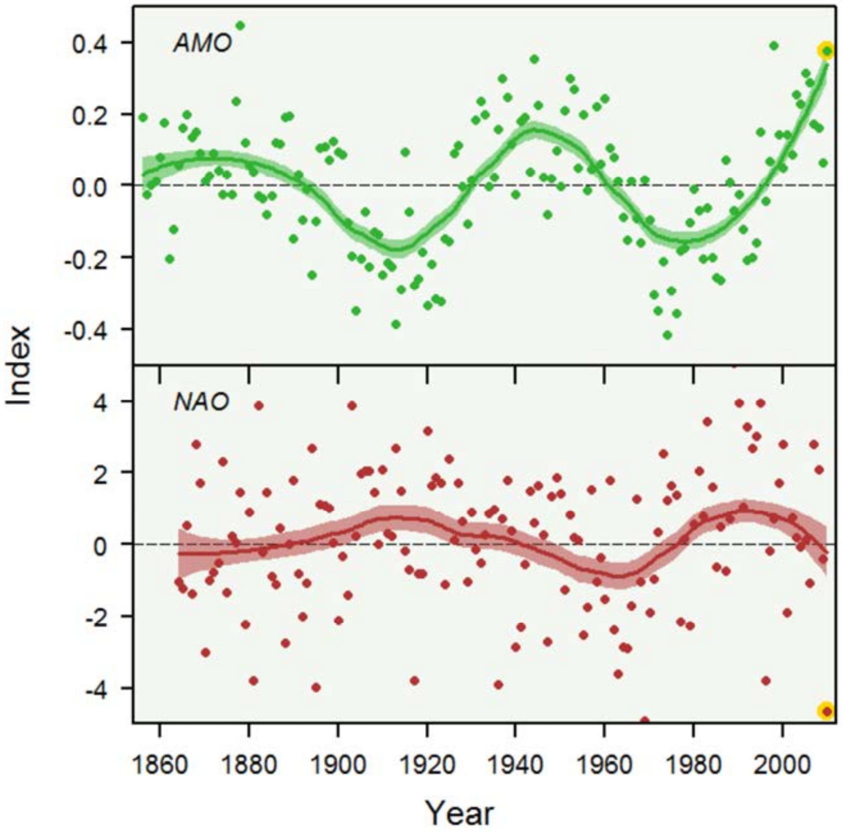


Figure 4. Example climate indicators. Smoothed trends in the winter AMO and NAO over the last ~150 years expressed as standardized anomalies. Data for 2010 highlighted in yellow. (Source: Ecosystem Assessment Program. 2012)

Indices of forage abundance

Forage species play an important role in ecosystem dynamics, and changes in forage availability may indicate changes in ecosystem health. The importance of forage in predator population management has led to the development of forage fish management plans (*e.g.* Bargmann 1998, Osmerth et al 2008), or the consideration for forage needs in management decisions (Overholtz et al 2008; ASMFC 2012). In addition, several organizations on the east coast are in the process of developing guidance for establishing reference points for forage species that account for predation needs (S. Gaichas, NEFSC, pers. comm. Sept 2014; T. Ihde, Chesapeake Bay Program, pers. comm. Sept 2014). The following is a discussion on the development of indices of abundance for forage species, and their potential use for ecosystem management.

Indices of forage abundance may be useful for ecosystem management because changes in forage availability often precede similar changes in predator abundance. When prey availability is low or begins to decline, managers may choose to be more precautionary in their management of predator species. When forage is abundant, management measures could be more liberal. Development of reference points for prey abundance, and actions to take (for both predator and prey species) when these reference points are triggered, would greatly simplify and expedite management decisions and remove uncertainty from the management process.

Conceptually, the use of forage fish indices as ecosystem reference points is simple and effective. Indices of abundance are used throughout fisheries management, so the general methodology is well known and understood by biologists. In addition, managers are presented with indices of abundance regularly, so they are familiar with the general concept behind their development as well as the interpretation of results. Also, abundance data are generally available for a wide range of species, and many methods of index development can be conducted in a very short amount of time, so management decisions can be made in a timely manner. Finally, forage indices are commonly used in more complex models to develop quantitative reference points. As such, they are an interim step in the management process, but may provide useful information of their own accord. These attributes suggest that indices of forage abundance would be useful tools as environmental indicators.

There are, however, a few potential drawbacks to this simple method. First, although development of indices is easily understood, the selection of reference values is subjective. There may be correlation between prey abundance and predator status, but in very few cases is it known if that correlation is a result of causation. This could result in the use of merely qualitative reference points or reference points that are overly cautious to account for the uncertainty in the data. Second, although index development is itself simple, there are concerns on how to interpret results from multiple indices and how to combine data from multiple sources into a single index. Different methods may produce different – and at the extreme, contradictory – results leading to management uncertainty. Third, the simplicity of the method may also be considered a drawback. Simple models, while useful, do not provide as much information as more complex models. For example, forage indices do not take into account prey availability (*e.g.* spatial and temporal overlap of prey and predators) or prey preferences, which would help guide management decisions.

The above pros and cons suggest that indices of forage abundance could provide useful information in the management process, but they must be used in the proper context and with appropriate caution. One way to minimize the uncertainty and increase the utility of forage indices is to have standardized protocols for their development. Below is a brief description of the key elements to be considered in developing these protocols. Many of these steps are followed, almost subconsciously, during routine development of indices for stock assessments and other purposes, but formalization of the process will lead to more consistency in results. This in turn will improve manager (and stakeholder) comprehension and interpretation, and minimize uncertainty during the decision making process.

1. Determine species of interest

The first step is to identify the species of interest, both predators and prey, and whether they will be presented individually or as species groups. Establishing specific selection criteria (*e.g.* species that account for ≥X% of a predator's diet, or species that co-occur with predators during certain times of the year) could be useful in identification of "important" prey species.

2. Identify data sources

The next step is to identify all available data sources with "sufficient" data for the forage species (or species group) identified in step 1. Identification of some standardized criteria, such as minimum time series length, percent of positive tows, or spatial or temporal scope of the survey could be used to justify the selection of data sources. It might also be necessary to process the data somewhat, such as by subsetting the data to certain strata, seasons, or size range of individuals sampled. In which case, criteria on when and how to subset would also be useful. Even with established criteria, some of the selected data sets will likely prove uninformative about the forage species, but developing criteria that are based on such aspects as life history of the species, survey design, or sample size will facilitate the initial selection of data sources and help justify the exclusion of others.

3. Develop analytical method

Once you have a set of data sources to use in the analysis, there are a number of considerations to make. The analytical method used could range from a simple arithmetic mean or alternative measures of central tendency (proportion of positive samples, geometric means, delta lognormal, etc.) to complex models such as GLM or GAM. Also, more complex models will require more consideration than a simpler model (such as selection of "appropriate" covariates and link function for GLM, or the order of differencing and number of lags in an ARIMA). Because all data sets are not created equal, a decision tree that identifies an appropriate analytical method based on the information available in a given data set is often useful.

Another consideration for the analytical method is how to deal with multiple surveys. If multiple indices are to be presented individually, there must be a framework for how conflicting trends will be interpreted. If multiple indices will be combined, consideration must be given on the best integration method. This is a key step in the process as different methods may lead to different conclusions or interpretations, which could affect management decisions.

4. Develop reference points

It is very unlikely that data are available to allow selection of a specific level of forage abundance that is "good" for predators or the ecosystem. In which case, reference points will be *ad hoc*, based on a perceived understanding of the ecosystem. Criteria for selection of the reference point should be established and justified fully to ensure transparency in the process for managers and stakeholders. Because of the *ad hoc* nature of the reference points, status determinations will be qualitative, such as with a traffic light approach. If possible, status determinations should convey the uncertainty of the results (***e.g.*** Helser and Hayes 1995)

5. Develop management protocols

The majority of the process for development of forage indices will fall to the technical committee or subcommittee; however, managers will play a role in their implementation as well. Managers may provide an alternative viewpoint on management triggers (reference points) than the AMTC and should be included in the decision process. In addition, managers may wish to preemptively establish specific actions to take for a given status determination to simplify and expedite the decision process. Finally, the Board should be involved in the decision for the frequency of updates and benchmark for index development.

Example

1. Determine species of interest

This example is based on data for Jonah crab, rock crab, blue crab, and American lobster evaluated collectively as benthic crustaceans. Modeled prey preferences from the MSVPA indicate that this prey category is consumed by a wide range of size or age classes of the MSVPA predators, and accounts for approximately 4-6% of each predator's diet (averaged across size or age classes).

2. Identify data sources

A number of data sources are available, ranging from Maine through North Carolina. Because this example is for demonstration purposes only, data sources were subset to just the May cruise of the Massachusetts Inshore Trawl Survey and the April cruise of the New Jersey Ocean Trawl Survey. Spring surveys were selected because the MA fall catch was very erratic, making it difficult to identify trends. Benthic crustaceans were observed in approximately 75-80% of tows for both surveys, with an overall (unstratified) mean catch of 3.0 to 3.25 kg per tow.

3. Develop analytical method

For this example, stratified geometric mean biomass (B) per tow was calculated for each survey. Because the surveys use different gears, B/tow was converted to B/km^2 using average net width, tow speed, and tow duration information. (Catchability was assumed to be 1.0 for both surveys.) A combined index was developed as a weighted mean based on each survey's total survey area (Figure 5).

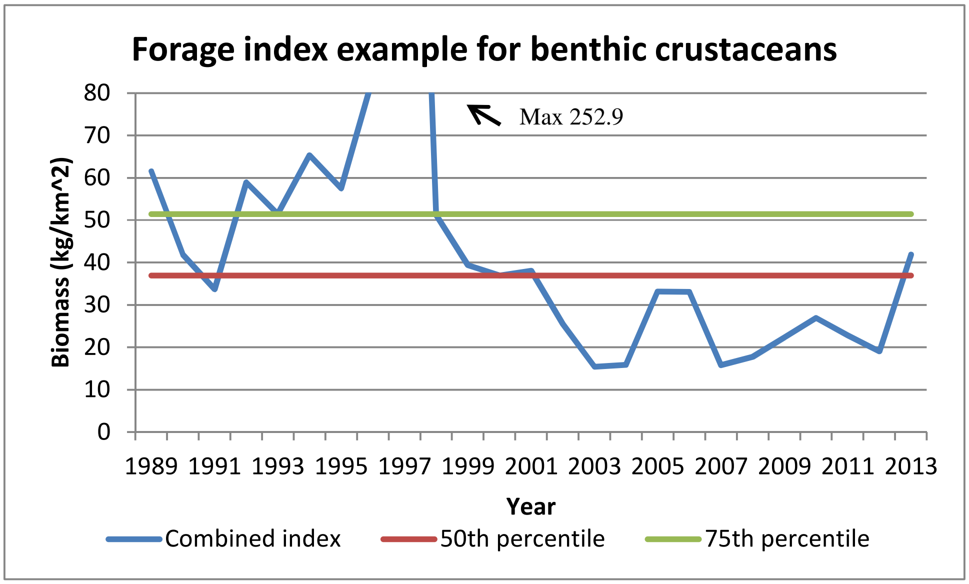


Figure 5. Example of forage index using benthic crustaceans catch from New Jersey and Massachusetts nearshore trawl surveys.

4. Develop reference points

No quantitative data are available to determine “adequate” levels of benthic crustacean biomass for predators, so *ad hoc* reference points were established for use in a traffic light approach. Lower and upper biomass cut-offs were established as the median (36.9 kg/km^2) and 75th (51.5 kg/km^2) percentiles of the combined time series.

Prey: predator ratios

We have already proposed prey indices of abundance as an ecological indicator above. Prey biomass to predator biomass ratios are a good compliment. In its most elemental form, the ratio of prey biomass to predator biomass (prey: predator ratio) represents an easily understood concept to allow resource managers to evaluate the amount of prey available for predators. The method at its core involves simply dividing prey biomass by predator biomass. A more challenging component of considering prey: predator ratios are descriptive and not explanatory. Translating this type of indicator into a reference point, or determining a target, therefore requires a degree of subjectivity.

This straightforward concept of a prey: predator ratio can be elaborated upon, potentially at the expense of ease of interpretation. For example, dividing model output prey biomass by model output predator biomass to develop a ratio does not take into consideration that not all prey are available to all predators due to for example, gape limitations or coincidence in space or time. Some straight forward methods do allow for dealing with gape limitations (e.g., consider only 'small' prey ages or sizes and 'larger' sizes and ages of predators – but here, a degree of subjectivity is needed to determine 'small' and 'large'). Temporal and spatial overlap are more challenging. As part of updating the MSVPA we have estimates of spatial overlap, prey preference, and size selectivity therefore we have the ability to incorporate those components into prey: predator ratios. The difficulty with this approach is that, at present, it results in season-, predator age-, and prey age[1]-specific ratios, which results in a very large number of ratios[2].

Other extensions of the basic premise of a prey: predator ratio include developing ratios from fishery independent surveys. Uphoff (2010) suggested that this approach allows for a validation of prey: predator ratios based on model output.

Other considerations include decisions about which prey items to include in the ratio – a single species approach (e.g., menhaden: striped bass) has the advantage that it is conceptually simply, but has the drawback that it does not account for other items in striped bass diet, and hence, total food availability for striped bass (or other predators of interest).

Advantages of prey: predator ratios include their inexpensiveness to develop, as long as the model output are available or fishery independent data are being collected. Incorporation of the

---

[1] In the case of age-structured prey items such as menhaden. For non-age structured prey items, the level of resolution is season and predator age.

[2] Also note that a multispecies statistical catch at age model under development is not currently configured with seasonal resolution, so using the feeding model components of that model would result in fewer ratios at present.

MSVPA feeding model increases the costs due to the work needed to estimate the model components (e.g., spatial overlap). The MSVPA feeding model is flexible, and can be easily modified as new methods or data sources are developed or become available (e.g., Curti et al. 2013).Regarding assumptions, where ratios are based upon model output, the ratios carry with them the same assumptions as the model that generated the data. This is not true where the ratios are based upon fishery independent data.

A potential drawback to the use of prey: predator ratios is that the ratio changes with the numerator or the denominator. So for example, the ratio may increase as the prey base remains stable, but predator biomass declines. This drawback could be addressed by looking at consumption ratios rather than availability ratios, but there is considerable added cost with this option and the need for diet sampling to verify the results (Uphoff 2010). Use of prey indices proposed above as a compliment to the prey: predator approach may be useful in this regard.

Additionally, since prey: predator ratios do not provide an explicit reference point (target or threshold) some expert professional judgment is needed to set reference levels. This later point however should not necessarily be viewed negatively. Hilborn and Stokes (2010) noted that targets and limits for fisheries management based on historical data have the advantage that they are based on experience, easily understood, and not subject to the vagaries of model assumptions (Uphoff 2010). This empirical approach is also not without precedent, as the striped bass single species biomass target and threshold are based on historical performance (NEFSC 2013).

Another drawback of the prey: predator approach is assessing uncertainty. Where measures of uncertainty are available for single species assessments (e.g., striped bass and menhaden) ratios can be developed that include estimates of uncertainty; where the MSVPA (or other) feeding model has been incorporated, additional work is needed to develop measures of uncertainty around the feeding model components (e.g., spatial overlap & prey preference).

A number of authors argue for a multiple indicator approach: Methratta and Link (2006) note that multiple ecosystem indicators can provide a more comprehensive ecosystem assessment than any single measure. Cury et al. (2005) noted that quantifying changes in an ecosystem is not a straightforward exercise, and no single indicator can track the complexity of the observed changes in fisheries and ecosystems.

The timeline involved in implementing the prey: predator approach varies from immediately (in the case of a ratio based on model output biomass generated as part of the MSVPA or single species models) to approximately one year (in the case of ratios based on incorporating the MSVPA's, or some other, feeding model). In the former case, managers would need to decide on a reference time period of desirable ratios to use as a target or a level at which they would be concerned. In the latter case, the continued use of the MSVPA is unclear, and so the availability of its feeding model components are also unclear, though a multispecies statistical catch at age model is currently under development, and components of its feeding model could be incorporated into the ratios discussed above.

Examples

As noted above, a very straightforward prey: predator ratio can be generated by considering age and size appropriate prey and predator model output. Figure 6 below depicts a time series of prey: predator ratios for age 0-2 menhaden & Age 2+ striped bass.

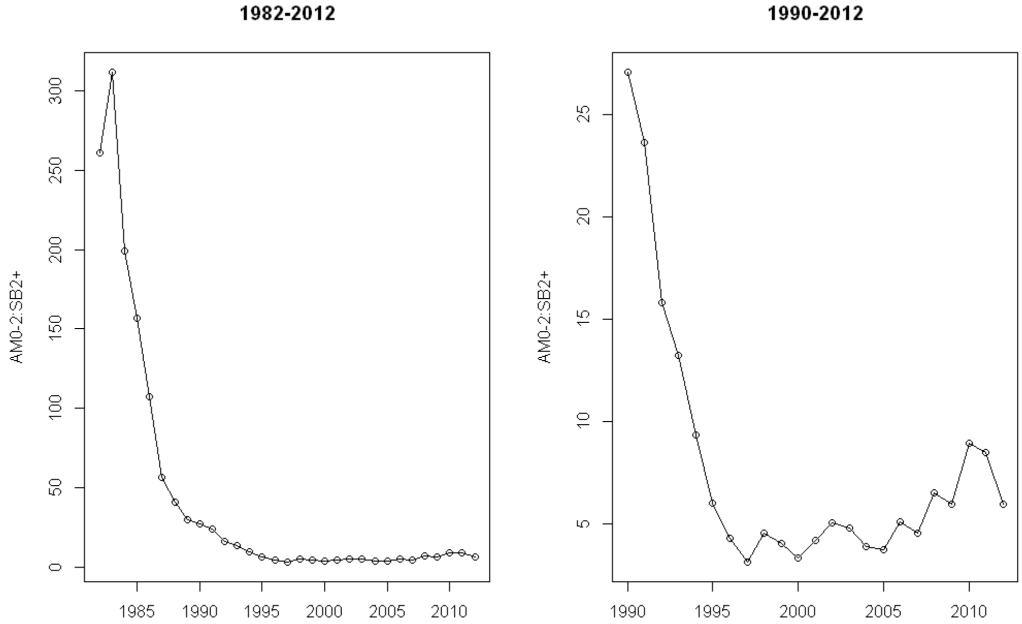


Figure 6. Prey: predator ratios for ages 0-2 menhaden and ages 2+ striped bass. To help illustrate trends in the ratio towards the end of the time series the plot on the right excludes ratios from 1982-1989. The figures are the same otherwise.

As currently configured, the MSVPA does not have an age 0-2 menhaden index, and so comparison with a survey index is not possible at this time.

Also as noted above, we can account for size preferences, prey size selection, and spatial and temporal overlap that were developed as part of the MSVPA update. The index is calculated as follows, where menhaden are a prey item (note that for all other prey groups, at present, the feeding model does not operate on a prey age-specific basis):

For an age m menhaden, and age s striped bass, in season n:

[spatial overlap$_{s,m,n}$ x size selection$_{s,m}$ x prey preference$_{s,m}$ x menhaden biomass$_{m,n}$] ÷ striped bass biomass$_{s,n}$

In the MSVPA spatial and temporal overlap are estimated seasonally, so all of the prey: predator ratios are estimated at the same level of resolution. As an example, Figure 7 below provides the ratio between age 0 menhaden and age 8 striped bass in season 1 (January – March, inclusive). This ratio is provided with and without applying the feeding model for comparison. Note the two y-axes.

We also have available to us an age 0 menhaden survey index and age 8 striped bass survey index. Due to differences in collection methods, for illustrative purposes, both indices were scaled and centered to put them on the same scale – a constant of 6 was added to the ratios to eliminate negative values. This work-around does illustrate a pitfall with the survey index approach.

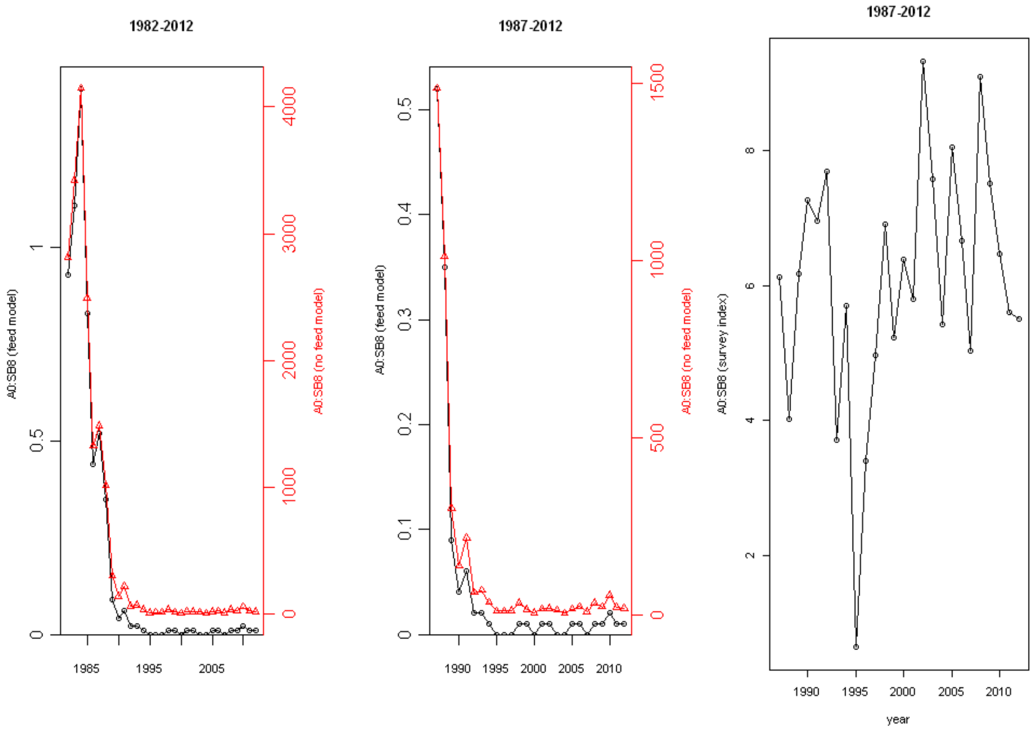


Figure 7. Prey: predator ratios for an age 0 menhaden and age 8 striped bass in season 1. The two plots on the left are derived from MSVPA model output biomass; the plot on the right was derived from survey indices (JAI_SCALEDAIR & MDSSN).

2.2 Predator nutrition reference points and consumptions indices

Reference points describing desirable and undesirable nutritional status of predatory fishes would be useful for judging available forage. Lipids are regarded as the energy currency in marine fish (Rose and O'Driscoll 2002) and complete depletion of lipid reserves could indicate vulnerability to starvation and increased natural mortality (Jacobs et al. 2013). To address nutritional status of striped bass through reference points, Jacobs et al. (2013) compiled five different studies where multiple, affordable indicators of lipid status could be compared to costly proximate composition analyses (the "gold standard"). Striped bass replaced depleted lipids with water, so weight-at-length indices were poorly related to lipid concentration. Percent tissue moisture and a body fat index (BFI; classification of 0 indicating absence of observable fat in the body cavity and classes 1-3 indicating progressively higher levels) adequately represented lipids and offered clear indications of lipid depletion. Based on data collected during favorable feeding conditions, an interim target of 75% of individual striped bass containing less than 80% moisture (lipid level indicative of complete depletion) was proposed by Jacobs (2013) as a management goal for Chesapeake Bay. These nutritional reference points were applicable to fall collections of striped bass (Jacobs et al. 2013). Bioelectrical impedance analysis (Cox and Hartman 2005) provides a non-lethal option for bluefish (model developed) and striped bass (model development near completion).

Maryland Fisheries Service began a year-round evaluation of striped bass nutritional status, average weight or calories of prey eaten, and forage availability in Maryland's portion of Chesapeake Bay. A preliminary analysis of October-November, 2006-2012, has been completed. The proportion of striped bass without body fat (Pf0; proportion with BFI = 0) provides a starting point for evaluating nutritional status because it represents a "language-in-common" between BFI's of a striped bass health monitoring program (1998 - present) and a citizen-science based diet and condition monitoring effort (2006-present; Uphoff et al. 2014). Attainment of target nutritional status was indicated when Pf0 equaled 30% or less of striped bass examined; this target was comparable to the Jacob's et al (2013) tissue moisture target. A threshold of 66% Pf0 was proposed based on clear separation of 95% confidence intervals of multiple high annual Pf0 estimates from those that reached the proposed target during October-November, 2006-2012. In Maryland's portion of Chesapeake Bay, most sublegal and legal striped bass sampled were vulnerable to starvation during fall 2006-2012. Chances of reaching the target were less than 1% for legal striped bass (457-860 mm, TL) in four of seven years and six of seven years for sublegal fish (290-456 mm, TL). In remaining years, there was a 44-100% chance that fish met the target. Nutritional state of sublegal fish was closely related to grams of prey consumed per gram of striped bass during October-November, but nutritional state of legal fish was not. Although five major prey items were identified, both grams and calories of prey eaten by both size classes of striped bass were usually dominated by young-of-year Atlantic menhaden even though their relative abundance was low. Indications of low striped bass survival in Chesapeake Bay (tag-based estimates and relative survival indices) were consistent with poor feeding success, nutritional condition, and forage availability (Uphoff et al. 2014).

In addition, diet data could be developed as simple consumption indices (grams of prey per gram of predator) analogous to catch per effort indices of relative abundance, used in conjunction with nutrition reference points, provide a basis for bioenergetics analyses, or used in multispecies models that may require estimates of consumption rates or consumption by age, size and prey type preference parameters, and diets.

2.3 ERPs generated using surplus production models

2.3.1 Steele-Henderson model

Biomass dynamic models with an additional sigmoidal type III predation function (Steele-Henderson or S-H model) have reproduced rapid shifts in abundance exhibited by marine fish populations (Steele and Henderson 1984) and have been useful in exploring the role of predation on management of Haddock (Spencer and Collie 1997) and weakfish (ASMFC Weakfish Technical Committee 2009). Virtues of a minimum-realistic S-H model are tractability in analyzing and parameterizing. The S-H model generates estimates of losses of undifferentiated prey biomass to key predators through their Type III terms without information other than boundary conditions. They can also provide estimates of prey biomass, M_2, F, surplus production (with and without predation), production, and reference points. S-H models are fundamentally different from other multispecies models that may require estimates of consumption rates or consumption by age, size and prey type preference parameters, evacuation rates, biomass of “other food” not explicitly modeled, and diets. S-H models can provide independent index-based assessments or use output from other multispecies models to provide another view of dynamics.

Biomass dynamics of prey fish (Schaefer model as base) are described as

$$(1)\ B_t = B_{t-1} + rB_{t-1}(1-(B_{t-1} / K)) - H_{t-1} - (\sum D_{t-1}) + \varepsilon;$$

where B_t was estimated prey biomass in year t; B_{t-1} = estimated prey biomass in t-1, r = intrinsic rate of population increase; K = carrying capacity; H_{t-1} = prey fish harvest in t-1; $\sum D_{t-1}$ = the sum of estimated predation losses of prey biomass from modeled predators in t-1 (equation 2); and ε = observation error (Collie and Spencer 1993; Spencer and Collie 1996). Prey biomass is estimated directly in the initial year as a separate parameter (B_0) that is projected forward.

Annual consumption of prey fish biomass (D_{t-1}) by predator biomass in the S-H model is estimated as

$$(2)\ [(dP_{t-1}(B_{t-1})^2) / (A^2 + (B_{t-1})^2)];$$

where d is estimated maximum per biomass consumption by predators; P_{t-1} is predator biomass (from another assessment or index); A is estimated prey biomass where predator satiation begins, and B_{t-1} represented estimated prey biomass. More than one predator can be specified.

Estimates of F in year t are calculated as

$$(3)\ H_{t-1} / [(B_t + B_{t-1}) / 2] \text{ (Ricker 1975).}$$

An equivalent M_2 equals

$$(4)\ D_{t-1} / [(B_t + B_{t-1}) / 2] \text{ (Miranda and Bettoli 2007).}$$

Average annual consumption of prey biomass per predator biomass from both models is estimated as

$$(5)\ D_t / P_t.$$

This estimate should be compared to published available estimates of individual consumption (generated by bioenergetics or other means) to check plausibility of consumption estimates and tuning to available estimates is possible.

Maximum useable production (MUP) reference points that account for M_2 losses from predators and F can be estimated (Overholtz et al. 2008; Moustahfid et al. 2009). A prey biomass MUP reference point is estimated as

$$(6)\ \mathrm{B}_{\mathrm{mup}}B_{MUP} = K / 2.$$

To estimate reference points for mortality when predation-competition losses are included, $F + M_2$ at MUP is estimated as

$$(7)\ \mathrm{Z}_{\mathrm{mup}}Z_{MUP} = r/2$$

Steele-Henderson and variable r production models (see next section) could be combined in a tandem approach to investigate predator-prey influences. Providing the two approaches can estimate comparable baseline parameters (*r* and *K*), estimates from the variable *r* model could be used for judging predator combinations that produce similar estimates in the S-H model.

2.3.2 Surplus production model with time-varying intrinsic growth rate

A surplus production model with a time-varying intrinsic population growth rate (r) was developed to explore the estimation of MSY-based reference points that incorporate time-varying predation effects on Atlantic menhaden. The time-varying r (TVr) approach assumes the following:

1. The menhaden population exhibits logistic population growth.
2. TVr parameter estimates reflect true changes in intrinsic growth rates and not model misspecification or other sources of error.
3. Estimation of TVr adequately accounts for all substantial changes in predation pressure on the menhaden stock without having to explicitly specify trends in predator biomass.

A Schaefer surplus production model (SPM; Quinn and Deriso 1999) was created in AD Model Builder (Fournier et al. 2012). The TVr SPM estimated biomass as follows:

$$\hat{B}_{t+1} = \hat{B}_t + \hat{r}_t \hat{B}_t \left(1 - \frac{\hat{B}_t}{\hat{K}}\right) - C_t, \tag{4}$$

where $\hat{B}_t$, $\hat{r}_t$, $\hat{K}$, C_t, were the estimated biomass in time *t*, intrinsic growth rate in time *t*, carrying capacity, and total fishery catch. The estimation model assumed total catch was known without error. The intrinsic growth rate, $\hat{r}$, was allowed to vary according to a random walk on the log scale,

$$\log_e \hat{r}_{t+1} = \log_e \hat{r}_t + \omega_t,$$

with annual deviations, ω_t, from a normal distribution with a mean of zero and a standard deviation of 0.1. The estimated index of biomass, $\hat{I}_t$, was the product of catchability and biomass,

$$\hat{I}_t = \hat{q}\hat{B}_t, \tag{5}$$

where $\hat{q}$ was survey catchability. Percent reduction from *K* in the first year of the model was also estimated. Parameter estimates were obtained by minimizing the concentrated negative log likelihood function,

$$-LL_1 = \frac{n}{2}\log_e\left(\sum\left(\log_e(I_t) - \log_e(\hat{I}_t)\right)^2\right). \tag{8}$$

Multiplicative lognormal observation error was assumed for the index of biomass; to account for the addition of time-varying growth or catchability, an additional likelihood term, $-LL_2$,

$$-LL_2 = \frac{1}{2\sigma^2}\sum \omega_t^2,$$

was included for the random walk deviations. As proof of concept, this model was fit to total coastwide landings and an index of biomass generated from CPUE in the Potomac River Fisheries Commission pound net fishery spanning the years 1969-2012. Not surprisingly, the SPM was sensitive to starting values. In order to constrain the results to biomass levels within the range of that predicted by the single-species model, BAM, a lognormal prior was applied to B_0 with a median of 300,000 mt and an approximate CV of 10%. The exploratory model's fit to the PRFC index was excellent and model parameters were within reason given our understanding of the biology of Atlantic menhaden and the history of its fisheries. Simulation testing, sensitivity to priors and model assumptions, and characterization of model and parameter uncertainty needs to be conducted before consideration for use in management.

This simple approach has the advantage of providing MSY-based reference points that implicitly account for time-varying predation and other potential regime shift effects (as well as time-varying recruitment/growth) on the menhaden stock without having to specify the predator field or the exact mechanism behind the changes experienced by the stock. Management quantities of time-varying exploitation rate at a given % of MSY_t ($UMSY_t = 0.5*r_t$), and biomass at any given % of MSY can be generated for management use (Quinn and Deriso 1999).

Note that the adoption of this approach would assume that either the influence of individual predators on menhaden cannot or need not be specified and that managers only wish to maintain enough biomass of menhaden to support its predators without knowing the relative contribution of each. This model could be used in conjunction with the Steele-Henderson approach to characterize change over time in relative predation pressure and other environmental factors that affect menhaden population dynamics. Alternatively, an index of consumption could be generated and used to tune annual deviations in r. The model's performance relative to simulation tests, single-species models, and other multispecies modeling approaches has yet to be assessed.

2.4 ERPs generated using single species statistical catch-at-age models

2.4.1 Forage services ERPs generated using the Beaufort Assessment Model (BAM)

An ecological reference point based on the single species statistical catch-at-age model would encompass the entire spatial extent of the population. Examples of ecological reference points based on single species assessments include $F=0.75M$, $F=M$, $B_{75\%}$, and $B_{40\%}$. These specific quantities have been advocated for and suggested by recent forage fish documents (Pikitch et al. 2012, and others), but are not based on analyses specific to menhaden and are generally based on expert opinion from other fisheries in different regions. Data requirements are those of the base case run for the single species stock assessment and include catch at age, indices of abundance, and life history parameters (see full stock assessment document).

For the calculation of F based on M, the methods are fairly straightforward and demonstrated below. The one decision is what value of M to use for the calculations. In the example, the smallest value of M was used, which was the value of M at age-6+ used in the stock assessment model.

Example calculations:

1) $F=0.75M=0.75*0.48=0.36$ (with 0.48 being the value of M at age-6+)
2) $F=M=0.48$ (which is the value of M at age-6+)

The deliverable for management use would be fishing mortality rate, which the fishery should not exceed. In order to translate that into landings values, projections would need to be run.

The metrics related to virgin biomass are based on equilibrium assumptions with zero fishing mortality. The Lorenzen M and average weights at age at the beginning of the year (averaged over 1955-2013) were used to get at biomass. Once this is done, one would use the multiplier on the equilibrium biomass to get the specific values for $B_{75\%}$ and $B_{40\%}$. For menhaden, this may be a particularly difficult set of assumptions to make because recruitment is variable, which implies that the population is not at equilibrium conditions.

Example calculations:

1) $B_{75\%} = 0.75 * B = 0.75 * 2406.45 = 1804.84$ (units = 1000s mt)
2) $B_{40\%} = 0.40 * B = 0.40 * 2406.45 = 962.58$ (units = 1000s mt)

The deliverable for management would be a biomass value that the fishery should target and one that the population should not fall below. As with the *F* metrics, projections would be needed to determine what level of landings would allow for a sufficient biomass level.

These two types of metrics are based on general expert opinion of forage fish management from a variety of different fish species. These metrics have not been tested to determine if these methods are appropriate for menhaden of if they address the Board's objectives. In addition, these reference points assume that you are accounting for ecosystem services in a general way, but they do not address specific services. As such, these methods represent more a "rule of thumb" than an actual accounting of removals.

2.4.2 ERPs resulting from time-varying natural mortality estimated internally in a statistical catch-at-age model using an index of predator consumption

The estimation of time-varying natural mortality (TVM) within a statistical catch-at-age model will be explored using an index of predator consumption. Coastwide predator diet data will be used to create an index of menhaden consumption by its major predators. That index will be incorporated into the Beaufort Assessment Model and used to inform annual deviations from an initial estimated *M*-at-age vector. In addition to the traditional assumptions made when using a statistical catch-at-age assessment model (Methot and Wetzel 2013), the TVM approach assumes the following:

1. Menhaden *M* varies over time and is estimable given the available data.
2. TVM parameter estimates reflect predation effects and not model misspecification or other sources of error.
3. Estimation of TVM using trends in predator consumption adequately accounts for all substantial changes in predation pressure on the menhaden stock.

As initial proof of concept, an index of Atlantic striped bass biomass was used to tune annual deviations in *M* using a draft assessment model for Atlantic menhaden built in Stock Synthesis. TVM was estimated in the model using one base parameter for *M* and annual deviations from that parameter as a function of striped bass biomass trends as an environmental forcing factor. A symmetric beta prior with a mean of 0.8 and sd of 0.2 (bounded between 0 and 3.5) was applied. The annual working value of the *M* parameters was equal to a multiplicative function of the striped bass index (*SBI*) such that:

$$M'(y) = M * \exp(link * SBI(y,g)),$$

where *M*' is the value after adjustment, *M* is the base parameter being adjusted, *link* is the environmental link parameter, and *SBI(y,g)* is the striped bass biomass index value *g* in year *y* (Methot 2012). Trends in *M* reasonably approximating the trend in striped bass biomass resulted without the parameter for *M* hitting bounds. As this approach is developed, a composite index of predator consumption for menhaden that characterizes changes in the predator field over time will need to be generated. In addition, simulation testing and explicit testing of the sensitivity to priors and model assumptions regarding the estimation of TVM must be conducted before consideration for use in management. This approach could provide SPR ($F_{x\%}$ and $B_{x\%}$) reference points that account for time-varying predation effects on the menhaden stock once assumptions about the appropriate time period across which to calculate these reference points were made.

2.5 Menhaden ERPs that account for the menhaden forage needs of their major predators at threshold levels

In recent years, fishery managers have expressed interest in ensuring adequate forage and, in particular, menhaden availably for striped bass, weakfish, and bluefish. One way to address this issue is to examine the menhaden population size in the absence of directed menhaden fishing, when striped bass, bluefish, and weakfish are at their threshold levels of stock abundance. In essence this would be the unfished condition of the menhaden population at these predator levels under the current regime of alternate prey availability. From this unfished menhaden level, managers could set various menhaden reference points using total abundance, SSB, or SPR. This requires a projection of the menhaden population in the unfished condition, under the current abundances of other prey and at the threshold population sizes of striped bass, bluefish, and weakfish. Resulting Ms are then projected forward from the terminal year of the assessment model to determine whether the stock would be overfished or overfishing at current *F* levels if menhaden predators were at their threshold population sizes.

The MSVPA projection module was used to estimate *M* on menhaden under unfished conditions with their major predators at their threshold levels. Given the most recent single species assessment (ASMFC 2014) assumes a complicated fleet and area configuration that would be difficult to recreate in the MSVPA, the built-in projection capabilities of the BAM were used to project the stock forward under fished conditions. Therefore, this exercise required a combination of projections conducted first in the MSVPA then the BAM models.

MSVPA Methods and Results

The most recent MSVPA-X configuration (ASMFC 2014) was used to initialize the projection portion of the MSVPA-X module with the goal of determining the predation mortality rate of menhaden assuming striped bass, weakfish, and bluefish were at their stock biomass thresholds. Fully described elsewhere (Garrison et al. 2010), the MSVPA software currently in use also comes with a projection module that can be configured for various testing and management evaluation of harvest and reference points scenarios.

The maximum projection length (20 years) was used, along with current levels of alternate (biomass) prey. Striped bass fishing mortality was set near current levels given striped bass are estimated to be near threshold SSB levels at present (ASMFC 2013). Due to low population size, weakfish fishing mortality were set near 0 initially and then increased as the population approached its threshold value. Because bluefish are a biomass-structured predator (not explicitly modeled) in the MSVPA-X, it was directly specified at its threshold value.

Overall, the MSVPA projection took 11 years of the 20 year run for weakfish to reach threshold values (Figure 8); once there, constant fishing removals kept the population relatively stable in terms of SSB and abundance (Figure 8). Striped bass showed a similar trend, though they were much closer to their threshold values. Menhaden SSB and abundance stabilized relatively quickly after both predator stocks came to equilibrium. On average (year 12-20, at equilibrium), estimates of unfished menhaden SSB were approximately 222,000t and age 1+ abundance was 4.5 billion fish. The MSVPA projections produced estimates of M_2 predation mortality (Table 3) that were then used as input into the BAM projections as described below.

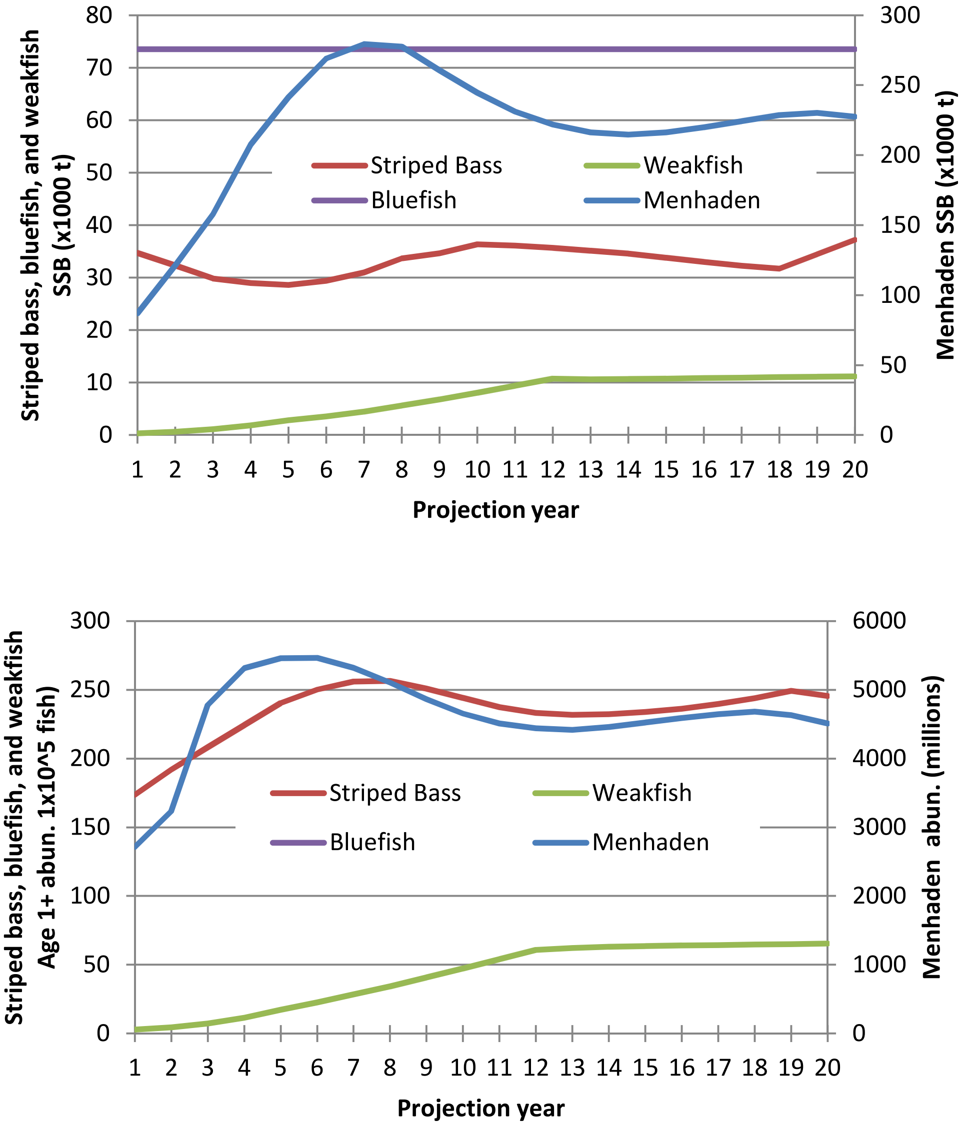


Figure 8. Menhaden, striped bass, bluefish, and weakfish projected SSB and age 1+ abundance during projection initialization.

BAM Methods and Results

Using the MSVPA-X produced M_2 values, a projection using constant landings was conducted using the BAM framework. Landings were set at 32,700 mt for the northern reduction fishery, 98,300 mt for the southern reduction fishery, 21,100 mt for the northern bait fishery, and 17,300 mt for the southern bait fishery. Thus, total landings are 169,400 mt. These constant landings values were based on the 2013 landings, which is the first year of the currently implemented quotas.

Data into and output from the Monte Carlo bootstrap (MCB) runs of the base run of the Beaufort Assessment Model (BAM) were used as the basis for the projections (see stock assessment report for details on base run and MCB runs). This projection is an example based on the 2013 landings. Projections were run for a total of 9 years (2014-2022) with constant landings set at 2013 values. The starting conditions of the projection analysis include initial numbers at age, which were the estimated numbers at age, N_a, for year 2014 from the BAM for each MCB run. Numbers at age after the initial year were calculated as:

$$N_{a+1,y+1} = N_{a,y} e^{-Z_{a,y}} \quad N_{a+1,y+1} = N_{a,y} e^{-Z_{a,y}}$$

where Z was age and year specific mortality and equals natural mortality for each age for that year plus the fishing mortality rate times the selectivity at age. Natural mortality was input into the projections as M_1 and M_2, where M_1=0.4 was the baseline value of natural mortality and M_2 was the value of natural mortality caused by maintaining bluefish, weakfish, and striped bass at their threshold levels as estimated by the MSVPA (Table 3). Selectivity was a vector from each MCB run for each fishery with the northern and southern commercial reduction fishery selectivities being the values in the last time period. Fishing mortality was estimated using the optimize function in R in order to match the annual landings (level of landings denoted above). Annual landings were calculated using the Baranov catch equation and weight of landings.

Year	Age-0	Age-1	Age-2	Age-3	Age-4	Age-5	Age-6+
2014	1.022	0.513	0.292	0.191	0.14	0.112	0.096
2015	1.02	0.509	0.29	0.189	0.139	0.111	0.095
2016	1.003	0.501	0.286	0.187	0.137	0.11	0.094
2017	0.989	0.494	0.282	0.185	0.136	0.109	0.093
2018	0.978	0.488	0.279	0.183	0.134	0.108	0.092
2019	0.972	0.483	0.276	0.181	0.133	0.106	0.091
2020	0.971	0.481	0.274	0.179	0.132	0.106	0.09
2021	0.992	0.491	0.279	0.183	0.134	0.108	0.092
2022	1.022	0.508	0.29	0.19	0.14	0.112	0.096

Table 3. Natural mortality as M_2 for each of the projection runs with M_2 being based on the natural mortality rate on menhaden in order to maintain bluefish, weakfish, and striped bass at their threshold levels.

Recruitment was projected without an underlying stock-recruitment function and was based on the median recruitment observed in each MCB run. Recruitment variability was included whereby for each year a deviation in recruitment was selected randomly with replacement from the deviations estimated in each MCB run.

The number of projections was the same as the number of filtered MCB runs. Outputs included the median and 5th and 95th percentiles for fecundity (ova) over time, fishing mortality over time, recruitment over time, and landings over time. Fecundity for each year was the number of fish in each age times the reproductive vector at age. Specifically, maturity from the final year of each MCB run, a 50:50 sex ratio, and a mean fecundity at age were used to produce the reproductive vector at age.

With increased natural mortality in the projections, fecundity values declined over time and fishing mortality rates increased over time, although both stabilized near the end of the projections (Figure 9). In order to finalize these ERPs for management, the M_2 values generated by the MSVPA would need to be incorporated into the BAM SPR calculations for proper comparison of stock conditions relative to reference points. Given time constraints, this was not performed, but it could be completed by spring 2015 if the Board is interested in pursuing this approach to generate ERPs.

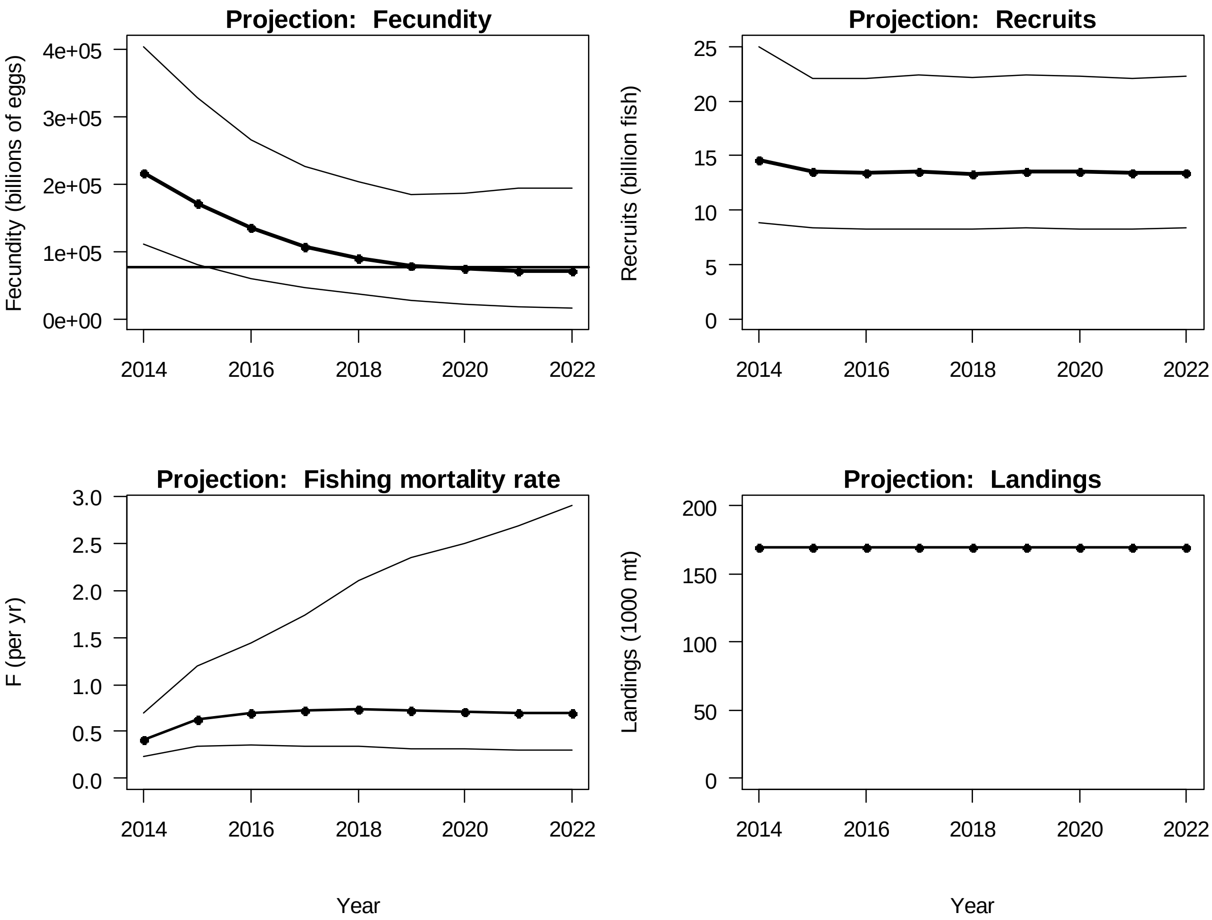


Figure 9. Fecundity, recruits, fishing mortality (*F*), and landings over time based on constant landings, median recruitment with variability based on estimated deviations for each MCB run, and natural mortality being a combination of M_1 (0.40) and M_2 (Table 1), which is the mortality rate on menhaden in order to maintain bluefish, weakfish, and striped bass at their threshold levels. The solid flat line in the fecundity panel is the target fecundity for menhaden based on the assessment in progress.

As usual, projections should be interpreted in light of the model assumptions and key aspects of the data. Some major considerations are the following:

- In general, projections of short lived highly fecund fish stocks are highly uncertain, particularly in the long term (e.g., beyond 5 years).
- Although projections included many major sources of uncertainty, they did not include structural (model) uncertainty. That is, projection results are conditional on one set of functional forms used to describe population dynamics, selectivity, recruitment, etc.
- Fisheries were assumed to continue fishing at their estimated current proportions of total effort, using the estimated current selectivity patterns. New management regulations that alter those proportions or selectivities would likely affect projection results.
- If future recruitment is characterized by runs of large or small year classes, possibly due to environmental or ecological conditions, stock trajectories may be affected.

- Projections apply the Baranov catch equation to relate F and landings using a one-year time step, as in the assessment. The catch equation implicitly assumes that mortality occurs throughout the year. This assumption is violated when seasonal closures are in effect, or when natural mortality is seasonal introducing additional and unquantified uncertainty into the projection results.

These projections are also reliant on the assumptions and caveats made in configuring the MSVPA model (ASMFC 2014), especially:

- Historical diet data and spatial and temporal overlap used in the MSVPA will reflect future diet data and overlap between species. If diets of predators change (e.g., prey switching) or spatial/temporal overlap of prey and predators change (e.g., climate change, range expansion or contraction), fewer or more menhaden could be consumed than expected.
- The MSVPA currently does not include a feedback loop between prey and predators, potentially limiting its ability to model realistic ecosystem situations.
- It should be noted with caution that menhaden-specific results generated by the MSVPA-X differ greatly from that of the BAM (ASMFC 2014). As such, the results from this projection should be viewed as exploratory; and are shown only to provide an example.
- Finally, the natural mortality in the current stock assessment model is constant and not based on outputs from a multi-species model. Therefore, these projections change the model assumption of natural mortality by making it time varying. Based on the sensitivity runs of the stock assessment model, if time varying natural mortality or increased natural mortality were included, parameter estimates such as R_0 would be at a different level, as would catchability, and potentially other parameters. Therefore, the direct comparability between the stock assessment with time invariant natural mortality and the projections with time varying natural mortality may not be appropriate.

2.6 Multispecies Statistical Catch-at-age Models

The effectiveness of single-species stock assessment and management has come under scrutiny in recent years. More holistic ecosystem based approaches to stock assessments are required to help inform managers when making the important and complex decisions that are the norm during our current fisheries management process. In this multispecies statistical catch-at-age framework the ecosystem species are Atlantic menhaden and scup as prey species, and striped bass, bluefish, and weakfish as predators. Using standard statistical catch-at-age techniques as described by Quinn and Deriso (1999), single species models are linked using trophic calculations to provide a predator-prey feedback between the population models. The statistical framework is believed to be an improvement from the existing MSVPA for a similar species complex due to the high recreational harvest component of many of the species in the framework and the uncertainty that this entails. Other sources of uncertainty exist for many of the data inputs, and using statistical techniques may help to estimate many of the model parameters while incorporating the inherent uncertainty in the data. Also, the MSSCAA assumes a constant, time-invariant total ecosystem biomass as opposed to the MSVPA which requires that trends and estimates of biomass for all prey items be explicitly input in the model. It is hoped that this MSSCAA model can continue to be developed with a goal of replacing the existing MSVPA for use in ecological and biological reference point work being conducted by the ASMFC. The MSSCAA may prove useful as a tool in other assessments as additional species are added to the framework and as a tool for conducting a multispecies Management Strategy Evaluation.

2.7 Ecopath with Ecosim (EwE)

EwE has become the most common ecosystem modeling framework for exploring and evaluating potential ecosystem consequences of different fisheries management strategies. The software is comprised of two main modules Ecopath and Ecosim, which are used to create a mass-balanced snapshot of an ecosystem and simulate perturbations to the system (Christensen and Walters 2004). Perturbations can include anthropogenic factors (esp. changes in fishing policies) and environmental (e.g., changes in primary production, temperature, and habitat). Other modules of EwE can be parameterized to consider additional factors (e.g., spatial dynamics, persistent pollutants, and socioeconomic drivers). The Ecopath module is used to quantify the trophic interactions among fisheries stocks and other trophic groups within an ecosystem. The time-dynamic module, called Ecosim, provides a simulation capability that facilitates policy exploration at the ecosystem level, with initial parameters inherited from the base Ecopath model.

The parameterization of an Ecopath model is based on satisfying two ‘master’ equations. The first equation describes how the production term for each group can be divided for an arbitrary time period:

production = catch + predation + net migration + biomass accumulation + other mortality.

The second ‘master’ equation is based on the principle of conservation of matter within a group and is designed to balance the energy flows of a biomass pool:

consumption = production + respiration + unassimilated food

To construct an Ecosim model, it is necessary to re-express the system of linear equations in as a system of coupled differential equations that describe the change in biomass of each group in the system:

Change in biomass = Consumption by predators + Consumption of prey + immigration – natural mortality – fishing mortality – emigration

The equation to express consumption uses information on the rate of effective search for prey by predator and the behavioral exchange rate between vulnerable and invulnerable prey pools. The vulnerability parameter replaces functional response curves used in many other multi-species/predator-prey models. Additionally, forcing functions of external environmental factors (e.g., temperature, dissolved oxygen) can be incorporated to drive changes in production, mortality or consumption for predator and prey groups.

Currently, an EwE model of the Chesapeake has been developed and fit to time series data of key fisheries species (Christensen et al 2009). The domain of this model is the tidal non-fresh waters of the Chesapeake Bay and its tributaries to the Bay Bridge Tunnel. Information on this model is available from Howard Townsend of NOAA/NMFS/Chesapeake Bay Office.

Additionally, an EwE model of the Northwest Atlantic Coast is under development by the Chesapeake Biological Lab (University of Maryland Center for Environmental Sciences). The spatial domain for the model in development spans the continental shelf and estuaries of the Northwest Atlantic Ocean from North Carolina to Maine. Information on this model is available from Andre Buchheister. This model is scheduled to be completed by the end of 2015.

Most of the proposed mortality and biomass based ERPs can be calculated with the standard EwE output. ERPs that include recruitment may be calculated if trophic group list included multi-stanza groups. EwE can be used to examine uncertainty in model outputs using Ecosim Monte Carlo simulations. A Management Strategy Evaluation submodule of Ecosim can be used to project likely future ecosystem and multispecies consequences of most ERPs (biomass, catch, and mortality based) by setting policy in the EwE management strategy evaluation module. In addition, the ecosystem-based MSE will provide information on the risks and tradeoffs associated with different ERPs.

3 Conclusions and Recommendations

The ERP subcommittee and the AMTC cannot make a recommendation on which ERP would be best to adopt for Atlantic menhaden management until:

a. a more explicit statement of ecological/ecosystem goals and objectives for menhaden management is provided by the Board, and
b. the performance of the proposed ERPs and the models used to generate them can be formally evaluated through multi-model comparisons, simulation testing, and the completion of single (and possibly multispecies) management strategy evaluations.

Although most options presented in this report are not ready for immediate management use, the BAM-based reference points that account for forage services (Section 2.4.1) could be adopted at any time using the most recent peer reviewed Atlantic menhaden model. The TC noted that these ad hoc “forage services” reference points may be more conservative than single species reference points. The TC also noted that density dependent effects and unpredictable recruitment could negate the benefits of setting aside more fish for predators. Additionally these approaches are based on different species spread throughout the globe, and may not be applicable to menhaden in this region. The performance of forage services reference points relative to single species reference points has yet to be tested under conditions exhibited by the coastwide Atlantic menhaden stock, or other forage fish in this region. Should managers wish to move forward with this approach, further testing and analysis should be conducted, in light of manager’s tolerance for risk, before full implementation.

The ERP subcommittee and the AMTC recommend the following next steps in ERP/EBFM development:

1. The Atlantic Menhaden Management Board should conduct a series of facilitated workshops during which specific ecosystem and fisheries goals and objectives for the management of Atlantic menhaden are developed and explicitly stated.

2. The ERP subcommittee should finalize development, comparison, simulation testing, and vetting of the suite of indicators and models described in this report.
3. The AMTC should conduct a Management Strategy Evaluation (MSE) for Atlantic menhaden during which single-species forage services reference points would be tested relative to traditional reference points and the management goals for the stock. Ideally, an MSE would be conducted within a structured decision-making process in which trade-offs among stakeholder interests and Species Board(s) would be addressed. This MSE should be expanded to include other ERPs as tools for conducting MS-MSEs are developed (e.g., MSSCAA, EwE).
4. An Ecosystem Indicators Report should be updated and reviewed annually by the ASMFC as described in Section 2.1 above.

   The AMTC recommends that the Management and Science Committee be asked to review this report in advance of the fall Annual Meeting and provide detailed comments on management implications of the scientific information provided in the report. The report would then be presented to the Interstate Fisheries Management Program (ISFMP) Policy Board at Annual Meeting each fall.
5. The ISFMP Policy Board should develop a framework for review and implementation of reference points that impact multiple ASMFC-managed species.

   A major challenge to the successful development and implementation of ERPs and EBFM at the Commission is the structure of the ASMFC management boards.

   The setting of reference points is the responsibility of single species management boards (e.g., the Atlantic Menhaden Management Board). Although the ISFMP Policy Board oversees all single species boards, a framework for considering implementation of multispecies or ecosystem-level reference points and management actions at that level has yet to be developed. The Policy Board has expressed an interest in moving toward an EBFM framework, but implementation details do not yet exist. Progress in ERP and EBFM development and implementation could be seriously hindered without the establishment of an official forum and deciding body for considering ecosystem-level scientific products and their use in management.
6. The collection of diet and nutrition data along the East Coast should be expanded to support the ASMFC's ERP and EBFM efforts.

   Accurate description of fish diets and feeding habits provides a basis for understanding trophic interactions (Chipps and Garvey 2007). Existing diet information has been gathered into a database used for the MSVPA-X, but seasonal, annual, and spatial gaps exist. Geographically widespread, annual, year-round monitoring of selected predator diets to provide information on prey-abundance and predator consumption will be needed for multispecies and ecosystem-based approaches to assessment and management. Directed diet sampling programs exist, but these may not be sufficient to characterize predator diets regionally and seasonally across the mid-Atlantic and New England regions. It is likely supplemental sampling will be needed from existing agency platforms that do not now sample diets. Information collected and data management should be coordinated across states to ease access and analysis. The varying uses of food habits data described in this report (especially Section 2.2) may require different approaches for collecting and analyzing data, so careful consideration should be given to matching sampling design, assessment approach, and management questions (including major effects of other species). Due to migratory patterns of prey and predators, and seasonality of diets, sampling should be stratified seasonally and regionally.

4. Literature Cited

Atlantic States Marine Fisheries Commission (ASMFC). Weakfish Technical Committee. 2009. Weakfish stock assessment report presented to the 48th Northeast Regional Stock Assessment Workshop (48th SAW): Stock Assessment Review Committee (SARC). Pages 439-834 in NEFSC reference document 09-10. National Marine Fisheries Service, Woods Hole, Massachusetts.

____. 2012. Amendment 2 to the Interstate Fishery Management Plan for Atlantic menhaden. December 2012. 114 pp.

____. 2013. Update of the Striped Bass Stock Assessment using Final Data. October 2013. ASMFC Striped Bass Technical Committee. 74 p.

____. 2014. Atlantic menhaden stock assessment report for peer review. December 2014. ASMFC Atlantic Menhaden Technical Committee.

Bargman, G. 1998. Forage Fish Management Plan: A plan for managing the forage fish resources and fisheries of Washington. Washington Department of Fish and Wildlife. September 1998. 77 pp.

Chipps, S. R., and J. E. Garvey. 2007. Assessment of diets and feeding patterns. Pages 473-514 in C. S. Guy and M. L. Brown, editors. Analysis and interpretation of freshwater fisheries data. American Fisheries Society, Bethesda, Maryland.

Christensen and Walters 2004. Reference: Christensen, V. and C.J. Walters. 2004. Ecopath with Ecosim: methods, capabilities and limitations. Ecological Modelling 172: 109–139.

Christensen, V., A. Beattie, C. Buchanan, H. Ma, S. Martell, R. Latour, D. Preikshot, M. Sigrist, J. Uphoff, C. Walters, R. Wood, and H. Townsend. 2009. Fisheries Ecosystem Model of the Chesapeake Bay: Methodology, Parameterization, and Model Exploration. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service. NOAA Technical Memorandum NMFS-F/SPO-106, 146 p.

Collie, J. S., and P. D. Spencer. 1993. Management strategies for fish populations subject to long-term environmental variability and depensatory predation. Pages 629-664 in G. Kruse, D. M. Eggers, R. J. Marasco, C. Pautzke, and T. J. Quinn, II, editors. Proceedings of the international symposium on management strategies for exploited fish populations. Alaska Sea Grant, Fairbanks, Alaska.

Cox, M. K., and K. J. Hartman. 2005. Nonlethal estimation of proximate composition in fish. Canadian Journal of Fishes and Aquatic Sciences 62:269-275.

Curti, K. 2012. Age-structured multispecies model of the Georges Bank fish community. University of Rhode Island PhD Dissertation. 192p.

Curti, K.L., J.S. Collie, C. M. Legault, and J. Link. 2013. Evaluating the performance of a multispecies statistical catch at age model. *Canadian Journal of Fisheries and Aquatic Science* 70:470-484.

Cury, P.M., L.J. Shannon, J-P. Roux, G.M. Daskalov, A. Jarre, C.L. Moloney, and D. Pauley. 2005. Trophodynamic indicators for an ecosystem approach to fisheries. *ICES Journal of marine Science* 62:430-442.

Daan, N. 1987. Multispecies versus single-species assessment of North Sea fish stocks. Canadian Journal of Fisheries and Aquatic Sciences 44(Supplement 2):360-370.

Durbin, A.G. and Durbin, E.G. (1992). "Seasonal changes in size frequency distribution and estimated age in the marine copepod Acartia hudsortica during a winter-spring diatom bloom in Narragansett Bay". Limnology and Oceanography, 37(2): 379-392

Ecosystem Assessment Program. 2012. Ecosystem Status Report for the Northeast Shelf Large Marine Ecosystem - 2011. US Dept Commer, Northeast Fish Sci Cent Ref Doc. 12-07; 32 p. Available from: National Marine Fisheries Service, 166 Water Street, Woods Hole, MA 02543-1026, or online at http://www.nefsc.noaa.gov/nefsc/publications/

Fournier, D.A., H.J. Skaug, J. Ancheta, J. Ianelli, A. Magnusson, M.N. Maunder, A. Nielsen, and J. Sibert. 2012. AD Model Builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. Optimization Methods and Software 27:233-249.

Garrison, L.P., J.S. Link, D.P. Kilduff, M.D. Cieri, B. Muffley, D. Vaughan, A. Sharov, B. Mahmoudi, and R.J. Latour. 2010. An expansion of the MSVPA approach for quantifying predator-prey interactions in exploited fish communities. ICES Journal of Marine Science 67:856-870.

Helser, T.E. and D.B. Hayes. 1995. Providing quantitative management advice from stock abundance indices based on research surveys. Fishery Bulletin 93(2):290-298.

Hilborn, R. and K. Stokes. 2010. Defining overfished stocks: have we lost the plot? *Fisheries* 30(3): 113-120.

Jacobs, J. M., R. M. Harrell, J. Uphoff, H. Townsend, and K. Hartman. 2013. Biological reference points for the nutritional status of Chesapeake Bay striped bass. North American Journal of Fisheries Management 33:468-481.

Methot, R.D., Jr, 2012. User Manual for Stock Synthesis: Model Version 3.24f. NOAA Fisheries, Seattle, WA. http://nft.nefsc.noaa.gov/SS3.html

Methot, R.D., Jr. and C. R. Wetzel. 2013. Stock synthesis: A biological and statistical framework for fish stock assessment and fishery management. Fisheries Research 142: 86-99.

Methratta, E. T. and J. S. Link. 2006. Evaluation of quantitative indicators for marine fish communities. *Ecological Indicators* 6:575-588.

Miller, W.D. and Harding Jr., L.W. (2007). "Climate forcing of the spring bloom in Chesapeake Bay". Marine Ecology Progress Series 331: 11–22

Miranda, L. E., and P. W. Bettoli. 2007. Mortality. Pages 229-277 in C. S. Guy and M. L. Brown, editors. Analysis and interpretation of freshwater fisheries data. American Fisheries Society, Bethesda, Maryland.

Moustahfid, H., M. C. Tyrrell, and J. S. Link. 2009b. Accounting explicitly for predation mortality in surplus production models: an application to longfin inshore squid. North American Journal of Fisheries Management 29(6):1555-1566.

Northeast Fisheries Science Center. 2013. 57th Northeast Regional Stock Assessment Workshop (57th SAW) Assessment Report. US Dept Commerce, Northeast Fish Sci Cent Ref Doc. 13-16; 967 pp. http://nefsc.noaa.gov/publications/crd/crd1316/

Ormseth, O.A., L. Conners, M. Guttormsen, and J. Vollenweider. 2008. Appendix 2: Forage Fishes in the Gulf of Alaska. In Gulf of Alaska Fishery Management Plan. December 2008. http://www.afsc.noaa.gov/refm/docs/2008/GOAforage.pdf

Overholtz, W.J., L.D. Jacobsen, and J.S. Link. 2008. An Ecosystem Approach for Assessment Advice and Biological Reference Points for the Gulf of Maine-Georges Bank Atlantic Herring Complex. N.Am. J Fish. Mgmt. 28(1): 247-257.

Ricker, W. E. 1975. Computation and interpretation of biological statistics of fish populations. Bulletin of the Fisheries Research Board of Canada 191.

Rose, G. A., and R. l. O'Driscoll. 2002. Capelin are good for cod: can the northern stock rebuild without them? ICES Journal of Marine Science 59(5):1018-1026.

Smayda, T.J. (1998). "Patterns of variability characterizing marine phytoplankton, with examples from Narragansett Bay". ICES Journal of Marine Science 55: 562–573.

Spencer, P. D., and J. S. Collie. 1996. A simple predator-prey model of exploited marine fish populations incorporating alternative prey. ICES Journal of Marine Science 53(3):615-628.

Spencer, P. D., and J. S. Collie. 1997. Effect of nonlinear predation rates on rebuilding the Georges Bank haddock (Melanogrammus aeglefinus) stock. Canadian Journal of Fisheries and Aquatic Sciences 54(12):2920-2929.

Steele, J. H., and E. W. Henderson. 1984. Modeling long-term fluctuations in fish stocks. Science 224:985-987.

Uphoff, J. 2010. Food web reference points and indicators estimated from Beaufort Assessment Model Atlantic menhaden biomass. A working paper for the ASMFC Multispecies Technical Committee. 21 pp.

Uphoff, J. H., J. Price, B. Pyle, and C. Hoover. 2013. Job 4. Development of ecosystem-based reference points for recreationally important Chesapeake Bay fishes of special concern: striped bass nutrition and forage availability benchmarks. Pages 87-109 in Performance Report for Federal Aid Grant F-63-R, Segment 4, Marine and Estuarine Finfish Ecological and Habitat Investigations, Maryland Department of Natural Resources, Annapolis. Available: http://dnr2.maryland.gov/fisheries/Documents/2013_FHEP_Annual_Report.pdf

Quinn, TJ, II, RB Deriso. 1999. Quantitative Fish Dynamics. Oxford University Press, New York, New York. 542 p.

SEDAR

Southeast Data, Assessment, and Review

SEDAR 40

Atlantic Menhaden

SECTION II: Addendum

January 2015

SEDAR
4055 Faber Place Drive, Suite 201
North Charleston, SC 29405

Addendum to the 2014 Atlantic Menhaden Stock Assessment Report

Purpose

The SEDAR 40 Review Workshop (RW) met in Atlantic Beach, North Carolina, from December 9 to December 11, 2014 to review the benchmark stock assessment of Atlantic menhaden prepared by the ASMFC Atlantic Menhaden Technical Committee (TC) and Stock Assessment Subcommittee. This addendum describes the revision that was made to the base run of the stock assessment as recommended by the peer review panel at the RW. To gain a full understanding of the stock assessment, the reader should also examine the original Stock Assessment Report and the Review Panel Report.

Revision and justification

One revision was made to the weight of the length composition data for the northern adult index (NAD) and southern adult index (SAD). Specifically, the weights on the likelihood component for the NAD and SAD length compositions were each divided by 10.

Briefly, the justification included a problematic mismatch between model predicted and observed length compositions. The panel's concern was that the lack of fit might be biasing other estimated quantities from the model (e.g., stock sizes). A few sensitivity runs were requested, and the run with the length composition data down-weighted by a factor of 10 was determined to be best. See the RW Report for full justification.

Clarification of reference point calculations

In addition to the one change to the base run of the model (above), a clarified description of the reference point calculations was requested. No changes were made from what was presented in the original stock assessment report; this section is simply for clarification.

Current fishing mortality reference points for Atlantic menhaden are $F_{30\%}$ (target) and $F_{15\%}$ (threshold) based on spawning potential ration (SPR). Population fecundity (***FEC***, number of maturing or ripe eggs) is the other current reference point and is a measure of reproductive capacity ($FEC_{30\%}$ = target; $FEC_{15\%}$ = threshold). Benchmark calculations were based upon landings-weighted selectivity across all fleets and areas (2011-2013), ***M***-at-age (which was constant), a 1:1 sex ratio, mean maturity-at-age, and mean fecundity-at-age. Means were computed using the entire time series of 1955 to 2013. Specifically, mean values were calculated from the mean length-at-age, which were then incorporated into each length-based equation to get mean maturity and fecundity.

Results

Goodness of fit

As with the base run presented in the stock assessment report, goodness-of-fit was governed by minimizing an objective function consisting of multiple likelihood components. Relative fit of the data components was governed by weighting terms and assumed error levels for each data source. Thus, this run has down-weighted length composition data relative to the base run presented in the original stock assessment report.

Reduction and bait fishery removals fit very well (1955–2013; Figures 1-4). Patterns in the annual comparisons of observed and predicted proportion catch-at-age for the northern and southern reduction and bait fisheries (Figures 5-8) indicate a good overall model fit to the observed data. Bubble plots for the northern and southern reduction and bait fisheries (Figures 9-12) indicate that the model fit performs fairly well at estimating catch-at-age over the time series.

Visual examination of the recruitment index fit suggests that the overall pattern matched reasonably well for the most recent time period (1959–2013; Figure 13). The residual pattern suggests that the recruitment index data did not fit well for larger year classes, especially those that occurred in the 1970s and 1980s.

The observed and predicted NAD index (1980–2013; Figure 14) and SAD index (1990-2013; Figure 15) values fit well with general patterns being captured. Patterns in the annual comparisons of observed and predicted proportion NAD and SAD measurements at length for the respective indices (Figures 16-17) indicate good fit to the observed data in some years, but problems in fitting to data in other years, similar to the base run (hence the down-weighting of the length composition data as suggested at the RW – see above). The bubble plots for the NAD and SAD index length compositions (Figures 18-19) show patterns that indicate the lack of fit.

Parameter estimates

Selectivity for each fishery and index was estimated using functional forms (Table 1). Selectivity parameters were estimated for each fishery and time period as four-parameter, double-logistic models with the parameters being the ascending slope and its A_{50} and the descending slope and its A_{50} (Figures 20-27). Selectivity for the NAD index was estimated as a two-parameter logistic function as shown in Figure 28, while selectivity for the SAD index was estimated as a four-parameter, double-logistic function as shown in Figure 29.

A single, constant catchability parameter was estimated for the NAD and SAD abundance indices, while two constant catchability parameters were estimated for the recruitment index using two time blocks: 1959-1986 and 1987-2013. Log-catchability was estimated as -0.55 for the NAD index with a 0.30 SE, while the log-catchability of the SAD index was -1.67 with a 0.13 SE. For the recruitment index, log-catchability was estimated as -2.52 for the first time period with a SE of 0.10, while the log-catchability of the second time period was -3.03 with a SE of 0.08.

Highest fishing mortality rates for the commercial reduction fishery in the north were in the 1950s (Figure 30), while the highest fishing mortality rates for the commercial reduction fishery in the south were during the 1970s to 1990s (Figure 31). Highest fishing mortality rates for the commercial bait fishery in the north were in the 1950s and 1990s (Figure 32), while the highest fishing mortality rates for the commercial bait fishery in the south were during the late 1990s and early 2000s (Figure 33). Fishing mortality rate over time was reported as the fishing mortality rate at age-2 and at age-3 (Table 2; Figure 34).

The BAM model estimated population numbers-at-age (ages 0-6+) for 1955–2013 (Figure 35; Table 3), population fecundity (Figure 36; Table 4), biomass (Figures 37-38; Table 5), and age-0 recruits (Figure 39; Table 6). Annual estimated recruitment values relative to the median are shown in Figure 40. The only recruitment parameter estimated in the model was log of R_0, which was estimated at 2.82 with a standard deviation of 0.066.

Stock status

With the proposed base run from the RW, the stock status for Atlantic menhaden remains **not overfished** and **overfishing is not occurring** (Figures 41-42; Table 6) using the current, formally adopted benchmarks.

With the proposed base run from the RW, the TC proposed reference points would become $F_{20\%}$ and $F_{39\%}$ along with the associated fecundity reference points of $FEC_{20\%}$ and $FEC_{39\%}$. With the proposed base run and the proposed reference points, the stock status for Atlantic menhaden remains **not overfished** and **overfishing is not occurring** (Figures 43-44; Table 6).

Table 1. Selectivity slope and A_{50} of the ascending and descending limbs with associated SE for the bait and reduction fisheries, and the NAD and SAD indices.

			Ascending Limb				**Descending Limb**			
Fishery/Index	**Region**	**Period**	**Slope**	**SE**	**A50**	**SE**	**Slope**	**SE**	**A50**	**SE**
Reduction	North	1955-1969	3.67	0.19	2.24	0.12	1.99	2.45	2.93	0.88
Reduction	North	1969-1993	5.49	0.98	2.00	0.17	1.52	1.12	1.91	1.37
Reduction	North	1994-2013	5.48	3.42	2.11	0.13	1.32	0.98	2.50	0.001
Reduction	South	1955-1971	4.01	0.32	1.11	0.16	2.75	3.36	1.67	0.65
Reduction	South	1972-2004	2.14	0.16	3.21	0.15	4.43	0.59	-1.00	0.001
Reduction	South	2005-2013	12.0	0.009	1.09	0.03	1.70	0.78	2.50	0.001
Bait	North	1955-2013	6.16	2.75	2.32	0.15	3.43	1.14	2.15	0.27
Bait	South	1955-2013	4.30	70672	1.07	117.5	0.84	0.74	1.27	1175
NAD	North		19.1	7352	2.01	2.87	NA	NA	NA	NA
SAD	South		35.0	0.056	0.15	0.057	4.43	1.87	1.40	0.43

Table 2. Fishing mortality rate at age estimates from 1955-2013.

Ages	0	1	2	3	4	5	6+
1955	0.006	0.220	1.116	2.359	2.138	1.328	0.364
1956	0.011	0.371	2.948	7.743	7.280	4.484	1.226
1957	0.008	0.297	2.470	6.525	6.133	3.757	1.026
1958	0.008	0.289	1.332	2.564	2.281	1.422	0.391
1959	0.008	0.266	1.720	4.043	3.742	2.323	0.638
1960	0.003	0.093	0.501	1.091	0.993	0.612	0.168
1961	0.006	0.203	0.649	0.791	0.608	0.373	0.103
1962	0.009	0.306	1.055	1.443	1.159	0.709	0.196
1963	0.009	0.307	1.095	1.503	1.205	0.723	0.200
1964	0.010	0.324	0.924	0.838	0.540	0.302	0.083
1965	0.010	0.359	1.048	0.929	0.596	0.343	0.096
1966	0.010	0.356	0.870	0.446	0.135	0.057	0.016
1967	0.006	0.214	0.554	0.354	0.164	0.087	0.025
1968	0.006	0.209	0.530	0.356	0.177	0.100	0.028
1969	0.005	0.183	0.453	0.244	0.085	0.042	0.012
1970	0.007	0.234	0.610	0.312	0.081	0.024	0.008
1971	0.006	0.195	0.513	0.293	0.087	0.025	0.007
1972	0.024	0.206	1.354	0.538	0.163	0.054	0.014
1973	0.013	0.116	0.880	0.512	0.219	0.073	0.019
1974	0.011	0.094	0.696	0.383	0.158	0.053	0.014
1975	0.010	0.089	0.629	0.290	0.106	0.037	0.010
1976	0.010	0.087	0.648	0.350	0.142	0.048	0.013
1977	0.010	0.086	0.579	0.237	0.076	0.026	0.008
1978	0.011	0.092	0.623	0.256	0.082	0.029	0.008
1979	0.013	0.108	0.709	0.281	0.085	0.028	0.008
1980	0.020	0.171	1.146	0.462	0.144	0.050	0.014
1981	0.020	0.172	1.165	0.492	0.162	0.056	0.016
1982	0.022	0.190	1.214	0.422	0.107	0.036	0.011
1983	0.024	0.209	1.333	0.461	0.116	0.039	0.011
1984	0.026	0.220	1.418	0.520	0.144	0.048	0.013
1985	0.009	0.084	0.794	0.670	0.351	0.111	0.027
1986	0.006	0.049	0.354	0.235	0.122	0.031	0.006
1987	0.009	0.075	0.523	0.264	0.108	0.033	0.008
1988	0.015	0.132	0.873	0.380	0.136	0.040	0.010
1989	0.020	0.177	1.296	0.698	0.290	0.094	0.025
1990	0.014	0.119	1.062	0.897	0.476	0.142	0.032
1991	0.015	0.129	1.012	0.742	0.384	0.107	0.023
1992	0.010	0.085	0.720	0.629	0.352	0.096	0.020
1993	0.013	0.112	0.775	0.445	0.209	0.054	0.011
1994	0.016	0.138	0.885	0.400	0.174	0.066	0.021
1995	0.030	0.260	1.799	1.087	0.586	0.263	0.091
1996	0.019	0.162	1.201	0.989	0.620	0.245	0.079

Ages	0	1	2	3	4	5	6+
1997	0.024	0.212	1.403	0.759	0.384	0.130	0.039
1998	0.030	0.266	1.720	0.789	0.349	0.109	0.032
1999	0.016	0.140	0.950	0.565	0.305	0.088	0.023
2000	0.008	0.073	0.583	0.549	0.360	0.144	0.047
2001	0.012	0.103	0.709	0.406	0.212	0.089	0.030
2002	0.010	0.093	0.638	0.334	0.164	0.066	0.022
2003	0.012	0.108	0.697	0.257	0.086	0.029	0.010
2004	0.007	0.066	0.467	0.279	0.150	0.059	0.020
2005	0.000	0.077	0.367	0.344	0.191	0.061	0.018
2006	0.000	0.047	0.278	0.374	0.246	0.101	0.033
2007	0.000	0.048	0.247	0.302	0.191	0.064	0.018
2008	0.000	0.038	0.204	0.258	0.167	0.056	0.016
2009	0.000	0.052	0.246	0.253	0.147	0.045	0.012
2010	0.000	0.069	0.327	0.367	0.222	0.068	0.018
2011	0.000	0.059	0.294	0.379	0.243	0.072	0.018
2012	0.000	0.046	0.235	0.327	0.217	0.059	0.014
2013	0.000	0.047	0.237	0.267	0.163	0.055	0.016

Table 3. Numbers at age in billions of fish estimated from the base run of the BAM model for 1955-2013.

Ages	0	1	2	3	4	5	6+
1955	26.334	4.401	2.747	0.579	0.000	0.000	0.000
1956	28.796	8.537	1.556	0.470	0.031	0.000	0.000
1957	13.527	9.296	2.595	0.043	0.000	0.000	0.000
1958	79.582	4.376	3.044	0.115	0.000	0.000	0.000
1959	12.492	25.748	1.444	0.420	0.005	0.000	0.000
1960	11.419	4.045	8.687	0.135	0.004	0.000	0.000
1961	11.236	3.716	1.624	2.748	0.026	0.001	0.000
1962	12.235	3.644	1.336	0.443	0.705	0.008	0.000
1963	9.711	3.956	1.182	0.243	0.059	0.131	0.003
1964	10.147	3.140	1.282	0.206	0.031	0.011	0.040
1965	9.576	3.279	1.000	0.266	0.051	0.011	0.028
1966	14.643	3.092	1.008	0.183	0.059	0.017	0.020
1967	8.725	4.728	0.954	0.220	0.066	0.031	0.022
1968	11.075	2.829	1.682	0.286	0.088	0.033	0.030
1969	14.844	3.591	1.011	0.517	0.113	0.044	0.037
1970	7.125	4.817	1.318	0.336	0.229	0.062	0.048
1971	19.568	2.309	1.679	0.374	0.139	0.126	0.066
1972	16.452	6.348	0.836	0.525	0.158	0.076	0.115
1973	17.582	5.240	2.275	0.113	0.173	0.080	0.114
1974	27.669	5.661	2.055	0.493	0.038	0.083	0.114
1975	42.175	8.931	2.270	0.535	0.190	0.019	0.117
1976	33.438	13.622	3.598	0.632	0.226	0.102	0.083
1977	32.613	10.802	5.498	0.983	0.252	0.117	0.109
1978	24.805	10.536	4.366	1.610	0.438	0.139	0.136
1979	36.093	8.008	4.232	1.222	0.705	0.240	0.165
1980	26.096	11.630	3.167	1.088	0.522	0.385	0.243
1981	28.639	8.348	4.317	0.526	0.387	0.268	0.370
1982	15.762	9.161	3.097	0.703	0.182	0.196	0.380
1983	35.256	5.031	3.336	0.480	0.261	0.097	0.347
1984	48.209	11.226	1.797	0.459	0.171	0.138	0.269
1985	35.895	15.333	3.970	0.227	0.154	0.088	0.244
1986	19.727	11.603	6.208	0.937	0.066	0.065	0.195
1987	13.814	6.401	4.868	2.275	0.419	0.035	0.158
1988	24.717	4.468	2.616	1.506	0.987	0.224	0.117
1989	19.422	7.943	1.725	0.570	0.583	0.512	0.202
1990	23.633	6.210	2.930	0.246	0.161	0.259	0.405
1991	18.987	7.607	2.428	0.529	0.057	0.059	0.379
1992	15.382	6.104	2.944	0.461	0.142	0.023	0.261
1993	7.609	4.971	2.470	0.748	0.139	0.060	0.171
1994	14.471	2.451	1.958	0.594	0.271	0.067	0.139

Ages	0	1	2	3	4	5	6+
1995	11.939	4.647	0.940	0.422	0.225	0.136	0.122
1996	9.994	3.780	1.578	0.081	0.080	0.075	0.132
1997	11.853	3.201	1.415	0.248	0.017	0.026	0.111
1998	12.876	3.774	1.140	0.182	0.066	0.007	0.080
1999	12.456	4.075	1.274	0.107	0.047	0.028	0.052
2000	9.784	4.001	1.561	0.257	0.034	0.020	0.046
2001	8.790	3.167	1.638	0.455	0.084	0.014	0.038
2002	18.126	2.835	1.258	0.421	0.171	0.040	0.031
2003	14.397	5.852	1.137	0.347	0.170	0.087	0.042
2004	15.602	4.641	2.314	0.296	0.152	0.093	0.076
2005	24.053	5.053	1.913	0.757	0.127	0.078	0.100
2006	16.325	7.848	2.061	0.692	0.304	0.062	0.105
2007	13.483	5.327	3.298	0.815	0.269	0.141	0.097
2008	17.081	4.399	2.236	1.346	0.340	0.132	0.139
2009	13.482	5.573	1.866	0.952	0.588	0.171	0.160
2010	26.954	4.399	2.330	0.762	0.418	0.302	0.197
2011	10.151	8.795	1.807	0.877	0.298	0.199	0.291
2012	8.623	3.312	3.651	0.703	0.340	0.139	0.289
2013	6.889	2.814	1.393	1.507	0.287	0.163	0.256

Table 4. Fecundity at age in billions of eggs during 1955-2013.

Ages	0	1	2	3	4	5	6+
1955	0	4046	73404	36107	37	0	0
1956	0	6373	37156	32019	3012	4	0
1957	0	5431	36529	2915	13	2	0
1958	0	4771	42860	6079	4	0	0
1959	0	7928	20450	21186	534	0	0
1960	0	9280	72838	6494	387	13	0
1961	0	3980	37653	109821	2359	127	7
1962	0	6060	27497	27609	58481	1220	74
1963	0	8333	25663	14796	6543	17873	587
1964	0	7936	30594	11308	3156	1783	8126
1965	0	7650	26148	15540	4304	1555	6509
1966	0	4505	31091	11737	5499	1858	3795
1967	0	14295	22549	18083	6789	3814	2892
1968	0	5920	67251	21535	13034	4717	4553
1969	0	10064	24888	51461	17590	10389	6515
1970	0	23578	38525	24709	40694	17403	16400
1971	0	8720	88104	29656	20326	33924	31131
1972	0	9185	45723	68726	24605	20069	42437
1973	0	3059	41551	14026	43447	21679	50660
1974	0	4122	48818	28780	7686	34198	50489
1975	0	3795	35198	34878	21499	5268	71427
1976	0	3801	24227	33632	22542	19250	27297
1977	0	1879	25251	33282	24597	14674	32026
1978	0	1872	15432	41708	32685	20369	19493
1979	0	2312	18165	29206	41061	30829	33184
1980	0	2038	12008	30699	31496	36792	49542
1981	0	1528	10846	11140	26788	28488	51120
1982	0	2723	14185	10982	9234	24447	64353
1983	0	1402	18271	12135	11269	8389	71176
1984	0	3251	11547	13413	9557	10827	34953
1985	0	2823	17172	8005	10020	7841	30271
1986	0	2070	26639	23491	4944	7023	24422
1987	0	1831	17252	55488	24744	4221	25679
1988	0	806	12837	35001	54958	22975	20795
1989	0	3342	8869	14902	34002	47260	32672
1990	0	5689	31354	7213	9194	26704	53976
1991	0	4481	43046	23506	3680	5402	62209
1992	0	10015	36603	23439	11929	2409	33284
1993	0	2183	47965	34630	11435	7491	25881
1994	0	3577	21725	34509	23161	7334	23639
1995	0	2029	22407	21466	23810	17400	15978
1996	0	1089	34398	5564	8974	12488	23088

Ages	0	1	2	3	4	5	6+
1997	0	890	25899	18610	2067	5263	26740
1998	0	1620	11353	13097	9041	1265	27565
1999	0	9356	18561	5401	6478	5759	12836
2000	0	4399	40482	14261	3606	4445	12982
2001	0	2315	58761	31135	8647	2521	11344
2002	0	6603	38709	40544	20368	6345	8130
2003	0	6292	30363	26282	28191	15488	8792
2004	0	5098	46126	16259	16872	21727	18743
2005	0	1450	34799	43904	9476	10446	29261
2006	0	5865	26246	37588	29509	5421	15617
2007	0	6822	65600	42535	25074	19088	9230
2008	0	7351	49926	67898	32401	17558	23842
2009	0	9401	43368	50213	42486	23579	27809
2010	0	8202	37673	39793	31733	26157	35234
2011	0	18241	41700	40557	21651	18346	27852
2012	0	6203	79399	35333	27108	12033	29439
2013	0	5269	27941	73736	19968	19197	24426

Table 5. Biomass of Atlantic menhaden by age from 1955 to 2013.

Year	0	1	2	3	4	5	6+	Total
1955	734.73	275.09	567.19	194.31	0.18	0.00	0.00	1771.50
1956	613.35	496.02	305.42	166.33	14.01	0.02	0.00	1595.16
1957	474.79	493.62	406.30	15.13	0.06	0.01	0.00	1389.90
1958	1496.13	287.53	476.64	34.63	0.02	0.00	0.00	2294.95
1959	559.62	1130.32	227.35	122.85	2.42	0.00	0.00	2042.56
1960	292.33	337.32	1124.14	38.31	1.82	0.05	0.00	1793.97
1961	382.03	238.55	314.53	699.36	11.14	0.53	0.02	1646.16
1962	485.72	274.42	245.35	148.57	285.70	4.97	0.28	1445.01
1963	414.68	325.22	221.53	79.98	29.14	74.69	2.06	1147.30
1964	412.98	271.02	251.48	63.48	14.44	6.88	29.33	1049.61
1965	332.28	279.08	204.99	85.40	20.89	6.33	22.15	951.12
1966	578.39	221.99	222.85	62.27	25.91	8.24	14.05	1133.70
1967	383.01	435.90	185.47	88.59	31.13	16.42	12.16	1152.67
1968	546.01	230.55	428.28	108.51	52.88	19.48	18.39	1404.11
1969	708.08	325.02	201.38	237.83	69.88	35.26	24.66	1602.11
1970	228.72	521.25	284.37	125.17	154.20	55.21	47.79	1416.72
1971	733.81	228.59	502.78	147.63	82.95	109.42	78.65	1883.83
1972	194.14	451.98	256.71	290.73	97.59	65.26	119.78	1476.20
1973	406.15	278.25	397.18	60.30	144.46	69.72	131.41	1487.48
1974	644.70	317.57	401.44	158.22	27.84	91.87	131.35	1772.99
1975	716.98	412.63	368.95	184.45	95.12	16.96	159.80	1954.90
1976	518.28	512.17	433.51	191.50	104.19	71.29	81.13	1912.07
1977	515.29	365.10	580.62	228.21	114.31	62.88	99.98	1966.39
1978	513.46	368.77	424.34	327.21	165.11	83.03	80.12	1962.04
1979	653.28	317.92	435.02	240.11	225.90	131.24	120.30	2123.77
1980	412.31	397.73	314.82	230.13	170.59	171.97	178.55	1876.11
1981	569.91	306.37	369.93	97.72	138.71	129.36	212.63	1824.63
1982	230.13	381.09	326.07	115.10	53.49	105.00	248.02	1458.90
1983	712.18	189.15	374.35	96.66	69.57	40.57	255.92	1738.40
1984	819.55	447.94	213.51	99.00	53.47	54.04	148.24	1835.74
1985	603.03	567.33	411.69	54.05	53.04	37.64	130.25	1857.03
1986	347.19	408.43	638.17	187.26	24.93	31.45	104.74	1742.16
1987	201.68	250.91	474.62	449.26	135.74	18.26	100.39	1630.86
1988	422.67	159.97	283.80	292.39	307.60	105.28	78.85	1650.55
1989	475.83	362.18	188.42	116.84	186.98	223.03	128.00	1681.28
1990	548.28	386.87	415.20	53.24	50.73	122.25	227.03	1803.60
1991	730.99	409.27	418.78	143.10	19.49	25.57	242.44	1989.64
1992	333.79	451.67	442.84	135.74	58.13	10.98	142.07	1575.23
1993	241.96	241.09	442.68	207.53	55.97	32.09	104.47	1325.79
1994	179.44	176.45	281.17	189.97	112.35	32.76	91.01	1063.15
1995	101.49	223.51	184.19	124.30	108.24	74.08	67.63	883.45
1996	118.93	149.71	296.89	28.87	39.88	48.32	88.07	770.67

Year	0	1	2	3	4	5	6+	Total
1997	184.90	119.71	247.55	93.84	8.97	18.94	90.36	764.26
1998	540.78	177.01	157.93	67.20	37.62	4.75	80.17	1065.47
1999	225.46	339.89	202.25	31.30	26.89	20.54	42.82	889.16
2000	96.86	266.05	317.62	79.88	16.42	15.63	41.32	833.78
2001	301.51	178.59	391.59	161.58	39.61	9.56	35.19	1117.64
2002	473.09	240.67	277.59	189.15	88.81	25.12	26.49	1320.91
2003	431.91	377.48	234.64	132.27	109.59	58.54	31.26	1375.69
2004	160.70	308.14	418.60	91.21	75.04	74.30	62.90	1190.88
2005	387.25	198.58	332.64	241.75	47.81	43.83	91.18	1343.04
2006	404.86	455.97	310.64	211.33	137.33	26.16	63.35	1609.64
2007	389.67	370.73	595.31	242.95	118.04	79.92	43.18	1839.79
2008	748.16	333.47	423.95	393.71	151.62	73.95	91.53	2216.40
2009	419.28	427.47	362.24	286.36	217.87	98.19	106.35	1917.76
2010	997.31	343.11	387.49	227.26	159.63	126.36	133.35	2374.50
2011	375.59	708.85	348.46	243.06	110.95	86.59	130.14	2003.64
2012	319.06	259.67	685.22	204.99	134.76	58.18	135.22	1797.09
2013	254.88	220.58	253.47	433.83	103.23	83.88	114.22	1464.10

Table 6. Current fishing mortality and fecundity benchmarks (targets and thresholds) along with terminal year values from the base run of the BAM. Fecundity (FEC) is in billions of eggs.

Current Reference Points	Benchmark	Current value
$F_{15\%\ (\text{threshold})}$	2.98	0.27 (age-3; full ***F***)
$F_{30\%\ (\text{target})}$	1.03	0.27 (age-3; full ***F***)
$FEC_{15\%\ (\text{threshold})}$	49,658	170,536
$FEC_{30\%\ (\text{target})}$	100,016	170,536
Recommended Reference Points	Benchmark	Current value
$F_{20\%\ (\text{threshold})}$	1.80	0.24 (age-2)
$F_{39\%\ (\text{target})}$	0.71	0.24 (age-2)
$FEC_{20\%\ (\text{threshold})}$	67,654	170,536
$FEC_{39\%\ (\text{target})}$	130,247	170,536

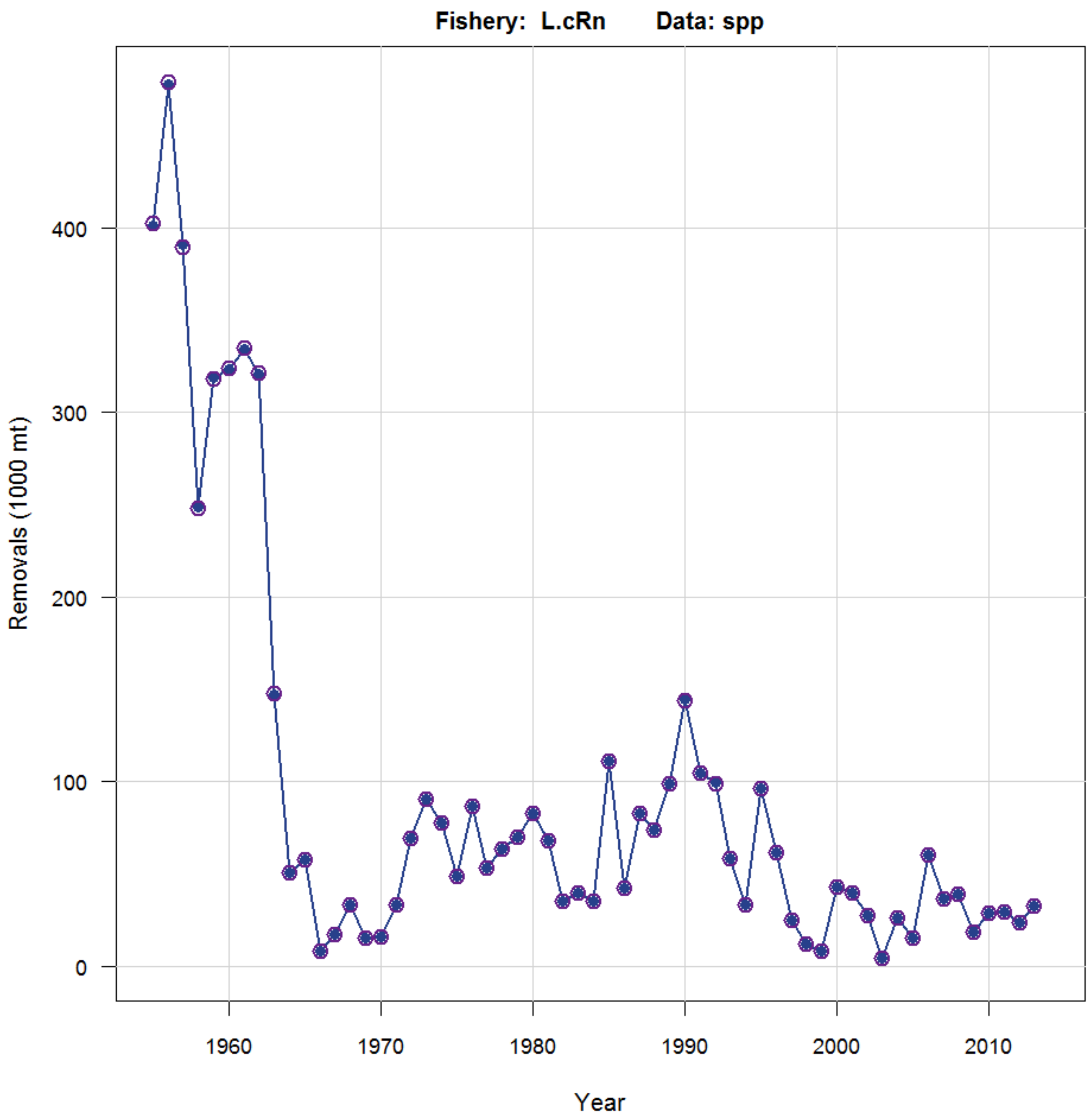


Figure 1. Observed and predicted removals of Atlantic menhaden from 1955-2013 from north of Virginia Eastern Shore by the commercial reduction fishery.

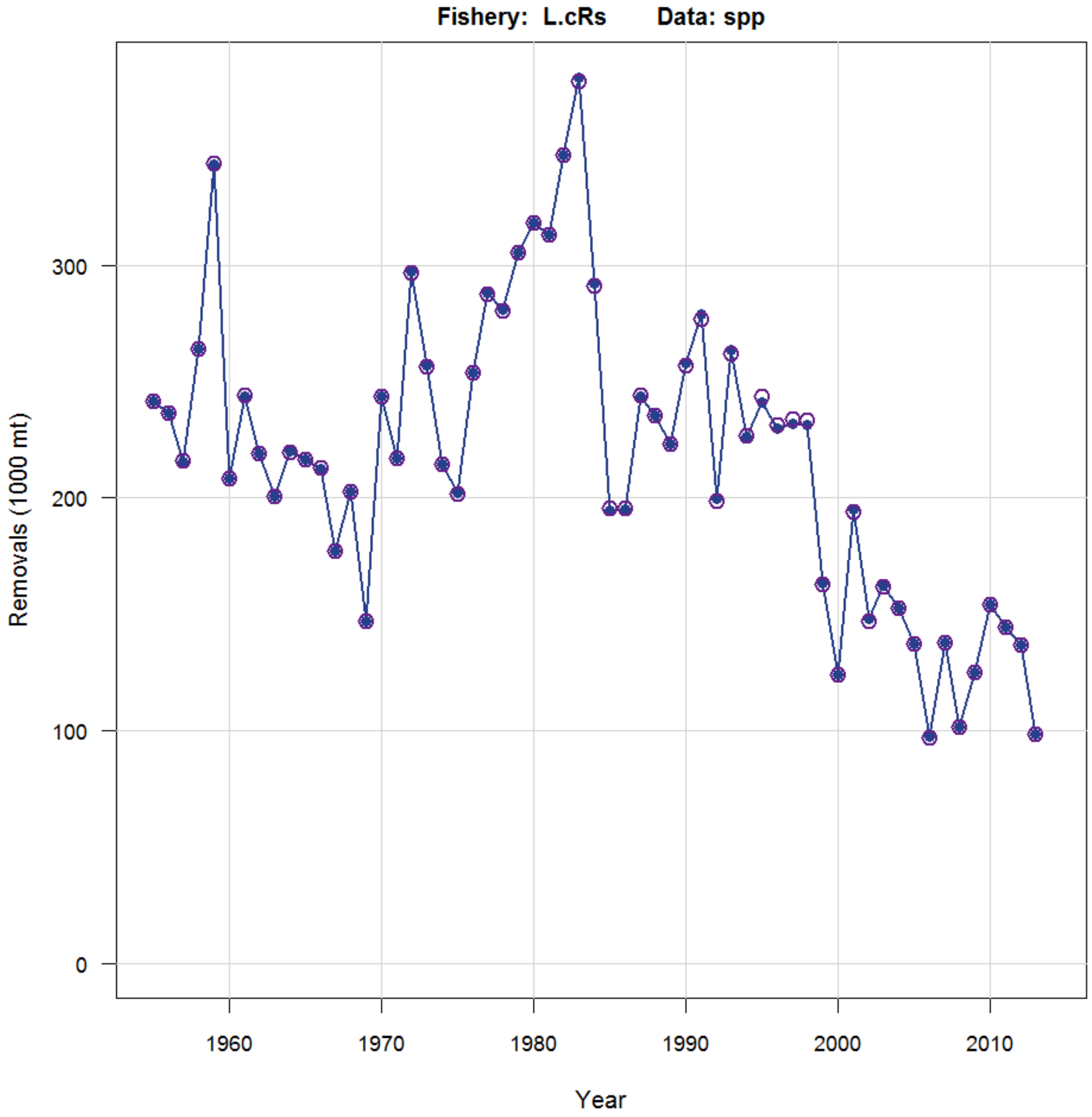


Figure 2. Observed and predicted removals of Atlantic menhaden from 1955-2013 from Virginia Eastern Shore and south by the commercial reduction fishery.

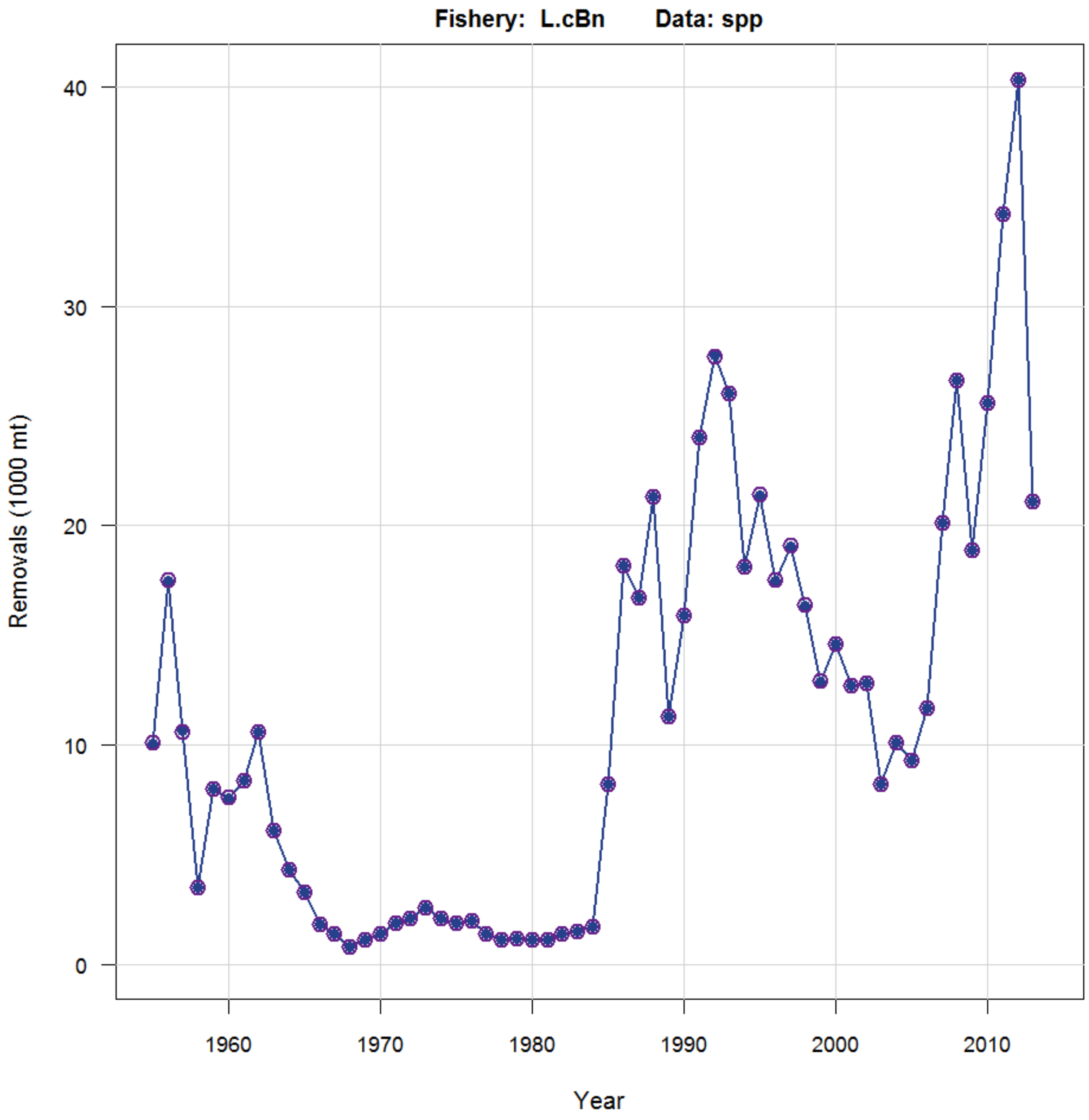


Figure 3. Observed and predicted removals of Atlantic menhaden from 1955-2013 from north of Virginia Eastern Shore by the commercial bait fishery.

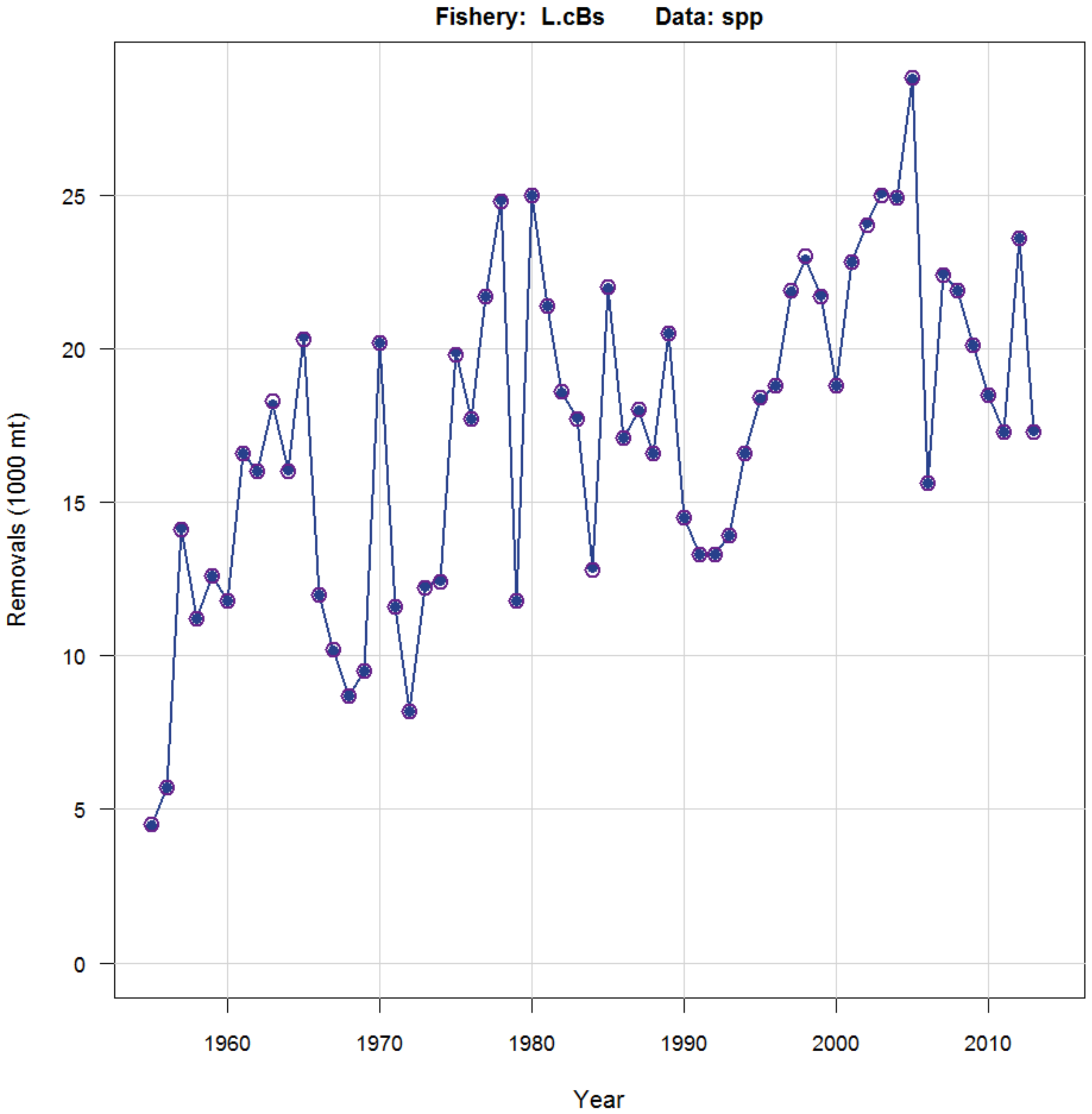


Figure 4. Observed and predicted removals of Atlantic menhaden from 1955-2013 from Virginia Eastern Shore and south by the commercial bait fishery.

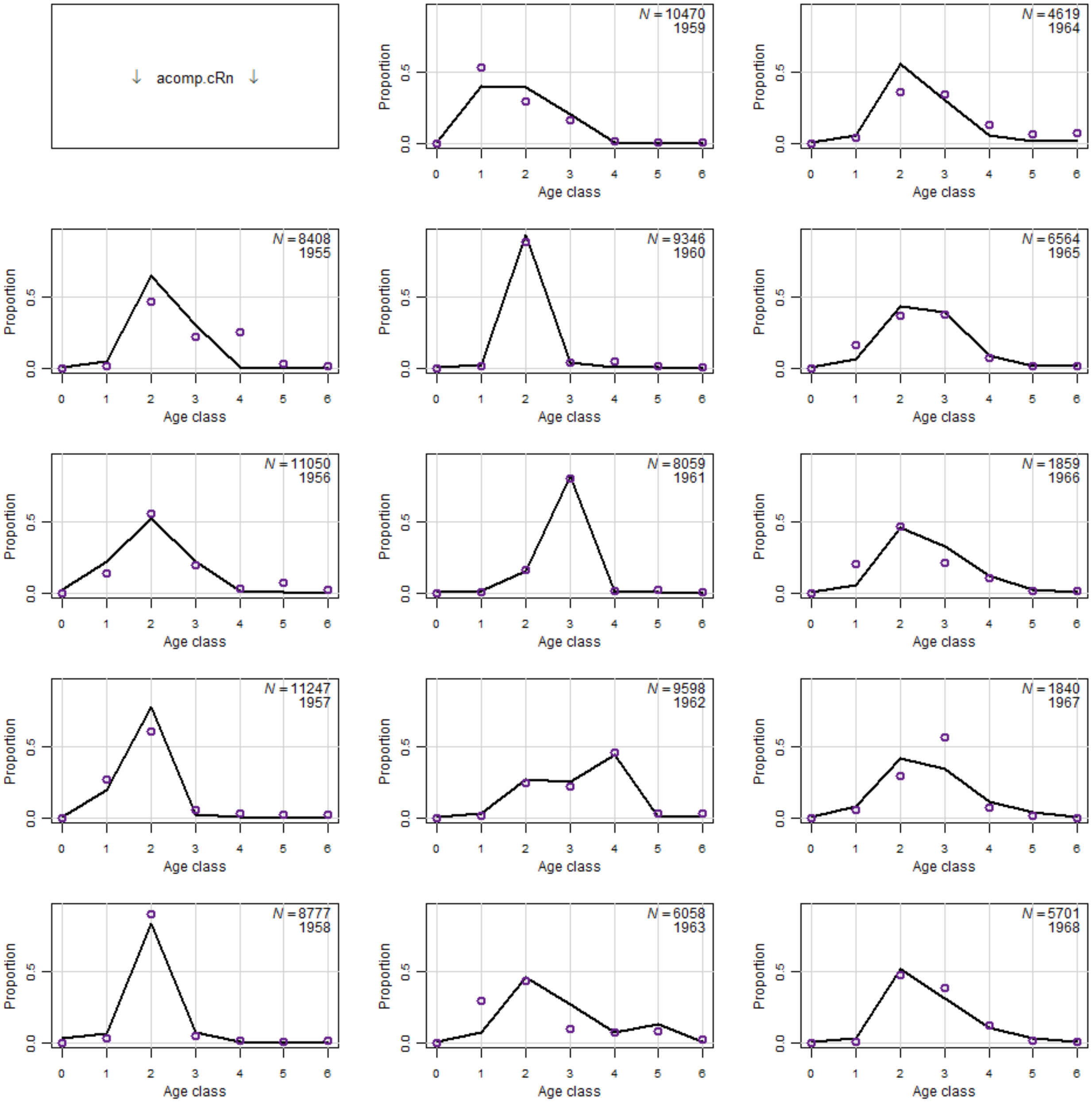


Figure 5. Annual observed and predicted catch-at-age of Atlantic menhaden from 1955-2013 from north of Virginia Eastern Shore by the commercial reduction fishery.

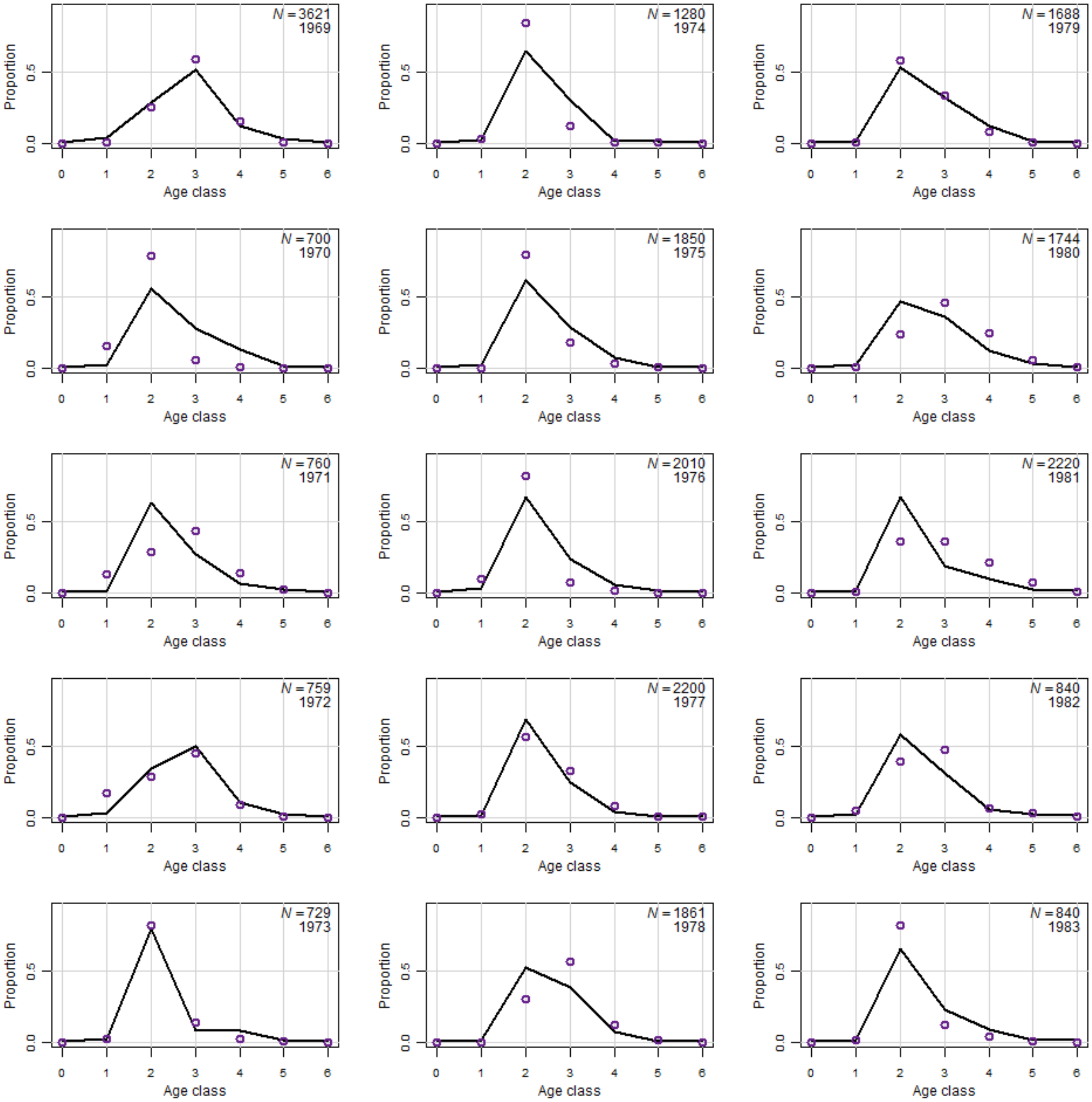


Figure 5. Continued.

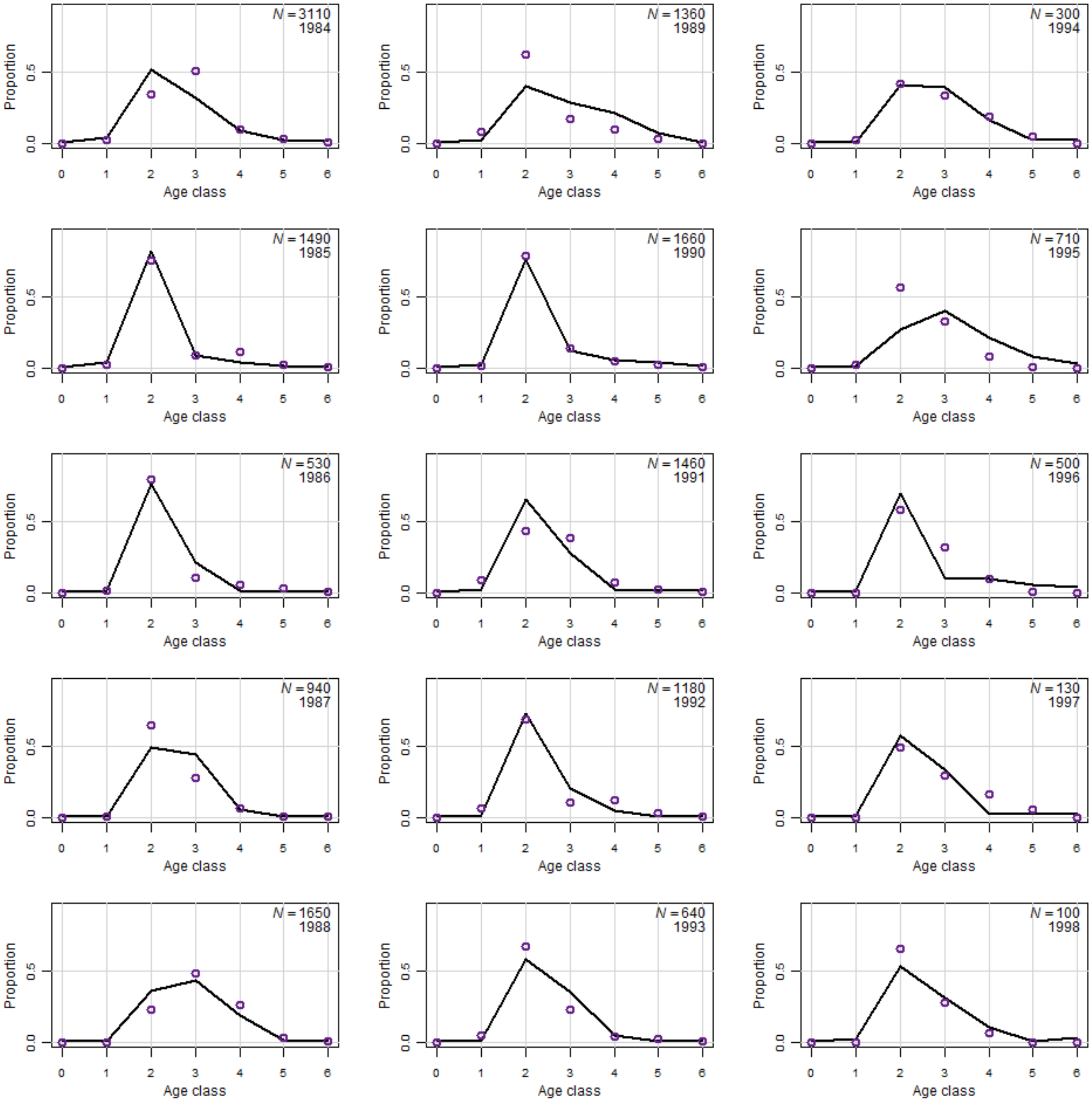


Figure 5. Continued.

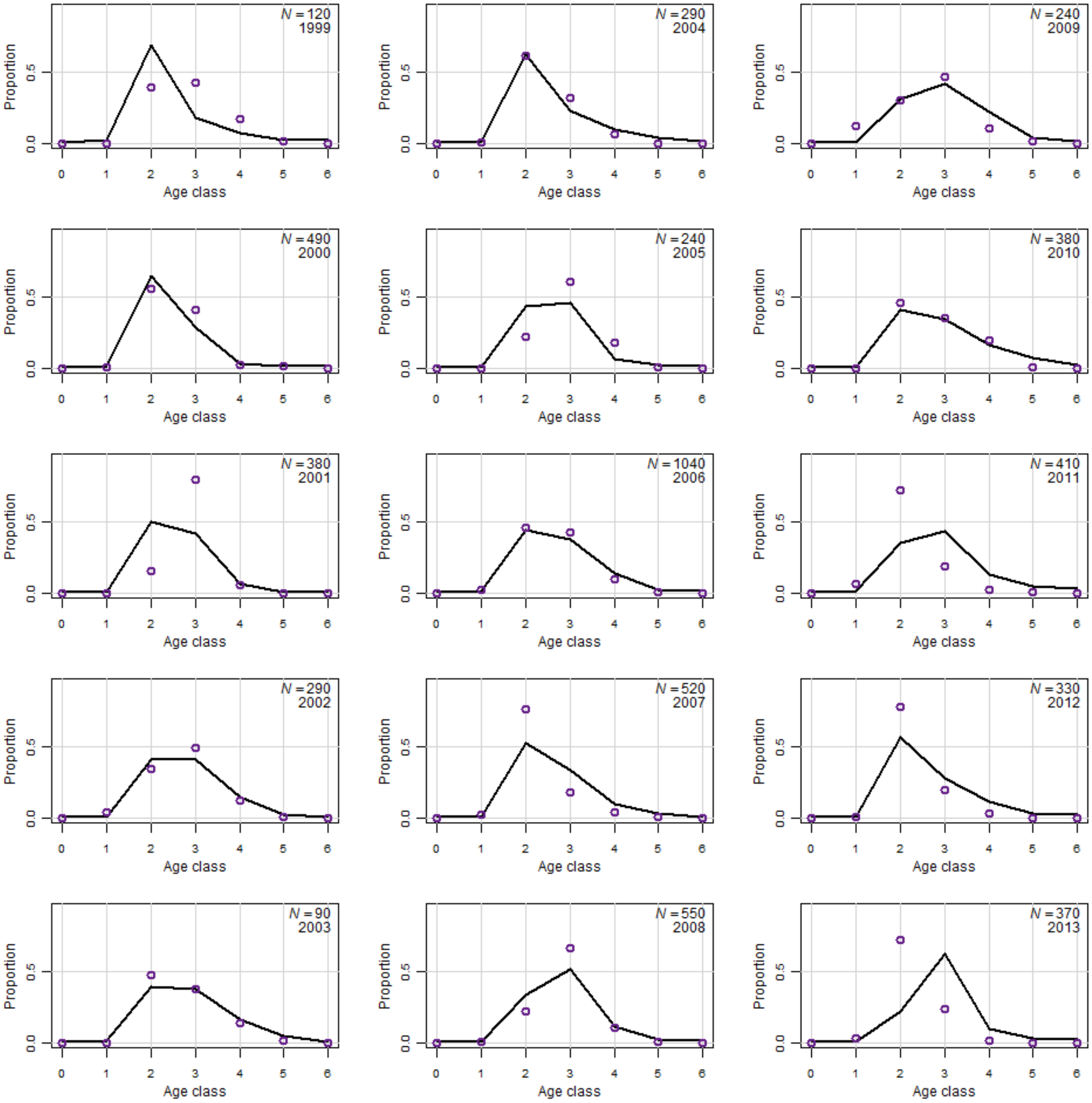


Figure 5. Continued.

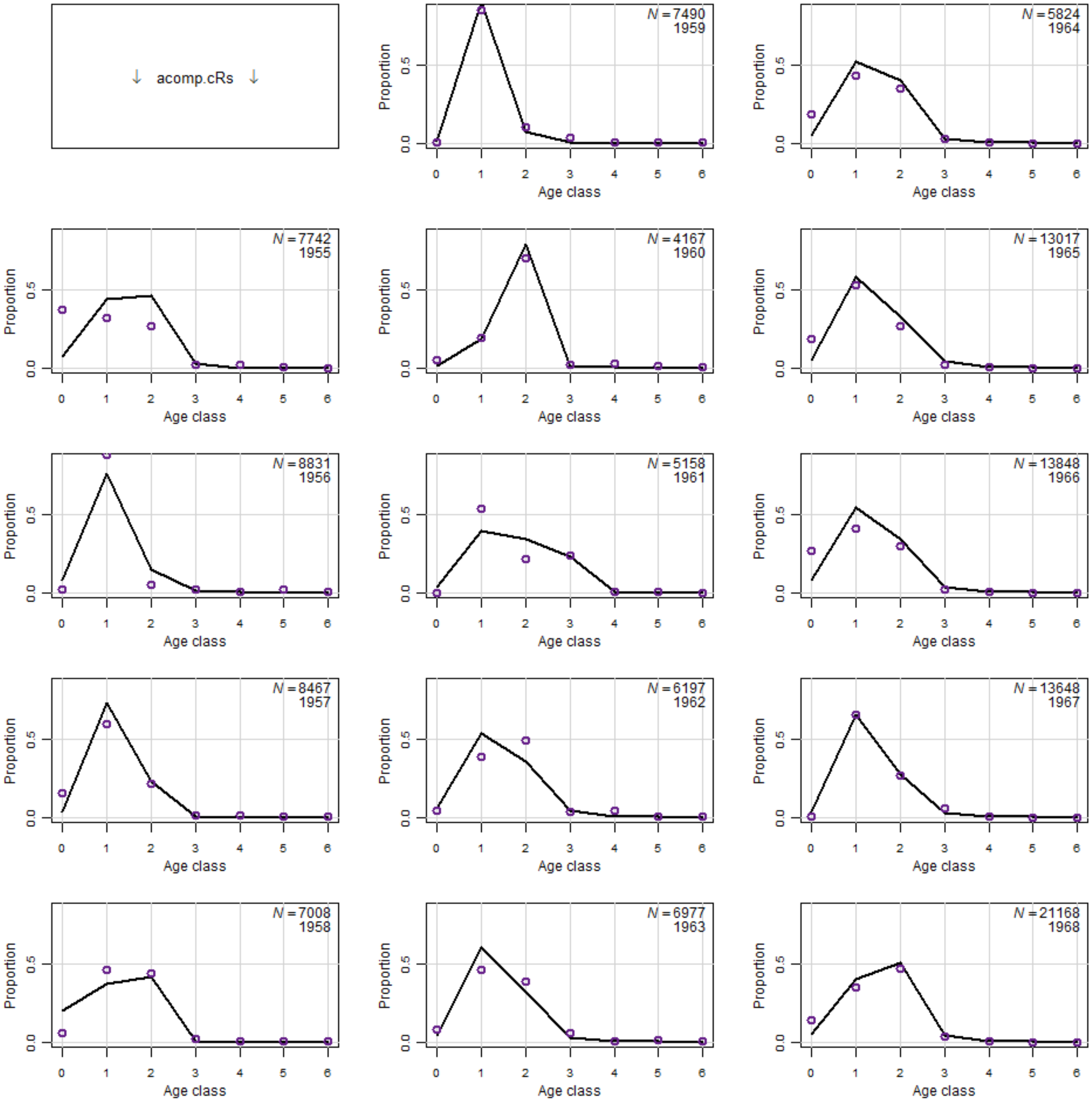


Figure 6. Annual observed and predicted catch-at-age of Atlantic menhaden from 1955-2013 from Virginia Eastern Shore and south by the commercial reduction fishery.

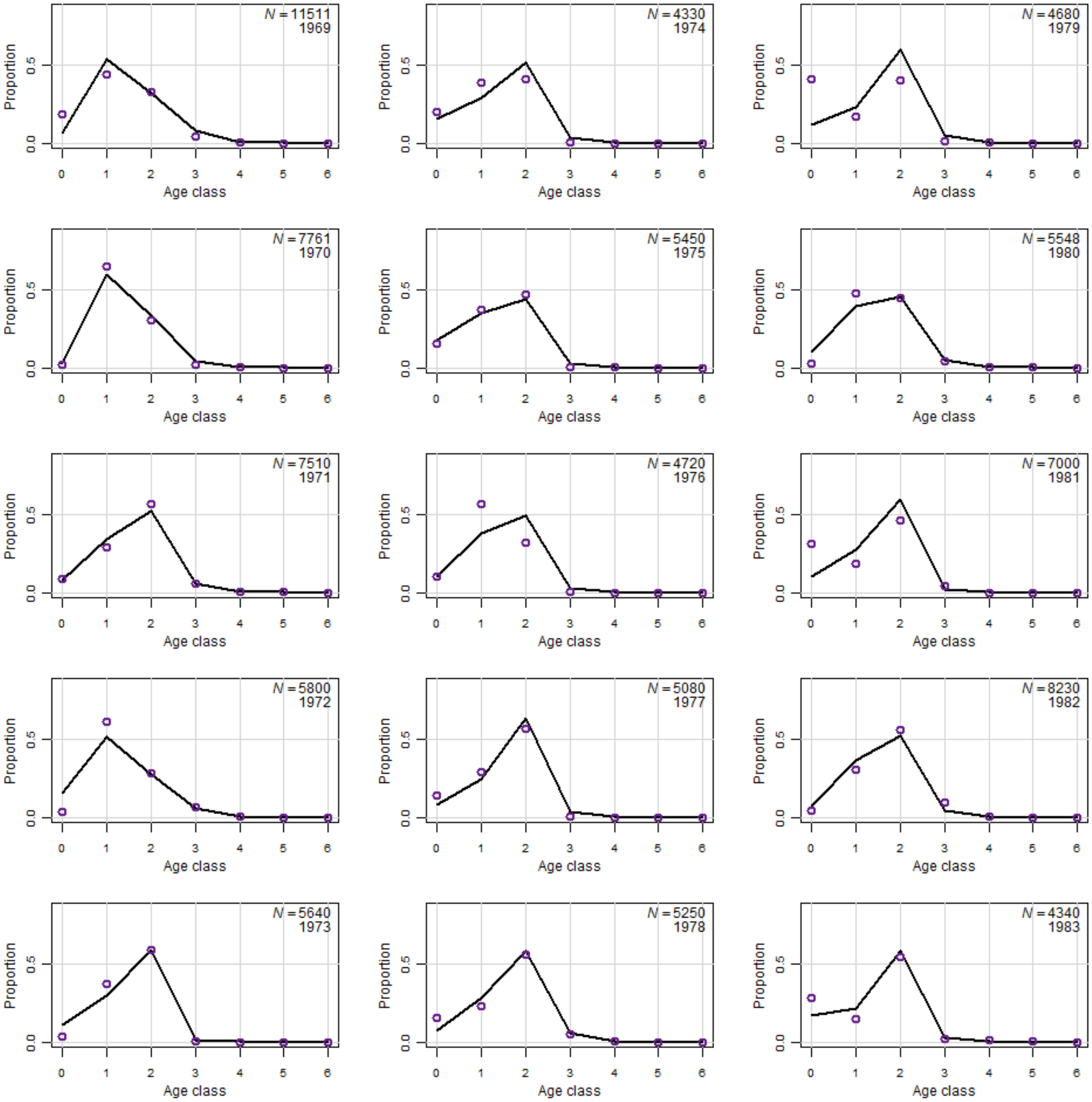


Figure 6. continued.

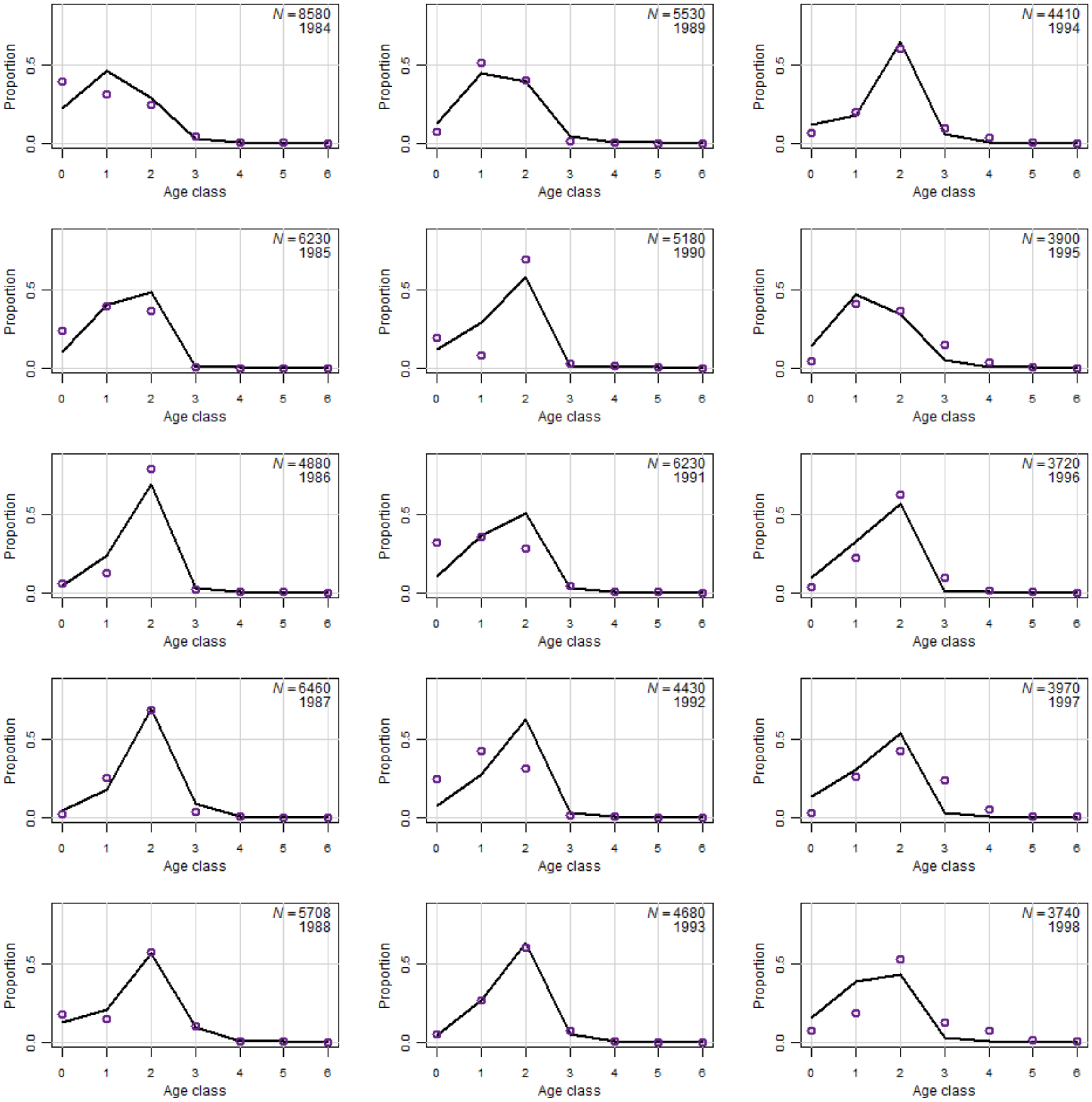


Figure 6. Continued.

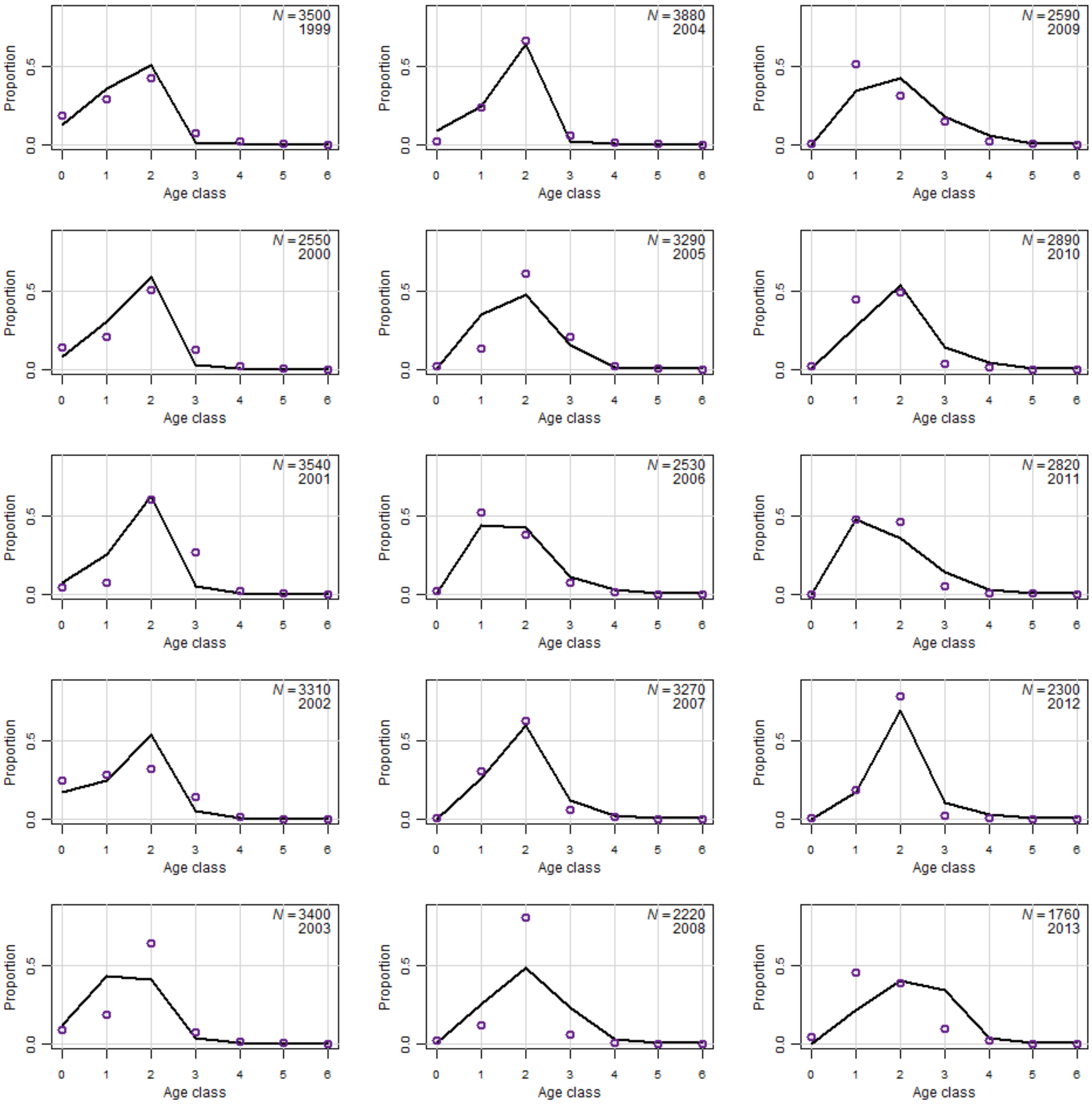


Figure 6. Continued.

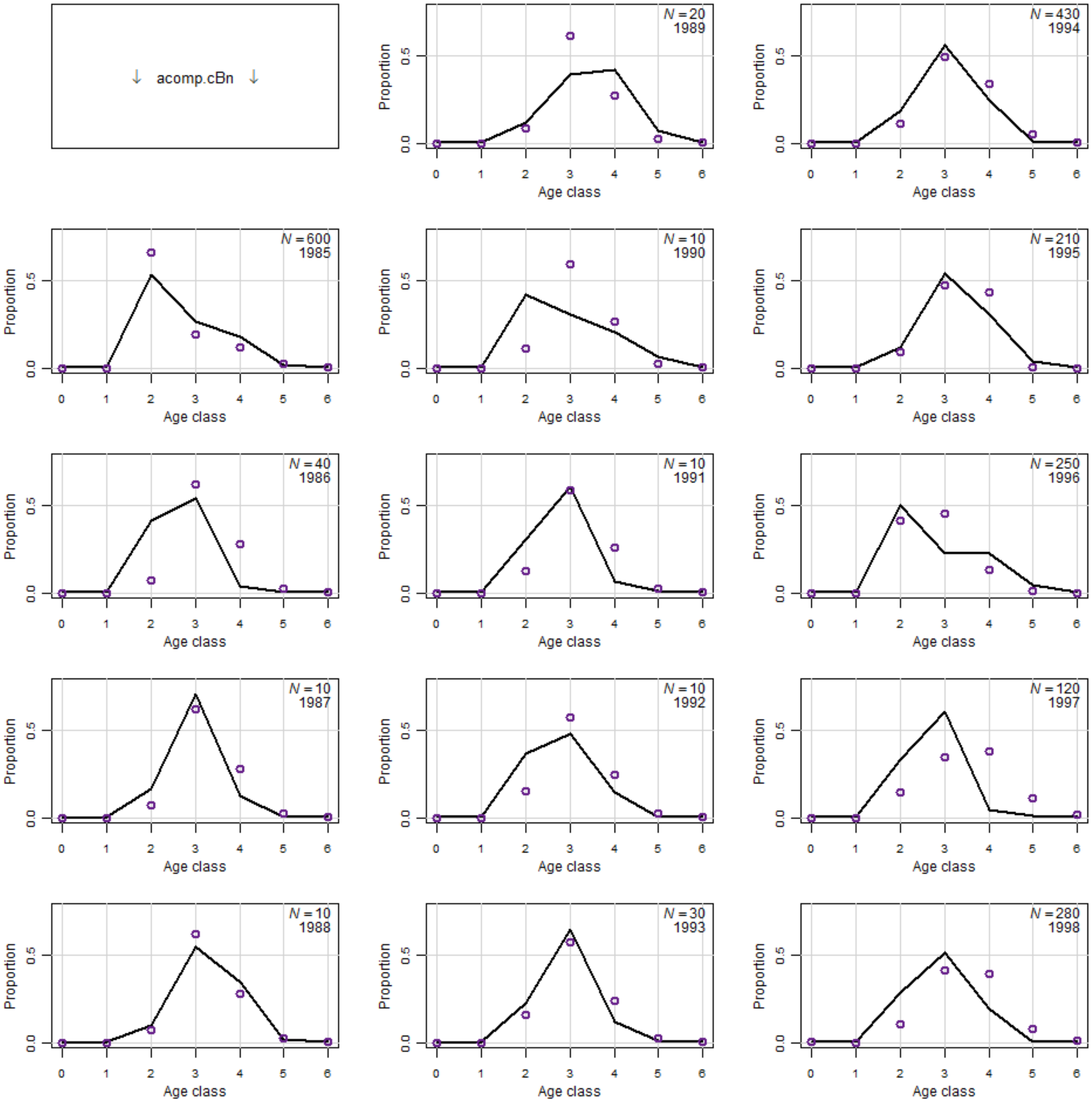


Figure 7. Annual observed and predicted catch-at-age of Atlantic menhaden from 1985-2013 from north of Virginia Eastern Shore by the commercial bait fishery.

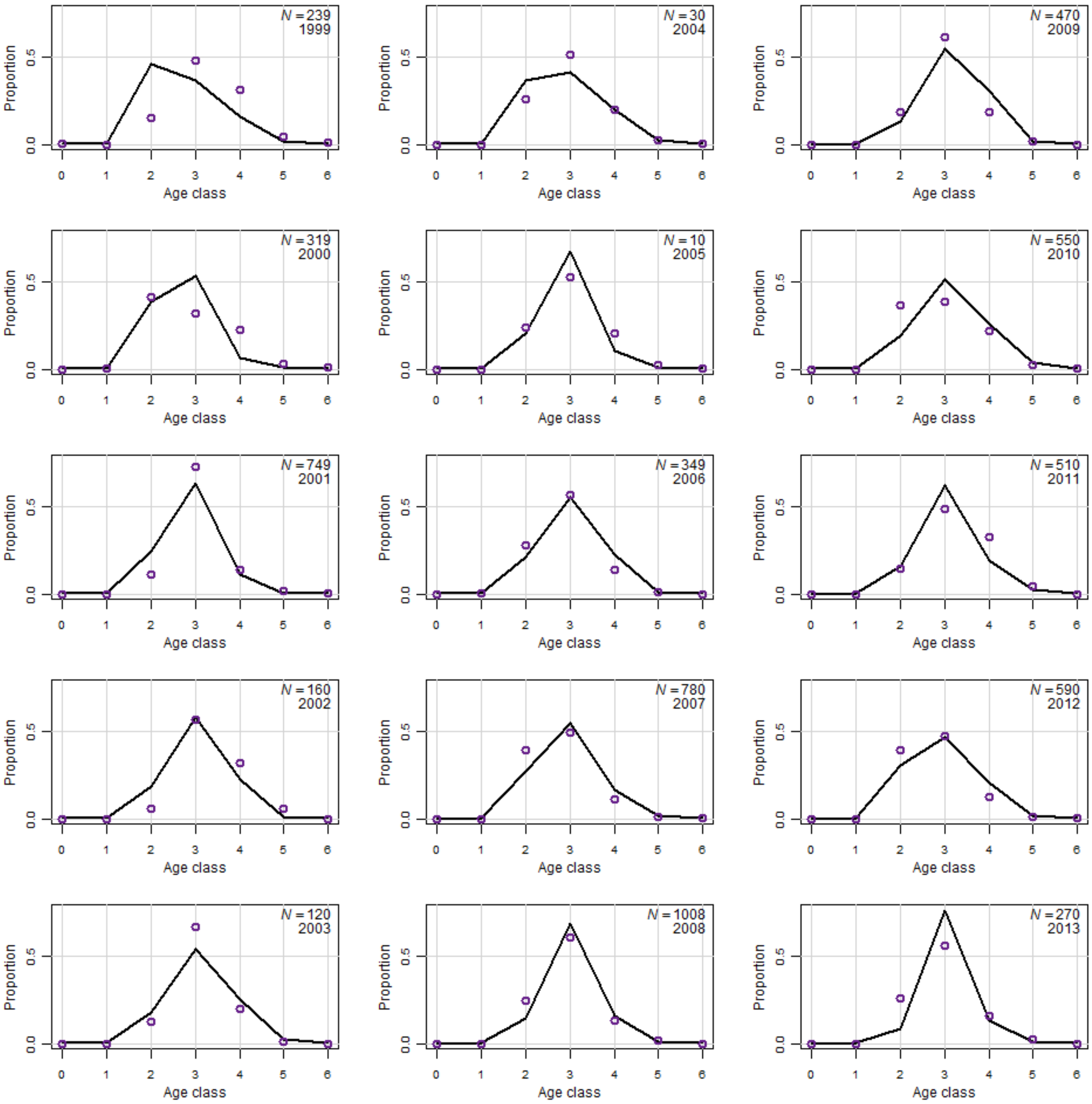


Figure 7. Continued.

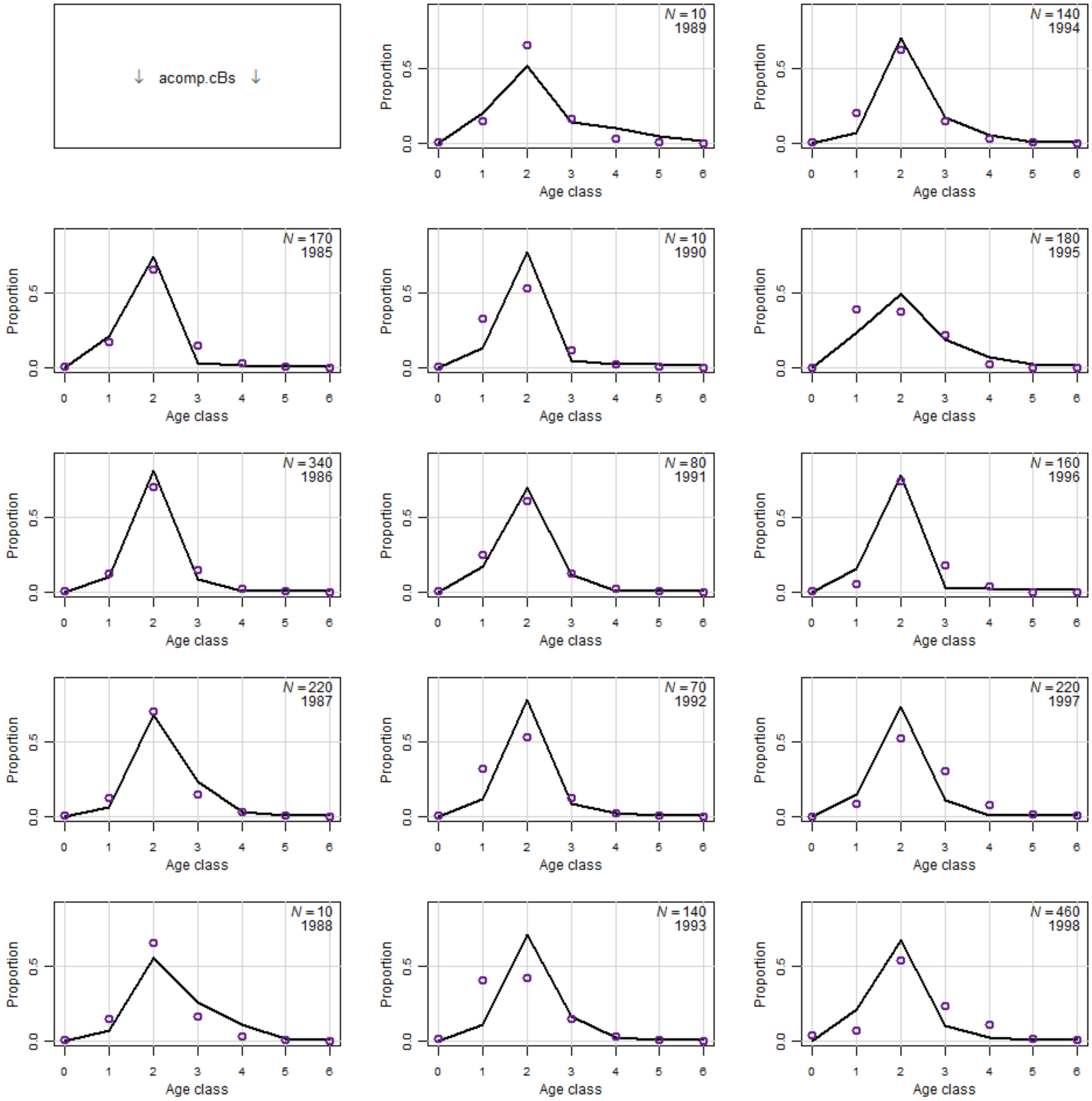


Figure 8. Annual observed and predicted catch-at-age of Atlantic menhaden from 1985-2013 from Virginia Eastern Shore and south by the commercial bait fishery.

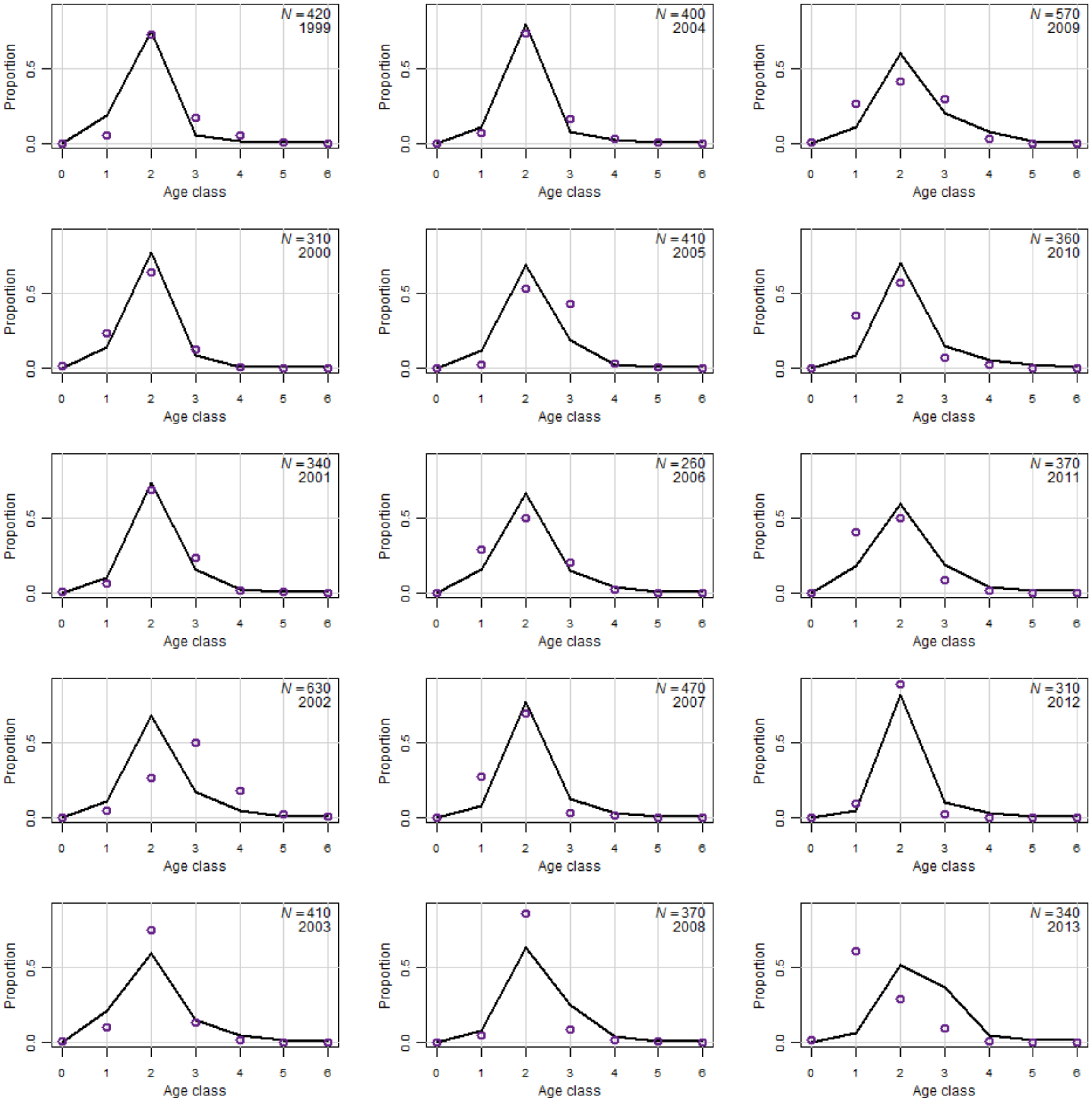
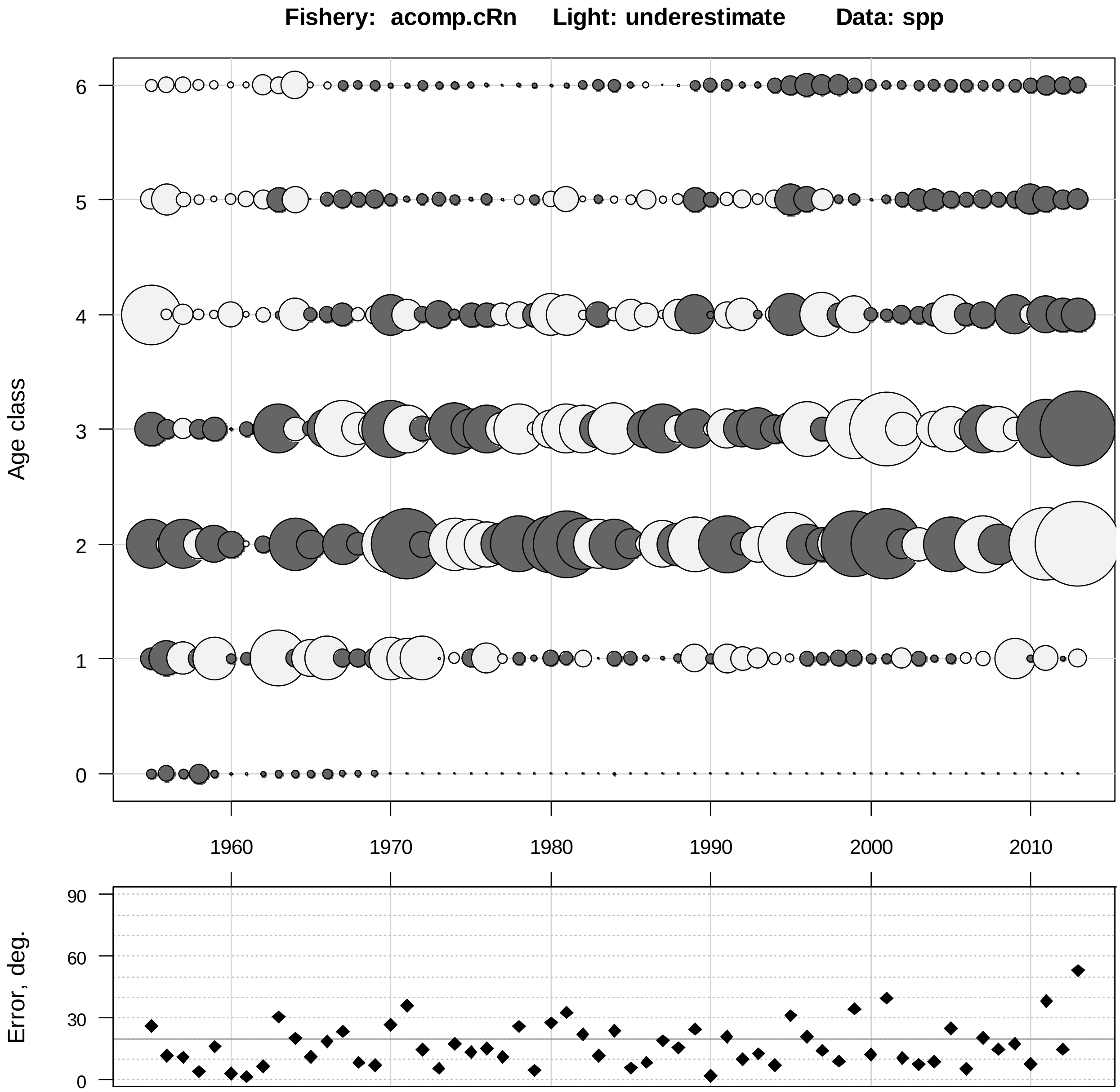


Figure 8. Continued.


Fishery: acomp.cRn Light: underestimate Data: spp
Age class
6
5
4
3
2
1
0
1960
1970
1980
1990
2000
2010
Error, deg.
90
60
30
0

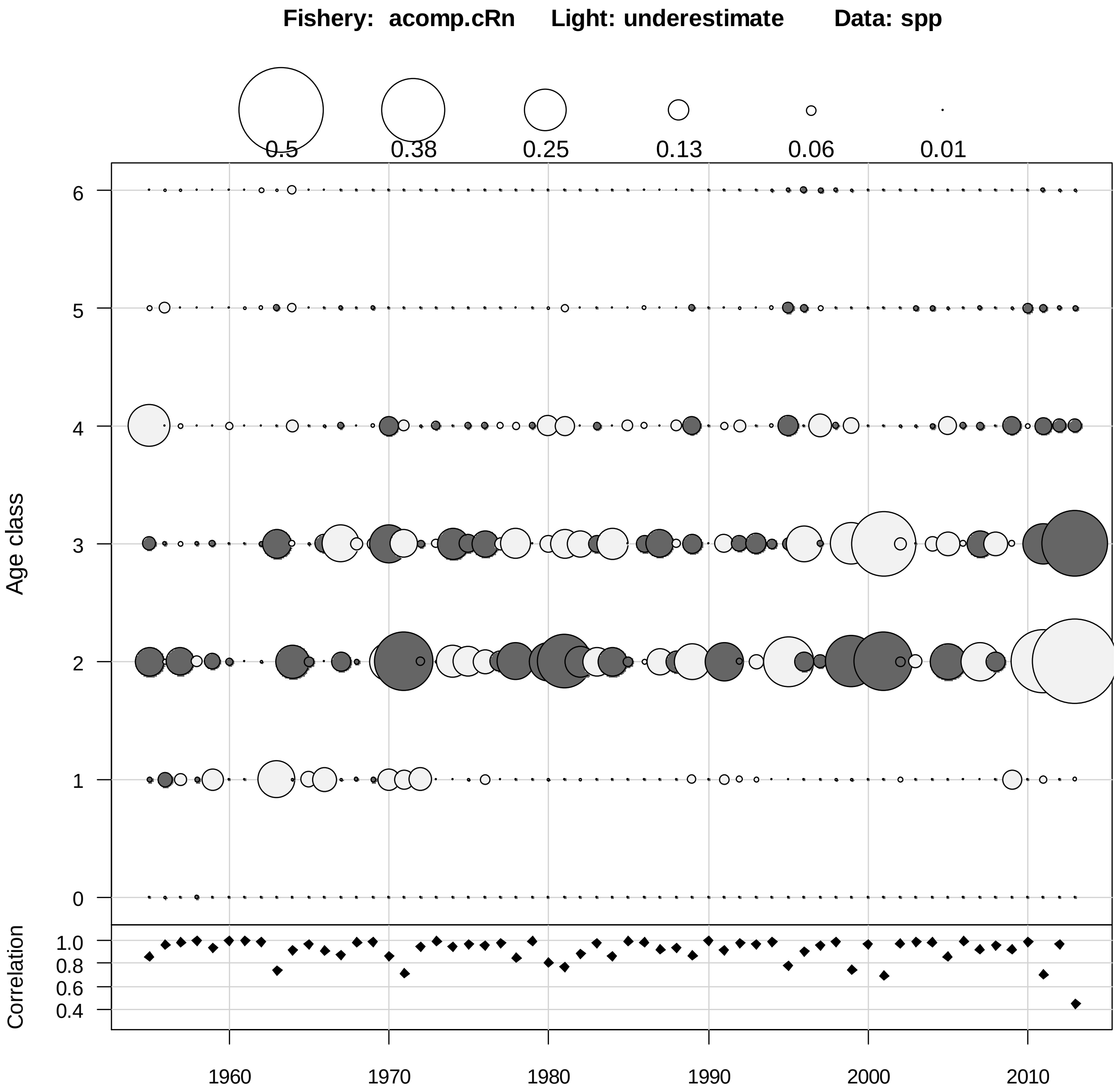
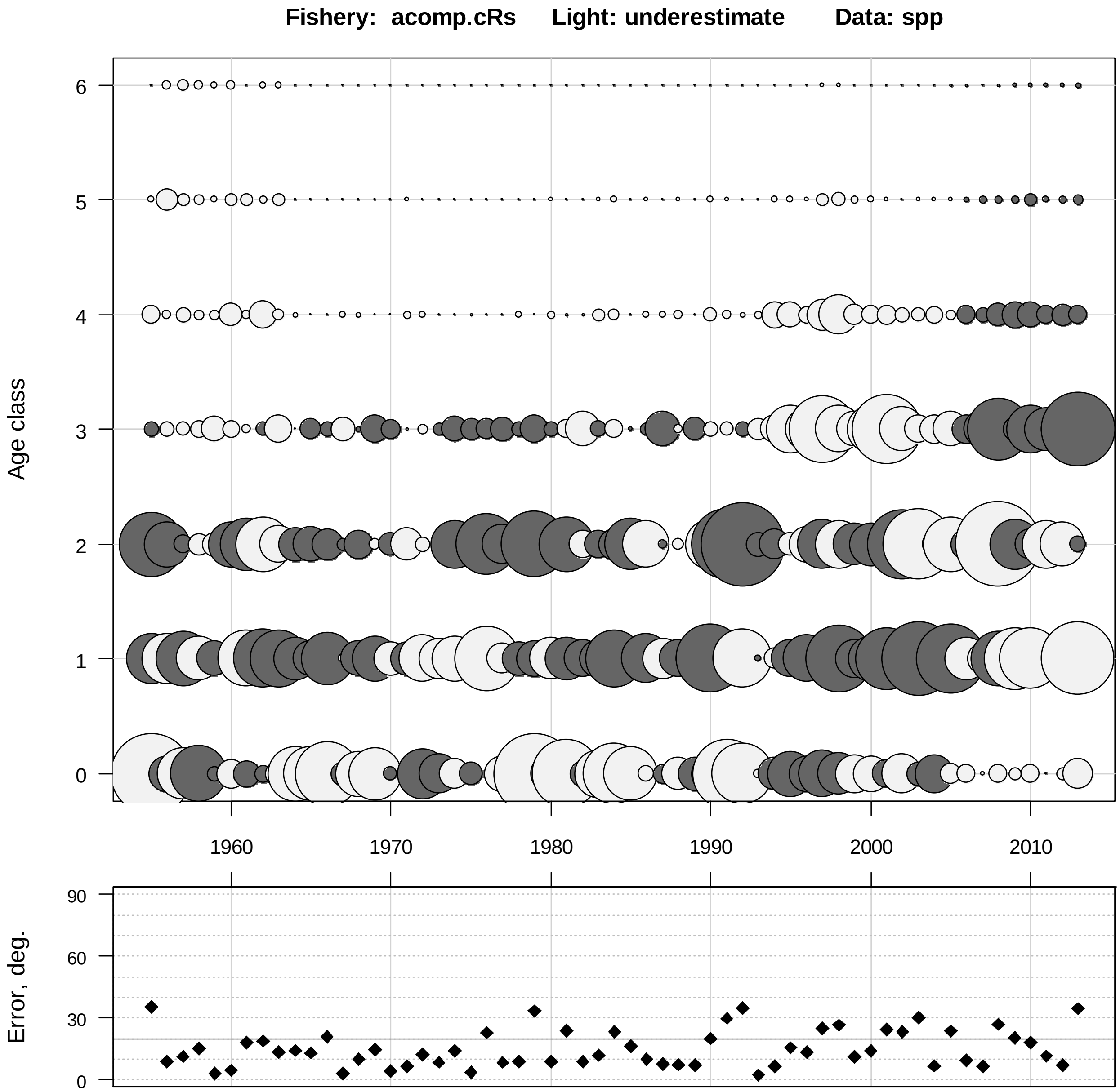


Figure 9. Relative (upper panel) and absolute (lower panel) bubble plots of the residuals of the predicted catch-at-age for Atlantic menhaden from 1955-2013 from north of Virginia Eastern Shore by the commercial reduction fishery. The error degrees in the upper panel represents a composite fit by year across ages, while in the lower plot contains correlations between years.


Fishery: acomp.cRs
Light: underestimate
Data: spp
Age class
6
5
4
3
2
1
0
1960
1970
1980
1990
2000
2010
Error, deg.
90
60
30
0

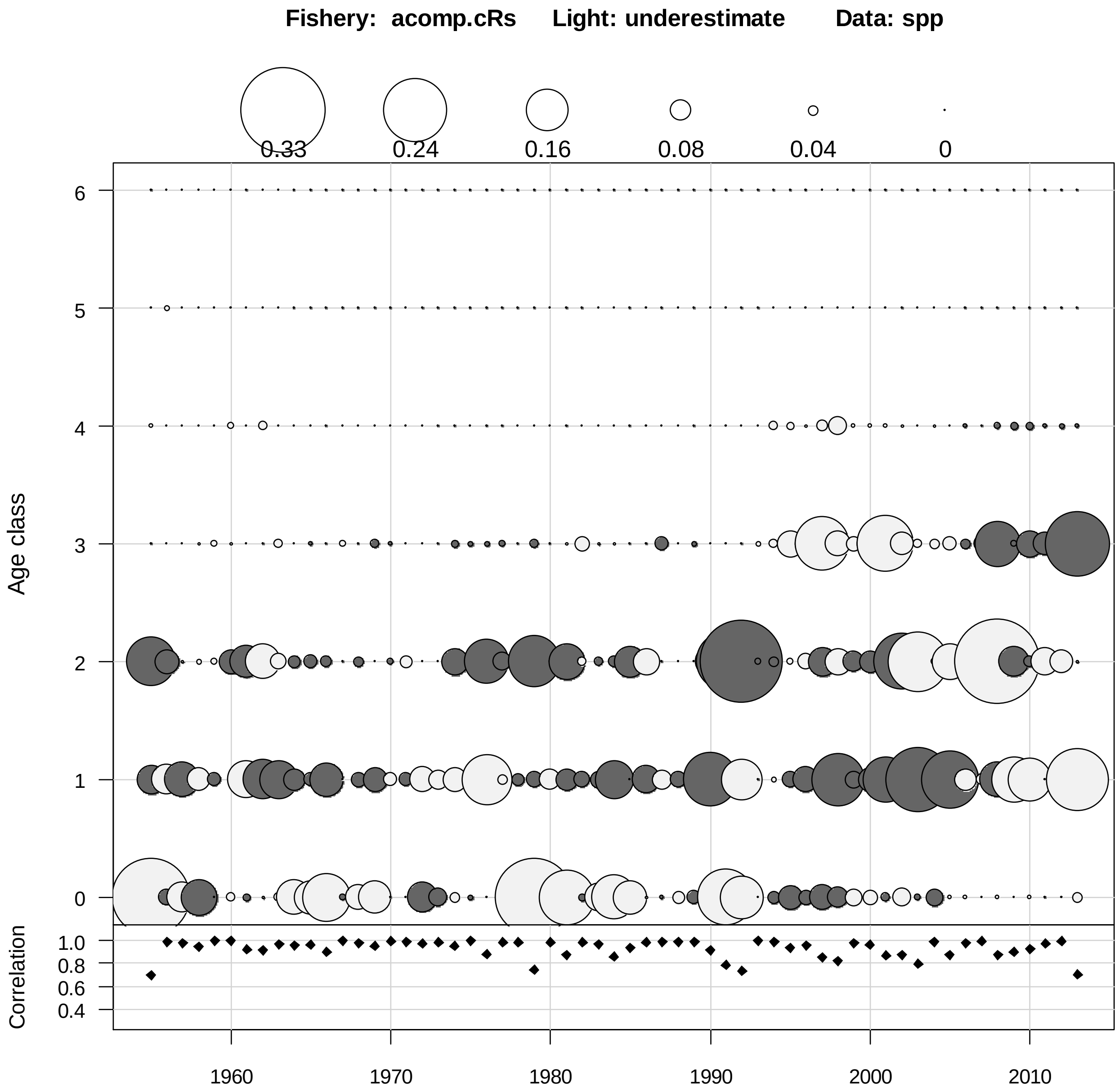
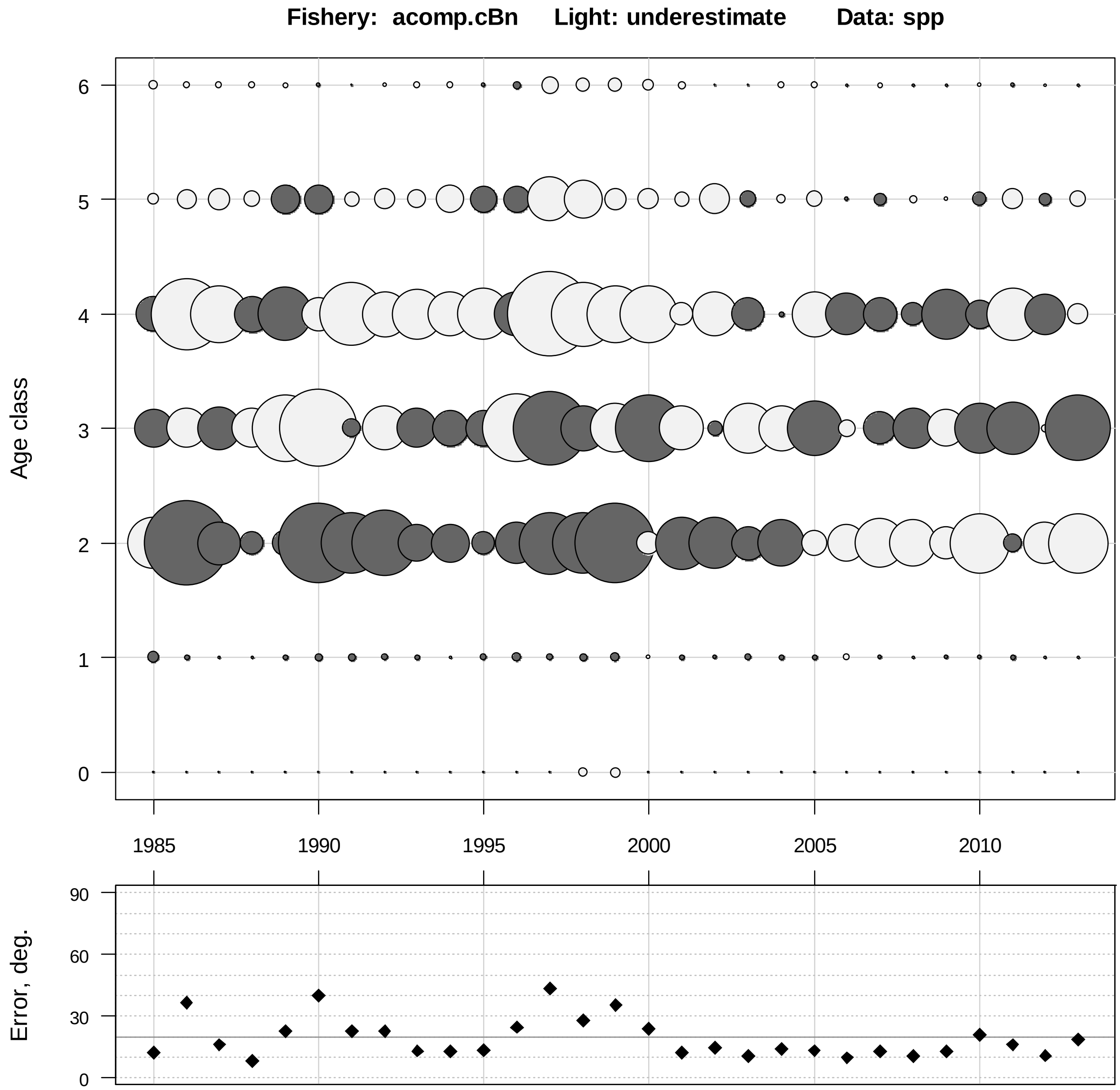


Figure 10. Relative (upper panel) and absolute (lower panel) bubble plots of the residuals of the predicted catch-at-age for Atlantic menhaden from 1955-2013 from Virginia Eastern Shore and south by the commercial reduction fishery. The error degrees in the upper panel represents a composite fit by year across ages, while in the lower plot contains correlations between years.


Fishery: acomp.cBn Light: underestimate Data: spp
Age class
0
1
2
3
4
5
6
1985
1990
1995
2000
2005
2010
Error, deg.
0
30
60
90

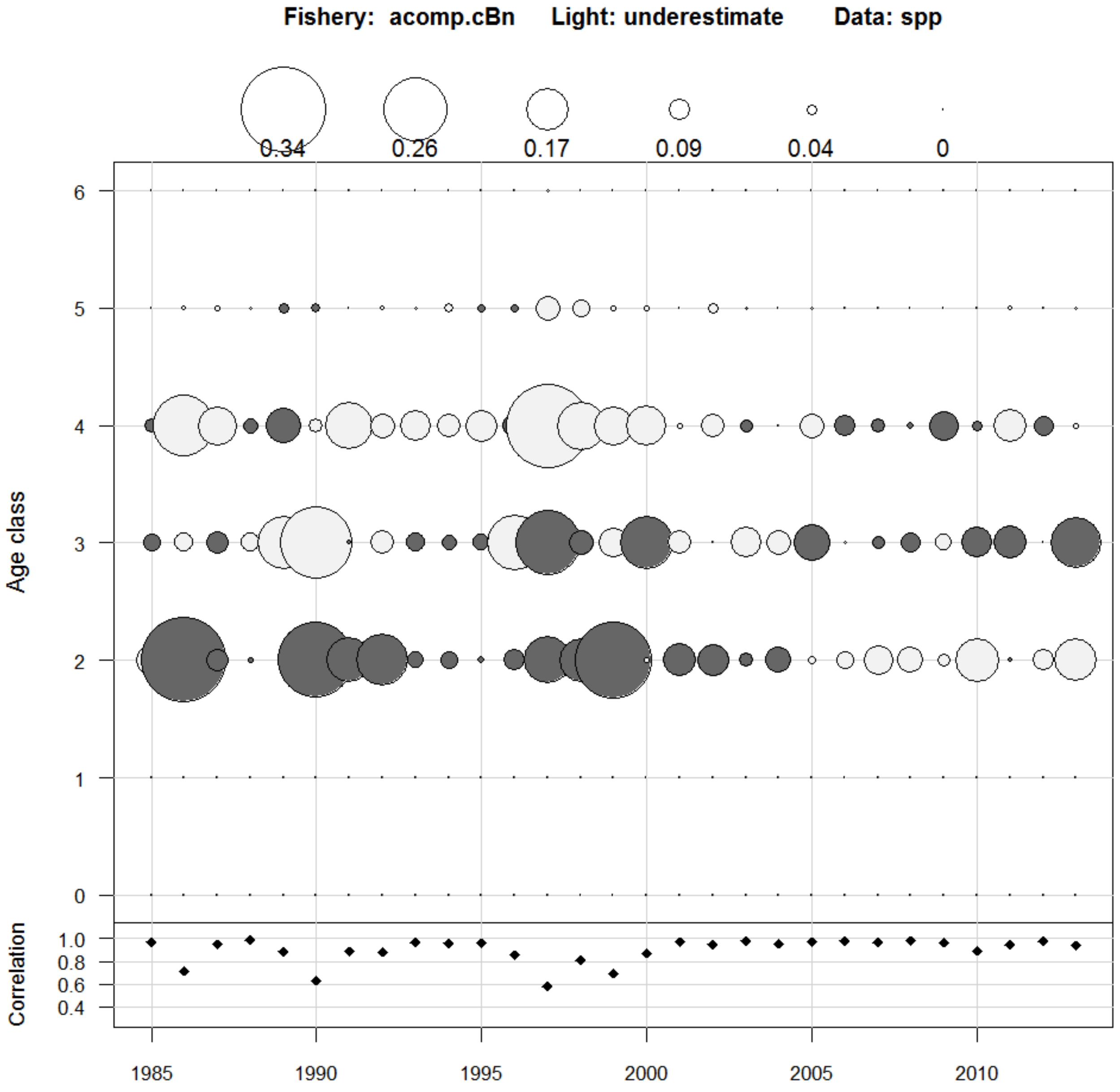
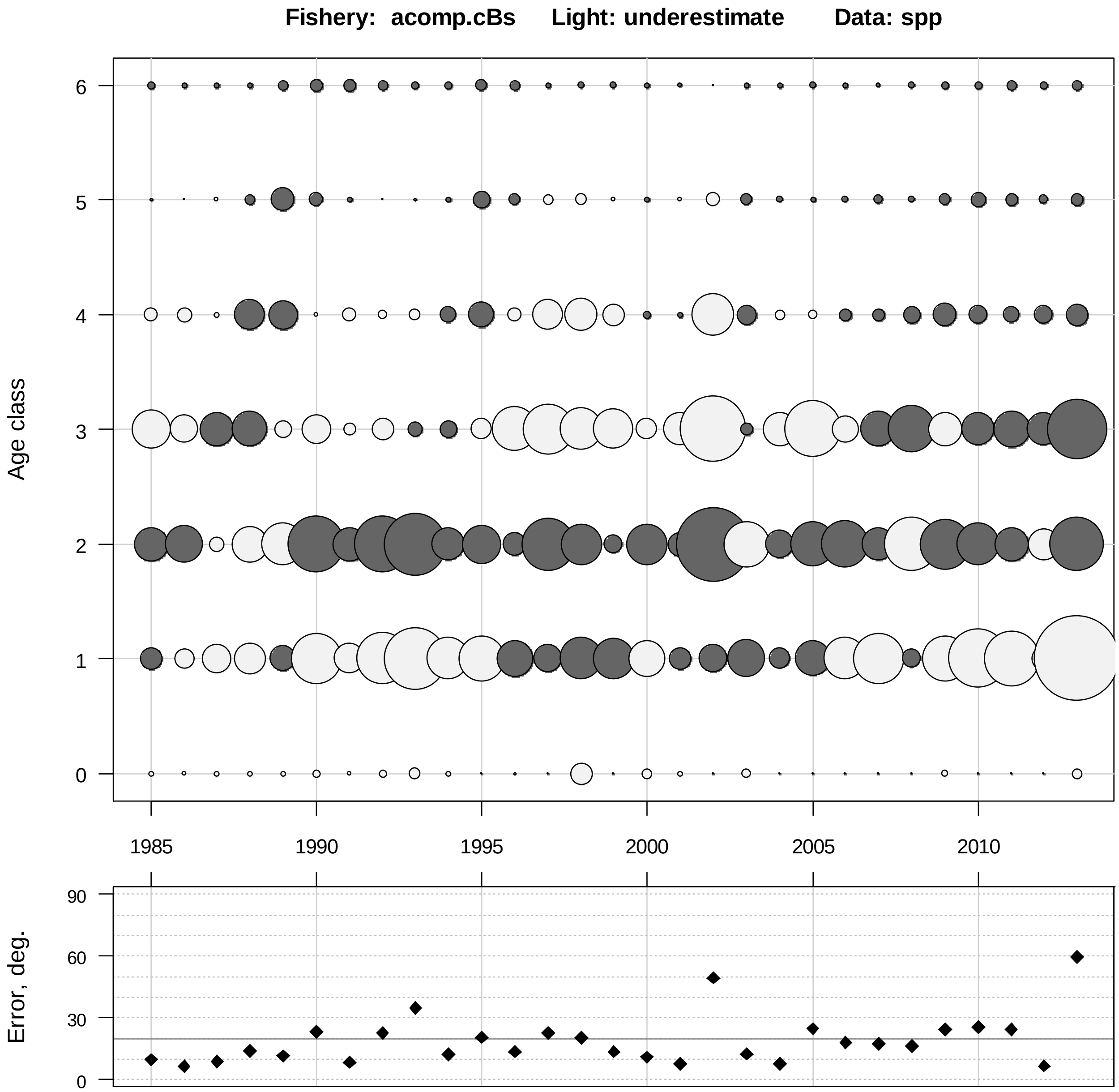


Figure 11. Relative (upper panel) and absolute (lower panel) bubble plots of the residuals of the predicted catch-at-age for Atlantic menhaden from 1985-2013 from north of Virginia Eastern Shore by the commercial bait fishery. The error degrees in the upper panel represents a composite fit by year across ages, while in the lower plot contains correlations between years.


Fishery: acomp.cBs Light: underestimate Data: spp
Age class
0
1
2
3
4
5
6
1985
1990
1995
2000
2005
2010
Error, deg.
0
30
60
90

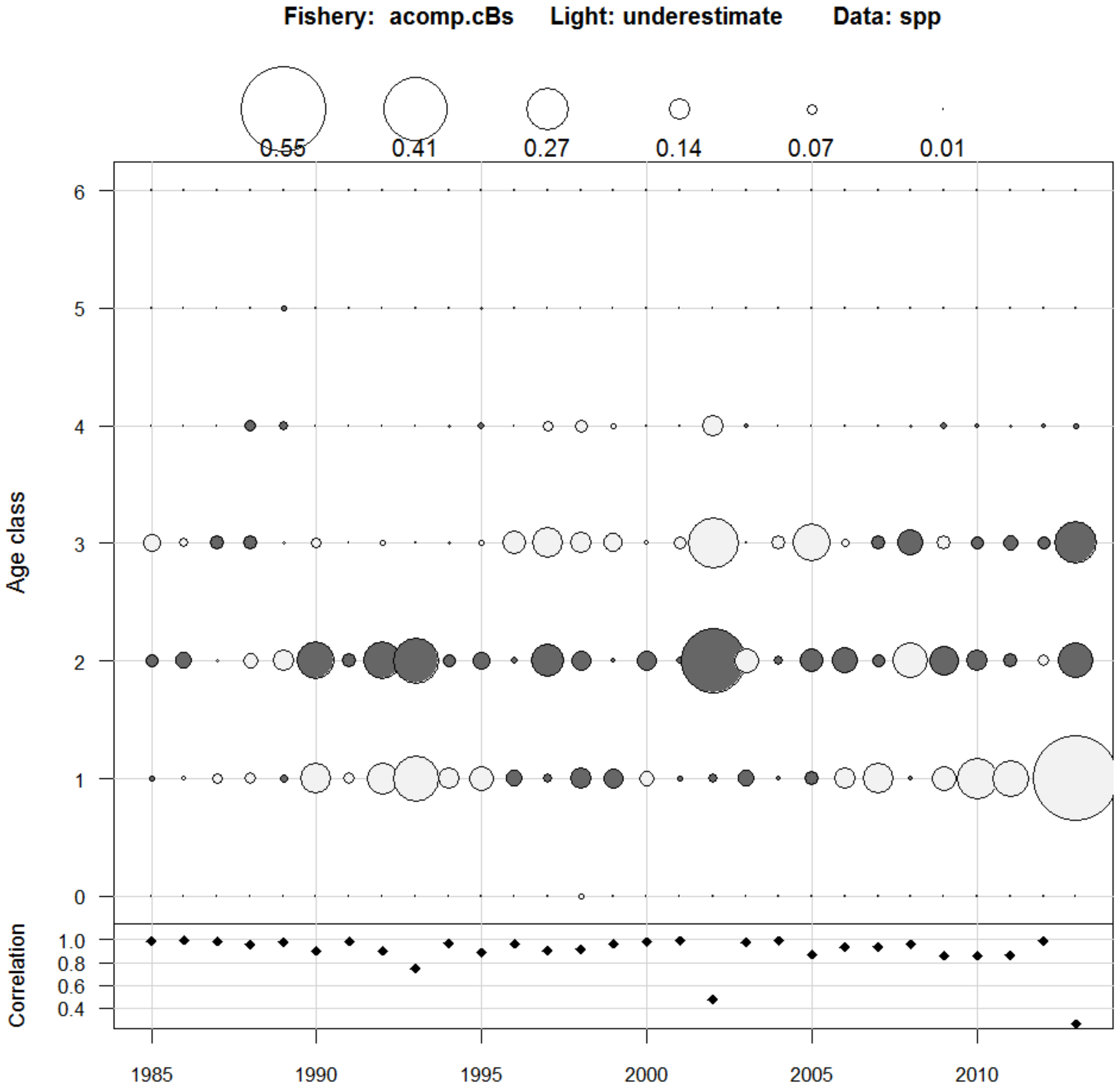


Figure 12. Relative (upper panel) and absolute (lower panel) bubble plots of the residuals of the predicted catch-at-age for Atlantic menhaden from 1985-2013 from Virginia Eastern Shore and south by the commercial bait fishery. The error degrees in the upper panel represents a composite fit by year across ages, while in the lower plot contains correlations between years.

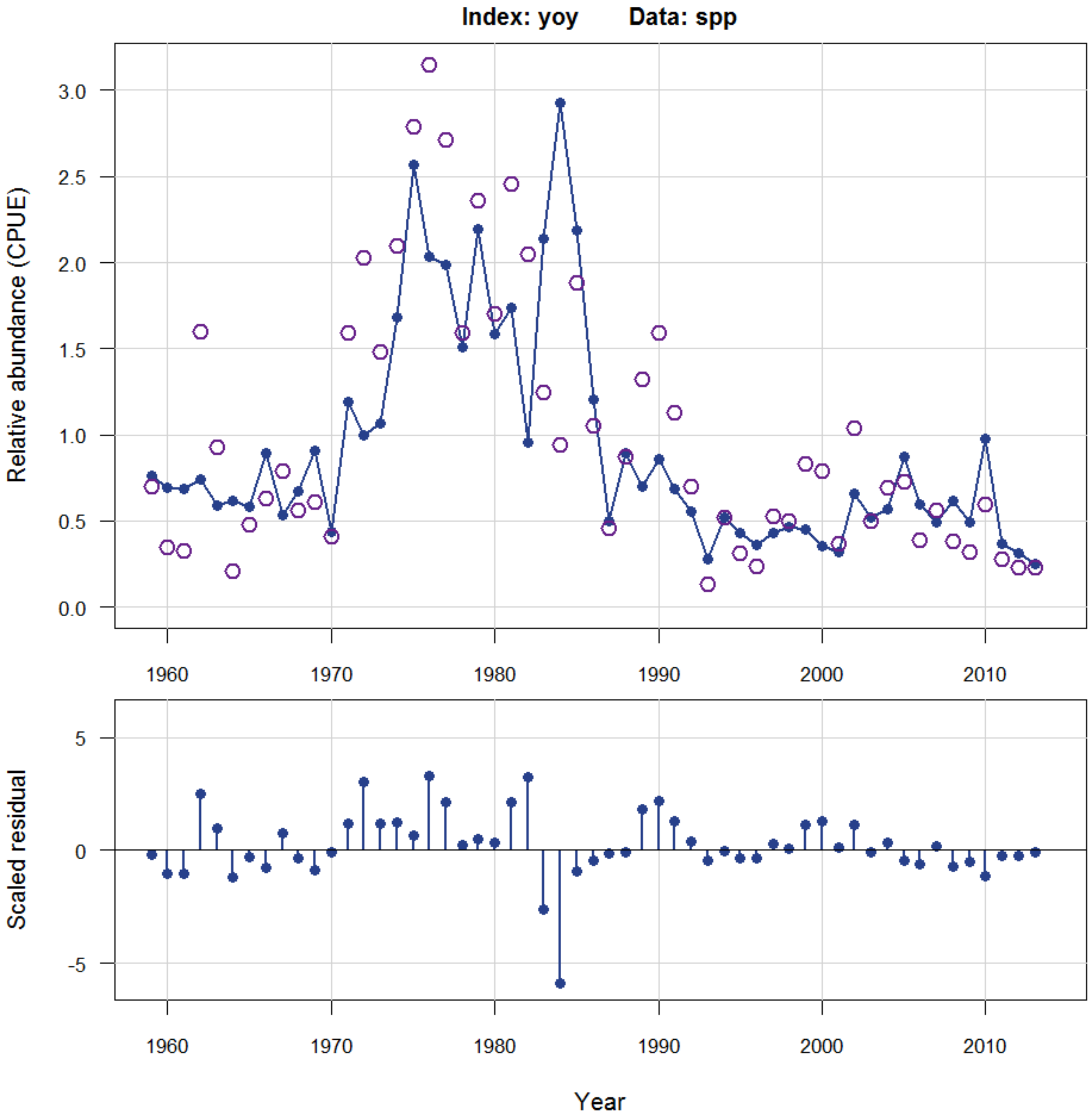


Figure 13. The observed and predicted recruitment index for 1959-2013 comprised of a series of state surveys.

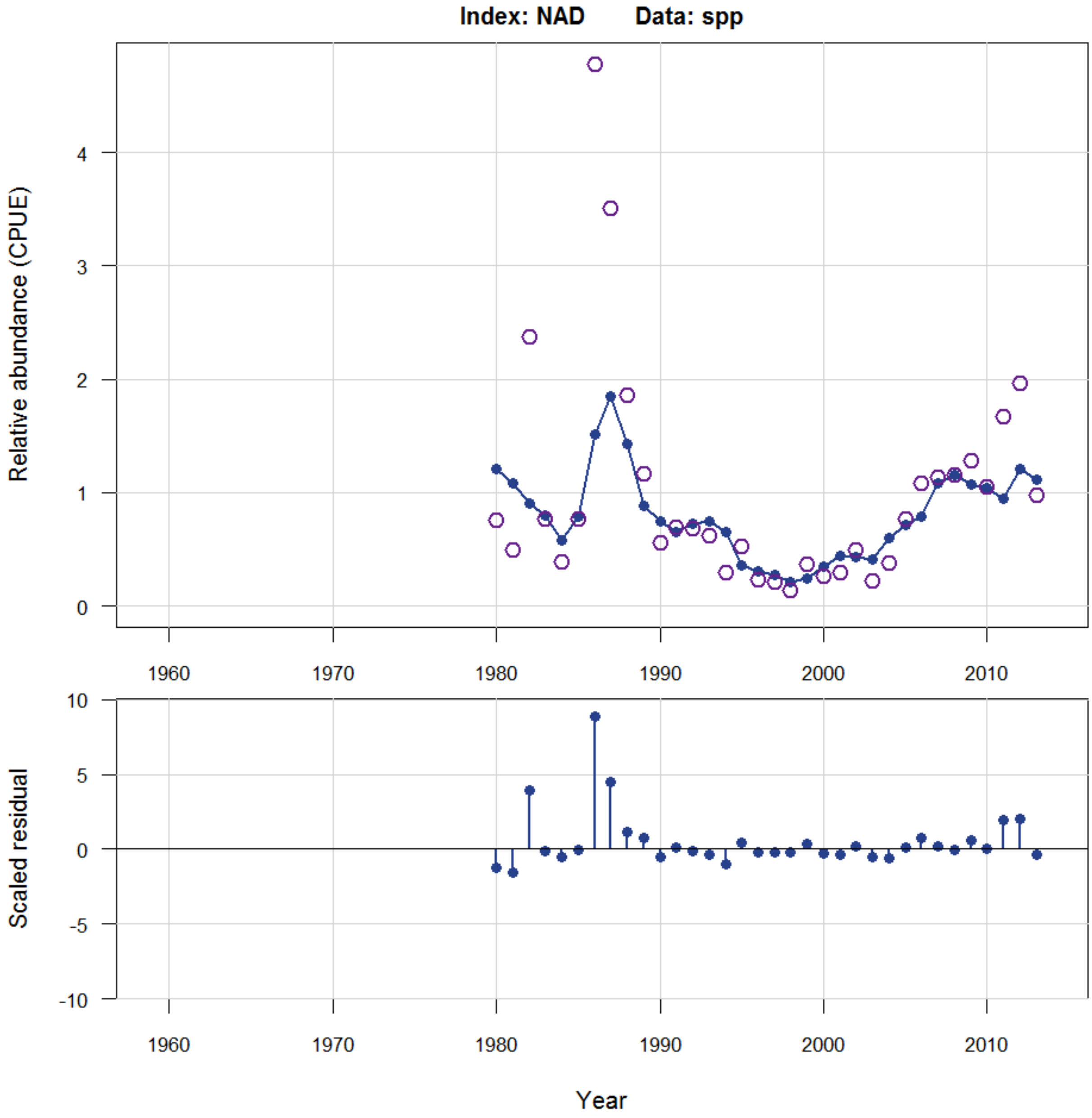


Figure 14. The observed and predicted NAD index for 1980-2013 comprised of a series of state trawl surveys in the northern region**.**

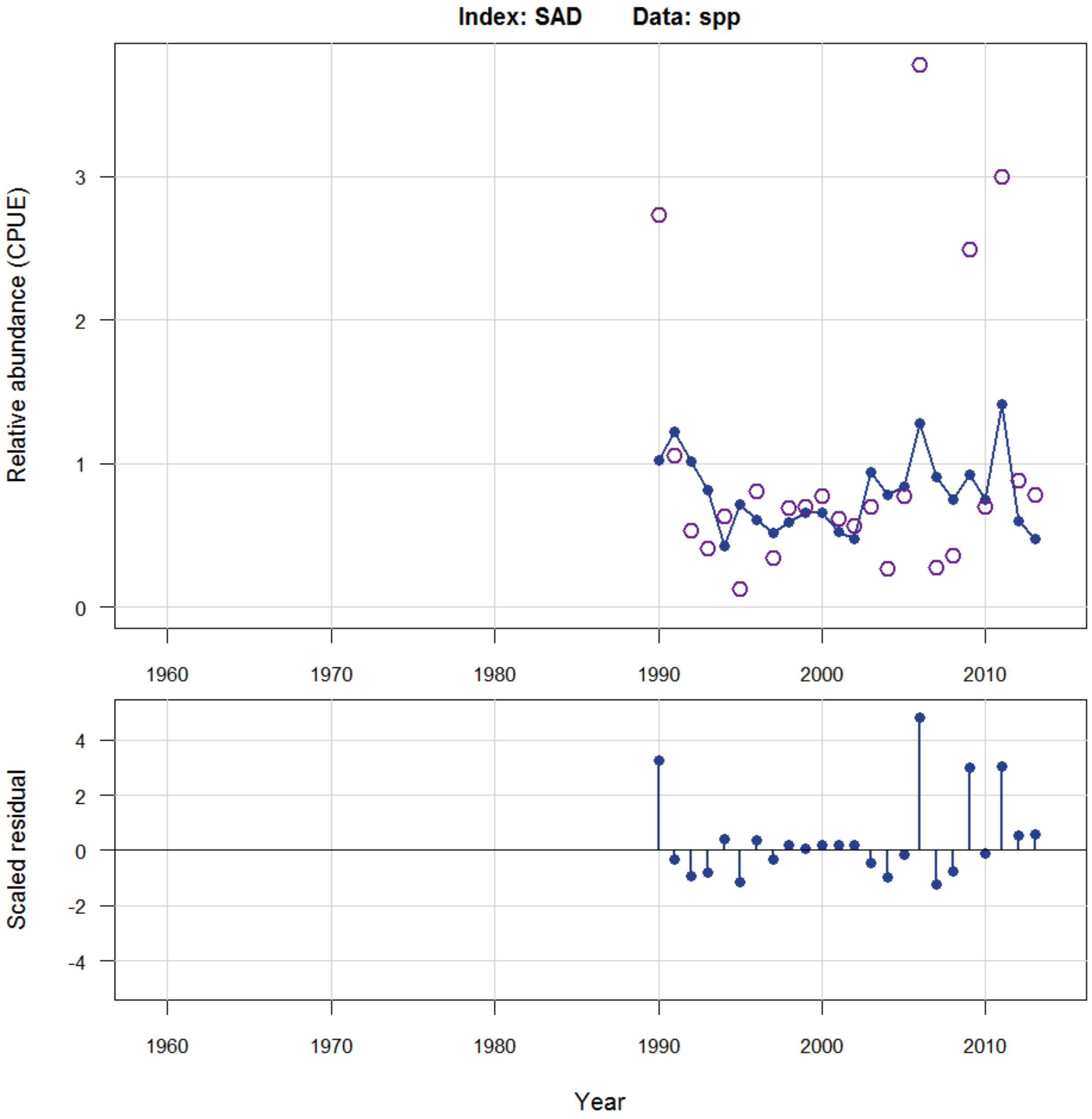


Figure 15. The observed and predicted SAD index for 1990-2013 comprised of two state trawl surveys in the southern region.

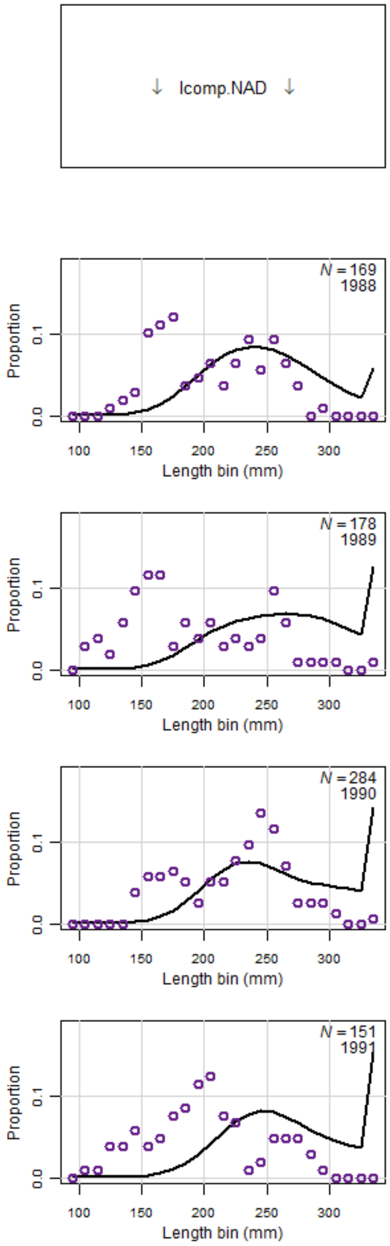


Figure 16. Annual observed and predicted length measurements of Atlantic menhaden from 1986-2013 for the NAD index.

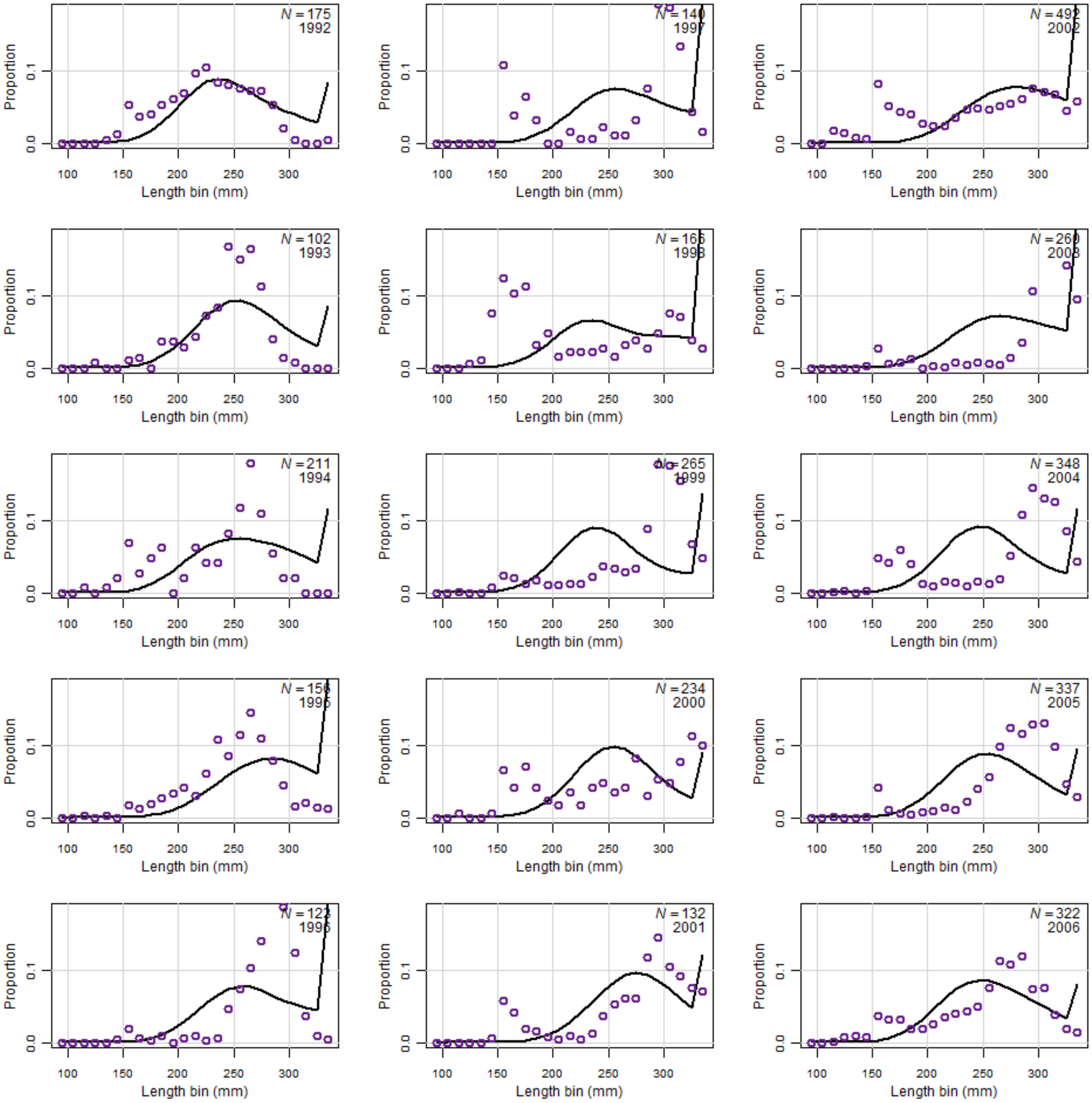


Figure 16. Continued.

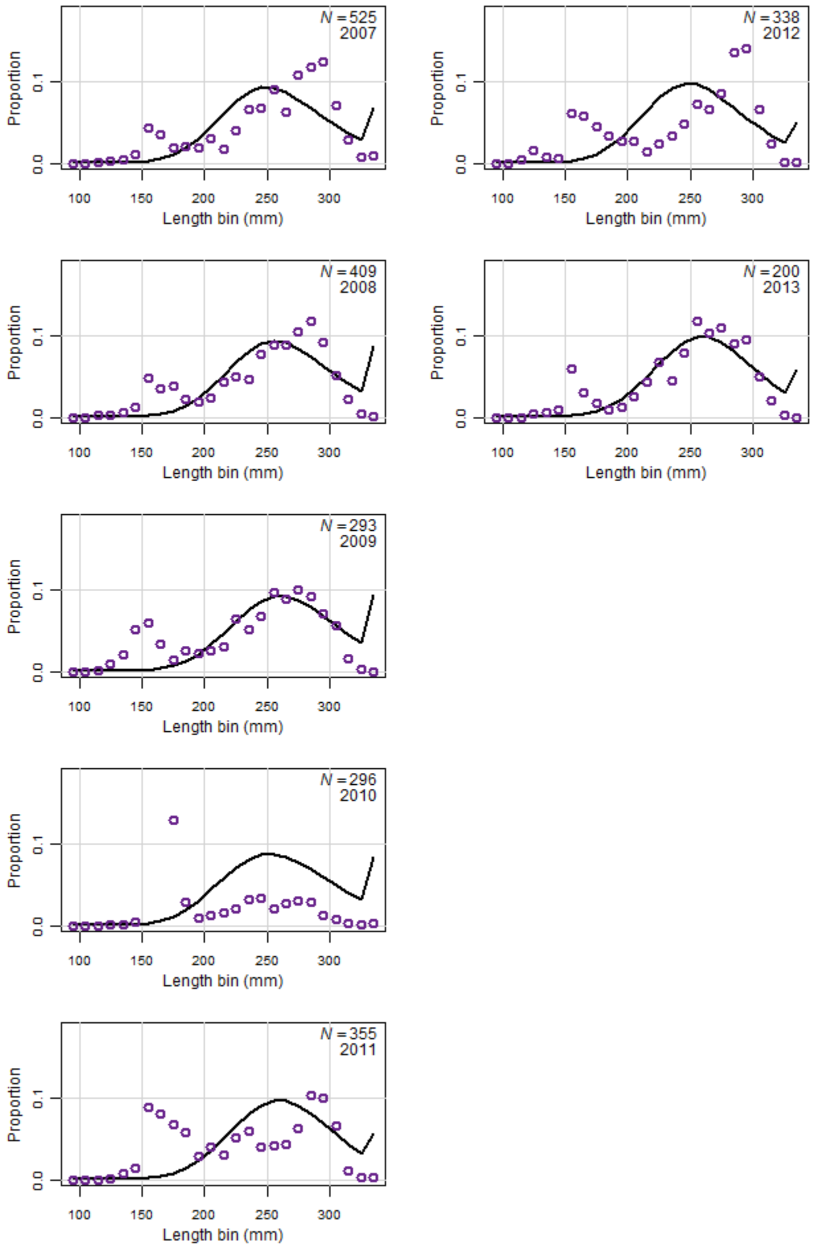


Figure 16. Continued.

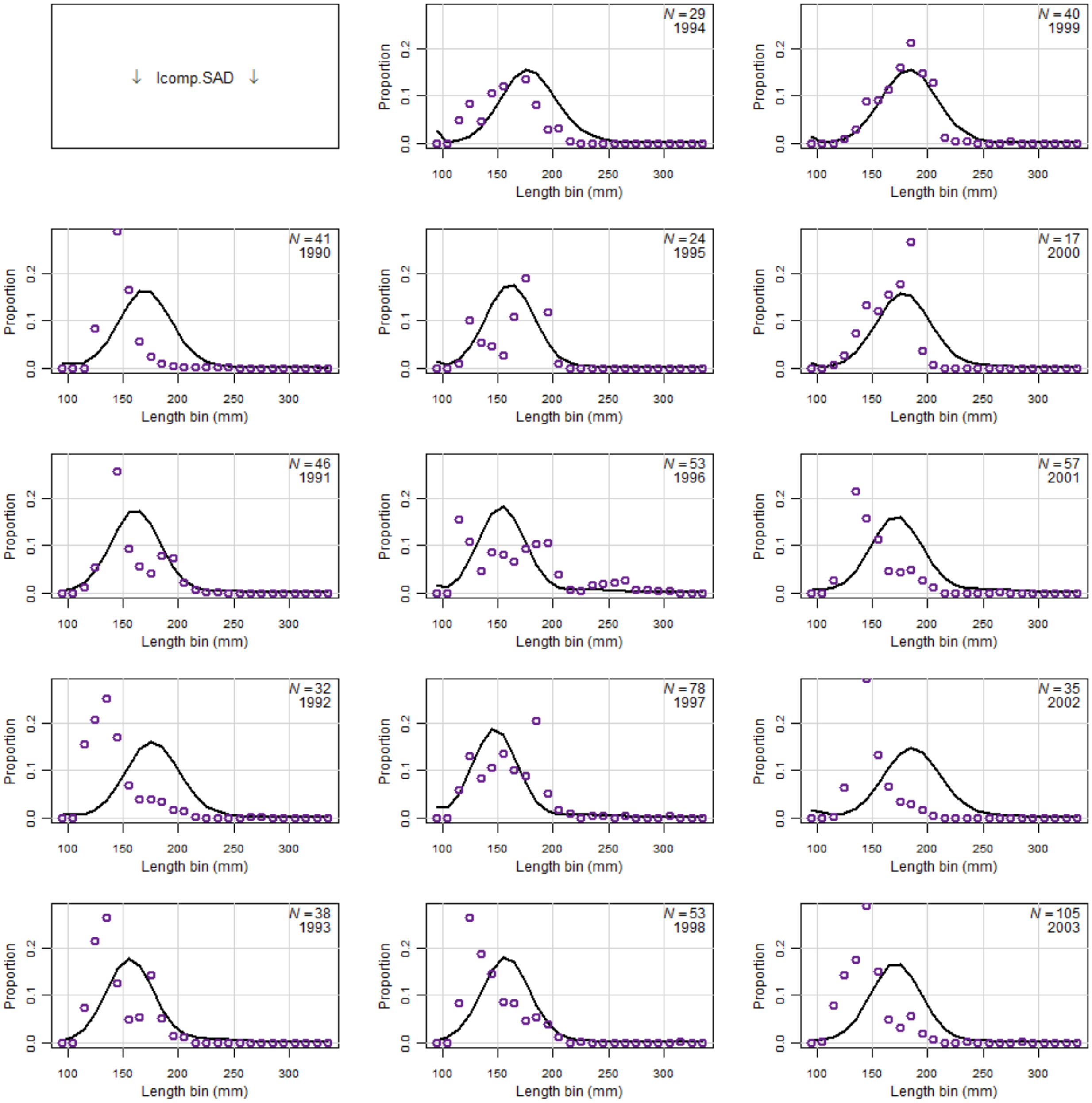


Figure 17. Annual observed and predicted length measurements of Atlantic menhaden from 1990-2013 for the SAD index.

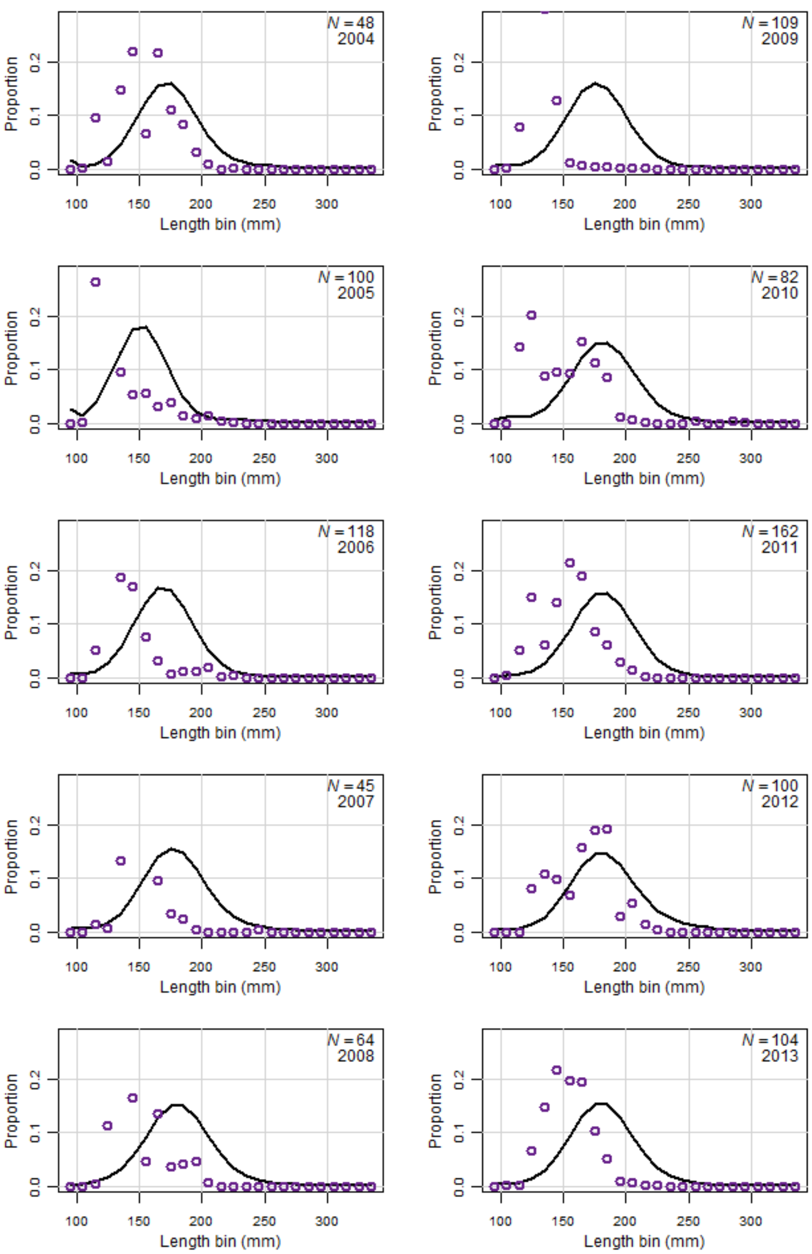
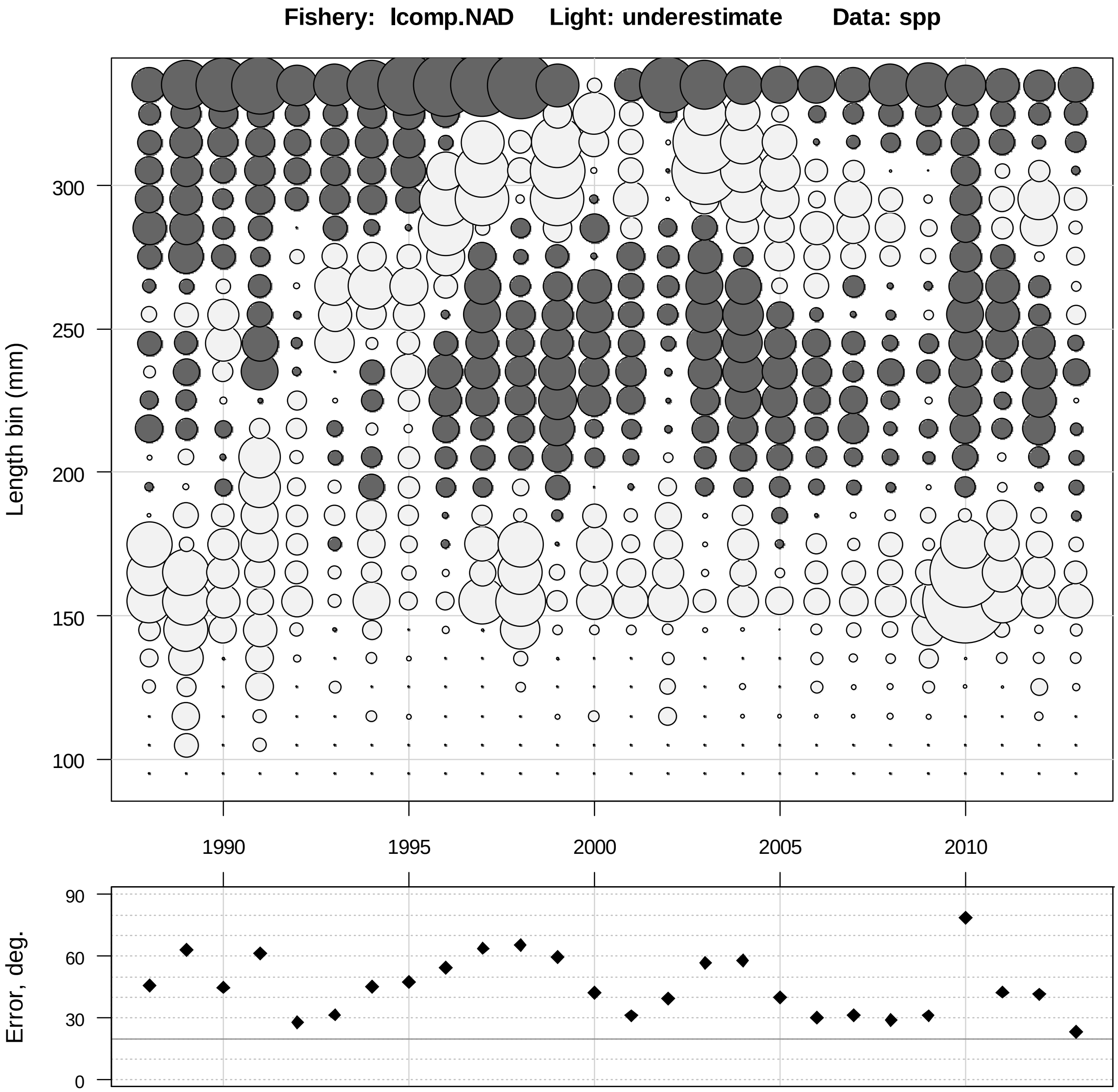


Figure 17. Continued.


Fishery: lcomp.NAD Light: underestimate Data: spp
Length bin (mm)
100
150
200
250
300
1990
1995
2000
2005
2010
Error, deg.
0
30
60
90

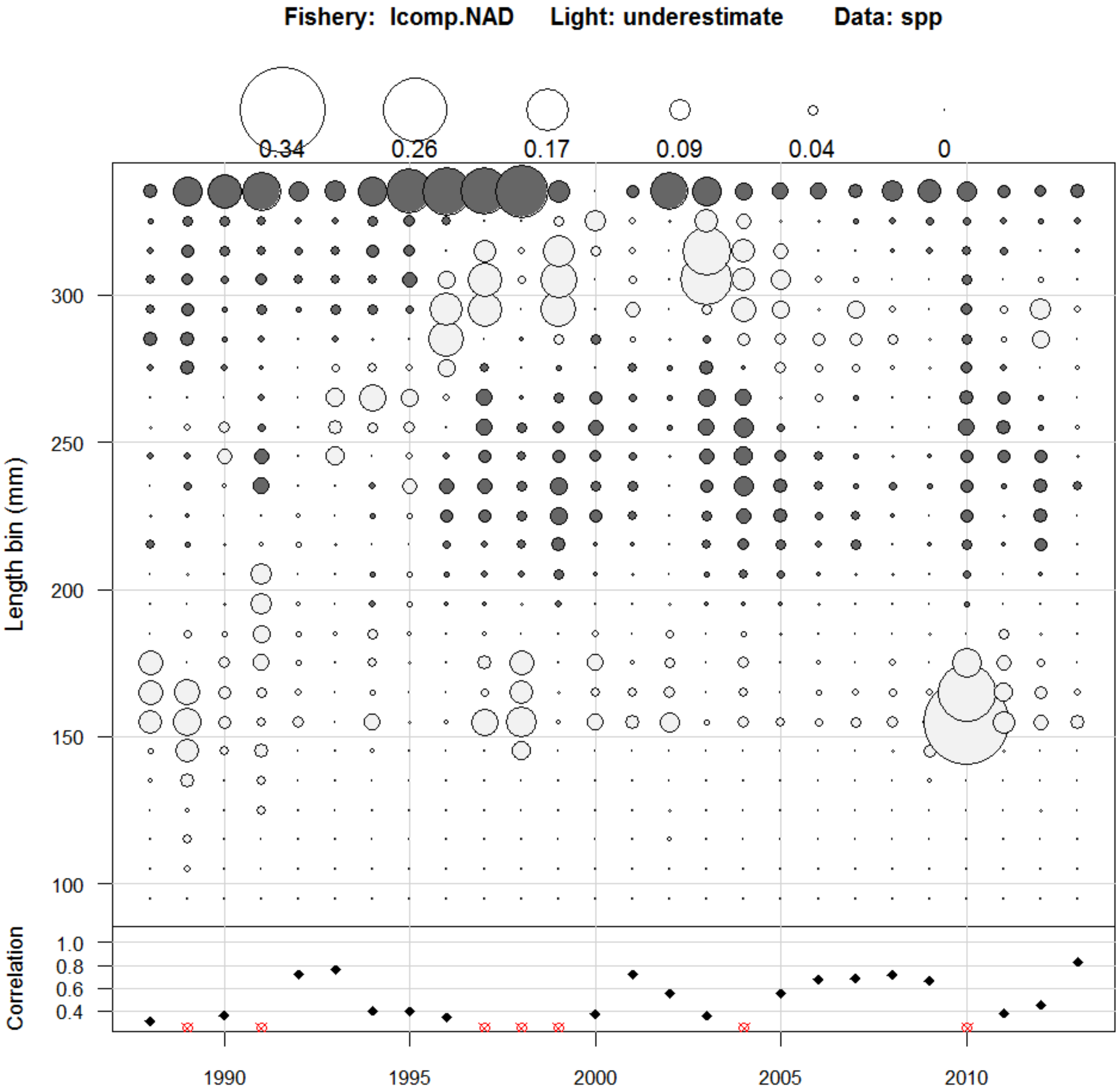
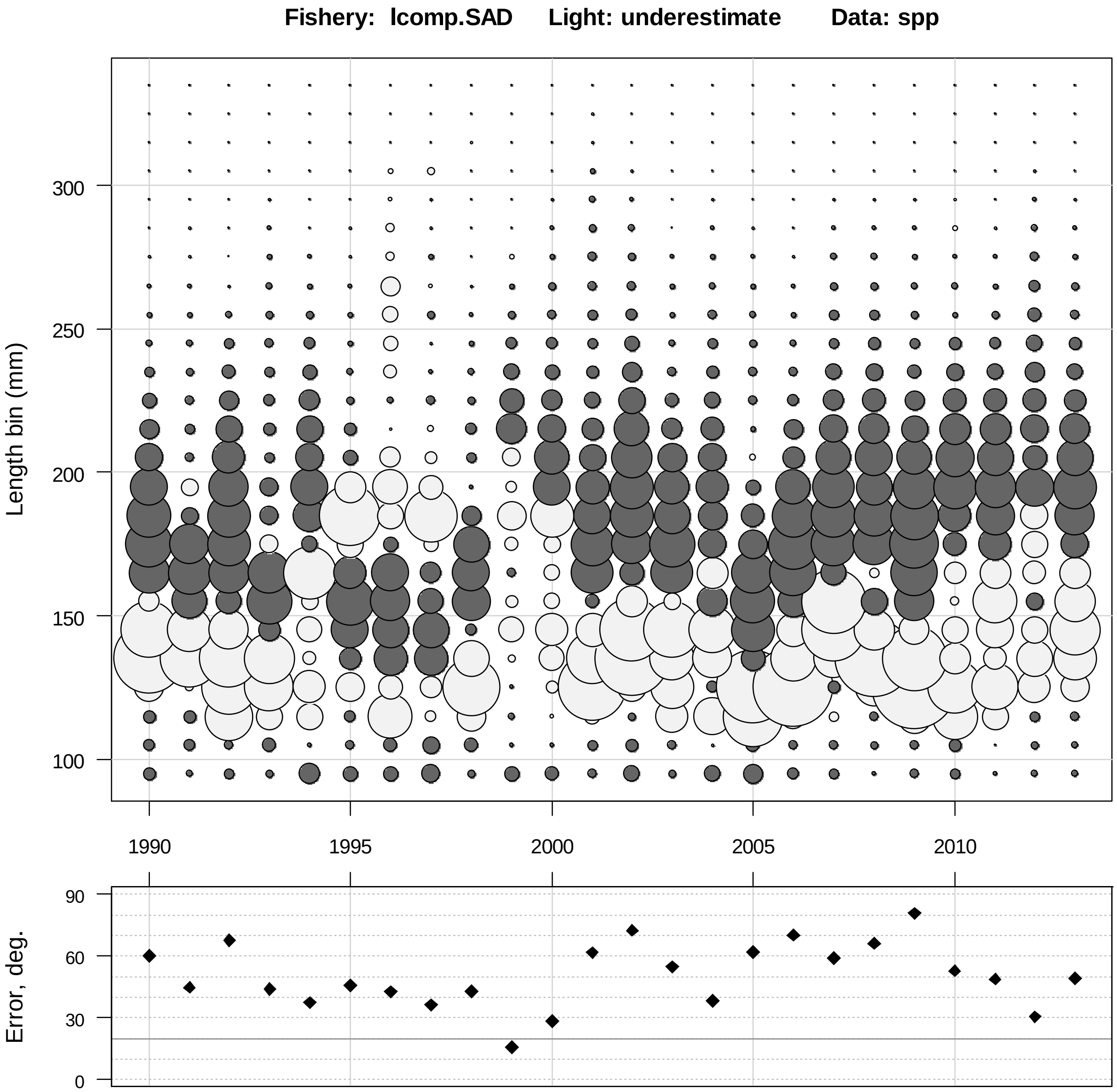


Figure 18. Relative (upper panel) and absolute (lower panel) bubble plots of the residuals of the predicted lengths for Atlantic menhaden from 1986-2013 from the NAD. The error degrees in the upper panel represents a composite fit by year across lengths, while in the lower plot contains correlations between years.


Fishery: lcomp.SAD
Light: underestimate
Data: spp
Length bin (mm)
100
150
200
250
300
1990
1995
2000
2005
2010
Error, deg.
0
30
60
90

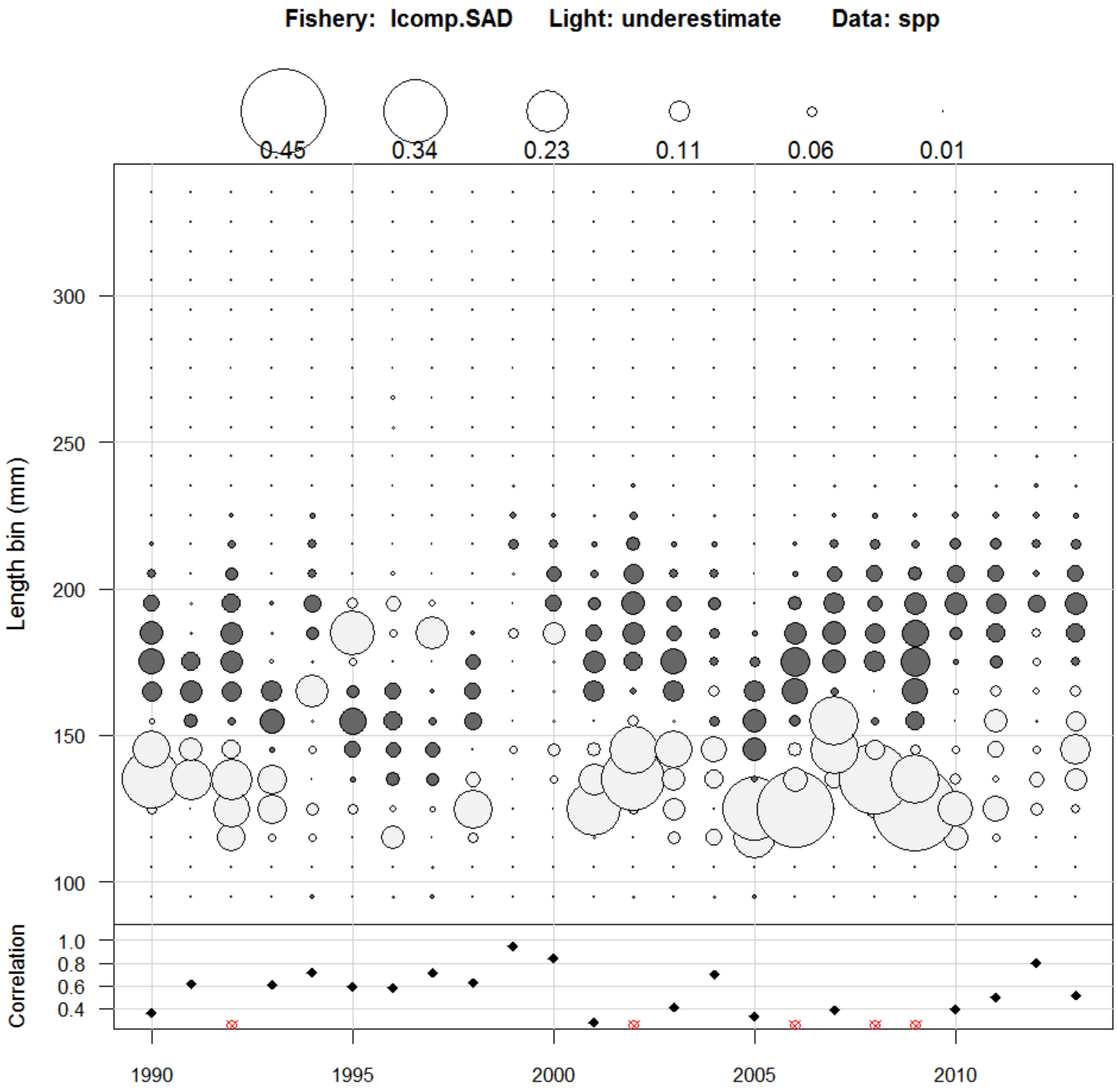


Figure 19. Relative (upper panel) and absolute (lower panel) bubble plots of the residuals of the predicted lengths for Atlantic menhaden from 1990-2013 from the SAD. The error degrees in the upper panel represents a composite fit by year across lengths, while in the lower plot contains correlations between years.

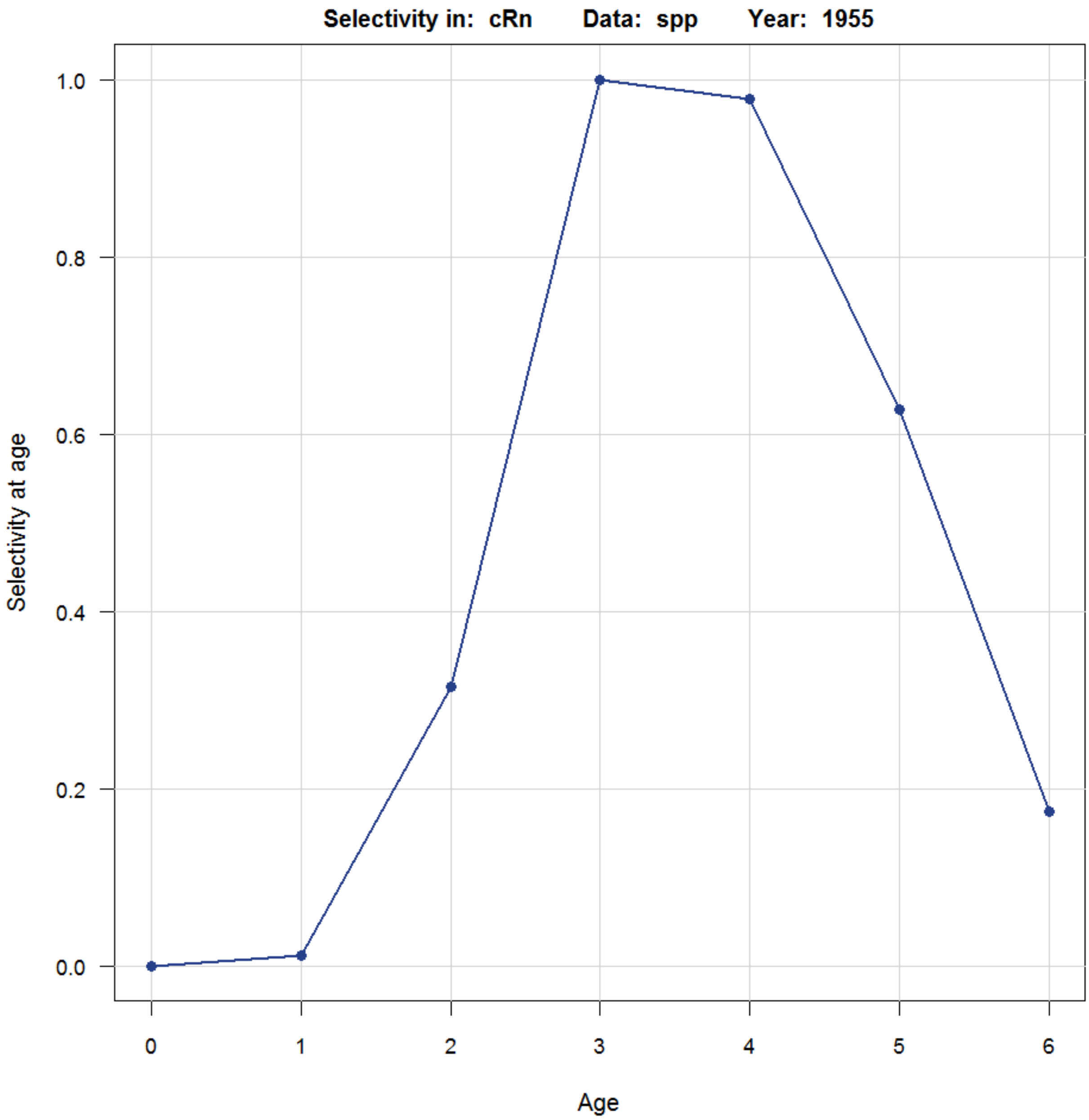


Figure 20. Selectivity for the northern commercial reduction fleet for 1955-1969.

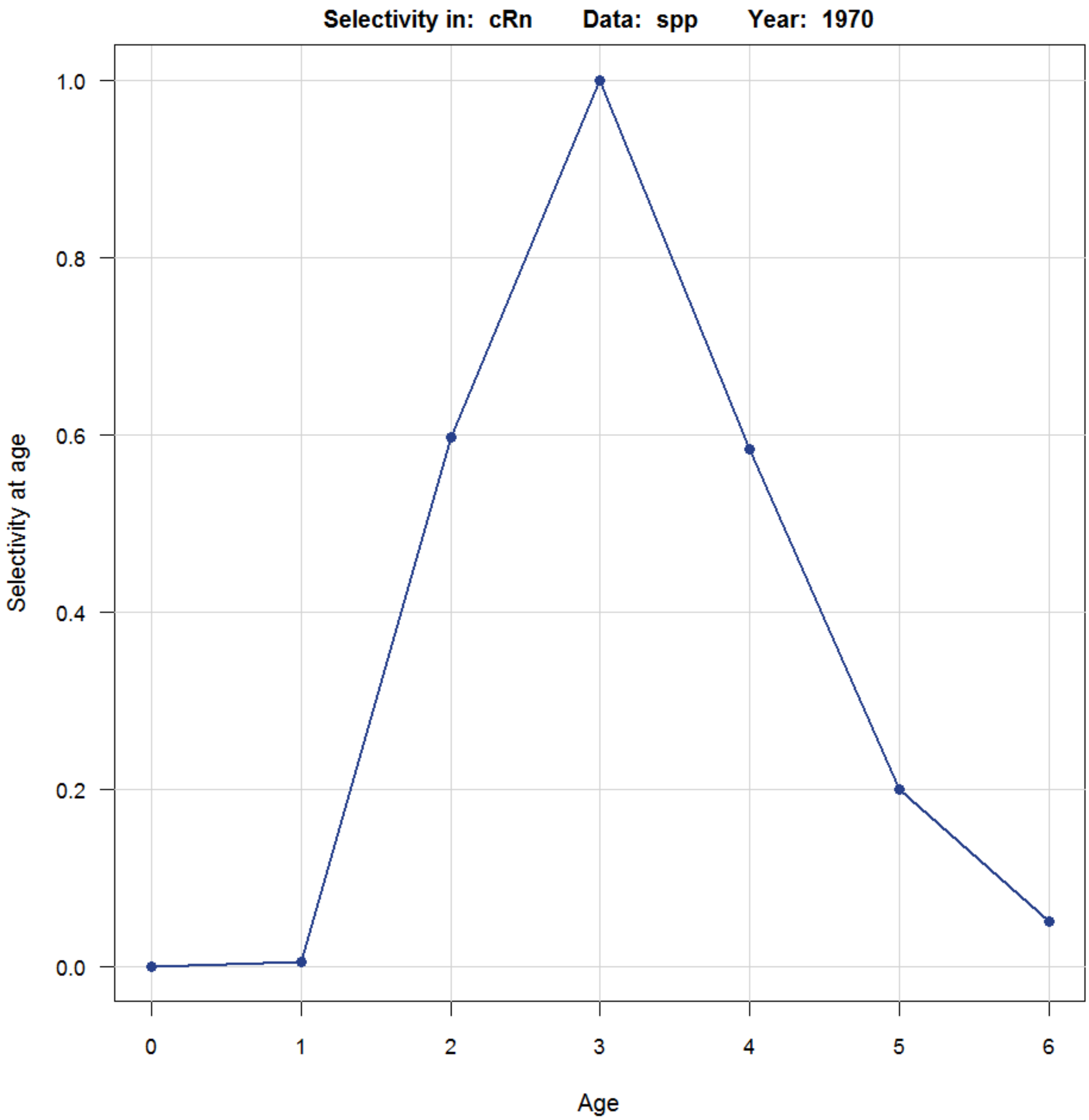


Figure 21. Selectivity for the northern commercial reduction fleet for 1970-1993.

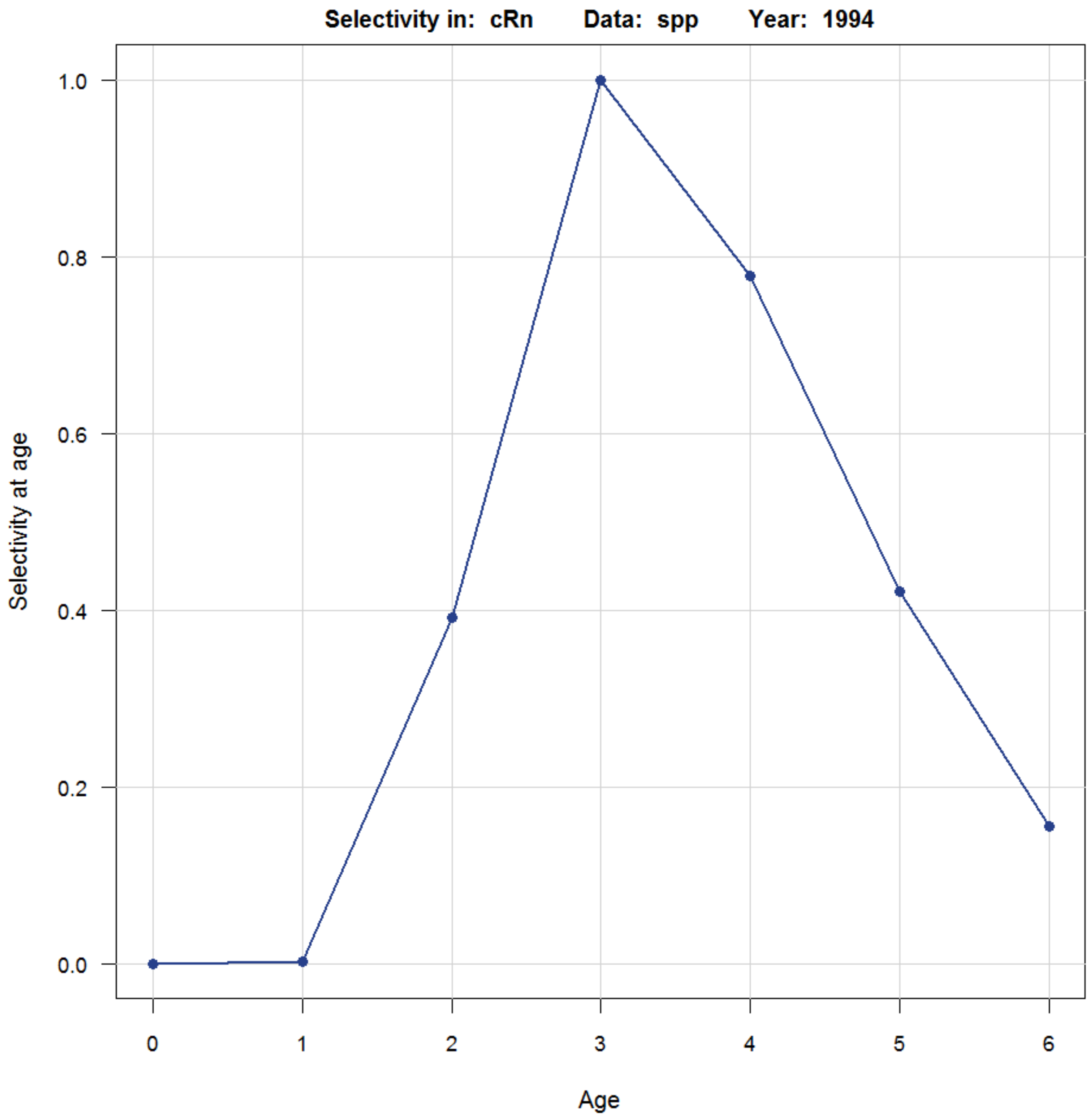


Figure 22. Selectivity for the northern commercial reduction fleet for 1994-2013.

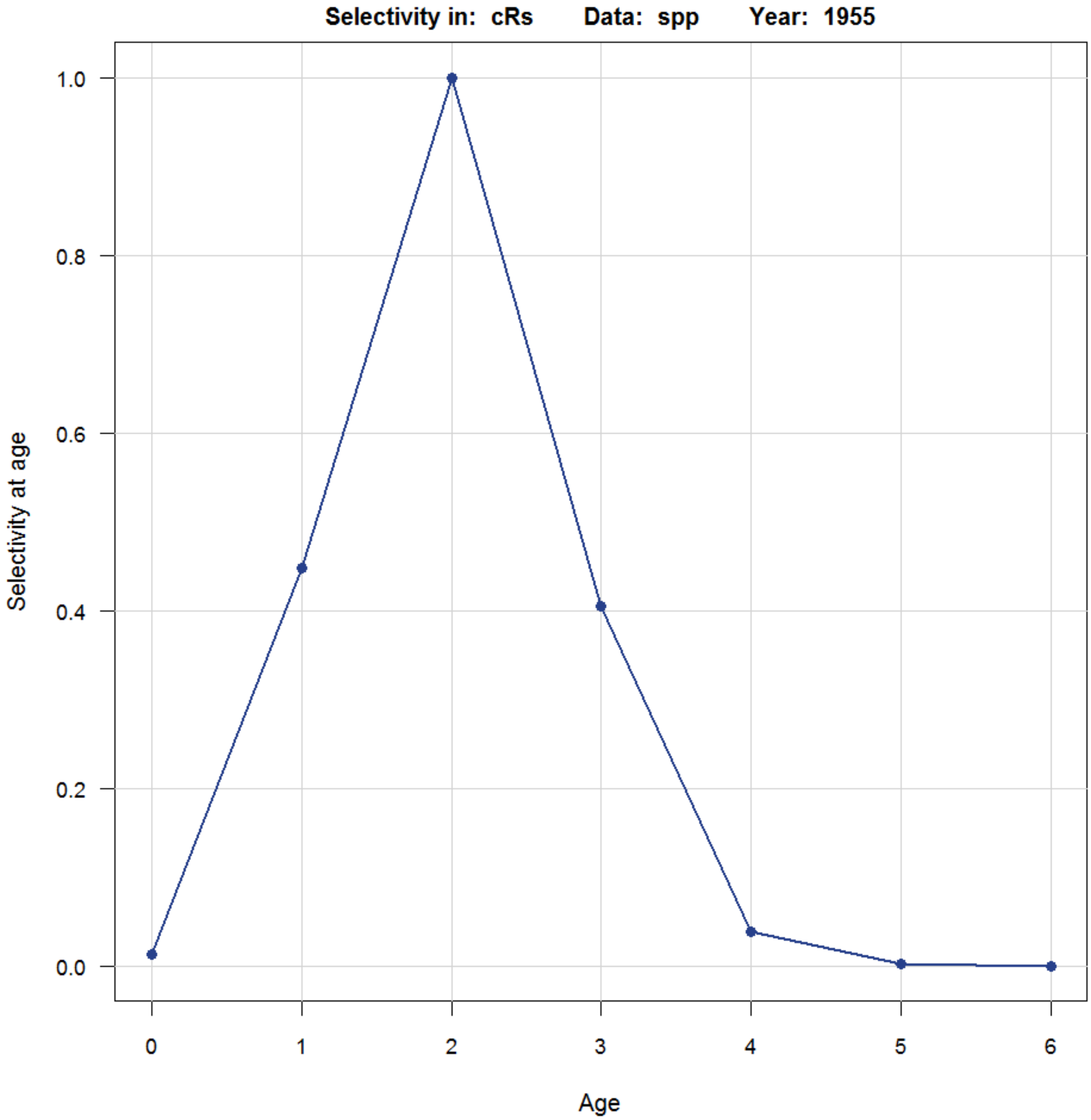


Figure 23. Selectivity for the southern commercial reduction fleet for 1955-1971.

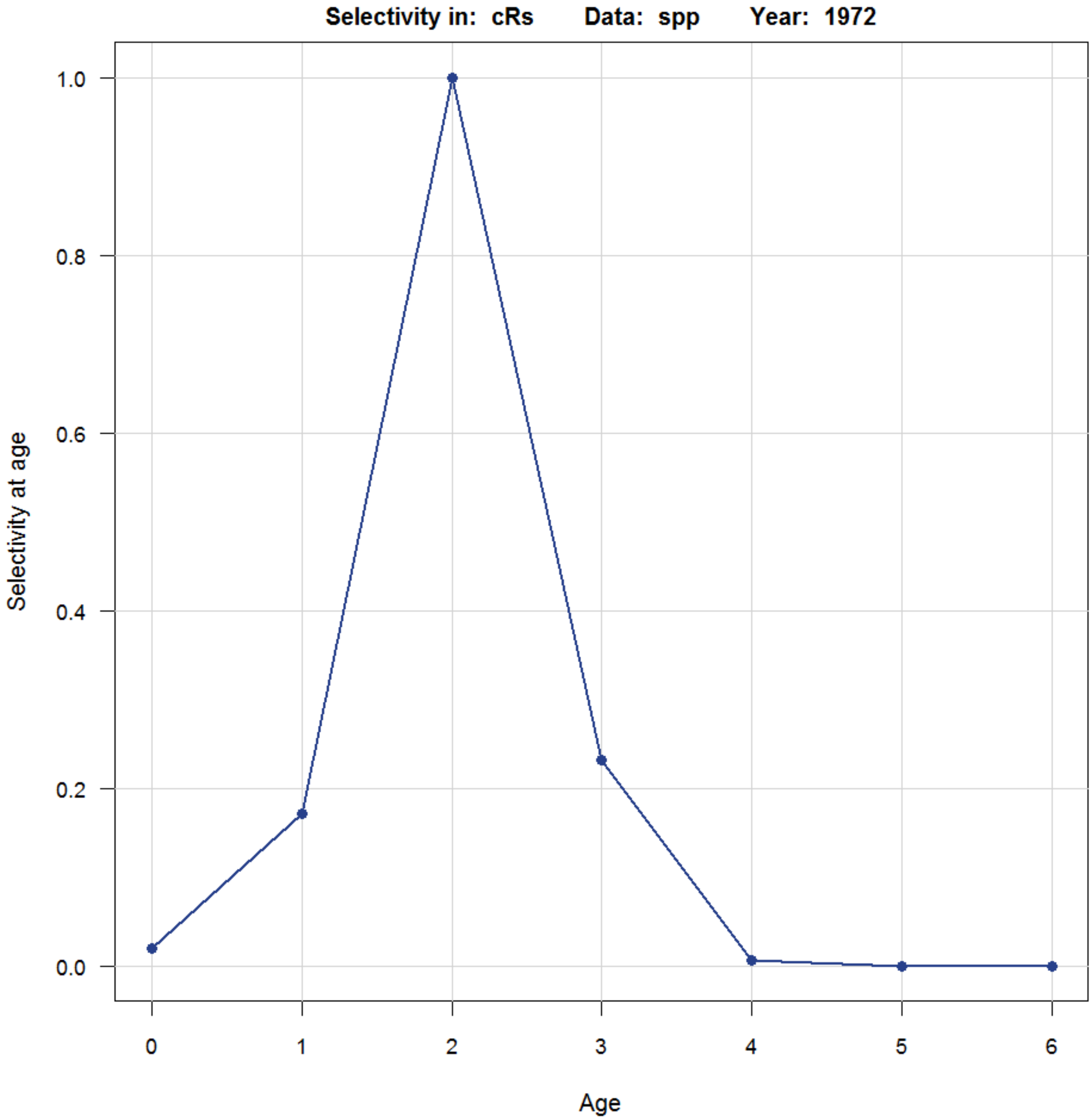


Figure 24. Selectivity for the southern commercial reduction fleet for 1972-2004.

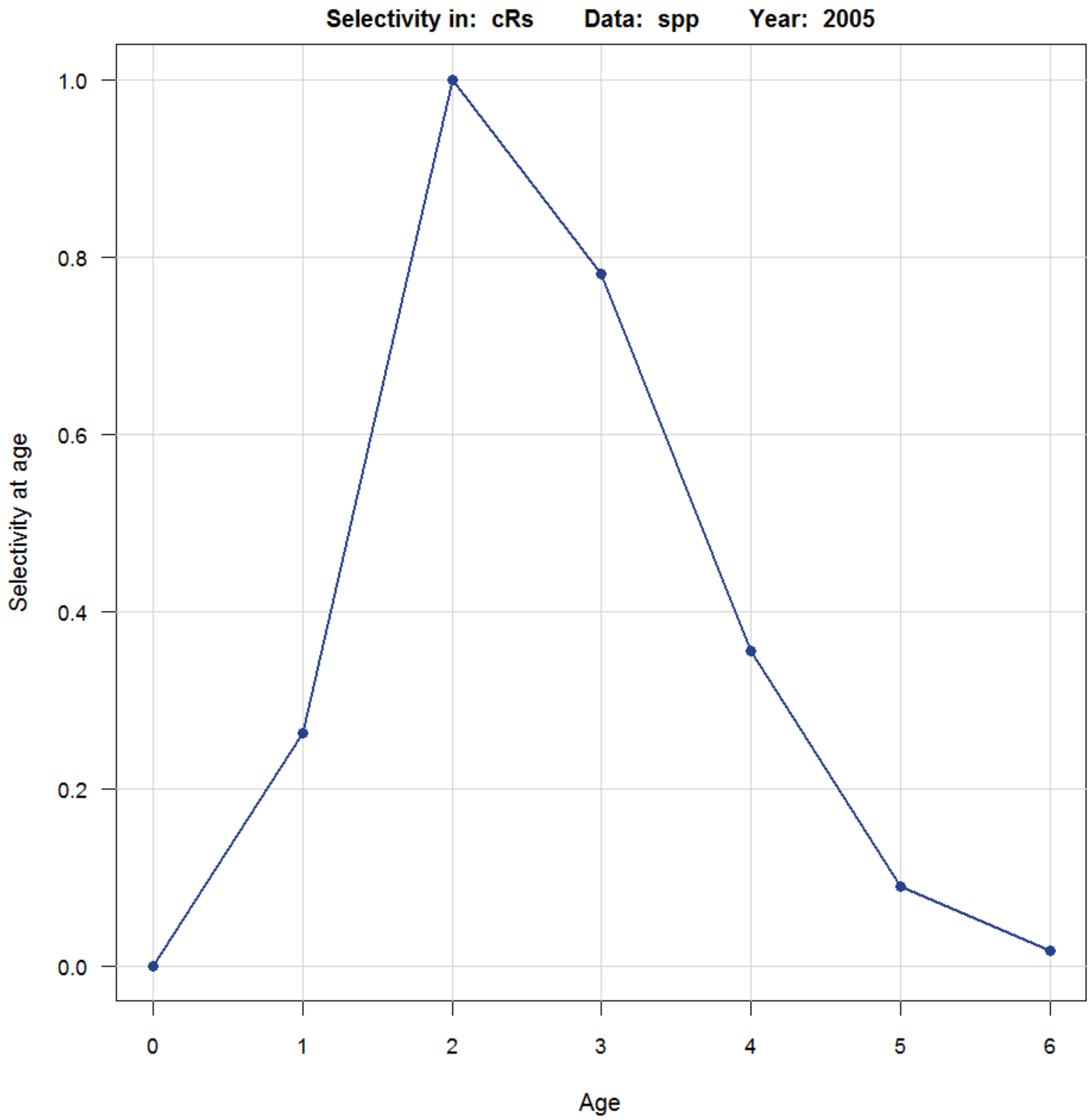


Figure 25. Selectivity for the southern commercial reduction fleet for 2005-2013.

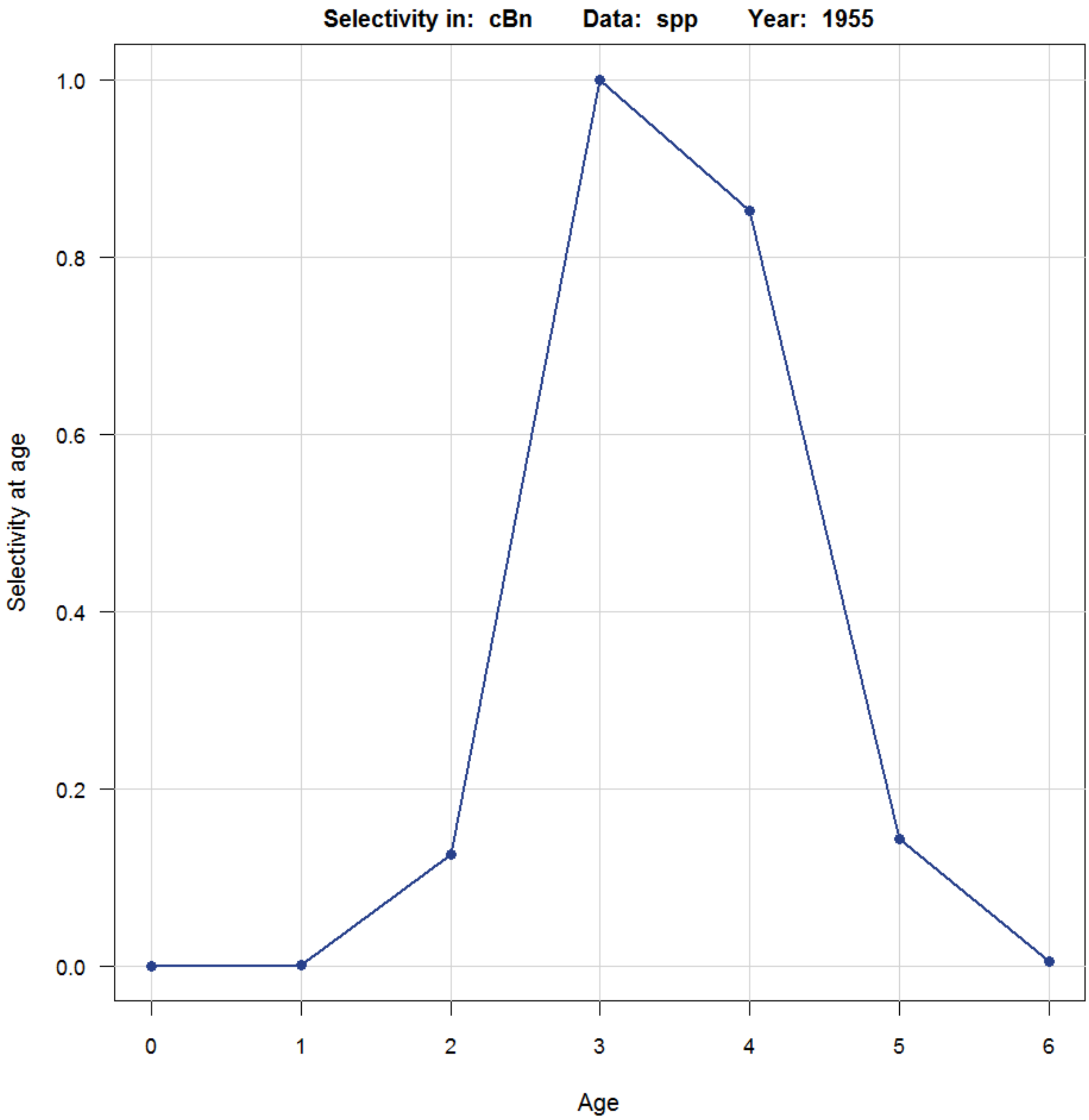


Figure 26. Selectivity for the northern commercial bait fleet for 1955-201**3.**

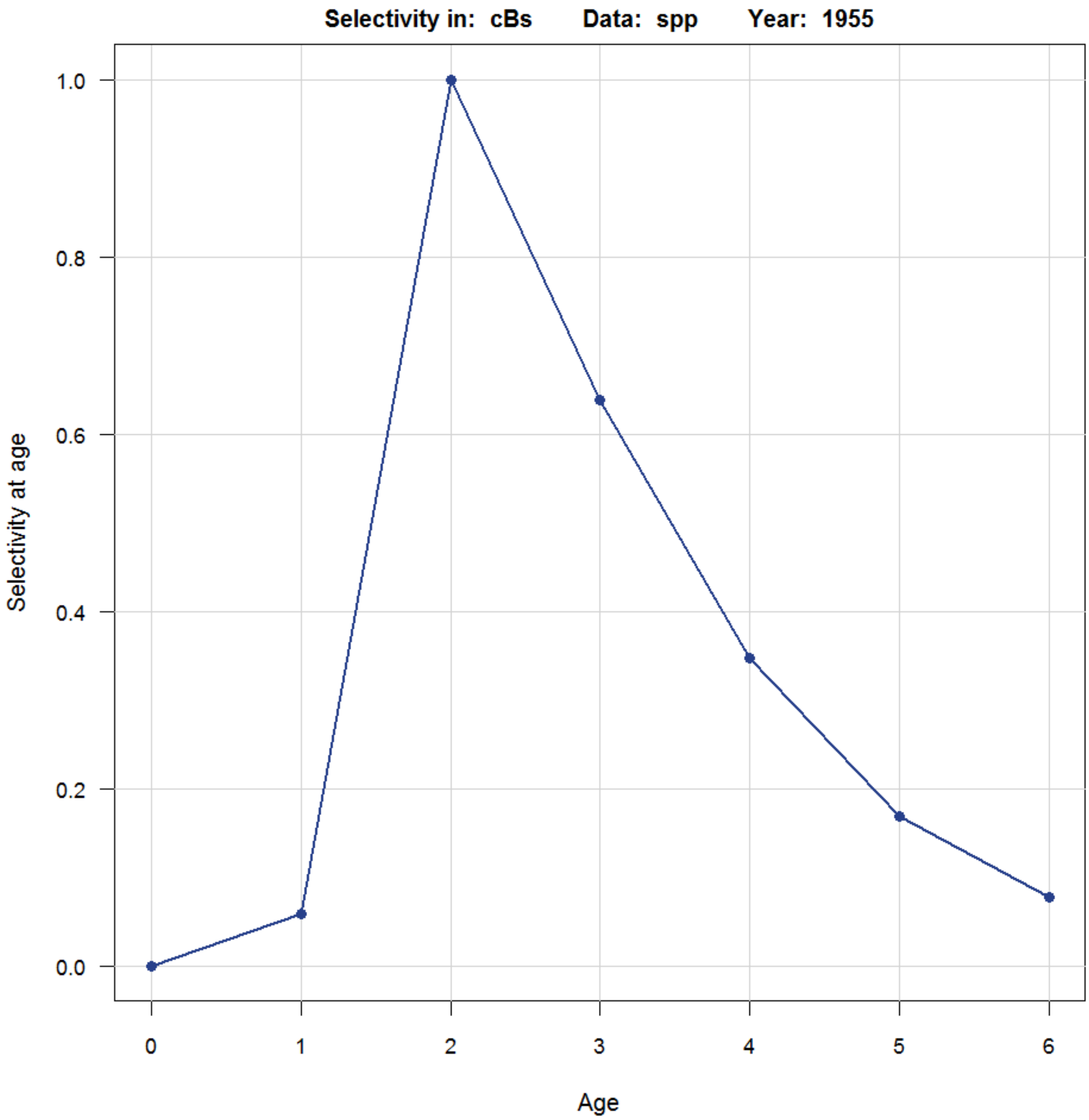


Figure 27. Selectivity for the southern commercial bait fleet for 1955-2013.

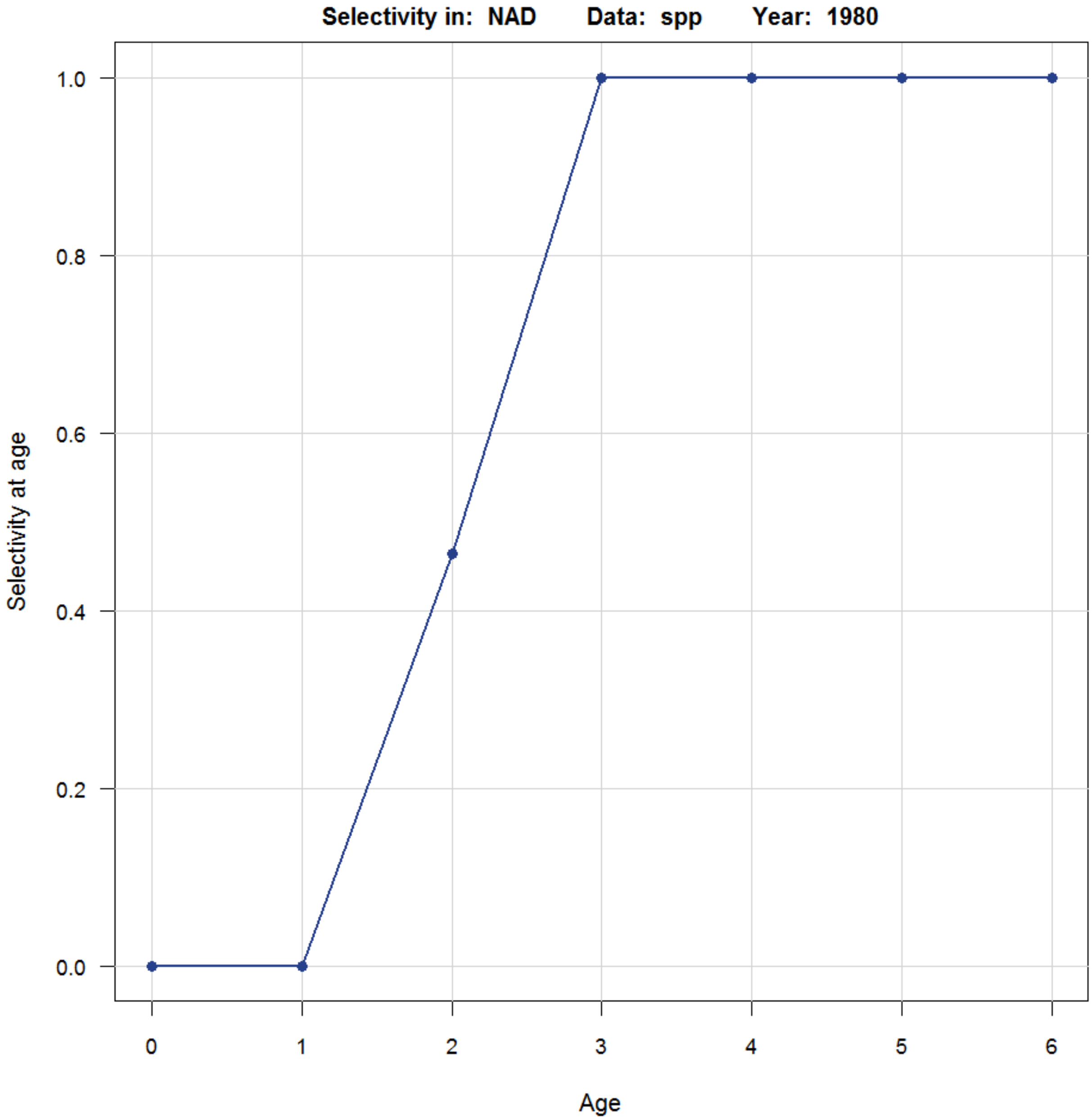


Figure 28. Selectivity for the NAD index for 1980-2013.

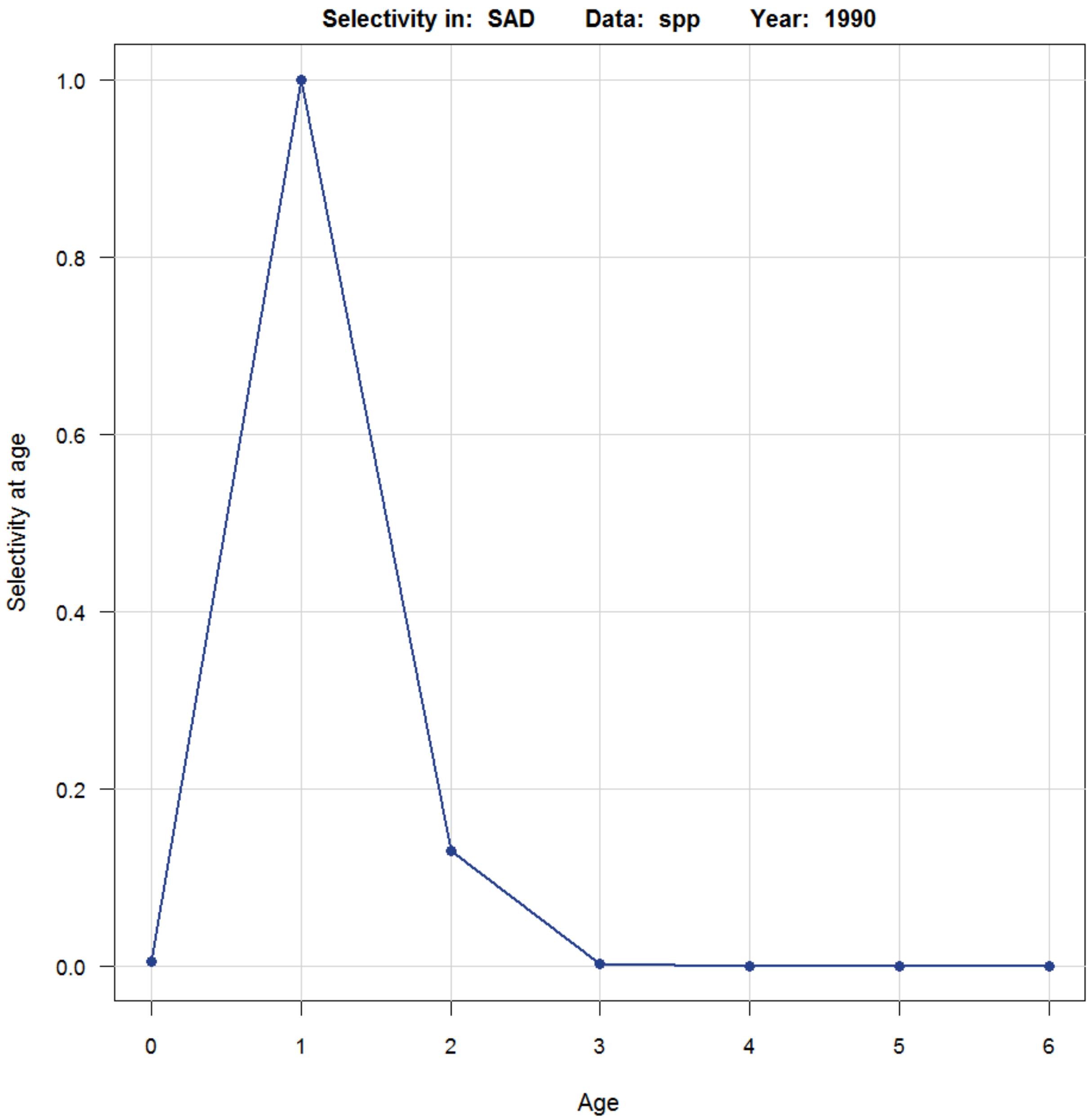


Figure 29. Selectivity for the SAD index for 1990-2013.

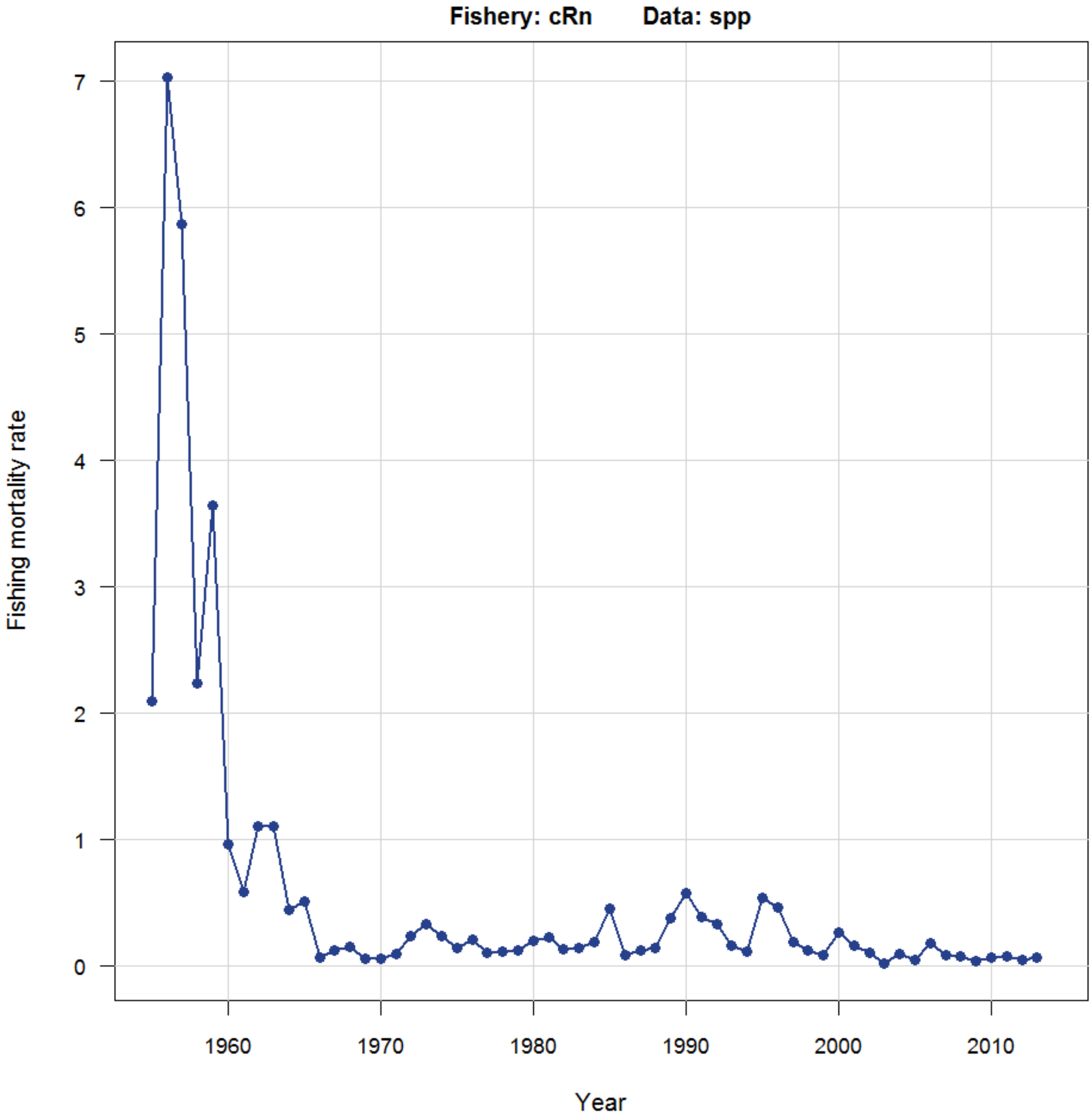


Figure 30. Fishing mortality rate for the northern commercial reduction fishery from 1955-2013.

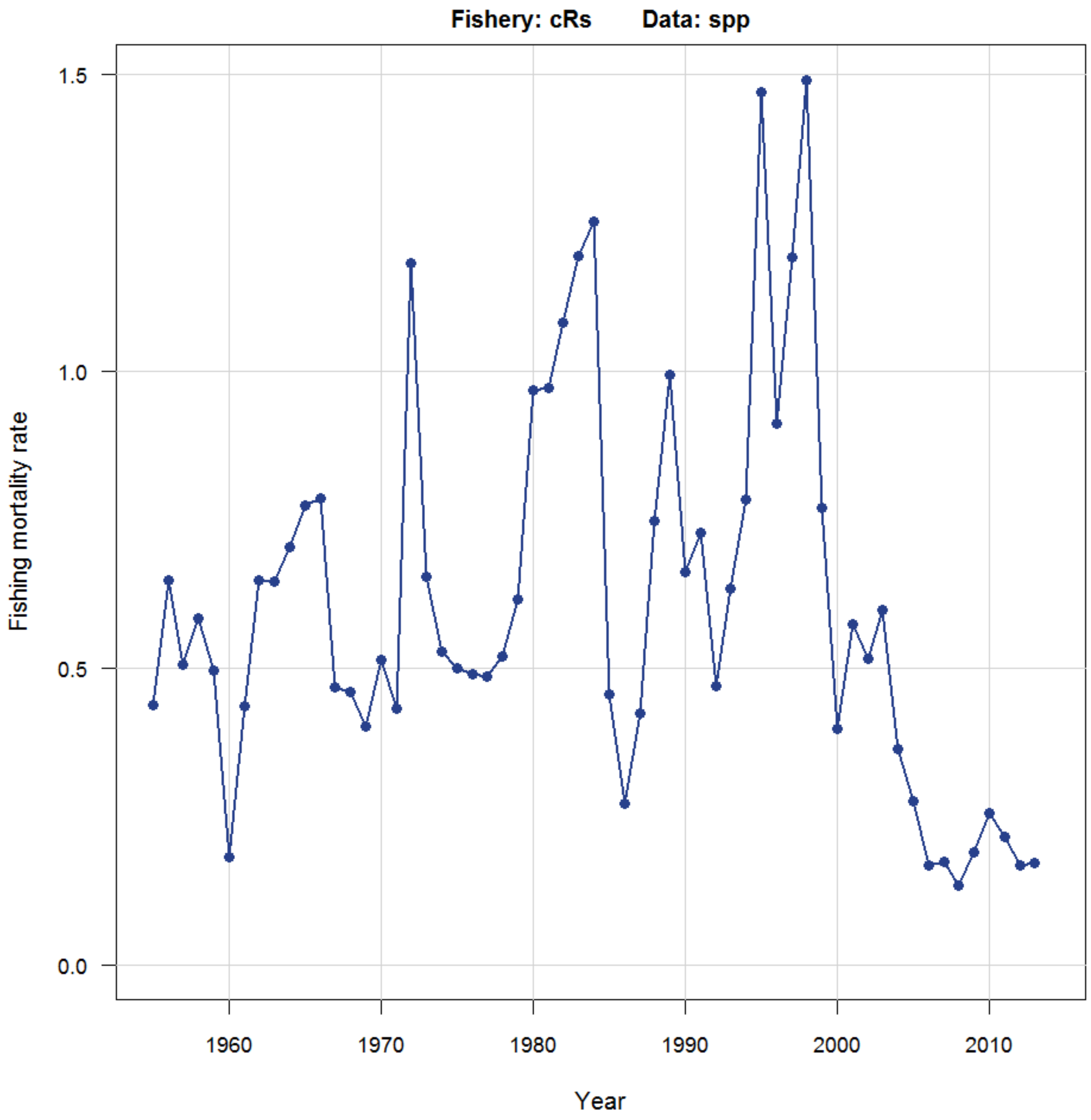


Figure 31. Fishing mortality rate for the southern commercial reduction fishery from 1955-2013.

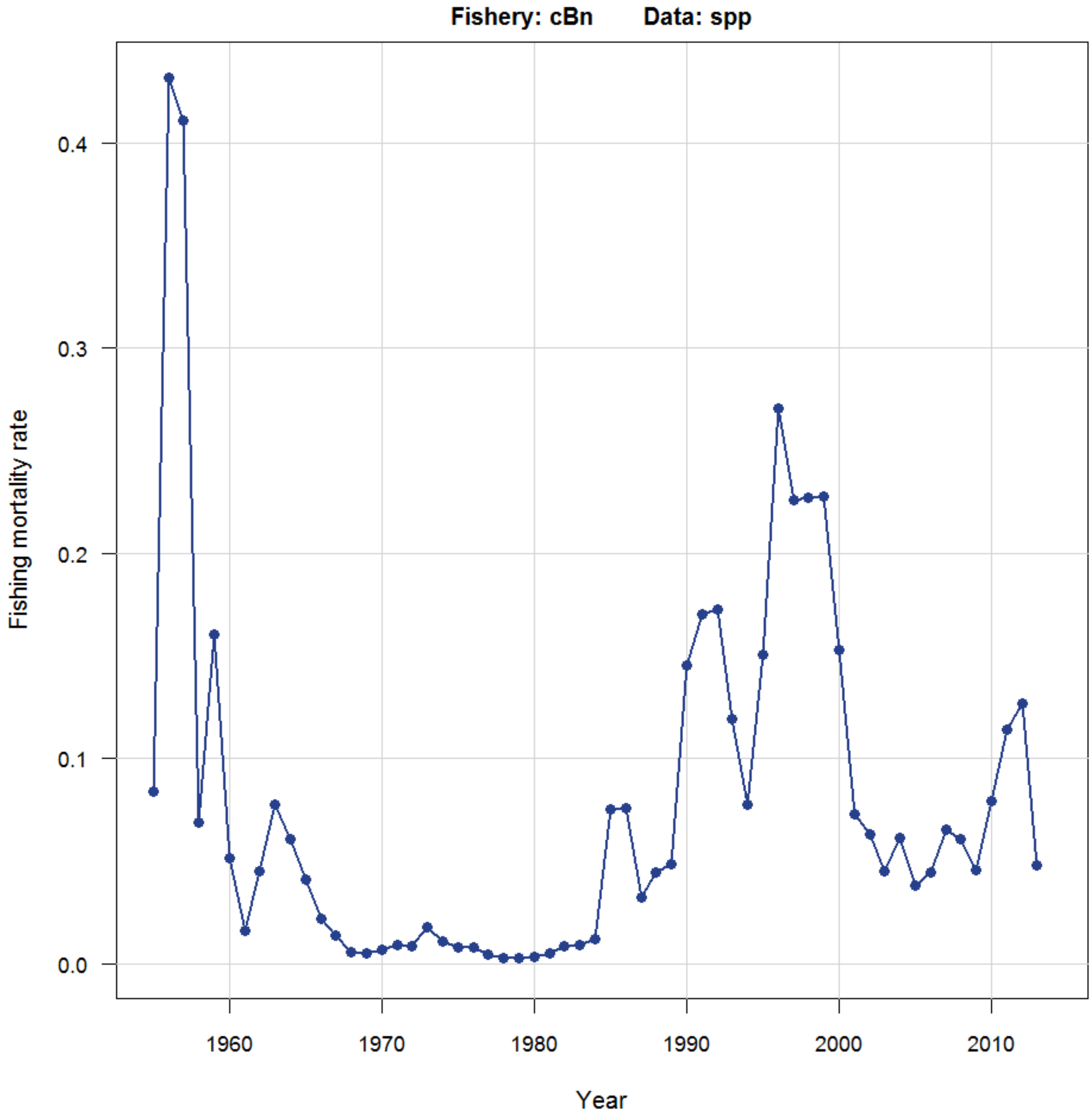


Figure 32. Fishing mortality rate for the northern commercial bait fishery from 1955-2013.

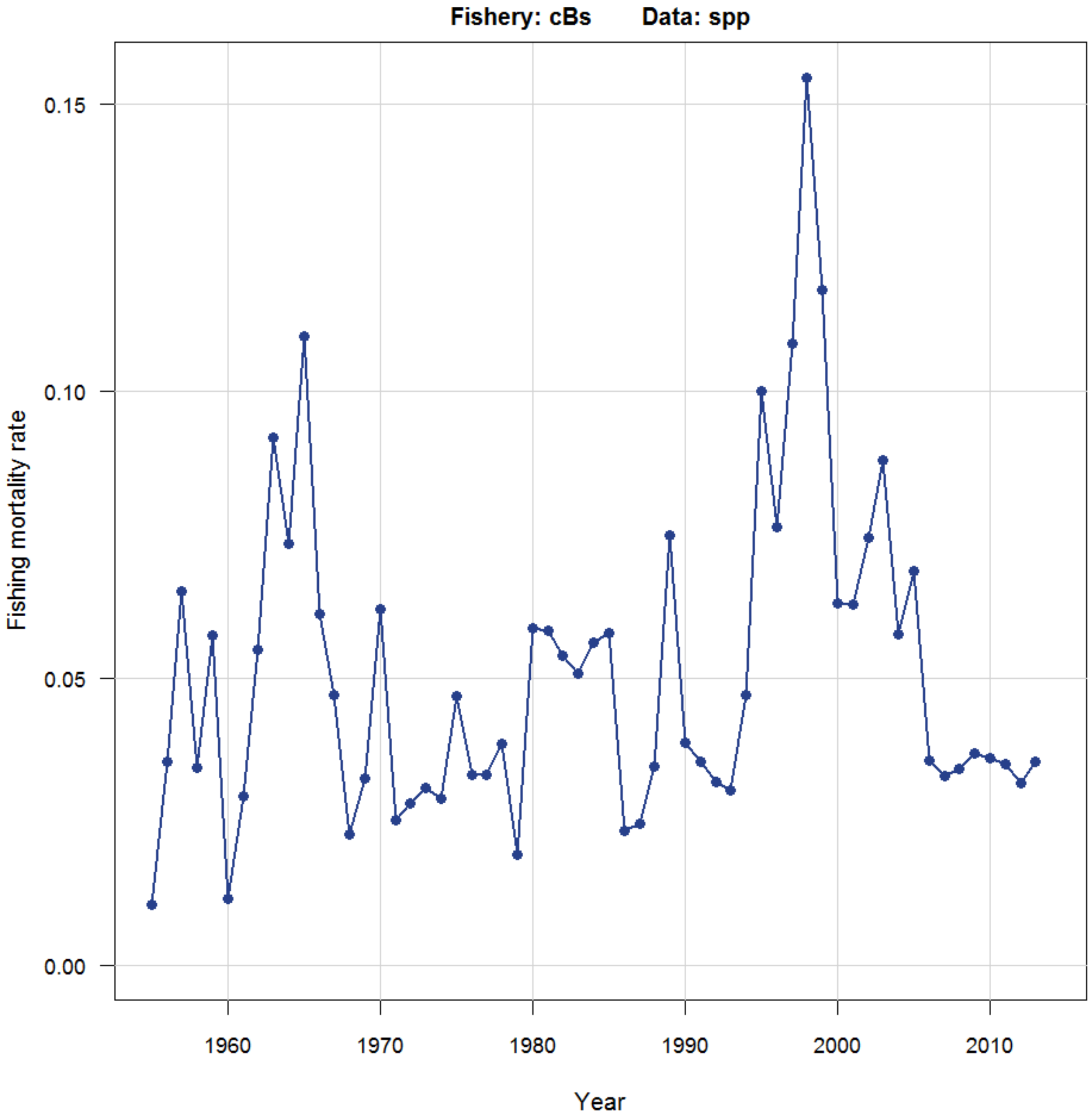


Figure 33. Fishing mortality rate for the southern commercial bait fishery from 1955-2013.

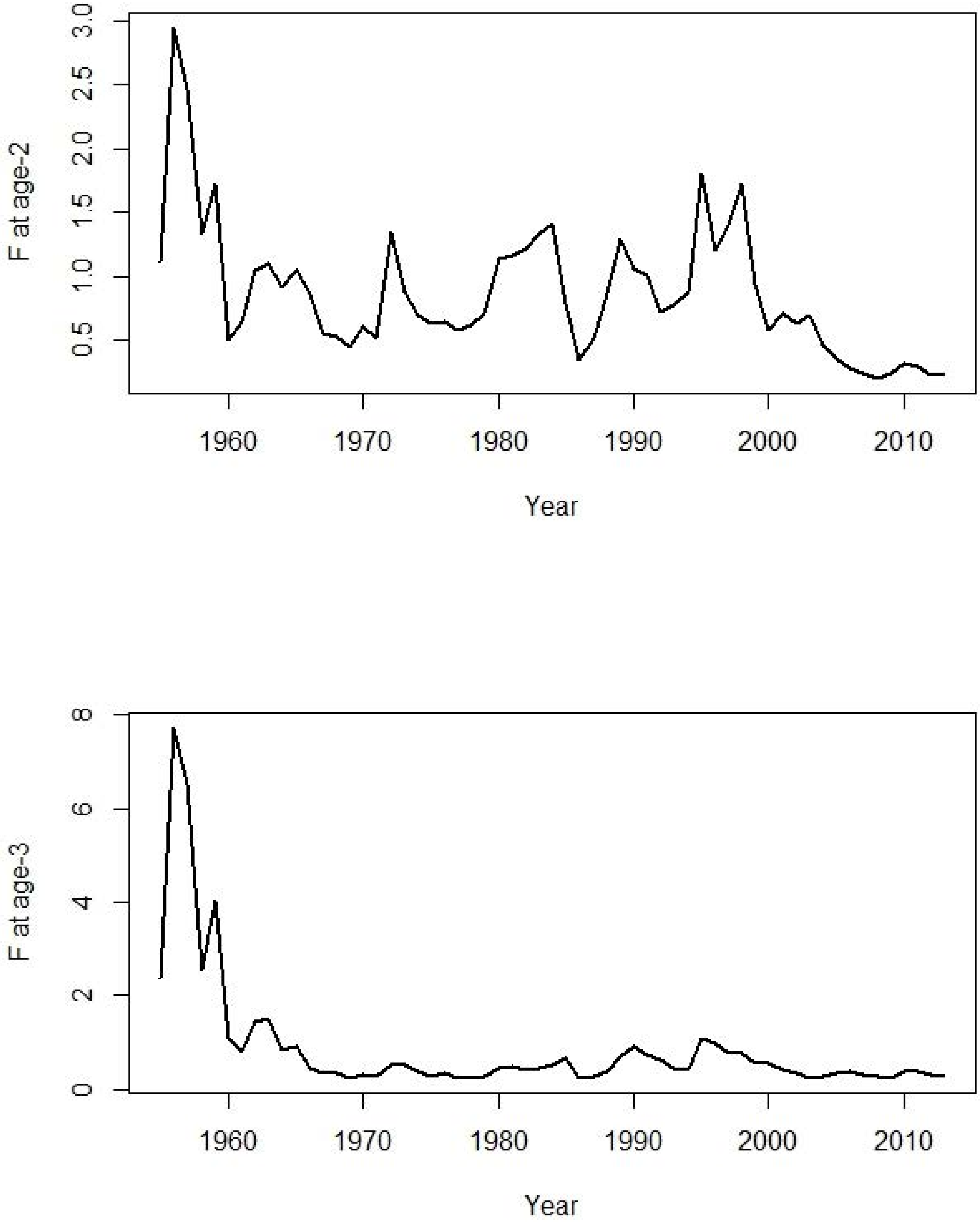
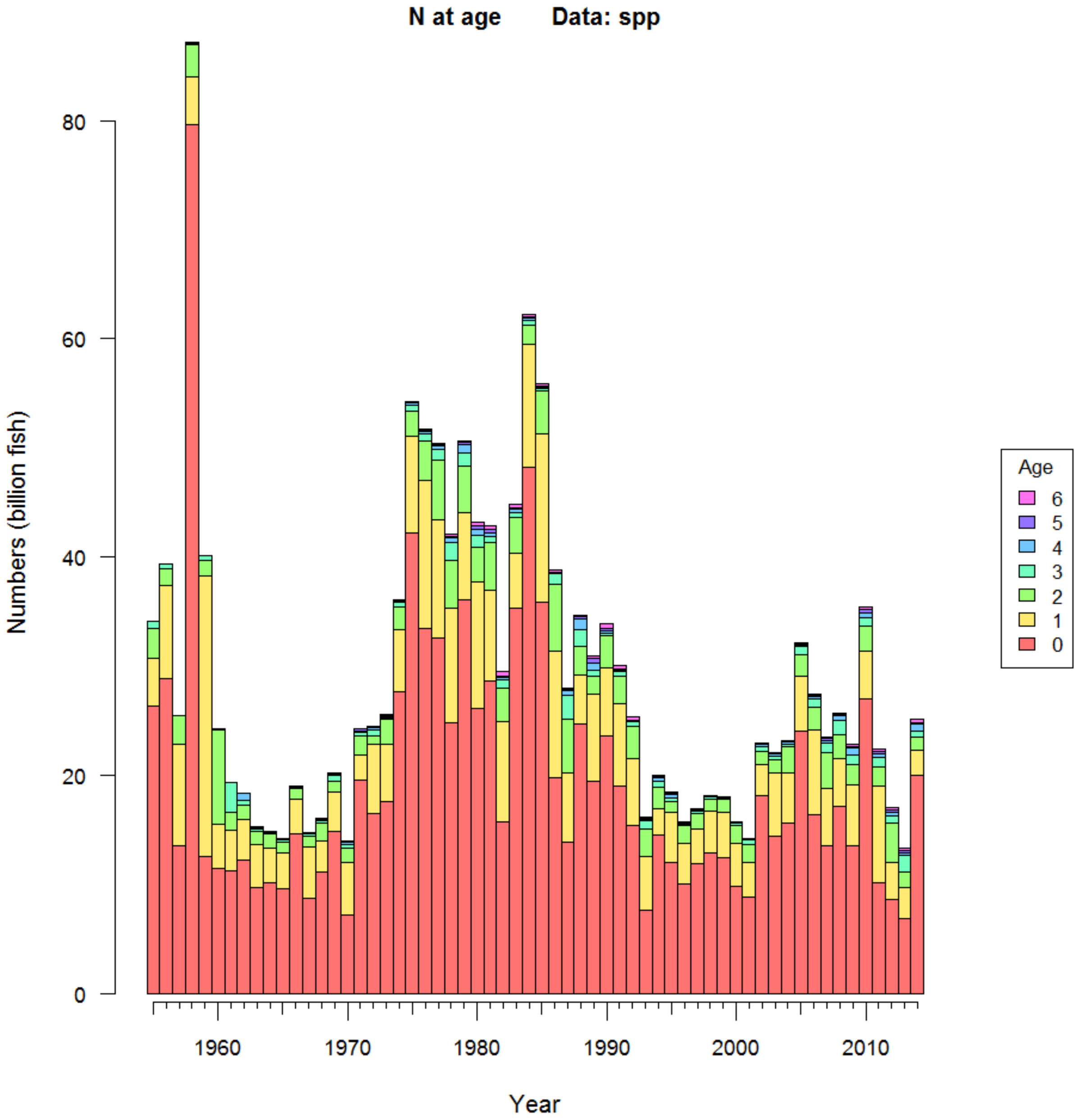


Figure 34. Full F at age 2 (upper panel) and at age 3 (lower panel) over the time course of the fishery from 1955-2013.


N at age Data: spp
Numbers (billion fish)
0
20
40
60
80
1960
1970
1980
1990
2000
2010
Year
Age
6
5
4
3
2
1
0

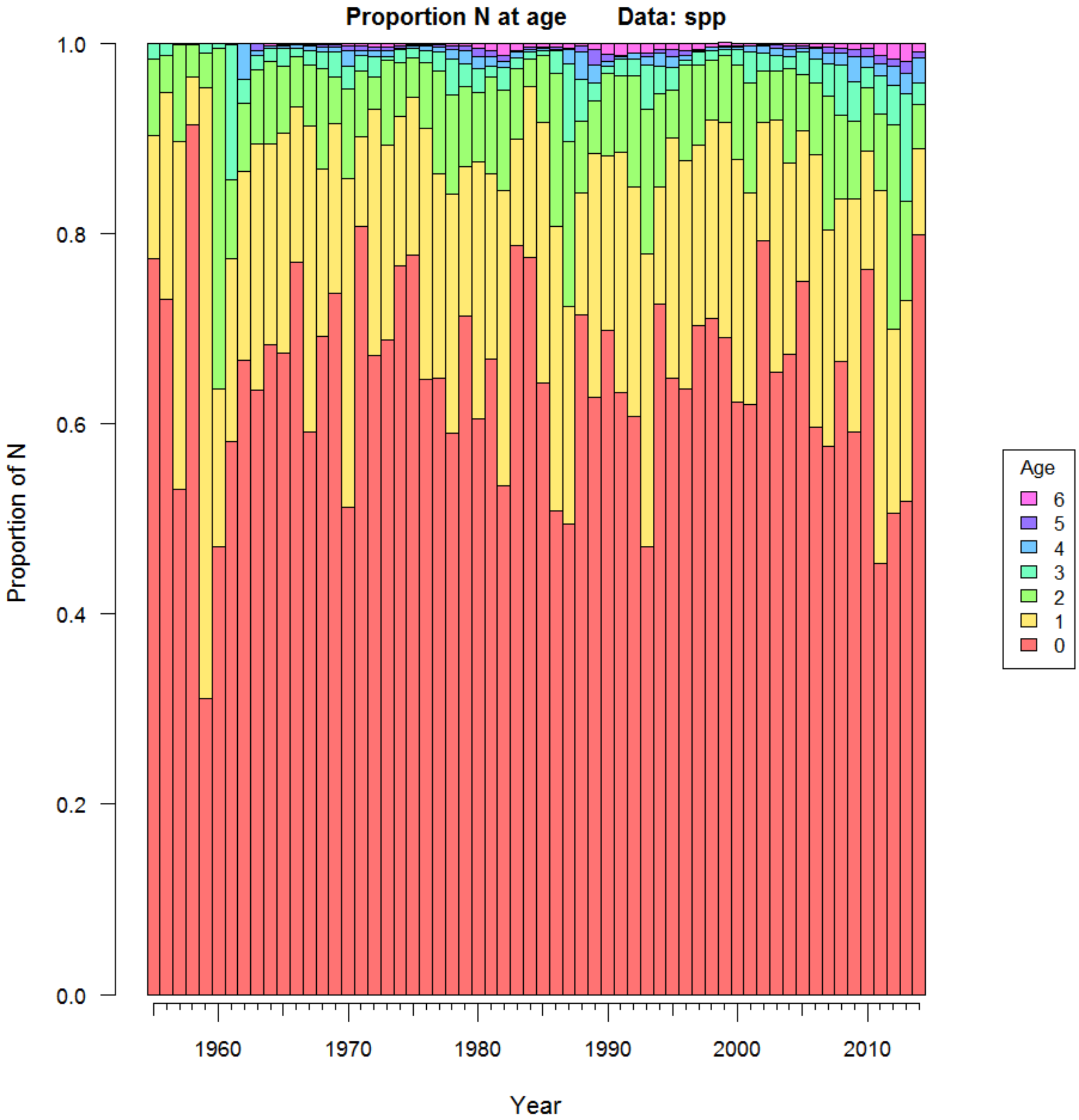


Figure 35. Numbers at age (upper panel) and proportion of numbers at age (lower panel) estimated from the base run of the BAM for ages 0-6+ during the time period 1955-2013.

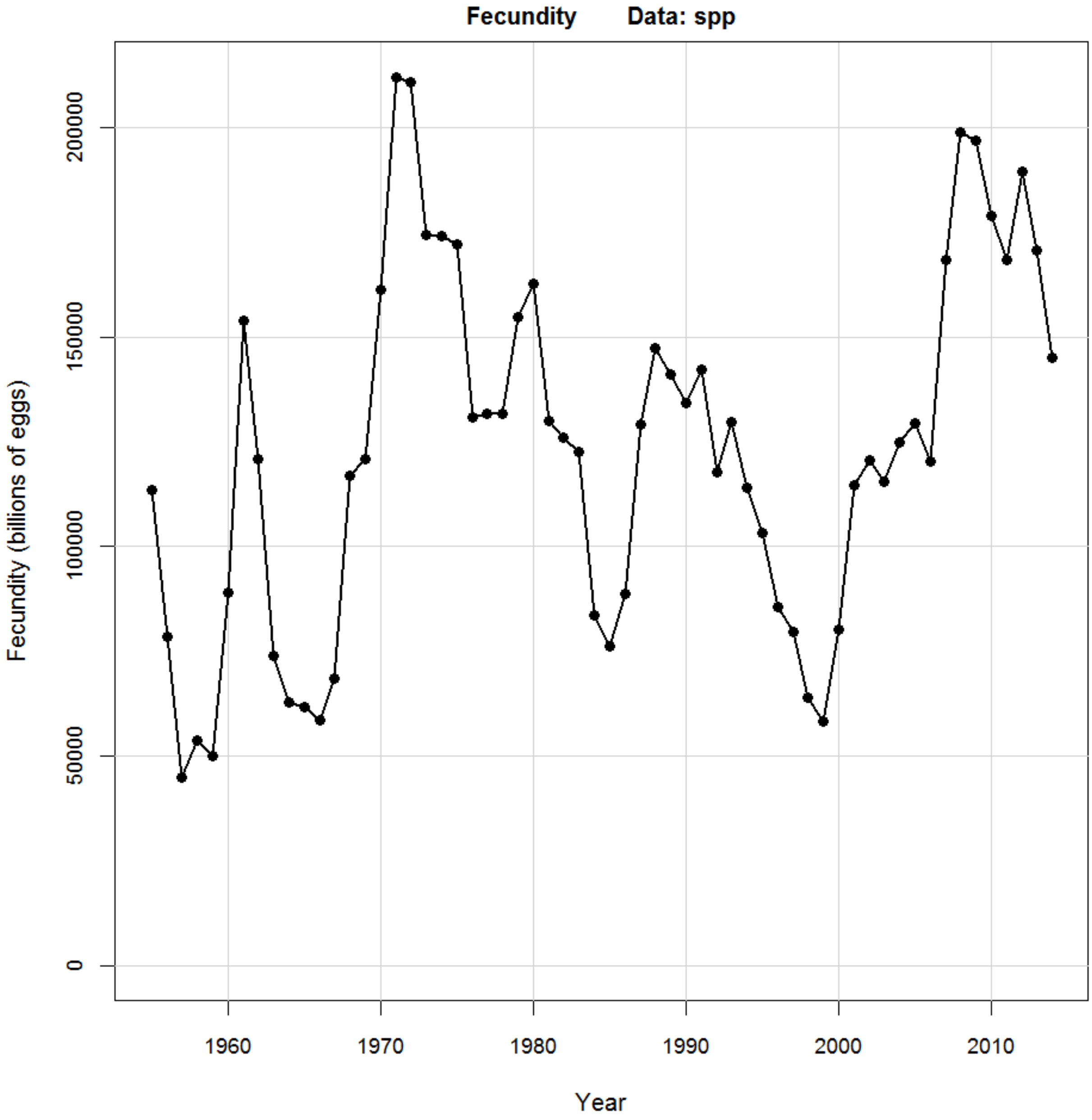
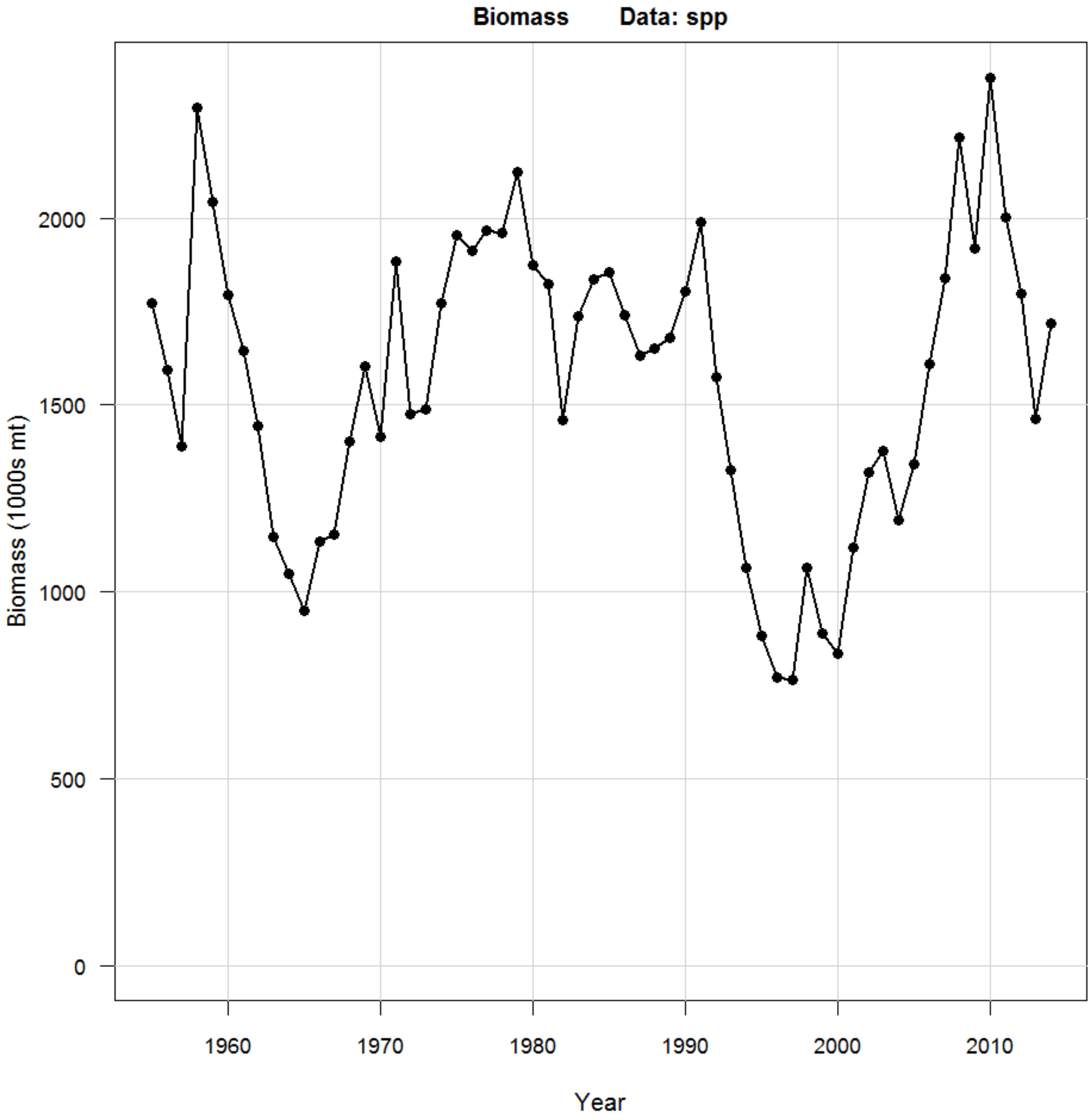


Figure 36. Fecundity in billions of eggs over time, 1955-2014, with the last year being a projection based on 2013 mortality.


Biomass Data: spp
Biomass (1000s mt)
0
500
1000
1500
2000
1960
1970
1980
1990
2000
2010
Year

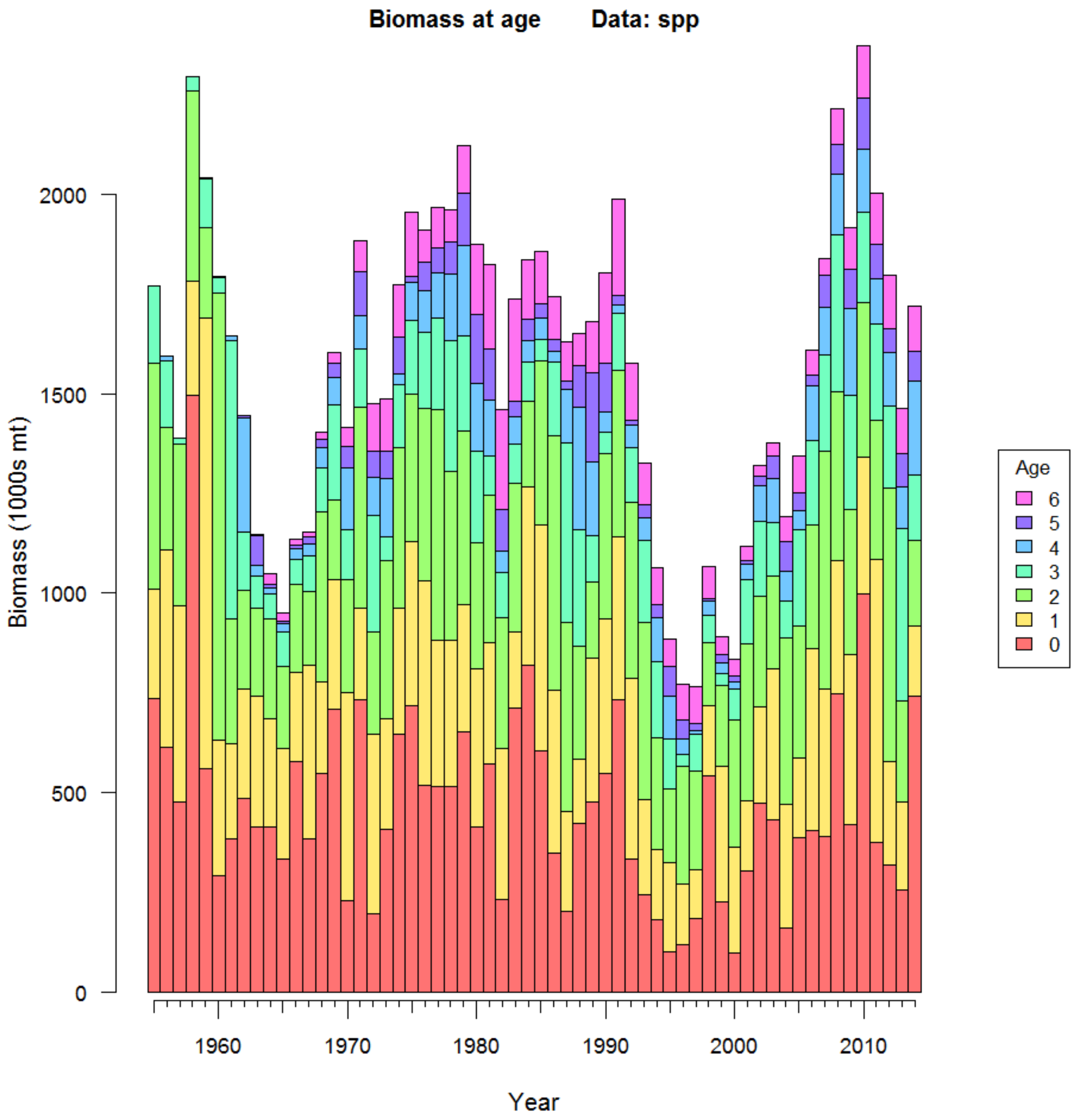


Figure 37. Biomass (upper panel) and biomass at age (lower panel) over time as predicted from the base run of the BAM for Atlantic menhaden.

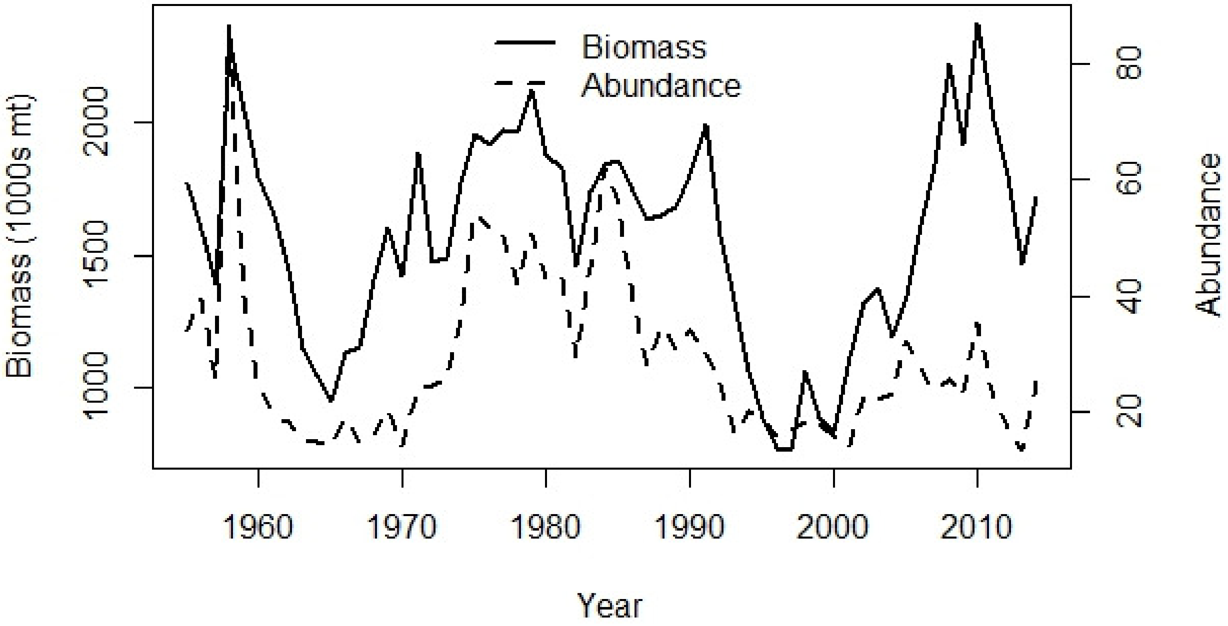


Figure 38. Biomass (1000s mt) and abundance over time for Atlantic menhaden from 1959-2013.

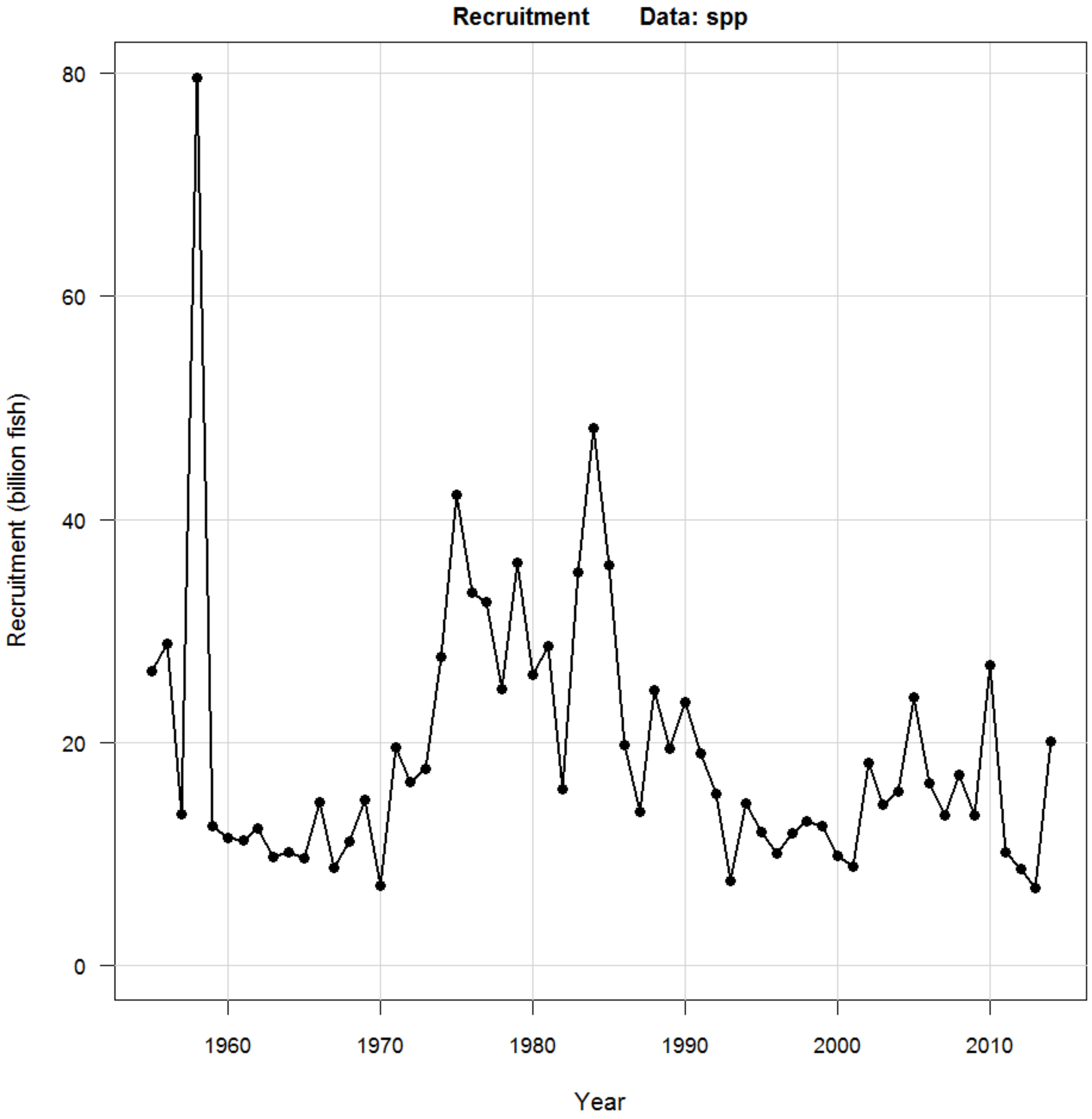


Figure 39. Number of recruits in billions of fish predicted from the base run of BAM for 1955-2013.

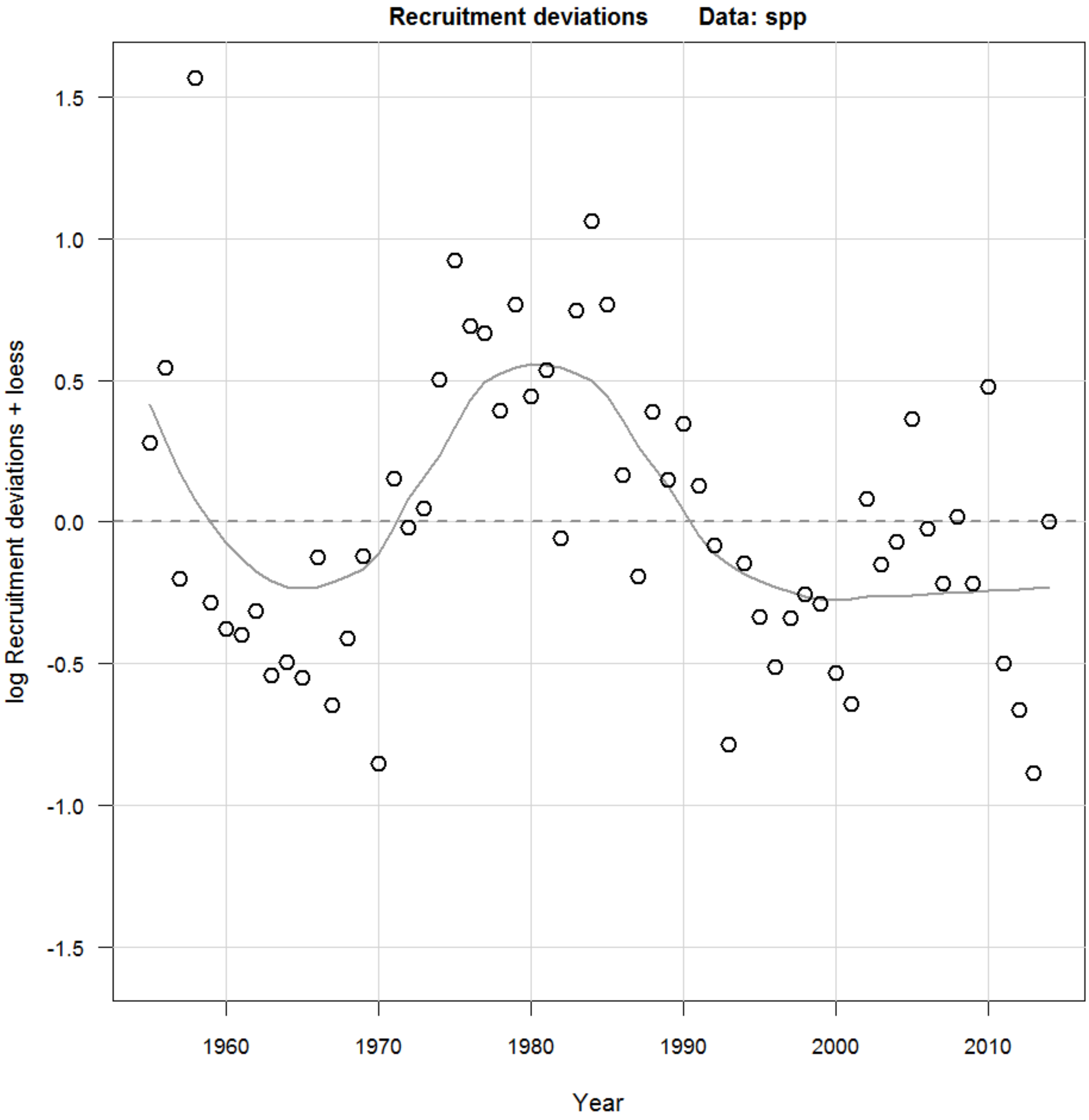


Figure 40. Deviations in log recruitment from 1955-2013 with a loess smoother.

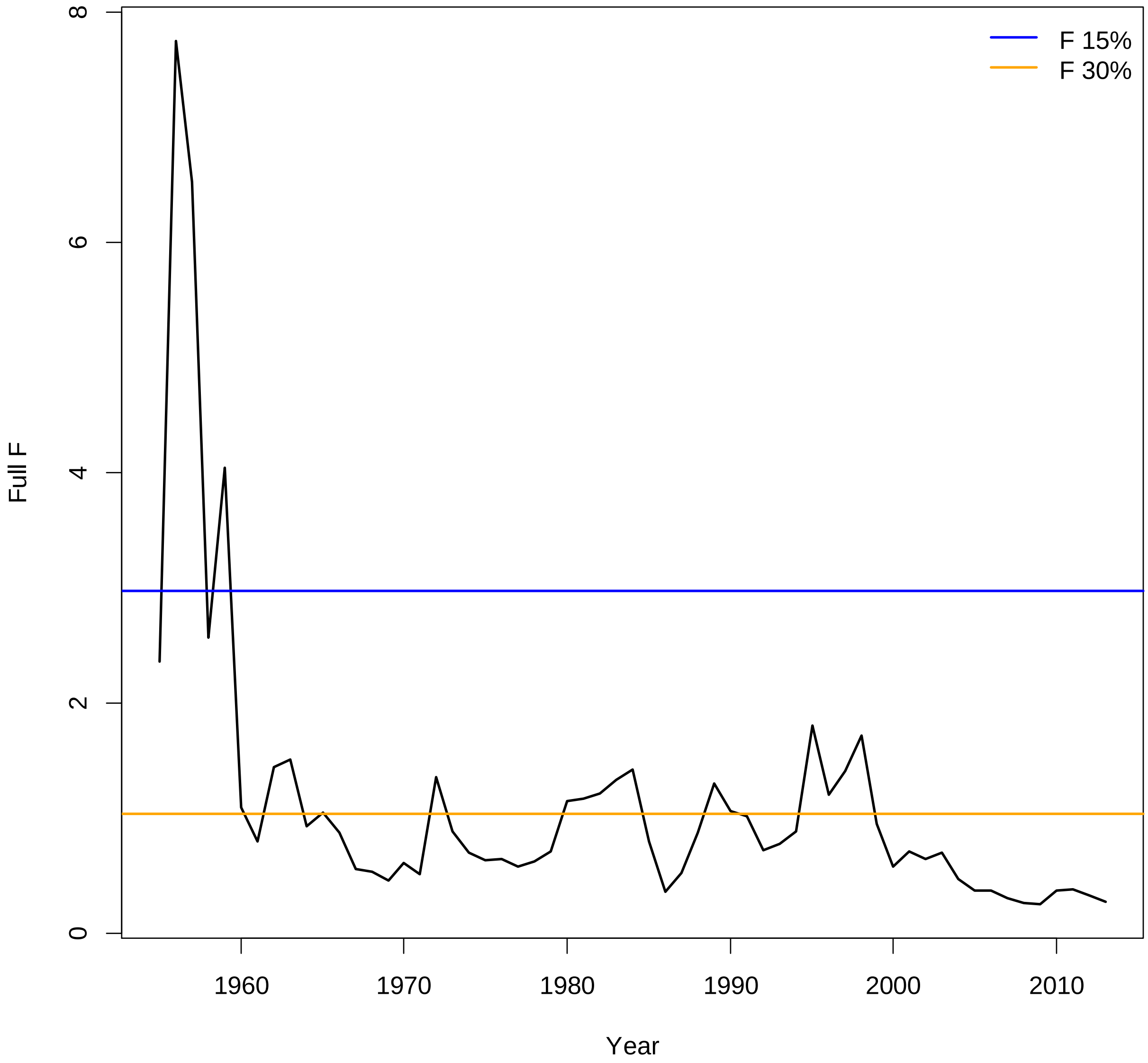


Figure 41. Full fishing mortality rate versus the benchmarks of ***$F_{15\%}$*** and ***$F_{30\%}$***.

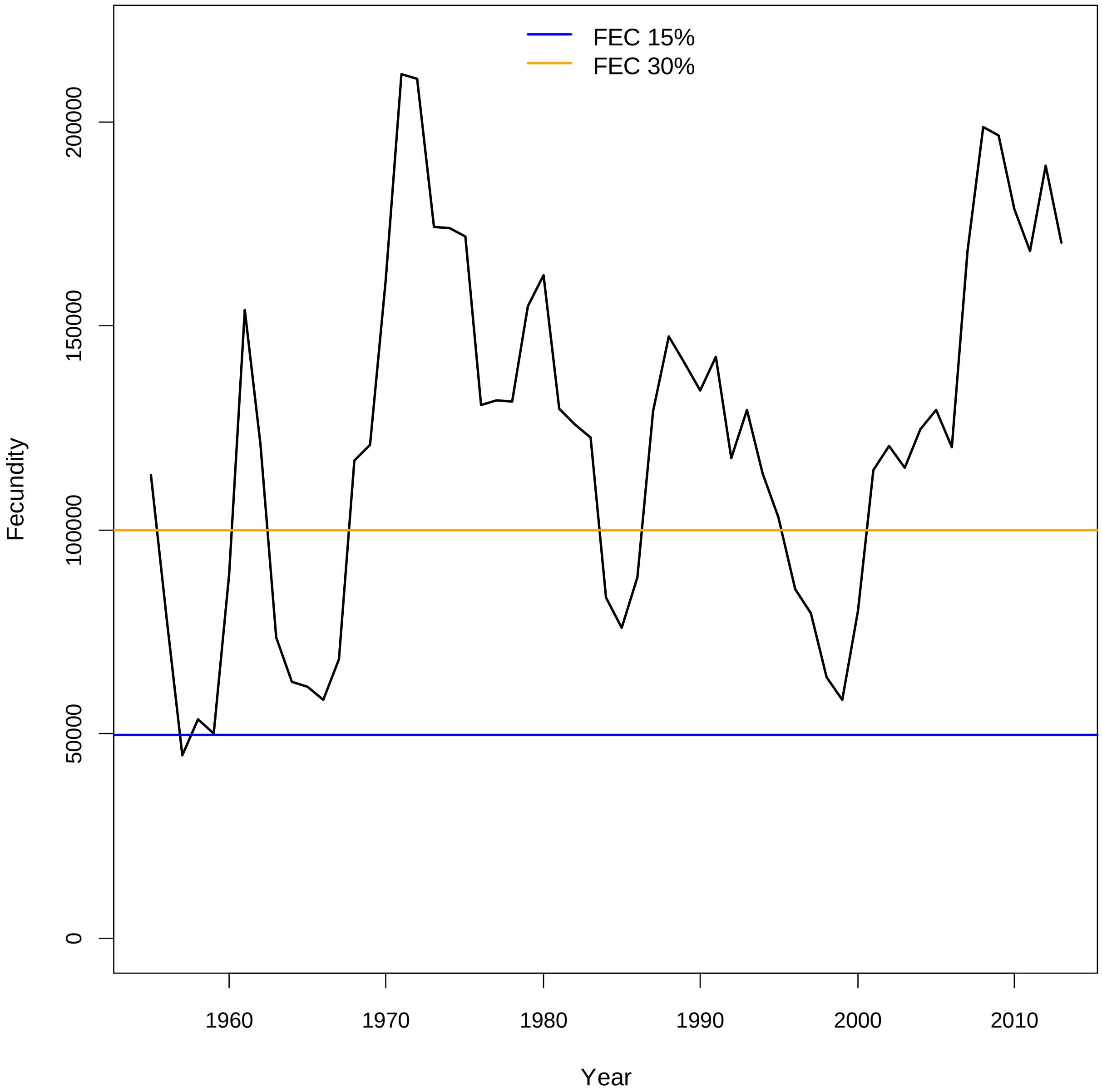


Figure 42. Fecundity versus the benchmarks of $\boldsymbol{FEC_{15\%}}$ and $\boldsymbol{FEC_{30\%}}$.

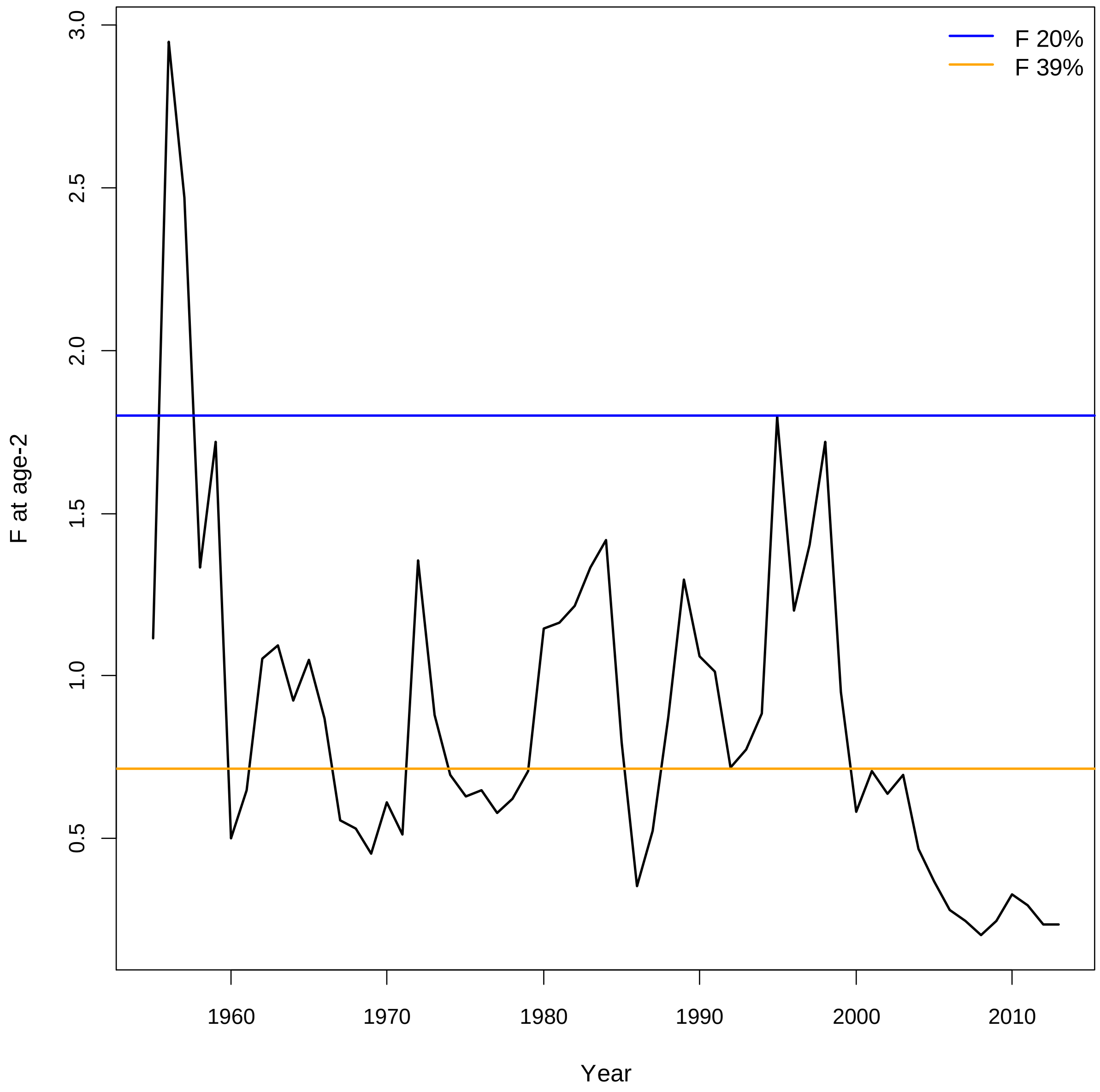


Figure 43. Fishing mortality rate at age-2 versus the benchmarks of $F_{20\%}$ and $F_{39\%}$.

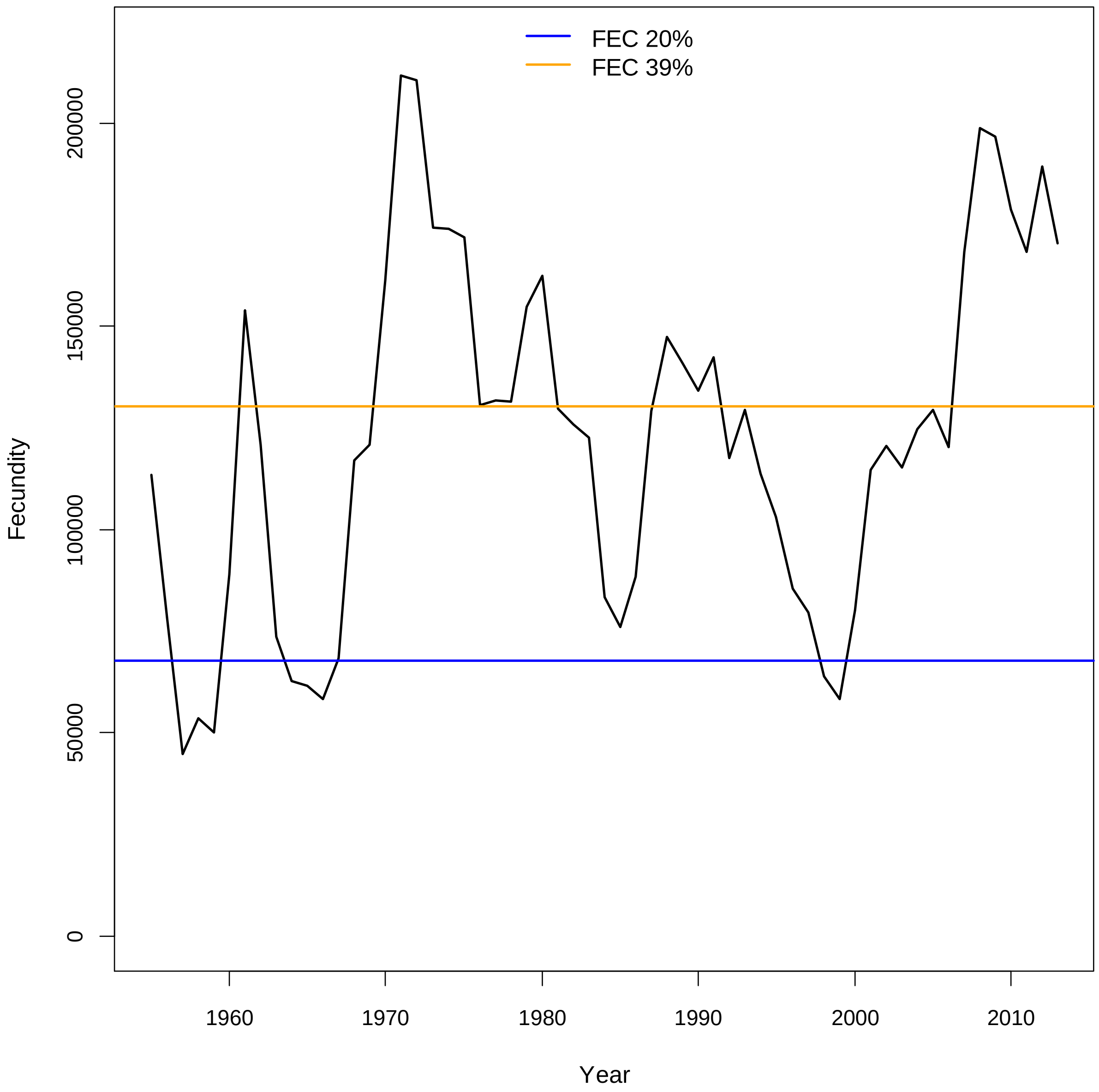


Figure 44. Fecundity versus the benchmarks of $FEC_{20\%}$ and $FEC_{39\%}$.

SEDAR

Southeast Data, Assessment, and Review

SEDAR 40

Atlantic Menhaden

SECTION III: Review Workshop Report

January 2015

SEDAR
4055 Faber Place Drive, Suite 201
North Charleston, SC 29405

Table of Contents

1. Introduction

1.1 Workshop Time and Place

The SEDAR 40 Review Workshop for Atlantic menhaden was held December 9-11, 2014 in Atlantic Beach, NC.

1.2 Terms of Reference

1. Evaluate the data used in the assessment.

    a. Are data decisions made during the DW and AW justified (i.e. sound and robust)?

    b. Are input data series reliable and sufficient to support the assessment approach and findings?

    c. Are data applied properly within the assessment?

    d. Are data uncertainties acknowledged, reported, and within normal or expected levels?

2. Evaluate the methods used to assess the stock, taking into account available data.

    a. Are methods scientifically sound and robust?

    b. Are assessment models configured properly and used consistent with standard practices?

    c. Are the methods appropriate for the available data?

    d. If multiple models or model configurations were considered, evaluate the explanation of any differences in results and justification of a base model.

3. Consider how uncertainties in the assessment, and their potential consequences, are addressed.

    a. Comment on the degree to which methods used to evaluate uncertainty reflect and capture the significant sources of uncertainty in the population, data sources, and assessment methods.
    b. Are the implications of uncertainty on technical conclusions are clearly stated?

4. Evaluate the assessment findings with respect to the following:

    a. Are estimates of biomass, abundance, and exploitation rate reliable and consistent with input data and population biological characteristics? Are they useful to support inferences on stock status?

    b. Is the stock overfished relative to biomass or abundance threshold reference points? Where is the stock relative to biomass or abundance management targets? What information supports this conclusion?

c. Is the stock undergoing overfishing relative to fishing mortality threshold reference points? Where is the stock relative to fishing mortality management targets? What information supports this conclusion?

d. Is there an informative stock recruitment relationship? Is the stock recruitment curve reliable and useful for evaluation of productivity and future stock conditions?

e. Are the quantitative estimates of the threshold reference points reliable for this stock? If not, are there other indicators that may be used to inform managers about stock trends and conditions?

5. If a minority report has been filed, review minority opinion and any associated analyses. If possible, make recommendation on current or future use of alternative assessment approach presented in minority report.

6. Review the Technical Committee's recommendations on research, data collection, and assessment methodology and make any additional recommendations or prioritizations, if warranted.

7. Provide guidance on key improvements in data or modeling approaches which should be considered when scheduling the next assessment.

8. Provide feedback on the proposed ecological reference points that account for Atlantic menhaden's role as a forage fish. Evaluate the appropriateness and feasibility of the proposed approach. Provide alternative suggestions, if necessary. *Note: this TOR is aimed at obtaining preliminary feedback on a proposed reference point development approach that would inform future ecosystem-based management plans. Further technical development and peer review would be required before these reference points would be used in management.*

9. Prepare a peer review panel advisory report summarizing the panel's evaluation of the stock assessment and addressing each peer review term of reference. Develop a list of tasks to be completed following the workshop. Complete and submit the report within 4 weeks of workshop conclusion.

1.3 List of Participants

Review Workshop Panelists

Mike Jones	Review Panel Chair	ASMFC Appointee
Carmen Fernandez	Reviewer	CIE
Anders Nielsen	Reviewer	CIE
John Simmonds	Reviewer	CIE

Analytical Representatives

Amy Schueller	Lead analyst	NMFS Beaufort
Genny Nesslage	Assessment Team	ASMFC
Jason McNamee	Assessment Team	ASMFC TC
Joe Smith	Assessment Team	NMFS Beaufort

Observers

Bob Beale	Executive Director	ASMFC
Louis Daniel	Chairman	ASMFC / NCDMF
Erik Williams	SEFSC	NMFS Beaufort

Council and Commission Staff

Julia Byrd	SEDAR Coordinator	SEDAR
Julie O'Dell	Admin.	SEDAR/SAFMC
Mike Waine	Menhaden Plan Coordinator	ASMFC
Shanna Madsen	Multispecies Coordinator	ASMFC
Pat Campfield	Science Program Director	ASMFC

Review Workshop Attendees

Nick Ballew, NMFS
Jud Crawford, Pew Trusts
Eric Fitzpatrick, NOAA
Aaron Kornbluth, Pew Trusts
Laura Lee, NCDMF
Ron Lukens, Omega Protein
Ray Mroch, NCDMF
Mike Prager, Prager Consulting
Kyle Shertzer, NOAA
Will Smith, NCDMF
Doug Vaughan

1.4 List of Background Documents and Review Workshop Working Papers

Atlantic menhaden review workshop document list.

Document #	Title
Assessment Report	
SEDAR40 – 1.1	Atlantic Menhaden Benchmark Stock Assessment (main body of report)
SEDAR40 – 1.2	Assessment Report Tables
SEDAR40 – 1.3	Assessment Report Figures

SEDAR40 – 1.4	Appendix A. 2014 MSVPA update report & appendices
SEDAR40 – 1.5	Appendix B. Atlantic menhaden tagging report
SEDAR40 – 1.6	Appendix C. Atlantic menhaden Beaufort Assessment Model (BAM) equations and code
SEDAR40 – 1.7	Appendix D. Projections methodology and example assuming constant landings
SEDAR40 – 1.8	Appendix E. Ecological Reference Points (ERP) report
Supplementary Materials	
SEDAR40 – 2	Fishery Dependent Indices
SEDAR40 - 3	Powerplant Impingement
SEDAR40 – 4	Fishery Independent Survey Standardization
SEDAR40 – 5	Fishery Independent Index Standardization Guidelines
SEDAR40 – 6	Atlantic Menhaden Stock Assessment Update – 2012
SEDAR40 – 7	Atlantic Menhaden Benchmark Stock Assessment and Review Panel Reports – 2010
SEDAR40 – 8	Hierarchical analysis of multiple noisy abundance indices. (P. Conn 2010)
SEDAR40 – 9	A proposed, tested, and applied adjustment to account for bias in growth parameter estimates due to selectivity (Schueller et al. 2013)

2. Review Panel Report

Executive Summary

The Atlantic menhaden assessment team (AT) provided a comprehensive set of reports, complemented by a series of presentations at the December 9-11 SEDAR 40 review workshop, which were reviewed and evaluated by a panel of four fishery experts, three from the Center for Independent Experts and a chair nominated by the Atlantic States Marine Fisheries Commission. The reports and presentations included thorough and extensive documentation of the stock assessment methods and results for Atlantic menhaden, a detailed explanation of how the assessment methods and data sources differed from previous assessments, sensitivity and uncertainty analyses of the stock assessment model, an evaluation of current reference points, a recommendation for new reference points, recommendations for future research and monitoring, and a discussion of options for future development of Ecological Reference Points to address the role of Atlantic menhaden as a forage species for other valued fish stocks as well as the object of commercial harvest. Overall the panel was very impressed with both the thoroughness and the clarity of the assessment reports and associated presentations. The panel commends the efforts of the AT.

The panel report addresses eight Terms of Reference (ToR), which were developed and shared with the panel prior to the December workshop. The ToR concerned (1) the data used in the assessment; (2) assessment methods; (3) treatment of uncertainty; (4) assessment results and conclusions; (5) any minority opinions; (6) recommendations for research; (7) improvements to data analysis or modeling approaches; and (8) Ecological Reference Points. The assessment utilized both fishery dependent and fishery independent data. The panel concluded that the data and assessment methods were generally appropriate and correctly used, with the only exception being the treatment of the length composition data from the fishery independent surveys. These data are used to inform estimates of selectivity for the fishery independent indices and examination of residuals indicated that predicted and observed length compositions for these indices did not match well. After testing several model options the panel recommended that the "Base Model" be modified slightly from the model presented by the AT to "down-weight" the length composition data in the model fitting procedure, to lessen the influence of these data on the overall model estimates. The AT was able to implement this change during the workshop, and demonstrate that the conclusions of the assessment – particularly regarding stock and exploitation status relative to reference points – were not affected by this change to the Base Model. There was also extensive discussion between the panel and the AT regarding the methods used to combine individual surveys into the three composite fishery independent indices. In the end the panel concluded that the methods used by the AT were appropriate.

The panel concluded that the AT had done a thorough and appropriate job of assessing model sensitivity and using Monte Carlo Bootstrap methods to propagate parameter and data uncertainty through to model output uncertainty. The panel suggested that future analyses consider, where possible, the covariance structure in the input parameters – ignoring this likely inflates the estimated magnitude of uncertainty. The panel also agreed with the conclusions of the AT regarding the status of the fishery relative to F- and Fecundity-based reference points (both the current and the recommended future reference points), even after the recommended change to the base model had been implemented. The proposed reference points were judged by the panel to be appropriate, but the panel did offer suggestions for possible modifications to the methods used to compute the reference points, including using an average F across multiple ages (instead of F at age 2), and possibly focusing on more recent time periods for the quantities (fishery and biological) used to estimate the reference points.

The panel reached consensus on all its recommendations and conclusions, so there is no minority report. The research, data collection, and assessment methodology recommendations of the AT were generally supported by the panel; the acquisition of age composition data for the fishery independent surveys, and completion of a Management Strategy Evaluation guided by an inclusive Structured Decision Making process were both strongly endorsed. The panel was less supportive of devoting substantial effort to the development of a comprehensive food web model for the Atlantic menhaden ecosystem. In addressing ToRs 1-4, and 8, the panel offered a number of suggestions for improvements to analytical methods, none of which were viewed as necessary to address critical flaws of the current assessment model but that might improve model performance and accuracy in the future. In addition to those already noted, these suggestions included considering strategies for coupling menhaden natural mortality with predator dynamics, to accommodate the likelihood that natural mortality varies substantially over time for this species, and considering estimating fishery and index selectivities as age-specific individual parameters, rather than assuming a functional form.

The panel urged the Atlantic Menhaden Technical Committee to continue development of Ecological Reference Points (ERPs), guided by input from decision makers and stakeholders about key potential management objectives (or measures that would be informative about the achievement of such objectives) that reflect a broad consideration of the role of this species in the Atlantic coastal ecosystem. The set of methods discussed in Appendix E of the Assessment Report were all viewed by the panel as having merit, but emphasis in developing ERPs should be on examining indices of predator and prey relative abundances informed by past experience with conditions deemed “acceptable” by different stakeholders, and “minimum sufficient complexity” models that couple Atlantic menhaden dynamics with those of their main predators. The panel briefly summarized two case studies of broadly similar circumstances – one from the Baltic Sea and a second from Lake Michigan – to illustrate how the challenge of developing ERPs has been confronted elsewhere. Finally, the panel stressed that, while the ultimate determination of quantitative ERPs for Atlantic menhaden requires a specific and comprehensive set of objectives, informed by consideration of trade-offs among potentially competing objectives, most of the technical work necessary to inform the development of ERPs can proceed with simply a general notion of what quantities (model outputs or ecological indicators) would be used by managers and stakeholders to evaluate these trade-offs.

2.1 Statements Addressing Each ToR

ToR 1. Evaluate the data used in the assessment.

a. Are data decisions made during the DW and AW justified (i.e. sound and robust)?

b. Are input data series reliable and sufficient to support the assessment approach and findings?

c. Are data applied properly within the assessment?

d. Are data uncertainties acknowledged, reported, and within normal or expected levels?

Two main sources of data are used for the menhaden assessment: commercial catch data (four fleets (reduction fishery north and south, bait fishery north and south) and fishery-independent survey composite indices (JAI representing age 0, and SAD and NAD representing ages 1+). Landings and age compositions are available for each of the four fisheries, index values are available for the three composite indices, and length compositions are available for the SAD and NAD composite indices. These data were explained in detail in presentations by the Assessment Team (AT).

The catch data is assembled in four fisheries based on area and type of fishery. The methods for assembling the data were well explained in the assessment report. The major fishery (which is the reduction fishery) is well sampled and the age composition data appears to be sufficient to allow allocation of catch to age and to obtain good estimates of selection in the assessment. The smaller bait fishery appears to be less well sampled but this is still sufficient as the contribution to historic catch is small. The need for more age samples in the bait fishery has been recognized and the AT are encouraged to improve data collection for this fishery. The importance of the bait fishery has increased in recent years and, while still smaller than the reduction fishery, its importance may grow in the future.

A very substantial part of the discussions that took place during the review concerned the assessment data, particularly the survey indices and their length compositions. A summary of the main points in the discussion follows:

The Panel requested information on the standardization procedures applied to the separate indices before they were combined into a composite index. A main aim of this request was to ensure that the variables used for standardizing the indices were factors that affected catchability and not abundance. The AT prepared a presentation explaining the Data Working Group decision tree in terms of the criteria used for potential inclusion of a survey and the standardization method applied to the survey index. The Data Working Group decision protocol emphasized that only variables that might affect catchability (not abundance) should be considered in the standardization. Graphs of all surveys used to form the JAI, SAD and NAD composite indices were presented before and after standardization; the changes due to standardization were, on the whole, not major. It was however noted that some changes to the NY Peconic Bay Trawl in the last 5 years, the VIMS Trawl Survey in the early 7 years, and the GA Trawl Survey throughout the time period seem to be substantial. Overall the Panel was satisfied that the survey selection protocol was sensible. It was noted that whereas between-index correlation evaluation was generally supportive, common variation among surveys is not a necessary condition for the inclusion of a dataset in the composite index.

The Panel also tried to get a better understanding of how Conn's procedure (Conn 2010 – see document SEDAR40-8) combines the separate surveys into a composite index and how this would compare to combining the surveys with weights based on their areal extent. The Panel wanted to know the weights that individual surveys had received in the composite JAI, SAD and NAD indices. The AT produced these values (as averages over time). SAD has two component surveys, which both received very similar weights. For NAD, the largest weight was on VIMS, and the spread of the weights between the component surveys was close to 10x. For JAI, there were differences between the weights of the component surveys, but not as big as in NAD (spread of the order of 4x). Some minor concern was noted regarding the spread of weights for the NAD surveys. A quick attempt was made to produce composite indices alternative to NAD and SAD, based on areal extent of the component surveys, but there was no time during the review meeting to do this with sufficient care and consequently it was not pursued further. There was some concern that the method quickly applied to create this area-based composite index during the review meeting had not correctly accounted for an early period with only one survey relative to a later period with several surveys.

As part of the sensitivity analysis presented in the assessment report, there was a run that used a replacement of the JAI index (based on Conn's method) with an area-weighted alternative using the same set of component surveys. This areal-based juvenile abundance index shows more annual spikes than the Conn method-based JAI index. The CVs assumed for this areal-based index (by year) were compared with the CVs of the JAI index (obtained from Conn's method) and observed to be substantially larger. Consistent with this, when this areal-based juvenile index was included in the assessment instead of JAI, the index had reduced influence on the assessment. This alternative index option was not recommended for the base run as the panel felt the method described by the AT, which relies on a published methodology, was equally if not more defensible than an areal-based method.

Overall the Panel concluded that the procedures used to produce the JAI, SAD and NAD composite indices were appropriate and thus that all three indices were acceptable for use in the assessment model.

The Panel also explored the length compositions (LFDs) used for the SAD and NAD composite indices. This was partly motivated by a misfit in the assessment results between the observed and model-predicted LFDs (Figures 7.1.16 and 7.1.17 in the assessment report document[1]). The AT additionally presented a plot of the LFDs of the seven separate indices that go into NAD (averaged over the years available for each of the indices), which indicated substantial heterogeneity between the LFDs of different component surveys. The AT also explained that the LFDs of the composite index had been formed by direct combination of the lengths observed in the component surveys without applying any type of weighting (either to the within-survey catches or across surveys according to the Conn's survey weights). The Panel requested exploration of several alternative model configurations in relation to these LFDs due to: (1) the less-than-ideal method for assembling the LFDs; (2) the observed heterogeneity in the length compositions among the component surveys; (3) the fact that they were assembled with equal weight per fish whereas the weights in the Conn's method were very different from uniform (for NAD); and (4) the misfit observed in the assessment model results to the length compositions of NAD and SAD (with the potential impact this can have on the assessment results, e.g. on the population abundance estimates). Following testing of several model options, the Panel recommended that the LFDs of NAD and SAD should be down-weighted in the stock assessment (relative to the weights selected in the base run proposed by the AT; more details can be found under ToR 2).

Therefore, the Panel reached the following conclusions regarding the questions in ToR 1:

a. Are data decisions made during the DW and AW justified (i.e. sound and robust)?

For the commercial data the Panel felt the decisions are justified (the Panel asked some questions, mainly for clarification, but agreed with the decisions made).

For the survey data, the Panel agreed overall, but had some concerns regarding the composite indices and, in particular, the length compositions of these indices.

b. Are input data series reliable and sufficient to support the assessment approach and findings?

The Panel considers that, taken as a whole, the data used in the assessment are reliable and sufficient to support the assessment approach and findings.

c. Are data applied properly within the assessment?

---

[1] Figure numbers referenced in this section (2.1) of the report refer to the figures from the Stock Assessment Report

For the reasons discussed above, the Panel recommended that the length frequency distributions of NAD and SAD be down-weighted in the stock assessment (relative to the weights selected in the base run proposed by the AT)

d. Are data uncertainties acknowledged, reported, and within normal or expected levels?
The Panel considers that this is the case.

ToR 2. Evaluate the methods used to assess the stock, taking into account available data.

a. Are methods scientifically sound and robust?

b. Are assessment models configured properly and used consistent with standard practices?

c. Are the methods appropriate for the available data?

d. If multiple models or model configurations were considered, evaluate the explanation of any differences in results and justification of a base model.

The stock assessment model used for Atlantic Menhaden is the Beaufort Assessment Model (BAM). BAM is a statistical catch-at-age model, which is a model type used for many statistical fish stock assessments worldwide. Other commonly applied statistical catch-at-age models are SCAA and SS3. BAM has previously been used in SEDAR assessments (e.g Spanish mackerel, Gulf Menhaden, and red grouper). The version of BAM was set up to match the data availability of Atlantic Menhaden. The assessment team clearly demonstrated that they were comfortable modifying both configuration and source code, and hence were not treating it as a `black box'. The BAM for Atlantic Menhaden was thoroughly documented both in mathematical terms and by sharing the source code (Stock Assessment Report – Appendix C), which allows for review at the most detailed level if desired. All of the above strengthens confidence that the model is scientifically sound, robust, and appropriate for the available data.

The predicted removals from the four fleets closely matched the observed (Figures 7.1.1-4), which is expected, as the model assumed a fixed low cv for error in total catch. The predicted commercial fishery age compositions captured all the main features in the observed age compositions (Figures 7.1.5-8). A minor indication of a shift in selectivity around the year 2003 is seen for the northern bait fleet (Figure 7.1.11). Predicted abundance indices for the three combined surveys (JAI, NAD, and SAD) were in agreement with the observed (Figures 7.1.13-15). The model was not able to predict the length compositions of the two adult combined surveys (Figures 7.1.16-17). The AT explained that they had intended to use the length composition data primarily to inform about the age-specific selectivity for the NAD and SAD indices. The different components of the likelihood were weighted generally following the suggestions of Francis (2011).

The AT chose to use an asymptotic selectivity for the NAD; all other fishery dependent and fishery independent data sources were assumed to have dome-shaped selectivity patterns. The panel concluded that this modeling strategy was justified, given the evidence presented for size/age composition differences among the different data sources (larger, older fish consistently represented in higher proportions in the NAD than the other data). The use of domed selectivity in the fisheries which are not spatially homogeneous is well supported by the cited references in the Assessment Report (e.g. Sampson and Scott 2011).

The overall conclusion of the panel was that BAM was configured properly and used consistently with standard practices. However, the panel was concerned about the mismatch between model predicted and observed length compositions. Examination of the input data raised concerns that the length compositions may not be well specified (see previous section re ToR 1), and the poor model fits to these data added to this concern.

This problematic mismatch between model predicted and observed length compositions was further investigated by the review panel and AT during the workshop. The panel's concern was that the misfit might be biasing other estimated quantities from the model (e.g. stock sizes). A sensitivity run was requested where the CV around the growth function was set to half of its estimated value in the base run, and the results showed that estimated stock sizes were influenced. To reduce the influence of the length composition data on the assessment model an additional model run was conducted in which the length composition data were down-weighted by a factor of 10. As well a run was conducted where the length composition data were completely removed and the estimated selectivity (from the base run, including the length data) were input as fixed values. Based on comparisons of estimated fecundity and recruitment time series, the panel concluded that these two options gave broadly similar results. A model run that attempted to estimate index selectivities (at age) without using any length composition data failed to converge. Down-weighting the length composition data by a factor of 20 was also attempted, but also resulted in failed convergence.

Based on the above, and extensive discussions held during the review meeting, together with the observation that down-weighting the length composition data by a factor of 10 resulted in a similar model fit to that obtained when no length composition data were included and index selectivities assumed known, the panel recommended a new base run be adopted for the assessment. The new base run would only differ from the base run presented by the AT in that the index length composition data is down-weighted by a factor of 10 from the weights used in the prior base run.

The assessment report states that a stock synthesis model was also configured for the stock, but results were not presented at the review meeting. The panel therefore has no recommendations to make with respect to this alternative model. As noted above, however, the panel concluded that the BAM was an appropriate assessment model for this stock.

ToR 3. Consider how uncertainties in the assessment, and their potential consequences, are addressed.

a. Comment on the degree to which methods used to evaluate uncertainty reflect and capture the significant sources of uncertainty in the population, data sources, and assessment methods.

b. Are the implications of uncertainty on technical conclusions are clearly stated?

The panel notes that the assessment team put a lot of effort into investigating uncertainties in the assessment. Minimum common practice would have been to supply uncertainties derived from the inverse Hessian matrix of the objective function at its minimum. This is a standard output from most model fitting software, but it would not have been valid here for two reasons. First of all many quantities of importance (e.g. natural mortality) are entered as known constants, even if knowledge about them is uncertain. Secondly assigning arbitrary weights to likelihood components and deviance variances also affects the Hessian derived uncertainties.

Instead the AT used a parametric Monte Carlo Bootstrap (MCB) method, where the data and some biological parameters (including natural mortality) were sampled using reasonable assumptions about input uncertainties. For each of 1000 complete re-sampled sets of inputs the model was re-estimated, which results in a simulated distribution of all estimated quantities. This approach correctly propagates the uncertainty through the nonlinear model equations to the quantities of interest.

Two minor concerns about the MCB sampling implementation details were raised during the review meeting: 1) The fixed assigned weights of the likelihood components were set in the model and were kept fixed and not part of the sampling; and 2) all quantities were sampled independently. The second of these concerns implies that, all else being equal, the overall model uncertainty may be considerably less than the MCB results would suggest. For instance the two parameters of a logistic function were each simulated uniformly from their 95% interval. If these model parameters are correlated, then sampling them independently will result in unlikely pairs (and hence unlikely logistic curves). The panel suggests that for future uncertainty analyses joint distributions of parameter uncertainty (i.e., variance-covariance matrices) be used whenever available.

In addition to the MCB method the AT prepared a wide range of sensitivity runs. These included: leaving out entire data sources, including ageing uncertainties, changing an index calculation method, different assumptions about natural mortality, different weighting of likelihood components, and different time varying assumptions. The assessment results were seen to be robust to most alternatives, and to react as expected to others (Figures 7.4.1.1-77). The results were most sensitive to changes in assumed natural mortalities (as is normally expected in stock assessment models) and omitting the NAD index (likely related to the fact that this is the only dataset in the model for which asymptotic selectivity is assumed).

Finally a retrospective analysis was presented, where the last 1, 2, 3, or 4 years of data were left out to demonstrate that the final years' estimates are not severely biased. For the estimates of fishing mortality no systematic retrospective bias is seen. For the recruitment estimates a negative bias is seen, and for biomass and fecundity a small positive bias, but these biases are modest and unlikely to affect the conclusions of the assessment.

The AT also presented results illustrating how uncertainty in the assessment model results might affect conclusions regarding stock status relative to reference points (Figures 7.4.1.50-77 – sensitivity runs; Figures 8.3.2.1-12 – MCB runs). The panel found these results informative and relevant to the assessment, and concluded that they lent support to the conclusions of the assessment. The AT also described an approach to incorporating uncertainty into short-term projections of changes to the stock conditional on a harvest strategy (Assessment Report, Appendix D). The panel acknowledged that this was an appropriate and useful approach to providing valuable advice to managers.

Overall the panel concluded that the methods used to evaluate uncertainty were appropriate and comprehensive, reflect and capture the significant sources of uncertainty in the population, data sources, and assessment methods, and that the implications of uncertainty on technical conclusions were clearly stated.

ToR 4. Evaluation of the assessment findings.

a. Are estimates of biomass, abundance, and exploitation rate reliable and consistent with input data and population biological characteristics? Are they useful to support inferences on stock status?

The review panel considers that the assessment provides reliable estimates of biomass, abundance and exploitation rates. A range of sensitivity analyses supports the view that the results are robust to a range of plausible alternative assumptions. A major sensitivity is in the estimated recruitment and biomass when uncertainty in M is considered. However, this sensitivity is to be expected and is comparable to other assessments

The panel paid particular attention to the sensitivity of the assessment to the newly derived fishery independent indices (NAD, SAD and JAI). The sensitivity analyses in the assessment report provide a good indication of the sensitivity of the assessment to inclusion or exclusion of each of these indices. The assessment showed some sensitivity to the NAD index (likely related to the fact that it is the only dataset with asymptotic selectivity in the model). It was noted that the base run proposed by the AT fitted rather poorly to the length composition data (as discussed earlier). It was concluded that the length compositions for these indices were not representative of the populations in the total area represented by these abundance indices (see ToR 1 for a discussion of the input data). Following exploration of a number of different configurations of the BAM model, it was concluded that running the model without including the length composition data was preferable (see ToR 2). However, problems were encountered with model convergence if all the length composition data was removed; therefore, an alternative parameterisation with down-weighted length compositions for the NAD and SAD indices was selected as an agreed baseline assessment. This change in configuration from the base run presented initially at the workshop did not change the conclusion on the state of the stock.

b. Is the stock overfished relative to biomass or abundance threshold reference points? Where is the stock relative to biomass or abundance management targets? What information supports this conclusion?

Based on the results of the recommended BAM assessment baseline run (ToR 2), the sensitivity runs, and the MCB-estimated uncertainty in the assessment (ToR 3), the review panel agreed with the AT's conclusion that the stock is not overfished relative to either the original biomass threshold reference point ($FEC_{15\%}$) or the revised biomass threshold reference point proposed by the AT ($FEC_{20\%}$). The stock is also estimated to be above (with more than 50% probability) the original target reference point ($FEC_{30\%}$) and the revised target point proposed by the AT ($FEC_{39\%}$[2]).

c. Is the stock undergoing overfishing relative to fishing mortality threshold reference points? Where is the stock relative to fishing mortality management targets? What information supports this conclusion?

Based on the results of the recommended BAM assessment baseline run (ToR 2), the sensitivity runs, and the MCB-estimated uncertainty in the assessment (ToR 3), the review panel agrees with the AT's conclusion that the stock is not undergoing overfishing relative to either the original fishing mortality threshold reference point ($F_{15\%}$) or the revised fishing mortality threshold reference point proposed by the AT ($F_{20\%}$). The stock is also estimated to be below (with more than 50% probability) the original target reference point ($F_{30\%}$) and the revised target point proposed by the AT ($F_{39\%}$).

d. Is there an informative stock recruitment relationship? Is the stock recruitment curve reliable and useful for evaluation of productivity and future stock conditions?

The AT stated that they tried to fit a Beverton-Holt stock-recruitment curve; however, the steepness parameter always ended up on a bound near 1.0. Given the interim reference points, the AT decided to fix the steepness value at 0.99, which allowed for the estimation of a median recruitment and annual deviations. A sensitivity analysis examined sensitivity of the state of the stock to shallower slope S-R relationships and concluded that the state of the stock was not influenced by this decision. The panel agrees with this conclusion. There is no clear indication of reduced recruitment at either low or high stock fecundity levels (across the observed historic range) and estimating an informative stock recruitment relationship does not seem to be possible

---

[2] The % indicated here (39%) differs from the value in the draft assessment report reviewed at the workshop (36%)because the reference points had to be re-calculated with the new base model recommended by the panel.

from the current assessment data. Given this, the modelling approach followed by the AT seems reasonable.

The use of S-R relationship will be particularly important in the context of conducting Management Strategy Evaluations (MSE), where simply assuming median recruitment with process error independent of biomass would not be a precautionary approach. Within an MSE, consideration might be given to the use of a hockey-stick S-R function with a breakpoint at or slightly above the lowest observed fecundity. While not biologically realistic in all aspects, such an approach has the advantage of assuming a conservative slope to the origin and no dependence of recruitment on fecundity at higher biomass.

e. Are the quantitative estimates of the threshold reference points reliable for this stock? If not, are there other indicators that may be used to inform managers about stock trends and conditions?

The Assessment Report states that 'the Technical Committee (TC) does not recommend that the current, interim SPR-based overfishing and overfished definitions continue to be used for management.'

The TC recommended that the Atlantic Menhaden Management Board adopt SPR reference points based on the maximum ***F*** value experienced at age-2 during the 1960-2012 time period as the threshold and the median ***F*** value experienced at age-2 during the 1960-2012 time period as the target, along with the associated FEC values.

The panel makes the following observations on the choice of single species reference points.

The use of an age-2 metric for the fishing mortality may not be a good choice. Although the assessment uses fixed selection for the recent period for each of the four fishing fleets, the distribution of catch among these fleets has changed in recent years and may be expected to change into the future. The bait fishery has increased and the reduction fishery declined in recent years. If the shift towards the bait fishery were to continue, this would result in further changes in selection across the combined fishery. Additionally, although the TAC allocations between States may be relatively fixed, different States fish different combinations at age, implying different partial Fs at age and variation in the distribution of F across ages and among years. The panel recommends using a mean F over ages 2-4, which would provide a more robust metric of fishing pressure under changing selectivity. The panel notes that application of the method proposed by the AT to derive the new reference points, but based on a mean F(ages 2-4) instead of F(age 2) will likely lead to %SPR values different from $F_{20\%}$ and $F_{39\%}$.

The AT recommended calculation of reference points based on the exploitation in the time period 1960 to 2012, average biological parameters for the period 1955-2013 and average fishery selectivity based on the last three years.

The panel supports the use of recent fishery selectivity for reference point calculation, based on the perception that a long-term trend in the selectivity of the fishery (when considering the total fishery on the stock, i.e. all fleets combined) is evident in the assessment output and the perception that these changes are unlikely to be reversed seems reasonable. The exact choice of period for selectivity (3 years or some other recent period) does not currently appear to be critical given the selectivity assumptions in this model (selectivity-at-age fairly constant since about 2006).

The panel also supports the use of long-term biological data to evaluate reference points and agrees with the removal of the few years at the start of the series. The use of the full time series appears to be an appropriate choice for limit (threshold) reference points. However, the panel notes that recruitment during the last 20 years has mostly been below average and the growth is currently different from that observed in the middle of the time series. When considering target reference points which are applicable for use in the near future it might be useful to at least check how the recent lower productivity might influence the biomass/fecundity- and exploitation-related target reference points.

The AT have proposed reference points based on historic exploitation levels (since 1960), rather than any other criteria. In the absence of any specific alternative agreed approaches for this stock, such as a Management Strategy Evaluation that defines and examines reference point performance relative to accepted management objectives and associated performance measures, the review group considers this is reasonable.

Some information on management goals is given in Amendment 2 to the Interstate Fisheries Management Plan for Atlantic Menhaden (2012), which states that the goal ‘is to manage the Atlantic menhaden fishery in a manner that is biologically, economically, socially and ecologically sound, while protecting the resource and those who benefit from it. When fully implemented, the Amendment is designed to minimize the chance of a population decline due to overfishing, reduce the risk of recruitment failure, reduce impacts to species which are ecologically dependent on Atlantic menhaden, and minimize adverse effects on participants in the fishery.’

In the context of these objectives, if fishing mortality is around the proposed target reference point it can be expected that the stock will remain above the lowest observed biomass of the historic series with high probability; this satisfies the requirement to ‘reduce the risk of recruitment failure’ due to depleted biomass. Fishing around the proposed target F would not be expected to lead to ‘overfishing’ with respect to the historic fishery. The other objectives are more difficult to define. The fishing mortality proposed as target is likely to maintain a stock that will give managers some flexibility for minimising ‘adverse effect on the participants in the fishery’, though it is unclear if an alternative MSY-based reference point would be more useful. Any F target based approach is expected to produce variable TACs between years, given the expected variability in recruitment. Assuming that the choice of M realistically accounts for the amount of predation menhaden undergoes, it could be argued that the proposed reference points (using this realistic M) should be sufficient to account for predators' needs; this would address the 'impacts to species which are ecologically dependent on Atlantic menhaden'. However, it is possible that the current or the resulting (at target reference point) menhaden abundance is not sufficient for unrestricted predator growth; if this is the case, the target F may need to be reduced if additional ecosystem services are identified. As well, should the biomass of predators change, consideration of different natural mortality rates may be needed. In this context, reference points for a forage species might be expected to change over time. For a discussion of other issues in setting reference points in a multispecies context see also the section on ecological-based reference points (ToR 8).

ToR 5. Minority report

No minority report has been filed.

ToR 6. Review the Technical Committee's recommendations on research, data collection, and assessment methodology and make any additional recommendations on prioritizations, if warranted.

The TC developed a set of "Research and Modeling Recommendations" that were categorized by time frame (short versus long term) and research type (data collection versus assessment methodology). The panel generally agreed with the TC's recommendations. There was strong agreement that developing a coast-wide fishery-independent index of abundance-at-age is the top priority for data collection. Related to this was a suggestion that collection of age composition data for the existing fishery independent surveys should also be a high priority. The AT noted that this was reflected in the existing recommendations under item 1 in the short-term data priorities: "work with industry and states to collect age structure data and biological data outside the range of the fishery". Given the challenges, discussed elsewhere in this report, of using index length-frequency data to inform index selectivity-at-age in the model, the panel concluded that having direct estimates of survey age composition would be a very valuable addition to the assessment data.

The panel also agreed that conducting a Management Strategy Evaluation to evaluate the performance of alternative harvest strategies and possibilities for reference points should be a high priority for the immediate future. Ideally the MSE should be informed by a structured Decision Analysis process (also listed as a research recommendation) that would both inform the MSE with respect to management objectives and options, and provide an opportunity for the MSE to be transparent for both stakeholders and decision makers.

The panel expressed some reservations about the recommendation to "develop an integrated length and age based model" and greater reservations about the recommendation to "develop a seasonal spatially-explicit model, once sufficient age-specific data on movement rates of menhaden are available". If the AT pursues the former, it may be more fruitful to adapt the BAM to integrate length and age than to use an alternative modeling platform, given the obvious expertise the AT has with the BAM. Regarding the latter, the panel cited previous experience with numerous challenges associated with developing spatial assessment models that explicitly incorporate movement, implying that the benefits (in terms of informing menhaden management) of pursuing this modeling strategy might not outweigh the costs (in terms of scientific effort).

The panel noted that two aspects of modeling are currently conducted in advance of the main BAM model:

1) Growth modeling.
2) Scaling of natural mortality based on tag data.

The panel suggests investigating the potential for including these aspects of the analysis as part of the assessment model. The model currently uses growth (length-at-age) as a basis for several aspects of the model. It may be possible to estimate selectivity-at-age using age data for the NAD and SAD survey indices, but if that is not the case and length composition data continue to be used in the assessment model, estimation of growth could be integrated in the assessment model.

If time-invariant mortalities are to be considered as part of future modeling, consideration should be given to estimating natural mortality in the assessment model, informed by the tagging data that are currently used externally. This would help to integrate the estimation process.

ToR 7. Provide guidance on key improvements in data or modeling approaches which should be considered when scheduling the next assessment.

The panel's recommendations on key improvements to data collection or modeling are included throughout this report, and particularly under ToR 6 and 8. A brief summary of the main recommendations is provided below:

- Improve data collection for the bait fishery, especially age composition information
- Consider changes to NAD and SAD indices to improve the assessment model by:
  - obtaining representative age composition data for the composite indices; or
  - developing more appropriate methods for deriving representative length compositions of the NAD and SAD composite indices; or
  - exploring model configurations that do not require the use of (age or length) composition data for the NAD and SAD indices.
  - evaluating the robustness of assessment results to alternative model configurations for the adult index data sources that may be considered plausible.
- Consider estimating (time-varying) growth within the assessment model (assuming length compositions remain in the model). However, this could substantially increase

model complexity. A relatively simple alternative may be to allow some flexibility (e.g. through a constrained prior distribution centered at the values estimated outside the assessment) in the growth parameters used in the fit to the length composition data.

- Consider modeling fleet and index selectivities using age-specific parameters (while assuming the same selectivity for a group of older ages) instead of pre-selecting functional forms (logistic or double-logistic in the current assessment).
- Consider accounting for co-variation among parameters and inputs in future uncertainty analyses of the assessment model.
- Use the mean F for ages 2-4, rather than F at age 2, to inform the calculation of reference points.
- Evaluate the sensitity of reference points to recent productivity trends.
- Reconsider models that allow M to vary over time. Given menhaden's role as a forage species, using a time-varying M (responding mainly to predator abundance changes) would seem appropriate.
- Continue exploring the development of multispecies models that can take predator-prey interactions into account. This should inform and be linked to the development of assessment models that allow M to vary over time.
- Conduct an in-depth evaluation of reference points using MSE, ideally informed by a Structured Decision Making process that engages managers and stakeholders.

ToR 8. Provide feedback on the proposed ecological reference points that account for Atlantic menhaden's role as a forage fish. Evaluate the appropriateness and feasibility of the proposed approach. Provide alternative suggestions, if necessary.

Appendix E of the Stock Assessment Report describes work completed by the Atlantic Menhaden Technical Committee (AMTC) to consider and evaluate options for development of Ecological Reference Points (ERPs) that might assist the Atlantic Menhaden Management Board with management of Atlantic menhaden in an ecosystem context. The appendix discusses both possible ERPs and broader analytical approaches (modeling) that are related to placing the management of Atlantic menhaden in the broad context of Ecosystem-Based Fisheries Management (EBFM). The AMTC considered a wide range of potential metrics and analytical methods that might inform the development of ERPs and potentially guide an approach for Atlantic menhaden EBFM, ranging from simple but relevant indicators of ecosystem status to complex multi trophic-level assessment and simulation models. The AMTC also stressed that the full development and adoption of ERPs requires articulation of more explicit objectives for menhaden management that reflect the "role" of this species in a broader food-web context. Here the panel provides comments on the various approaches presented in the appendix, and offers some general advice on moving forward with the development of ERPs for Atlantic menhaden.

First, the panel agrees that development of Ecological Reference Points should be a priority for Atlantic menhaden management. As a species both valued commercially in its own right, and as an important prey species for other valued predatory Atlantic coast fish species, Atlantic menhaden management should examine trade-offs among these two potentially, but not necessarily conflicting values for the species. As we discuss further below, assessing these trade-offs requires knowledge of the range of relevant management objectives, but progress towards development of ERPs does not require agreement on clear, unambiguous, quantitative management objectives in advance. Table 2 in Appendix E lists a range of potential management goals/objectives developed by the AMTC that are, in the opinion of the panel, adequate to guide development of ERPs. In particular, the panel believes that the objectives “Enough prey to support key predator species @ desired levels” and “sustainable AM commercial reduction and/or bait fisheries” effectively capture the primary trade-off that has motivated the discussion about developing ERPs. Ultimately, of course, specification of quantitative ERPs will either follow from, or imply, a more explicit characterization of the trade-offs among at least these two alternative management objectives, but the selection and development of preferred methods for defining ERPs does not require this specificity at the outset.

The Appendix first discusses a suite of ecosystem indicators related to environmental conditions experienced by menhaden that might help inform managers about changing conditions in the broader ecosystem. The panel agreed that monitoring such indicators would likely be informative, but did not see a strong connection between these indicators and triggers for management action – the usual motivation for reference points. Tracking these indicators will likely have value for some sort of EBFM “dashboard”, but they are expected to be less important to the development of ERPs for the Atlantic menhaden fishery itself.

The Appendix also listed two types of biological indicators as potential ecosystem indicators: abundance of forage species and predator-prey ratios. The panel viewed these two types of indicators as more directly relevant to the development of ERPs because they have the potential to be directly related to key management objectives. This would require either an empirical (based on previous experience with these quantities) or theoretical (based on trophodynamic principles) argument that particular levels of forage abundance or predator-prey ratios are associated with consequences germane to ERP targets or thresholds. As we note below, it would be desirable to explicitly couple the analysis of these biological indicators with models that aim to capture relevant predator-prey, or food web, dynamics. Nutritional indicators were also discussed, and likewise might be useful for ERP development if empirical relationships between nutritional status and demographic (e.g., survival, production) or economic (fish value) effects could be established.

The panel generally liked the suite of modeling approaches that focused on menhaden and predators that depend on them for forage, including both biomass dynamic and age-structured models. It will be desirable to explore a range of modeling strategies from simple surplus-production models to more complex age-structured models that include menhaden and their primary predators. A primary goal of this modeling strategy should be to determine the extent to which the dynamics of menhaden and their predators are connected. The Appendix did not present results showing evidence for a coupling of Atlantic menhaden dynamics with those of their predators – formally assessing the evidence for this is an essential step towards developing an objective rationale for ERPs that account for the trade-off between the two objectives mentioned above. Along similar lines, model development should consider whether important effects are likely to be only from predators on menhaden (in which case, the model may consider only menhaden dynamics and treat predator abundances as fixed inputs to the model), or whether menhaden abundance can also affect the abundance of its predators. In the latter case, a multi-species approach, jointly modeling the dynamics of both menhaden and menhaden's predators, will provide a more realistic representation of population dynamics and better opportunities to develop useful ERPs. If there is evidence that predator and prey dynamics are coupled, the panel recommends the development of such a multi-species model, possibly in parallel to simpler approaches that may provide interim solutions until the multi-species model is ready.

Regarding multi-species models, the panel is hesitant to encourage investment of considerable effort into developing models that include many species and particularly many trophic levels. The ideal approach is one of "minimum sufficient complexity" – perhaps a two trophic level predator-prey model constructed within an MSSCAA modeling framework. The panel was not enthusiastic about utilizing a "whole food web" model such as EwE or Atlantis, at least at the expense of developing models more specifically focused on Atlantic menhaden and their primary predators.

The panel agrees with the statement made by the AMTC in the conclusions to Appendix E that "AMTC cannot make a recommendation on **which ERP would be best to adopt** for Atlantic menhaden management until…a more explicit statement of ecological/ecosystem goals and objectives for menhaden management is provided by the Board" (our emphasis added). The selection of specific reference points requires agreement on the goal(s) of management, and on how trade-offs will be evaluated where there exist contradictory goals. However, much of the critical technical work to support the development of ERPs relevant to the management of Atlantic menhaden can proceed without formal agreement on a specific set of management objectives. The analysts need to know what performance measures (indicators) managers are likely to consider as they evaluate the success of a policy option – this is necessary to frame the analysis so that models are capable of forecasting policy outcomes that are informative about these performance measures. Having been informed of an inclusive set of performance measures, the analysts could proceed with an MSE-style harvest policy analysis, using an appropriate multi-species model to determine the nature of trade-offs among potentially conflicting objectives as different management strategies (harvest policies) are tried. Ideally this MSE work would be informed at the start by a process of engagement between managers, stakeholders, and analysts, such as a Structured Decision Making workshop whose purpose would be to reach agreement upon goals, harvest policy options, and performance measures.

To provide further guidance on the development of ERPs, we include brief descriptions of two case studies where fishery managers and analysts have faced similar challenges. There is also an ICES working group on multispecies assessment methods (WGSAM) that meets annually and whose work may be of interest. The group can be found online at http://www.ices.dk/community/groups/Pages/WGSAM.aspx.

1. Baltic sea cod-herring-sprat

Multispecies models will not provide direct estimates of reference points; they will however, give indications of trade-offs between predator abundance and menhaden natural mortality. The information can be used to provide a framework to discuss the trade-off between forage fish exploitation and the exploitation / abundance of their predators. An illustration of such trade-offs for managers is given in a multispecies management plan evaluation for the Baltic Sea (STECF 2012). The study is based on a basin-scale, single-area multispecies model, which is parameterised for only a small range of species, herring and sprat as the forage fish and cod as the main predator. The current issues and the main interdependencies are well described in Casini et al. (2010) and Casini (2011). The fisheries, which are dominated by cod, are described in Bastardie et al. (2010a and 2010b). The management of the five main pelagic stocks, four herring stocks and one sprat stock, which form the forage fish in this area, was previously evaluated in 2009 (ICES 2009). There was also some knowledge of environmental drivers and response to climate change in the Baltic (Mollman et al 2009 and MacKenzie et al 2007). All of this work was brought together under the STECF study (STECF 2012), which also involved stakeholder and managers. The results provided managers with evidence of the sensitivity of the predators on the abundance of forage fish. This could potentially be used as a framework to consider suitable multispecies target and limit reference points for the forage fish. The difficulty that was encountered with this relatively simple model was that the predation data was quite good for cod predation on sprat and herring, but sparse to characterise cannibalism of cod except at basin scale, yet this was critical for understanding the dynamics at higher cod biomass. Potential interactions such as cod-egg mortality or density-dependent growth of the forage fish were not explicitly included in the model. Both these effects might be expected to change the trade-offs and understanding of the implications of higher and lower exploitation rates. Currently in the Baltic cod are found to be growing slowly (ICES 2014), more slowly than any of the model predictions. There is some debate regarding the causes of this, the two main competing hypotheses are shortage of food, or parasite load. The first of these is not explained at basin scale as sprat and herring are relatively abundant, but the effect might be dominated by local scale distributional changes, as the result of reduced area overlap and local depletion. Cod are currently occupying only part of the area of the Baltic Sea they previously occupied and the abundance of sprat and herring in this area is low. For the parasites, this may be either causal or the effect of poor condition: parasites inducing poor growth, or poor growth resulting in greater vulnerability to parasites; the abundance of the parasites is linked to increases in seal populations in the Baltic. Thus this study gives some guidance regarding the type of information used to develop a multispecies management plan, both of a scientific nature and information for stakeholder involvement. However, the study does not provide direct ideas for reference points. Rather it illustrates the difficulties that can be encountered and gives simple ideas of the trade-offs that are considered in this ‘simple’ case.

References

Bastardie, F., Nielsen, J. R., and Kraus, G. 2010a. The eastern Baltic cod fishery: a fleet-based management strategy evaluation framework to assess the cod recovery plan of 2008. – ICES Journal of Marine Science, 67: 71–86.

Bastardie, F., Vinther, M., Nielsen, J. R., Ulrich, C. and Storr Paulsen, M. 2010b. Stock-based vs. fleet-based evaluation of the multi-annual management plan for the cod stocks in the Baltic Sea, Fisheries Research, 101: 188–202.

Casini M., Bartolino, V., Molinero, J.C. and Kornilovs, G. (2010). Linking fisheries, trophic interactions and climate: threshold dynamics drive herring Clupea harengus growth in the central Baltic Sea. Marine Ecology Progress Series, 413:241-252.

Casini, M., Kornilovs, G., Cardinale, M., Möllmann, M ., Grygiel, W., Jonsson, P., Raid, T., Flinkman, J. and Feldman, V. (2011). Spatial and temporal density-dependence regulates the condition of central Baltic Sea clupeids: compelling evidence using an extensive international acoustic survey. Population Ecology, 53:511-523.

ICES 2009. Report of the Workshop on Multi-annual mana gement of Pelagic Fish Stocks in the Baltic. 23-27 February 2009, ICES Headquarters, Copenhagen. ICES CM 2009/ACOM:38

ICES 2014 Report of the Baltic Fisheries Assessment Working Group. 12-19 April 2014, ICES Headquarters, Copenhagen. ICES CM 2011/ACOM:10

Mackenzie, B.R., Gislason, H., Möllmann, C. and Köster, F.W. 2007. Impact of 21st century climate change on the Baltic Sea fish community and fisheries. Global Change Biology,13:7, pp 1348–1367.

Möllmann, C., Muller-Karulis, B., Kornilovs, G., and St John, M. A. (2008). Effects of climate and overfishing on zooplankton dynamics and ecosystem structure: regime shifts, trophic cascade, and feedback loops in a simple ecosystem. ICES Journal of Marine Sciences, 65: 302–310.

STECF 2012. Scientific, Technical and Economic Committee for Fisheries. Multispecies management plans for the Baltic (STECF-12-06). EUR – Scientific and Technical Research series – ISSN 1831-9424 (online), ISSN 1018-5593 (print) ISBN 978-92-79-24799-6 doi:10.2788/25697

Vinther, M and Lewy, P., 2012. SMS, a stochastic age-length structures multispecies models applied to North Sea and Baltic Sea stock. Working document to ICES WKMULTBAL, March 2012

2. Lake Michigan salmon-alewife

Recreational fisheries in Lake Michigan depend heavily on stocking of Pacific salmon, particularly Chinook salmon. Pacific salmon stocking began in earnest in the 1960s and continues to the present, although today 50% of Chinook salmon harvested in Lake Michigan are naturally produced. The salmon and trout in Lake Michigan rely very heavily on alewife – an exotic species in the Great Lakes – for their forage. In the late 1980s an epizootic of Bacterial Kidney Disease in Lake Michigan led to sharp declines in Chinook salmon production, believed in part to be due to nutritional stress brought on by low alewife abundance. Since that time Lake Michigan fishery managers have paid very close attention to stocking rates and alewife abundance, and have reduced stocking rates on three occasions, based largely on evidence from stock assessments (Tsehaye et al. 2014a, b) and Decision Analysis models (Jones et al. 2008).

Until recently, Lake Michigan managers also relied on a collection of fishery performance measures, known as "Red Flags" as a form of reference points intended to guide decision making (Clark 2012). The Red Flags serves as broad and variously redundant indicators of whether the balance between salmon predators and their alewife prey showed signs of stress; however, the linkage between quantitative levels of a particular Red Flag indicator and the estimated risk of predator-prey imbalance was not defined, making it difficult for managers to use the Red Flags objectively to inform decisions about salmon stocking.

In 2013 the Quantitative Fisheries Center was funded to lead a series of workshops and analytical tasks to develop a new Red Flags analysis that addressed the deficiencies identified by Clark (2012) and alluded to above. The result was the development of a new index – a Predator-Prey ratio – that quantifies the current assessed abundance of Chinook salmon relative to the current assessed abundance of alewife. Estimation of the ratio depends on the outputs of stock assessments for Chinook salmon (Tsehaye et al. 2014a) and alewife (Tsehaye et al. 2014b). A retrospective examination of the ratio for prior years on Lake Michigan, and for a similar lake (Huron) where a predator-prey imbalance has led to a persistent suppression of alewife abundance, allowed the development of target and limit reference points for the Predator-Prey ratio, designed to avoid undesirably high risks of predator-prey imbalance in Lake Michigan. The details of this analysis and its application for management of the Lake Michigan salmon fishery can be accessed in Jones et al. (2014).

References:

Clark, R. D., Jr. 2012. Review of Lake Michigan Red Flags Analysis. Quantitative Fisheries Center Technical Report 2012-01, Michigan State University, East Lansing, MI.

Jones, M. L., J. R. Bence, E. B. Szalai, and Wenjing Dai. 2008. Assessing stocking policies for Lake Michigan salmonine fisheries using decision analysis. *In*: D. F. Clapp and W. Horns editors. The State of Lake Michigan in 2005. Great Lakes Fishery Commission Special Publication 08-02. pp 81-88.

Jones, M.L., R.D. Clark, and I.W. Tsehaye. 2014. Workshops to revise and improve the Lake Michigan Red Flags analysis. Great Lakes Fishery Commission Project Completion Report. May 2014.

Tsehaye, I., M. L. Jones, T. O. Brenden, J. R. Bence, and R. M. Claramunt. 2014a. Changes in the Salmonine community of Lake Michigan and their implications for predator–prey balance. Transactions of the American Fisheries Society 143:420-437.

Tsehaye, I., M. L. Jones, J. R. Bence, T. O. Brenden, C. P. Madenjian, and D. M. Warner. 2014b. 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 71:1-18.

In conclusion, the panel strongly encourages the AMTC and the Management Board to initiate a formal dialog, ideally inclusive of key stakeholder groups, to inform the development of Ecological Reference Points. The goals of this initial dialog would be to define metrics that managers might use to gauge management performance relative to objectives, to identify a suite of analytical (modeling) tasks to inform development of ERPs, and – perhaps most important – to develop a common perspective among scientists, managers, and stakeholders about the strategy for defining reference points that reflect a broader ecological perspective on the Atlantic menhaden fishery. The AMTC has done a thorough job of investigating and summarizing the options. Now it is time for managers and stakeholders to guide the way forward.

2.2 Summary Results of Analytical Requests

The panel made a number of requests for additional model runs or sensitivity tests during the workshop. The requests are summarized below, along with brief comments on their outcomes, where relevant. The AT was able to fulfill all of these requests during the workshop and the results aided the panel in reaching the conclusions summarized in this report. See the discussions of ToR 1, 2, and 4, above, for further details. The majority of the requests were intended to aid interpretation of the survey indices and their influence on model fits. These evaluations resulted in a new recommended base model – see ToR 2.

1. Mismatch of LFDs in surveys: must come from length at age assumptions: a run was conducted fixing the CV at ½ of estimated CV value in base run.

2. Remove LFDs completely and fixed the survey selectivities-at-age at the values estimated in the base run (run converged fine, results somewhat different from base run).

3. Settings as in base run, except for LFDs (of surveys) sample sizes, which were downweighted. Variance was divided by 10.

4. A run was conducted following from request 3, where LFDs were removed completely and it was attempted to estimate the survey selectivities. The run did not converge.

5. A run was conducted following from requests 3 and 4, where variance of LFDs was divided by 20. The run did not converge.

6. There was an extra run where all the selectivities (surveys and commercial catch) were treated as free parameters (instead of assuming a functional form). The run converged but selectivities looked “strange” at older ages (i.e. not dome-shaped or asymptotic).

7. Plot residuals in log-scale and standardised (for log-Normal distributions for survey indices).

8. CV values of the areal-based JAI index (they turned out to be considerably larger than those for the Conn's JAI index, so that areal-based index with those CVs probably did not influence the fit much).

9. Information on standardisation procedures for the indices used in the assessment, and information on the standardisation conducted for each separate state index. For each index, the AT showed the raw index (before standardisation) and the resulting standardised index. They also gave an explanation of how the standardisation had been done (variables used, protocol...).

10. Plot of LFDs of the separate state indices that go into NAD. Each index LFD had been aggregated over the years available for that index. VIMS and CT were at the 2 extremes (the panel thinks lengths < 15 cm were removed from the VIMS survey to make up the NAD).

11. Information on how the Conn's method combined the separate state indices into a composite one. The AT calculated average weights (resulting from Conn's) over time for the components going into the NAD, SAD and JAI indices. For SAD, the 2 weights were very similar. For NAD, the largest weight was on VIMS (the spread close to a factor 10). For JAI, there were differences but less big than in NAD (the spread of the order of a factor of 4).

12. Areal weighting adult indices. A graph was produced, but the resulting NAD index looked strange, with a totally unexpected breakpoint after 9 years when more than 1 index gets into the mix. This was not pursued further.