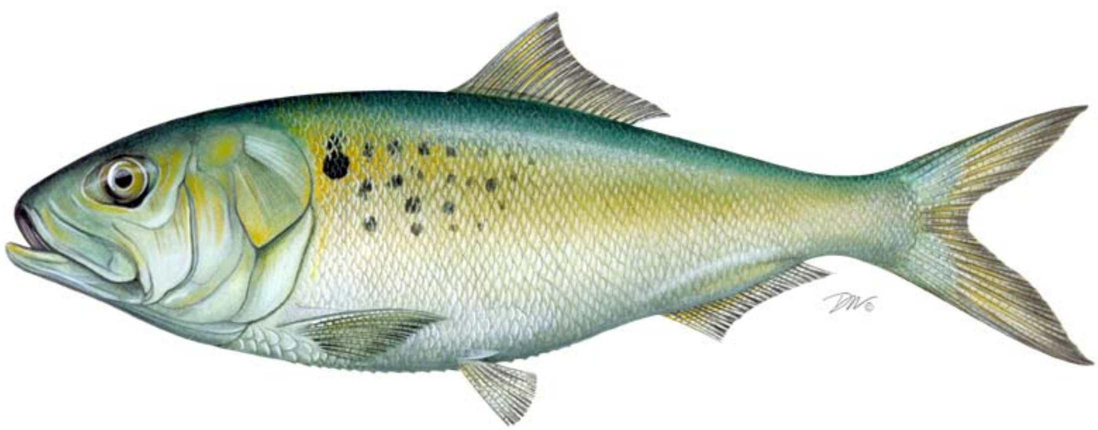
Stock Assesement Report No. 10-02
of the

Atlantic States Marine Fisheries Commission

Atlantic Menhaden Stock Assessment and Review Panel Reports



May 2010

Working towards healthy, self-sustaining populations for all Atlantic coast fish species or successful restoration well in progress by the year 2015

Preface

The development and peer review of the 2010 Atlantic Menhaden Stock Assessment occurred through a joint Atlantic States Marine Fisheries Commission (ASMFC) and Southeast Data, Assessment, and Review (SEDAR) process. ASMFC organized and held a Data Workshop May 12–13, 2009 in Richmond, Virginia and an Assessment Workshop October 19-22, 2009 in Beaufort, North Carolina. SEDAR coordinated a Review Workshop from March 8-12, 2010 in Charleston, South Carolina. Participants included members of the Atlantic Menhaden Stock Assessment Subcommittee, and a Review Panel consisting of a chair, a reviewer appointed by ASMFC, and three reviewers appointed by the Center for Independent Experts.

This document contains the following reports:

Section A – Executive Summary (Pages 1 – 4)
This section provides a summary of major findings and recommendations from the Stock Assessment and Review Panel Reports.

Section B – 2010 Stock Assessment Report Submitted for Peer Review (Pages 5 – 307)
This report outlines the background information, data used, model calibration and results for the assessment submitted to the Review Panel.

Section C – Consensus Review Panel Report for the 2010 Stock Assessment (Pages 308 – 325)
This report, provided by the Review Panel Chair, provides the consensus opinions of the Review Panel on the final stock assessment for peer review. The report includes the Review Panel's summary findings, detailed discussion of each Term of Reference, and a summary of the results of analytical requests made at the Review Workshop.

Section A – Executive Summary

Status of Stock
The Panel supports the recommendation of the Assessment Team that the stock status determination is “not overfished” and there is “no overfishing”, relative to the current reference points. Further, the Panel also agrees with the Assessment Team that the uncertainties in the assessment are such that there could have been overfishing in 2008 (removal of the JAI from the base model gave that determination and many bootstrap runs also fell in the overfishing zone).

The Panel also notes that a strictly valid determination of the overfishing status requires comparison of full Fs and not number-weighted Fs. This is not a well-known result, but it is obvious once the problem is identified.

Stock Identification and Distribution
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 from Maine to Florida. The highest concentrations of this resource are regularly seen from Massachusetts to North Carolina.

Management Unit
The management unit for Atlantic menhaden (*Brevoortia tyrannus*) is defined in Amendment 1 as throughout the range of the species within U.S. waters of the northwest Atlantic Ocean from the estuaries eastward to the offshore boundary of the EEZ. The unit is coastwide from Maine to Florida.

Landings
The reduction fishery landings and biological sampling information have been collected since the 1950s in a consistent manner and represent one of the longest and most complete fisheries information series in the United States. Daily logbooks (Captains Daily Fishing Reports) have been collected since 1985, and detail purse-seine set locations and estimated catch.

As reduction landings have declined in recent years, menhaden landings for bait have become relatively more important to the coastwide total landings of menhaden. Commercial landings of menhaden for bait occur in almost every Atlantic coast state and have been reported since 1985.

Data and Assessment
The Atlantic Menhaden Stock Assessment Subcommittee used commercial and recreational landings at age from Florida to Maine, a fishery dependent adult index developed from Potomac River Fisheries Commission (PRFC) pound net survey, and a juvenile index (JAI) developed from coastwide beach seine information. In addition, growth, weight, and maturity at age were developed using fishery dependent and independent information, while age and time variant natural mortality was estimated using a multi-species virtual population analysis (MSVPA-X).

The Beaufort Assessment Model (BAM) was the only model used to produce final assessment results. This is a statistical forward-projection model with separable selectivities using the Baranov catch equation. The Panel identified several strengths and potential weaknesses in the base model. The Panel formulated an alternative BAM run which addressed the main problems identified with the base run. Given the other uncertainties, the differences in the assessment results between the two models are relatively minor

Biological Reference Points

Addendum I established the biological reference points used currently: F_{TARGET} = 0.75, $F_{THRESHOLD}$= 1.18, fecundity target (trillions) = 26.6, and fecundity threshold (trillions) 13.3. The results indicate that the fecundity estimates for the terminal year are well above the threshold (limit), with not a single bootstrap estimate falling below 1.0. The results for the terminal year fishing mortality rate suggest that the base run estimate is just below the F_{MED} threshold (limit) with 36.8% of the bootstrap runs exceeding the F_{MED} threshold.

The use of F_{MED} based reference points is of concern. It appears that the stock has been at low levels of population fecundity for many years and yet the current reference points (and the F_{MED} reference points of previous years) provide a determination of "not overfishing" and "not overfished". The Panel recommends that alternative reference points be considered and chosen on the basis of providing better protection for SSB or population fecundity relative to the unfished level.

Fishing Mortality

When the fishing mortality rate (F) exceeds the F-limit, then overfishing is occurring; the rate of removal of fish by the fishery exceeds the ability of the stock to replenish itself. The Panel was concerned that the 2008 F estimate was very close to the threshold. If uncertainty in the estimate was considered there is a significant probability that overfishing occurred in 2008.

Recruitment

Recruitment was generally poor during the 1960s, with values below the 25^{th} percentile (20.5 billion) for the recruitment time series. High recruitment occurred during the late 1970s and early 1980s to levels above the 75^{th} percentile (59.6 billion). These values are comparable to the late 1950s (with the exception of the extraordinary 1958 year-class). Generally low recruitment has occurred since the early 1990s. There is a hint of a potential long-term cycle from this historical pattern of recruitment, but not enough data are present to draw any conclusions regarding the underlying cause at this point.

There is no evidence for a relationship in the model estimates of fecundity and recruitment. However, recruitment is quite variable and there could be a stock-recruit relationship which is not discernable for this reason.

Environmental factors that affect recruitment are generally viewed as density independent. These factors include physical processes, for example transport mechanisms, water temperature, DO, freshwater inflow and nutrient loadings. Biological factors, such as amount of food and competition for food, or predation by higher trophic levels which control survival and growth of young-of-the-year menhaden prior to recruitment to the fishery, can be either density independent or density dependent.

Fecundity

Population fecundity (FEC, number of maturing ova) was high in the late 1950s and early 1960s, low in the late 1960s, and generally increasing since then. The Panel was concerned about the use of F_{med} and the fecundity associated with it as reference points. The concern is that there is no information on the relationship of the target and threshold fecundity in relation to virgin fecundity levels. Projections were run to examine this, and the estimated annual fecundity since 1998 was only 5 to 10% of the virgin fecundity.

Bycatch

Discard or bycatch information in the bait and reduction fisheries is undocumented. However, it is suspected that bycatch and discards of menhaden are trivial compared to total landings.

Section B - 2010 Stock Assessment Report Submitted for Peer Review

Atlantic States Marine Fisheries Commission

2010 Atlantic Menhaden Stock Assessment for Peer Review

Submitted to the Atlantic Menhaden Management Board on February 2010

Prepared by the
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Stock Assessment Summary

The Atlantic States Marine Fisheries Commission (ASMFC) convened a stock assessment workshop (AW) at the NOAA Center for Coastal Fisheries and Habitat Research, Beaufort, North Carolina, on Monday, October 19, 2009. The workshop's objective was to conduct a new benchmark assessment of the Atlantic menhaden (*Brevoortia tyrannus*) stock along the U.S. Atlantic coast. Members of the ASMFC Technical Committee's Stock Assessment Subcommittee participated in this assessment (including state, commission, federal and university scientists), as well as several observers (Appendix A). The AW convened at Beaufort through October 22, 2009. All decisions regarding stock assessment methods and acceptable data were made by consensus.

Available data on the species were evaluated during a Data Workshop (May 12–13, 2009) in Richmond, Virginia. These data were subsequently finalized for inclusion in the assessment model(s). Data included abundance indices, recorded landings, and samples of annual size and age compositions from the landings. Juvenile abundance seine indices from seven states were developed (two more than in the last peer reviewed assessment in 2003). The pound net index from the PRFC was improved to reflect a better unit of fishing effort. Landings and catch-in-numbers-at-age data were updated from the reduction and bait fisheries, and reconstructed historically back to 1873 for use in an alternate model configuration. A matrix of natural mortality at age was obtained from a recent update of the peer-reviewed MSVPA-X model (SARC 2005), allowing for age- and year-varying estimates of *M*.

During the assessment workshop, alternate assessment models were considered as potential base models. The statistical catch at age model developed at Beaufort was selected as the base assessment model. A base assessment model run was developed and sensitivity model runs were made to evaluate performance of the assessment model to different assumptions regarding input data and stock dynamics.

Benchmarks for stock status were based on Addendum 1 to Amendment 1. F_{MED} (= F_{REP}) provides the reference value for judging overfishing (F-limit). The population fecundity (FEC_{TARGET}) corresponding to F_{MED} provides the proxy for B_{MSY}. FEC_{LIMIT} is one-half of FEC_{target}. A discussion of alternative benchmarks is provided in Section 8.2, including a discussion of the F_{MSY} concept, equilibrium yield-per-recruit and spawner-per-recruit reference points, and environmental variability. This latter issue resulted in some debate on poor recruitment during last the two decades and implication for benchmarks.

Given the currently accepted benchmarks, status of stock was determined based on the terminal year (2008) estimate relative to its corresponding limit. Benchmarks have been estimated based on the results of the base run. The terminal year fishing mortality rate (*weighted by number average for ages 2+*) was estimated to be 0.93 year-1, which is 92% of its limit (and 195% of its target). Correspondingly, the terminal year estimate of population fecundity was estimated at 95% of its fecundity target (and 190% of its limit). Hence, the stock is not considered to be overfished, nor was overfishing occurring in 2008. However, annual variability and uncertainty in the F estimates and proximity of the terminal year estimates to its F_{LIMIT} raise concerns about frequent overfishing in the past and potential overfishing in 2008. In addition, other indicators of stock status, such as trends in recruitment and fishing mortality on fully recruited ages, raise concerns about the appropriateness of the current reference points for Atlantic menhaden.

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Terms of Reference

1. Evaluate precision and accuracy of fishery-dependent and fishery-independent data used in the assessment:
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    b. Report metrics of precision for data inputs and use them to inform the model as appropriate.
    c. Describe and justify index standardization methods.
    d. Justify weighting or elimination of available data sources.
2. Evaluate models used to estimate population parameters (e.g., F, biomass, abundance) and biological reference points.
    a. Did the model have difficulty finding a stable solution?
    b. Were sensitivity analyses for starting parameter values, priors, etc. and other model diagnostics performed?
    c. Have the model strengths and limitations been clearly and thoroughly explained?
    d. Have the models been used in other peer reviewed assessments? If not, has new model code been verified with simulated data?
    e. Compare and discuss differences among alternative models.
3. Evaluate the potential for conducting assessments at a sub-regional level (e.g. Chesapeake Bay).
4. State and evaluate assumptions made for all models and explain the likely effects of assumption violations on model outputs, including:
    a. Calculation of M.
    b. Choice to incorporate constant or time-varying M and catchability.
    c. Choice of selectivity patterns.
    d. Choice of time steps in models.
    e. Error in the catch-at-age matrix.
    f. Choice of a plus group for age-structured species.
    g. Constant ecosystem (abiotic and trophic) conditions.
    h. Choice of stock-recruitment function.
    i. Choice of reference points (e.g. equilibrium assumptions).
5. Evaluate uncertainty of model estimates and biological or empirical reference points.
    a. Choice of weighting likelihood components.
6. Perform retrospective analyses, assess magnitude and direction of retrospective patterns detected, and discuss implications of any observed retrospective pattern for uncertainty in population parameters (e.g., F, SSB), reference points, and/or management measures.
7. Recommend stock status as related to reference points.
8. Develop detailed short and long-term prioritized lists of recommendations for future research, data collection, and assessment methodology. Highlight improvements to be made by next benchmark review.

1.0 Introduction

1.1 Brief Overview and History of Fisheries

The Reduction Purse-Seine Fishery. Some fishing for Atlantic menhaden has occurred since colonial times, but the use of purse-seine gear began in New England by the mid-1800s (Ahrenholz et al. 1987b). 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. At the time, over 20 menhaden factories ranged from northern Florida to southern Maine (ASMFC 2004a). 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, primarily because of a series of above average year classes entering the fishery. 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. In 1987, a reduction plant in New Brunswick, Canada, processed menhaden harvested in southern Maine, but transported by steamer 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.

During the 1990s the Atlantic menhaden stock contracted again (as in the 1960s) mostly due to a series of poor to average year classes. Fish became scarce again north of Long Island Sound. The Russian-Maine IWP and the Canadian plants last processed menhaden during summer 1993. After 1993, only three factories remained in the reduction fishery, two factories in Reedville, VA, and one factory in Beaufort, NC. Virginia vessels (about 18-20) ranged north to New Jersey and south to about Cape Hatteras, NC, while the North Carolina vessels (generally two) fished mostly in North Carolina waters.

A major change in the industry took place 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 3 more vessels were removed prior to the 2000 fishing year, reducing the Virginia fleet to generally 10 vessels from 2000 through 2008. Another major event within the industry occurred in spring of 2005 when the fish factory at Beaufort, NC, closed and the owners sold the property to coastal developers.

Since 2005 there has been only one operational reduction factory for processing Atlantic menhaden on the Atlantic coast of the US. This plant is owned by Omega Protein Inc., and is located at Reedville, VA. The Omega Protein plant has a fleet of ten purse-seine vessels, which range in length from about 160 to 200 ft and in gross tonnage from about 500 to 600 tons. Fully loaded, these vessels on average carry about 500 tons of menhaden. Most of the catch and fishing effort by the Reedville fleet is in the Virginia portion of Chesapeake Bay and adjacent ocean waters. However, in summer and early fall the Virginia vessels may move north into Maryland, Delaware, and New Jersey ocean waters in search of fish. Regulations in these states prohibit harvest for reduction purposes in state waters, so the fishery is limited to the U.S. EEZ. In fall, the fleet may travel farther south and harvest migratory menhaden schools along the North Carolina Outer Banks. In 2008, landings of Atlantic menhaden for reduction at Reedville amounted to 141,133 metric tons. In recent years (2005-08) landings at Reedville have averaged 154,980 metric tons. The reduction process for menhaden yields three main processed products: fish meal, fish oil, and fish solubles.

The Bait Purse-Seine Fishery. As reduction landings have declined in recent years, menhaden landings for bait have become relatively more important to the coastwide total landings of menhaden. Commercial landings of menhaden for bait occur in almost every Atlantic coast state. Recreational fishermen also catch Atlantic menhaden as bait for various game fish. A majority of the menhaden-for-bait landings are used commercially as bait for crab pots, lobster pots, and hook-and-line fisheries.

The bait fishery utilizes a wide variety of gear and fishing techniques. Landings come from both directed menhaden fisheries, which make up the majority of the bait landings, and from non-directed, by-catch fisheries. Total landings of menhaden for bait along the US East coast have been relatively stable in recent years, averaging about 37,100 metric tons during 2001-2008, with peak landings of about 46,700 metric tons in 2008. In 2001, total Atlantic menhaden bait landings comprised 13% of total Atlantic menhaden landings (270,000 metric tons) increasing to 25% of total landings (187,800 metric tons) in 2008. Regional landings of menhaden for bait are dominated by harvests in Chesapeake Bay and New Jersey. Menhaden for bait landings in Maryland, Virginia, and the Potomac River combined amounted to about 21,200 mt in 2008, or 45% of the total menhaden-for-bait landings on the U.S. Atlantic coast, while New Jersey contributed nearly 37% of coastwide landings, primarily from purse-seine gear.

Bait landings of menhaden in Virginia are dominated by purse-seine gear called ‘snapper rigs’, whose nets are somewhat smaller than the gear employed by the larger reduction vessels. ‘Snapper rig’ vessels are also smaller (about 100 ft long) than reduction ‘steamers’, and make fewer sets of the net each fishing day. In recent years, three ‘snapper rig’ vessels have operated from Northern Neck, VA, near Reedville. “Snapper rig’ vessels supply daily logbooks to the NMFS at Beaufort, from which their daily and annual catches are tabulated. A NMFS port agent also samples ‘snapper rig’ landings for age and size composition. Bait landings of menhaden in Maryland and the Potomac River are dominated by pound net catches. Purse seine and pound net bait fisheries for menhaden in New England occur intermittently and depend on whether northward migrating fish enter the northern estuaries. When they occur, bait catches are sampled for age and size composition in RI, MA, and ME by state agencies, and the samples are sent to the NMFS Laboratory for analysis.

Sport fishermen catch menhaden for bait primarily with cast nets. Anglers use menhaden as a live or "cut" bait for many species of game fishes, such as striped bass, bluefish, and sharks. Ground menhaden is preferred as a chum to attract many sport fishes. Quantities of menhaden harvested by sport fishermen are unknown, but thought to be minor in comparison to landings by the reduction fishery.

1.2 Management Unit Definition

The management unit for Atlantic menhaden (*Brevoortia tyrannus*) is defined in Amendment 1 as throughout the range of the species within U.S. waters of the northwest Atlantic Ocean from the estuaries eastward to the offshore boundary of the EEZ. The unit is coastwide from Maine to Florida. The Amendment 1 definition is consistent with recent stock assessments (including this one; see Section 2.1) which treat the entire resource in U.S. waters of the northwest Atlantic as a single stock.

1.3 Regulatory History

Throughout much of its history, the Atlantic menhaden fishery has been managed by unilateral regulatory actions imposed by individual states. The first coastwide management plan (FMP) for Atlantic menhaden was passed in 1981 (ASMFC 1981). At the time the FMP was passed, Maryland and Virginia were the two most restrictive states along the Atlantic coast. Maryland was the only state to prohibit the use of purse seine nets in its waters, thereby eliminating a commercial reduction fishery. Virginia was the only state to use both a closed season and mesh size limits to regulate the menhaden fishery.

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. The 1992 Revision included six "management triggers" used to annually evaluate the menhaden stock and fishery:

- Landings in weight – recommend action if landings fell below 250,000 metric tons
- Proportion of age-0 menhaden in landings – recommend action if more than 25% harvested (by number) were age-0 fish
- Proportion of adults in landings – recommend action if more than 25% harvested (by number) were age 3 and older

- Recruits to age 1 – recommend action if estimates of age-1 fish fell below 2 billion
- Spawning stock biomass (SSB) – recommend action if SSB fell below 17,000 metric tons
- Percent maximum spawning potential (%MSP) – recommend action if %MSP dropped below 3%

The Atlantic Menhaden Advisory Committee (AMAC) comprised of technical and industry representatives annually evaluated the "management triggers". If one or more of the "management triggers" was reached and it indicated a problem, the AMAC was to recommend regulatory action to the Board. The 'recruitment trigger' was exceeded during several years while the triggers were in place. However, AMAC never recommended action because SSB was at high levels during those years, and they felt reduced recruitment was caused by environmental factors (as opposed to fishing pressure). Also, a retrospective bias was associated with the recruitment estimates. Scientists calculated initial low values for recruits in the terminal years, and higher values were obtained in subsequent years.

Representation at 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 one amendment and four addenda to the 1992 FMP revision. Amendment 1, passed in 2001, provides specific biological, social/economic, ecological, and management objectives. Addendum I (2004) establishes the biological reference points that are currently in use. Addendum II (2005) initiated a five-year research program for Chesapeake Bay aimed at examining the possibility of localized depletion. Addendum III (2006) instituted a harvest cap for reduction landings from Chesapeake Bay during 2006 through 2010. The cap was set at 109,020 metric tons which could be increased to a maximum of 122,740 metric tons if there was a harvest underage of 13,720 metric tons or greater in the previous year. Addendum IV (2009) extends the Chesapeake harvest cap three additional years (2011-2013) at the same cap levels.

1.4 Assessment History

1.4.1 History of Stock Assessments

There is a long history of analyses on the Atlantic menhaden population. Quantitative analyses began in the early 1970s, as the time series of detailed data developed (accurate reduction landings have been recorded since 1940, and detailed biostatistical sampling began in 1955). The first quantitative analysis was that of Henry (1971) who addressed the significant decline in the menhaden stock during the 1960s. Henry suggested that "(O)f major importance to the proper management of any fishery is the ability to estimate the strength of the year class, before it enters the fishery." He noted that several large year classes were apparent in the catch data during the 1950s, including the "superabundant 1958 year class". However, "(w)hen the 1958 year class virtually disappeared from the catch in 1963 and there were no subsequent strong year classes, it is not surprising that the landings declined." Schaaf and Hunstman (1972) conducted a more detailed analysis of the catch-at-age data to obtain estimates of age and year specific fishing mortality rates, and explore yield-per-recruit and stock recruitment relationships. Dryfoos et al. (1973) conducted a detailed analysis of the Atlantic menhaden population based on tag returns from a large tagging study. Various population-level analyses were conducted during the 1970s, building on the work of Schaaf and Huntsman (1972). Most notably was an investigation of the effects of Ekman transport on menhaden recruitment (Nelson et al. 1977; Schaaf 1979). In the early 1980s, a stochastic population model was developed under contract with NMFS to investigate among other things migration, density-dependent growth, and harvesting strategies (Reish et al. 1985; Ruppert et al. 1985).

Two formal stock assessments were completed during the 1980s. The first (Ahrenholz et al. 1987b) included data through 1979, and the second (Vaughan and Smith 1988) included data through 1984. These assessments used an "untuned" virtual population analysis (VPA) approach based on the cohort-linked method described by Murphy (1965) to estimate age- and year-specific fishing mortality and population numbers from the catch-at-age matrix computed from the reduction fishery landings and biostatistical samples. Surplus production models, spawner-recruit relationships, and yield-per-recruit analyses were then developed. A similar set of analyses was later conducted to address the developing Internal Waters Processing agreement with Russian factory ships in Maine (Vaughan 1990). Stock assessment results were summarized in a special menhaden issue of Marine Fisheries Review (Vaughan and Merriner 1991).

Further updates of Atlantic menhaden assessments were conducted during preparation of the revised fishery management plan for Atlantic menhaden (ASMFC 1992). Annual assessments were conducted by Dr. Douglas Vaughan for the ASMFC Atlantic Menhaden Advisory Committee (AMAC) from 1993-2002. These annual reports were initially limited to estimation of the trigger variables developed for the revised fishery management plan, but expanded beginning in 1998 to include additional analyses. A detailed retrospective analysis was conducted on these annual assessments (through 1996) by Cadrin and Vaughan (1997). This analysis of historical retrospective patterns has been recently updated by Dr. Douglas Vaughan for assessments through 2006 and is included in this assessment (see Section 1.5). Uncertainty and risk analyses of these assessments were explored by Vaughan (1993) and Vaughan et al (2002).

As noted above, assessment methods used the "untuned" VPA method of Murphy (1965) as the primary assessment methodology through 2002. This method was accepted by a formal peer review in 1998 (ASMFC 1999a, 1999b). Amendment 1 to the Atlantic Menhaden Fishery Management Plan (ASMFC 2001) was issued in 2001. Among other changes, this amendment dropped the six triggers from the 1992 revision (ASMFC 1992) and replaced them with two benchmarks that conformed to the 1997 revision to the Magnuson-Stevens Fishery Conservation and Management Act (Restrepo et al. 1998). Concurrently, new statistical assessment methods (e.g., forward projection model) were introduced in 2001 and explored further in 2002 in parallel to the "untuned" VPA approach. Indices of juvenile abundance, and an "adult" abundance index (menhaden landings per poundnet license from the Potomac River Fishery Commission, PRFC) were developed for the statistical catch at age model, which then went through a formal peer review in 2003 (ASMFC 2004a, 2004b). In preparation for a formal peer review in 2003 (ASMFC 2004a, 2004b), several additional changes were made during the data workshop.

Conversion of bait landings to catch at age were further refined. The concept of age-varying *M* was introduced based on the multi-species VPA under development by ASMFC, and later peer reviewed (NEFSC 2006a, 2006b). The maturity schedule was modified, reflecting that some age 2 and most, but not all, age 3 were mature. A coastwide index of juvenile abundance and "adult" index from PRFC were developed for use in "tuning". The most recent assessment was the update assessment conducted in 2006 with additional data through 2005 (ASMFC 2006).

The most recently completed assessment of the status of the Atlantic menhaden stock was an update of the 2003 peer-reviewed assessment, and it included data through 2005 (ASMFC 2006). Data included abundance indices, recorded landings, and samples of annual size and age compositions from the landings. Six state juvenile abundance seine indices were developed; five of which were used in the 2003 peer-reviewed or benchmark assessment (ASMFC 2004a). The new seine index (New Jersey) was only used in an alternate model run. The pound net index from the PRFC was improved to better reflect fishing effort (from number of licenses which has been fixed at 100 licenses since 1994 to number of days fished). Landings and catch-in-numbers-at-age data were updated from the reduction and bait fisheries. A new vector of natural mortality at age was obtained from the recently peer-reviewed MSVPA-X model (NEFSC 2006a, 2006b) to replace the vector used in the benchmark assessment.

The statistical model from the benchmark assessment was applied to these updated data. A base assessment model run was developed and sensitivity model runs were made to evaluate performance of the assessment model to these updated data. Because unrealistically high levels of adult natural mortality were estimated when the new M-at-age vector from the recent MSVPA-X base run was used, the ASMFC Menhaden Stock Assessment Subcommittee scaled this vector so that adult natural mortality matched historical tagging results ($M_{\text{adult}} = 0.5$). This was in keeping with the peer-reviewed results which found that adult *M* from the peer-reviewed assessment (0.55) was reasonable because it provided an estimate of adult *M* similar to the historical adult *M* obtained from tagging (Reish et al. 1985).

Status of stock was based on the terminal year (2005) estimate relative to its corresponding limit (or threshold). Benchmarks were estimated based on the results of the updated base run. The terminal year estimate of fishing mortality rate ($F_{2+\text{ weighted}}$) was estimated to be 56% of its limit (and 91% of its target). Correspondingly, the terminal year estimate of population fecundity was estimated at 158% of its fecundity target (and 317% of its limit). Hence, the stock was not considered to be overfished, nor was overfishing occurring.

1.4.2 Historical Retrospective Patterns

"Historical retrospective" can be investigated using annual stock assessments that have been conducted consistently over the years (Cadrin and Vaughan 1997). These analyses compare estimates of important management variables from the most recent assessment with contemporary estimates from prior stock assessments. In particular, Cadrin and Vaughan (1997) compared three management variables (or "triggers") in their analysis, including spawning stock biomass, recruitment to age 1, and maximum spawning potential (%MSP). Amendment 1 to the

Atlantic Menhaden Fishery Management Plan (ASMFC 2001) dropped the six triggers from the 1992 revision (ASMFC 1992) and replaced them with two benchmark (management) variables that conformed to the 1998 revision to the Magnuson-Stevens Fishery Conservation and Management Act (Restrepo et al. 1998). So, for the purpose of this analysis, we have replaced %MSP with adult fishing mortality (F). The management variables analyzed in this section are:

- Fishing Mortality (F) – calculated historically as catch-weighted age-specific F for ages 2 and older; this was changed to N-weighted in the 2003 peer-reviewed assessment.
- Spawning Stock Biomass (SSB) – calculated as the weight of mature females in the population. Initially, all females age 3 and older were assumed mature, and younger fish were assumed immature. This was modified in 2003 to reflect that some age 2 may be mature (11.8%), and most, but not all age 3 are mature (84.6%).
- Recruits to Age 1 – directly estimated as number of age 1 fish in the population at the start of the fishing year (March 1 for Atlantic menhaden).

As already noted, a consistent assessment methodology was applied from 1990 through 2002, and this approach was accepted by a formal peer review in 1998 (ASMFC 1999a, 1999b). This consistent approach included the following:

- “Untuned” VPA method of Murphy (1965)
- Catch at age matrix based on reduction fishery only (through 2000)
- Constant natural mortality (M = 0.45)
- Knife-edge maturity beginning with age 3

Two types of comparisons have been developed for the annual estimates of management variables. First, the time series of estimated values are overlayed for each of the management variables (**Figures 1.1a, 1.2a, and 1.3a**). These plots include annual assessments with terminal years 1990, 1992-2001, with the exception of fishing mortality in 1990. Second, proportional deviations were developed between the time series with terminal year 2000 and earlier terminal years (**Figures 1.1b, 1.2b, and 1.3b**). Note that bait landings were included in assessments beginning with 2001 (terminal year 2000). The primary effect of adding bait landings was to decrease estimates of F and increase estimates of SSB and R_1. The selectivity of bait landings tends towards larger, older fish.

Concurrent with the “untuned” VPAs, the new statistical catch-at-age (“forward projecting”) assessment model was introduced in 2001 and explored further in 2002. These analyses appeared as appendices to the 2001 and 2002 assessment reports. Results from the two assessment methods are compared in the next series of figures (**Figures 1.4-1.6**) for each of the three management variables. The last series of figures (**Figures 1.7-1.9**) compare fishing mortality rates, spawning stock biomass, and recruitment between the peer-reviewed and updated assessments.

2.0 Life History

2.1 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 2008) support the single stock hypothesis.

2.2 Migration Patterns

Adult Atlantic menhaden undergo extensive seasonal migrations north and south along the US East coast (ASMFC 2004a). 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 North Carolina 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 2004a). 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-0's) 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 and in greater numbers than smaller age-1 fish, which tend to remain along the south Atlantic coast; however, some age-1's move from the south Atlantic and into Chesapeake Bay through mid-summer.

2.3 Age

Background: The seminal study on ageing Atlantic menhaden was conducted by June and Roithmayr (1960) at the NMFS 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 (generally March through May) and marginal increment analyses. Comparison of independent readings of scale ages showed a high percentage of agreement (= precision, >90%). Additionally, they examined scales from fish impounded for up to 14 months to further demonstrate that only one ring forms annually on menhaden scales. Based on these studies, menhaden are assigned to ages based on a March 1 "birthdate".

Menhaden field sampling protocols remain relatively unchanged from the 1950s. In the field, port agents measure specimens for fork length (mm) and weight (grams), then remove a scale patch (ca. 20-25 scales) from the mid-portion of the flank below the dorsal fin. Six scales per specimen are mounted between two microscope slides and labeled with a unique specimen number. At the laboratory, scales are viewed on an Eberbach macro-projector under 40x magnification. Specimens are assigned an age (in yrs) based on the number of scale rings.

Precision: During the early decades of the Menhaden Program at the Beaufort Laboratory scales from individual menhaden specimens were read by two independent readers, with a third reader used to decide discrepancies. By the early 1970s – and probably because of budget constraints - only a single reader was retained on staff to age menhaden scales. This employee, Ethel A. Hall (EAH), has read menhaden scales at the Beaufort Laboratory beginning in 1969 to the present.

In an effort to estimate contemporary precision of Atlantic menhaden age estimates, EAH re-read scale samples from the 2008 fishing season. Re-ageing efforts occurred during summer 2009. EAH was instructed to re-assign estimated ages, but not to make measurements to successive annuli (as per protocols for general menhaden ageing). Both sets of age estimates were stored in dBase files and analyzed in SAS.

Overall, 80.3% (2,978 of 3,711) of the paired readings agreed. Younger age classes (age-0 through age-3) showed better agreement than older age classes (ages-4 and -5; **Figure 2.1**). Most disagreements were +/- one year for ages-1 through -3 (98.1%, 86.3%, and 96.5%, respectively). See Section 4.1.6 for additional details.

Accounting for error in age estimation is important for age composition data used in stock assessments (Punt et al. 2008). Thus, to account for any error associated with the age estimation process for Atlantic menhaden and to get contemporary precision estimates, an aging error analysis was completed using a program called "agemat" provided by André Punt. The data used for this analysis were the paired scale age estimates from the 2008 fishing season (n = 3,711). Agemat can use age estimation data from one reader at two points in time in order to estimate the standard deviation associated with age estimates. The data in **Figure 2.1** were input to agemat, and a standard deviation maximum of 12 (which resulted in a coefficient of variation of 1 (A. Punt, personal communication) for the oldest age class was specified in the model. The standard deviation output from agemat was then used to provide the error associated with the age composition data for each age in the stock assessment models for Atlantic menhaden. These standard deviations were assumed constant over time.

Scale-Otolith Paired Age estimates: Menhaden program managers at the Beaufort Laboratory realized it was impractical to utilize otoliths to age Atlantic menhaden because 1) sagittae were 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 the ageing tool of choice for Atlantic menhaden (June and Roithmayr 1960).

Ongoing work at Old Dominion University indicates good agreement between paired scale and otolith age estimates for Atlantic menhaden ages-0 through -3 (n = 70-80 fish), although relatively few age-2 and -3 have been processed (J. Schaffler, ODU, pers. comm., June 17, 2009). Indeed, menhaden otoliths are reported to be difficult and time consuming to age.

Longevity and Contemporary Age Composition: Atlantic menhaden as old as age-8 were present in the spawning population during the 1950s and early 1960s, but fish older than age-6 have been uncommon since 1965. The oldest specimens aged from NMFS biological sampling were several 10-year old fish landed in 1955 (2), 1956 (3), 1958 (1) and 1964 (1) from more than 495,000 Atlantic menhaden aged between 1955 and 2008 (**Table 2.1-2.2**). Smith and O'Bier (1996) described an exceptionally large (433 mm FL; 1,551g; age-7) Atlantic menhaden from Chesapeake Bay taken in August 1996.

In two of three years since 2006, age-2 Atlantic menhaden have comprised 65% or more of the total numbers of fish landed by the commercial reduction fishery. In 2006 the age composition of the coastwide landings was 1% age-0s, 40% age-1s, 40% age-2s, and 19% age-3+s; in 2007, it was <1% age-0s, 26% age-1s, 65% age-2s, and 8% age-3+s; and in 2008, it was 1% age-0s, 9% age-1s, 68% age-2s, and 22% age-3+s.

2.4 Growth

The growing season begins in spring and ends in fall as water temperatures rise above and decline below 15^{o} C (Kroger et al. 1974). Atlantic menhaden reach lengths of about 500 mm total length (TL) and weights of over 1.5 kg (Cooper 1965). 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 weights of individual Atlantic menhaden at age sampled when calculating mean fish weights (**Figure 2.2**) for 1955-2008. These "weighted" mean weights increased during the 1960s when stock size and recruitment are known to have declined, and then mean weights declined dramatically during the 1970s, and remained low during most of the 1980s when the stock was thought to have rebuilt. Increasing mean weights are estimated during the 1990s while recruitment was declining, followed by recent declines in mean weight. It has been suggested in various publications that density dependent growth is prevalent with Atlantic menhaden (Reish et al. 1985, Ahrenholz et al. 1987b, 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. In **Figures 2.3**, we plot annual values of weighted mean weight of age-0 menhaden against estimated recruits to age 0 from the last Atlantic menhaden stock assessment (ASMFC 2006). A statistically significant correlation of this inverse relation explains 49% of the annual variability in weighted mean weights ($R^2 = 0.49$).

Weighting by catch in numbers by year, season and fishing area is also applied to calculate average fork lengths (mm) and weights (g) by age and year (**Tables 2.3 and 2.4**). 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 is available. These mean values represent mean size at age at approximately mid-fishing year (August-September).

Pair-wise Pearson correlations were estimated for these time series of weighted mean lengths and weights aligned by cohort (year class) or by calendar year (**Table 2.5**) for age 0-4. The differences in these correlations between these two alignments suggest that the relationship is stronger when aligned by cohort, so that density-dependent size at age is more characteristic of the cohort than of calendar year.

Annual regressions of weight (W in g) on fork length (FL in mm) are conducted based on the natural logarithm transformation:

$$\mathit{ln}\ \mathrm{W} = \mathrm{a} + \mathrm{b}\ \mathit{ln}\ \mathrm{FL}, \qquad (1)$$

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

$$\mathrm{W} = \mathrm{a}(\mathrm{FL})^{\mathrm{b}}. \qquad (2)$$

Annual estimates for parameters ***a*** and ***b*** along with sample size and root MSE are summarized in **Table 2.1**. We also have plotted annual estimates of b against recruits to age 0 to test whether there is a density dependent component to this parameter over time. No significant correlations were found.

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

$$FL = L_{\infty}(1 - \exp(-K(age - t_0))) \tag{3}$$

using the Marquardt algorithm for the nonlinear minimization (PROC NLIN in SAS). Annual parameters for these regressions are summarized with sample sizes in **Table 2.1**. Matrices of weight at ages-0 to -8 for 1955-2008 were developed from these equations to represent the average size-at-age of menhaden at the start of the fishing year (e.g., spawning biomass for appropriate ages) and middle of the fishing year (i.e., weight of fish landed) for use in population modeling. Parameters from regressions for equations (2) and (3) were averaged for the most recent eight years (2001-2008) and used to calculate lengths and weight at age at the middle of the fishing year (age+0.5; **Table 2.6**). Note that length and weight for age-0 menhaden is offset to 0.75 since they are not recruited to the fishery until late summer.

An alternate set of von Bertalanffy fits were made with the size at age data aligned by cohort (year class) (**Table 2.2**). Because of concerns that density-dependent growth is a characteristic of the cohort, it was felt that this would 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 2008 (age 0 in 2008). For most cohorts, a full range of ages were available (1955-2001). 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). However, these fits are only used for interpolation and not extrapolation, and were found useful for this limited purpose. Similarly, incomplete cohorts for the recent time period (2002-2008) generally converged with the exception of the last two years (2007-2008). With the exception of the two years for which the fits did not converge, reasonable estimates of the von Bertalanffy parameters were obtained, and estimates of size at age were interpolated from these fits.

We compare the estimated lengths at ages 2 and 3 (mid-year) from the two series of fits to the von Bertalanffy growth equation with observed weighted mean lengths (**Figure 2.4**). Based on these two series of fits to the von Bertalanffy growth equation, annual estimates of fork length at age are interpolated from the annual and cohort based von Bertalanffy growth fits to represent the start of the fishing year (March 1) for use in estimating population fecundity (**Tables 2.7 and 2.8**). Similarly annual estimates of length-at-age were interpolated to represent the 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. (**Tables 2.9 and 2.10**).

2.5 Reproduction

Spawning Times and Locations. Analysis of eggs and larvae collected at various locations along the Atlantic coast during 1953-75 (e.g., Judy and Lewis 1983) generally confirmed earlier knowledge of spawning times and location based on observations of adults with maturing or spent ovaries (e.g. Reintjes and Pacheco 1966). During December-March, most spawning-age fish congregate in offshore waters south of Cape Hatteras. Maximum spawning probably occurs at this time. Checkley et al. (1988) reported maximum spawning off North Carolina in January 1986 during periods of strong northeast winds in up-welled water near the western edge of the Gulf Stream. Spawning continues at a decreasing rate closer inshore as fish migrate north in late March. By May, most spawning is restricted to coastal waters north of Cape Hatteras. Spawning reaches a minimum in June, but continues at a low level until September north of Long Island. As mature fish migrate south in October, spawning increases from Long Island to Virginia.

Adults move inshore and northward in spring and stratify by age and size along the Atlantic coast (Rogers and Van Den Avyle 1989). During this northern migration, spawning occurs progressively closer inshore and by late spring, some spawning occurs within coastal embayments. There are definite spring and fall spawning peaks in the middle and north Atlantic regions, with some spawning occurring during winter in the shelf waters of the mid-Atlantic region. Atlantic menhaden mature at smaller sizes at the southern end of their range - 180 mm fork length (FL) in the south Atlantic region versus 210 mm FL in the Chesapeake Bay area and 230 mm in the north and middle Atlantic regions because of latitudinal differences in size-at-age and the fact that larger fish of a given age are distributed farther north than smaller fish of the same cohort (Lewis et al. 1987).

Some limited spawning activity has been suspected during summer in the Gulf of Maine based on juvenile collections along the Maine coast (T. Creaser, Maine DMR, pers. comm.. as cited in ASMFC 1992) and the occurrence of ripe females (S. Young, Maine DMR observer on the M/V RIGA, pers. comm. as cited in ASMFC 1992). Indeed, Stokesbury and Stokesbury (1993) collected 209 young-of-year Atlantic menhaden (mean total length = 66.25 mm, range: 41-109 mm) in the Annapolis River, Nova Scotia, Canada, during 1985, 1986, and 1989. Coupled with citations of ripe fish in several rivers of New Brunswick, they argued that some spawning probably occurs in the Bay of Fundy during summer. Unfortunately, historic egg and larval surveys directed at Atlantic menhaden were restricted to waters south of Cape Cod (Judy and Lewis 1983) and did not produced any evidence for spawning in the Gulf of Maine.

Maturity. Some Atlantic menhaden become sexually mature during their second year (late age-1), but most do not mature until their third year (late age-2) (Higham and Nicholson 1964; Lewis et al. 1987). Spawning occurs year-round throughout much of the species' range, with maximum spawning off the North Carolina coast during late fall and winter. Thus, most Atlantic menhaden spawn for the first time at age-2 or -3 – prior to laying down their third annulus (by convention March 1) and continue spawning every year until death. First-spawning age-3 fish has accounted for most of the stock's egg production since 1965 (Vaughan and Smith 1988).

Lewis et al. (1987) tabularized maturity schedules (number and percent of specimens by ages-1 and -2) for female Atlantic menhaden from their field collections and those of Higham and Nicholson (1964). Percent age-1 females with active ovaries ranged from 1.5% to 27.8%, while percent age-2 females with active ovaries ranged from 67.4% to 97.1% (see table below). All age-3 and older females were judged to be sexually mature.

	1956[a]		1957[a]		1958[a]		1959[a]		1981[b]	
Age	N	%	N	%	N	%	N	%	N	%
1	292	7.5	67	1.5	187	27.8	77	2.6	38	2.6
2	103	97.1	179	67.6	262	96.6	123	92.7	138	67.4

[a] From Higham and Nicholson (1964, Table 7)

[b] From Lewis et al. (1987)

The last peer review panel (ASMFC 2004b) made the following recommendation regarding maturity of Atlantic menhaden:

> • *Conduct new size/age at maturity research by geographic regions along the Atlantic coast.*

Although Atlantic menhaden may spawn year-round, previous age-at-maturity work was conducted during the fall fishery along the North Carolina coast, no doubt because of the availability of specimens and proximity to the NMFS Beaufort Laboratory. In an attempt to replicate studies by Higham and Nicholson (1964) and Lewis et al. (1987), ripening female Atlantic menhaden were collected from ocean catches (purse seines) along the North Carolina coast during November and December 2004, and again in November (purse seines) and December 2008 (gill nets). Specimens were measured for fork length (mm) and weighed (g), then a scale patch was removed for ageing. Ovaries of females were removed and weighed to the nearest 0.1 g. An 'ovary index' (OI), analogous to a gonosomatic index or GSI, was computed based on the formula of Higham and Nicholson (1964):

$$OI = (\text{ovary weight}*10^7) / \text{fork length}^3 .$$

Specimens with an OI >= 4 were considered sexually mature with maturing and ripe ova (*in sensu* Higham and Nicholson [1964]), while those with an OI < 4 were considered sexually immature. Results of maturity observations on female Atlantic menhaden from fall 2004 and 2008 based on these criteria are shown below.

Age	N	FL range (mm)	<u>Immature</u> n w/ OI < 4	<u>Mature</u> n w/ OI < 4	Percent Mature
1	11	190-247	5	6	54.6
2	137	192-308	16	121	88.3
3	99	219-338	2	97	97.8
4	24	260-331	0	24	100
5	1	342	0	1	100
Total	272				

Clearly, the sample size of age-1 specimens (n = 11) is inadequate to resolve the question of the proportion of fish in this age class that reach sexual maturity as they approach their second birth date. However, the results for age-2+ specimens tend to support earlier work of Higham and Nicholson (1964) and Lewis et al. (1987) that indicate a high proportion of age-2 fish become sexually mature as they approach their third birth date, while nearly all fish age-3 and older are sexually mature.

Fecundity. Atlantic menhaden are relatively prolific spawners. Predicted fecundities range from 38,000 eggs for a small female (180 mm FL) to 362,000 for a large female (330 mm FL) (**Figure 2.5**) according to the equation derived by Lewis et al. (1987):

$$\text{Number of maturing ova} = 2563 * e^{0.015*FL} \qquad (4)$$

This equation was derived by fitting an exponential model to length-specific fecundity data for fish collected during 1956-1959 (Higham and Nicholson 1964), 1970 (Dietrich 1979), and 1978, 1979, 1981 (Lewis et al. 1987). Fish in all three studies were collected from the North Carolina fall fishery, which harvests fish of all ages. In addition, fish were collected from Gloucester, MA, Port Monmouth, NJ, and Reedville, VA in 1978 and 1979. Lewis et al. (1987) concluded, "…no detectable changes have occurred in the fecundity relationship. The among-year variation in the annual fecundity of Atlantic menhaden prevents the determination of any historical trends from the limited amount of earlier data available … and the lack of fish above 310 mm available in the current fishery". Such fecundity-length relationships are useful in stock assessments to the extent that they accurately reflect the relative (not absolute) increase in egg production of a female with increasing size. 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 a better measure of reproductive output of a stock of a given size and age structure. Most importantly, fecundity better emphasizes the importance of older, and larger individual menhaden contribution to population egg production. Annual estimates of fecundity (no. of maturing or ripe ova) at age are summarized for both annually-based von Bertalanffy growth fits (**Table 2.11**) and year class-based von Bertalanffy growth fits (**Table 2.12**).

Related to this issue, is the contribution of young (e.g., first age spawners) to the overall reproductive effort. This was noted in Vaughan and Smith (1988), and we have updated this analysis from output from the last menhaden stock assessment (ASMFC 2006). In assessments prior to 2003, females were assumed to be fully mature with age 3 (late age 2) and immature at younger ages. For this analysis age 2 (11.8% mature) and age 3 (86.4%) females are treated as "first age spawners". We compare the number and biomass of these first year spawners to total, 1955-2005, in **Figure 2.6**. With the exception 1955 and 1962, these proportions have been high (generally >70% for biomass and >80% for numbers) for the full assessment period. The exceptions result from the passage of two exceptionally large year classes (1951 and 1958) through the stock. Otherwise a general decline in this proportion can be seen since the peak values in 1967.

Lewis et al. (1987) surmised that Atlantic menhaden "are probably determinate multiple spawners, which spread their spawn over a broad geographical and temporal range." Ahrenholz (1991) summarized spawning seasonality noting, "some spawning occurs during virtually every month of the year…some spawning occurs in the more northerly portions of the fishes' range as the fish begin moving southward in September…spawning continues with increasing intensity as the fish move progressively farther southward in October and November…spawning intensity is believed to peak in waters off the North Carolina coast in winter…spawning continues, but with decreasing levels of intensity as the fish move northward in the following spring and early summer." Despite the broad geographic range of spawning activity, most fecundity studies of Atlantic menhaden have concentrated on acquiring gravid females off the North Carolina coast 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). It can be argued that existing fecundity studies of Atlantic menhaden are underestimates of absolute spawning potential. Nevertheless, the extant studies focused on fall or early winter concentrations of gravid fish off the North Carolina coast, which is believed to be the area of greatest spawning intensity (Ahrenholz 1991). For assessment purposes, modeling increasing egg production with size is preferable to female biomass as a measure of reproductive ability of the stock. With density-dependent growth and fecundity a function of growth (in length), there is the potential that a larger, slower growing cohort will produce fewer eggs overall than a smaller, faster growing cohort.

2.6 Natural Mortality

Age-structured models attempt to reconstruct the fish population and fishing mortality rates by age and year, where total instantaneous mortality rate (Z) is the sum of instantaneous rates of fishing (F) and natural (M) mortality. Historically, natural mortality has been assumed to be constant over ages and years. In many stock assessments, constant values for M have been obtained from life history analogies (e.g. maximum age, growth rate parameters, etc.). Because it is thought that younger fish are more vulnerable to predation, natural mortality may decline with size or age. Several approaches have been considered to provide such size-varying estimates of natural mortality. For purposes of stock assessments, sizes are related to age to provide age-varying estimates of natural mortality.

This section summarizes material found in the SEDAR 20 Data Workshop report: S20DW03. This report provides an overview of menhaden natural mortality (*M*), and then describes several life history based approaches for developing estimates of *M*. While methods that relate life history traits with natural mortality were reviewed in Vetter (1987), newer methods have been developed since that land mark paper. A variety of methods have been explored during past menhaden SEDAR data workshops, and results of some of these methods are summarized in this section. Often *M* is related to the parameters from the von Bertalanffy growth equation (K, L_∞), or as an inverse function of size at age, so consideration of growth of Atlantic menhaden is relevant to this section.

Age-Constant M Approaches

There are several methods 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 2.13**.

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)	$M = exp(-0.0152+0.6543*ln(K)-0.279*ln(L_\infty, cm) +0.4634*ln(T^oC))$
"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 North Carolina]. 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 compare this 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*. It is believed that with sufficient age sampling over a long period of time, as in the case of Atlantic menhaden, a useful tool for determining *M* can be utilized. We have calculated 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) and Pauly (1980) (**Figure 2.7**).

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}) was used routinely in Atlantic menhaden assessments beginning with Ahrenholz et al. (1987b).

Beginning in 2003, age-varying estimates of M from the MSVPA-X have been favored in Atlantic menhaden stock assessments due to the MSVPA's ability to explicitly account for predation effects through the incorporation of diet data (ASMFC 2004a). During the SEDAR 20 Data Workshop, all approaches were discussed, but the MSVPA-X results were recognized again as the favored approach due to the MSVPA's estimation of both age- and year-varying *M*.

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). All use an inverse relationship between size and natural mortality (*M*). The method of Peterson and Wroblewski (1984) recently was used to describe natural mortality 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 in Vaughan et al. (2007). However, the method of Lorenzen (1996) has gained favor in recent years, especially in the SEDAR arena (e.g., S10, S15, S17 S18, and S19). When applying the method of Lorenzen (1996), estimates of age-varying *M* are scaled such that cumulative survival from age 1 through the maximum age is equal to 1.5%. This cumulative survival value comes from the fixed *M* method of Hoenig (1983) as described in Hewitt and Hoenig (2005). When scaled, the resulting M from Peterson and Wroblewski (1984), Boudreau and Dickie (1989) and Lorenzen (1996) provide very similar results (**Figure 2.8**). Unscaled age-varying estimates of M are summarized for ages 0-10 (**Table 2.14**). During the course of the SEDAR 20 Data Workshop, the need for age-varying estimates of *M* that recognize higher natural mortality for the youngest ages was discussed.

Natural Morality from Multi-Species VPA (MSVPA-X)
Using an Expanded Multi-Species Virtual Population Analysis model (MSVPA-X) allows further decomposition of natural mortality (*M*) into predation mortality, M_2, and other sources of natural mortality, M_1. M_2 is more appropriately described as natural mortality due to predators. 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 natural mortality; particularly when the bulk of the increased natural mortality comes before full recruitment to the fishery. It should be noted that whether using age-variable and/or multi-species derived *M*, some component of the natural mortality is normally 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 the MSVPA-X in 2001. 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 also 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 Atlantic Menhaden Technical Committee 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 natural mortality was derived in some part by that version of the MSVPA-X. As with the scaling for age-varying *M* (previous section), scaling of M at age is carried out for ages 1-10 (maximum age observed). *M* for ages 6+ are assumed constant. These results were then used as a vector in the single species formulation for menhaden during the most recent bench mark assessment (ASMFC 2004a).

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 2006a, 2006b). 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. An open literature publication of the work that went to peer review in 2005 has recently been accepted for publication by the ICES Journal of Marine Sciences (Garrison et al., In press).

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, squid)
- Other clupeids (Atlantic herring, Atlantic thread herring, and others)
- Benthic invertebrates (worms)
- Benthic crustaceans (lobster, blue crab, rock and Jonah crab)
- Macrozooplankton (shrimps, mysids, and amphipods)

Estimates of age- and year-varying *M* from the MSVPA-X were updated during the Assessment Workshop (see Section 6.1.4). 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 2.8**). In the last peer reviewed assessment (ASMFC 2004a), an average vector of age-specific M from an earlier version of MSVPA-X was scaled within the model. This approach failed to produce reasonable scaling in the subsequent update (ASMFC 2006). In that assessment, the age-specific vector of M was scaled to historical estimates of M from tagging studies. The average age-varying estimates of *M* from MSVPA-X are computed for 1982-2008 (**Table 2.15**) to minimally provide input for a continuity model run.

Because the age- and year-varying estimates of *M* from MSVPA-X are only available for 1982-2008 and the menhaden assessment includes the years 1955-2008, it was necessary to develop approaches for developing age- and year-varying estimates of *M* for the earlier years (i.e., 1955-1981). During the Data Workshop, alternate approaches were considered for developing year-varying estimates of M from the MSVPA-X estimates which were only available for 1982-2008. During the Assessment Workshop, it was determined to use the average age-varying M vector for the earlier period (1955-1981), rather than the M vector for 1982 considered earlier. This approach is summarized in **Table 2.15**.

Annual estimates of *M* from MSVPA-X (averaged across ages) were compared with both the fixed, but annually varying, estimates of *M* (e.g., Alverson and Carney, Jensen, and Pauly) (**Figure 2.7**), and with the annually varying estimates of *M* from the inverse weight approaches of Peterson and Wroblewski, Boudreau and Dickie, and Lorenzen (also averaged across ages) (**Figure 2.8 & 2.9**).

During the course of the SEDAR 20 Data Workshop, the following topics were discussed and decisions made:

- Given the availability of MSVPA-X, the SASC favored this approach over that of age-varying natural mortality based on inverse relation to weight at age.
- The SASC considered using the average age-vector for *M* from the MSVPA-X and scale to tagging as in the last assessment (2006 update), but prefered to explore using year- and age-varying estimates of *M*.
- The average age-varying estimates of *M* (1982-2008) from the MSVPA-X was provided as at least continuity with previous assessments, but the SASC wished to pursue year-varying *M for the base run*.

2.7 Environmental Factors

Environmental factors that affect recruitment are generally viewed as density independent. These factors include physical processes, for example transport mechanisms, water temperature, DO, freshwater inflow and nutrient loadings. Biological factors, such as amount of food and competition for food, or predation by higher trophic levels which control survival and growth of young-of-the-year menhaden prior to recruitment to the fishery, can be either density independent or density dependent.

Physical Processes: Nelson et al. (1977) developed a Ricker spawner-recruit model relating coastwide spawning stock of Atlantic menhaden as number of eggs produced to subsequent recruits. These authors further developed a recruit survival index from the deviations around the Ricker curve, which they then regressed on several environmental parameters. Most significant was zonal Ekman transport, acting as a mechanism for transporting larval menhaden from offshore spawning areas to inshore nursery grounds. William Schaaf later conducted a retest in the mid-1980s (referred to in Myers (1998)). Because one value (1958 year class) had high statistical leverage in the original analysis, the addition of more years diluted the significance of the metric for Ekman transport, thus reducing its statistical significance. Such indices, while valuable in exploratory analysis, often fail in long time series. For example, Myers (1998) reviewed environment-recruitment correlations, finding that "the proportion of published correlations that have been verified upon retest is low."

Wood (2000) investigated synoptic scale climatic forcing of multispecies fish recruitment patterns in Chesapeake Bay. He developed recruitment patterns from five fishery-independent data sets which he then compared to spring climatic variability using a variety of multivariate statistical techniques. He found "that spring conditions in March, brought on by an early appearance of the Azores-Bermuda High, favor recruitment of shelf spawners [i.e., menhaden] while prolonged winter conditions, brought on by relative dominance of the Ohio Valley High, favor spawning success of anadromous fishes. Wood et al. (2004) later fit a modified Ricker model, with days of Azores-Bermuda High in spring months included, and obtained a fairly good fit to the coastwide recruitment time series for Atlantic menhaden. Austin (2002) and Wood and Austin (2009) suggested that a statistically significant regime shift occurred in 1992, when recruitment in anadromous fishes became favored at the expense of shelf-spawning, estuarine-dependent fishes.

Stone (1976) conducted a series of stepwise regressions of gulf menhaden, *B. patronus*, catch and effort related to a wide range of environmental data (air temperature, water temperature, rainfall, tides, and wind speed and direction). Not unexpectedly, several significant correlations were found including minimum and mean air temperature, maximum water temperature, and wind direction at several locations, resulting in an R^2 value of 0.86. Subsequently Guillory refined much of this work to forecast Louisiana gulf menhaden harvest (Guillory et al. 1983; Guillory 1993). As a congener of gulf menhaden, Atlantic menhaden might be expected to respond to similar environmental factors.

Govoni (1997) demonstrated an inverse relationship between freshwater discharge from the Mississippi River on gulf menhaden recruitment. Subsequent analyses have shown this relationship continues to hold (Vaughan et al. 2000; and subsequent revisiting). This approach was applied to Atlantic menhaden using freshwater inflow to Chesapeake Bay from the major rivers in Maryland and Virginia without obtaining statistically significant results, presumably because the freshwater inflow to Chesapeake Bay does not dominate the recruitment success of Atlantic menhaden as it does for gulf menhaden affected by Mississippi River flow. Although not statistically significant in Chesapeake Bay, recruitment strength is negatively correlated with freshwater flow in spring and positively correlated with Secchi depth (Houde and Harding 2009). Overall, recruitment of menhaden to Chesapeake Bay tends to be low in years when late winter-early spring conditions are dominated by climatic patterns characterized by high precipitation and freshwater flow (Kimmel et al. 2009).

Biological Processes: Predation is a process that potentially plays a major role in controlling recruitment level. Ahrenholz et al. (1991) noted that all life stages of menhaden are potential prey for a variety of predators, and describe in general terms how some of these predators may impact life stages of menhaden. Juvenile and adult menhaden are prey to piscivorous fishes (including of course striped bass and bluefish), seabirds and marine mammals. Food and nutrition during the larval and juvenile stages are dependent on amounts and types of available prey and, as such, may serve to control recruitment. As larvae, menhaden eat zooplankton, which are captured as individual particles. As juveniles and adults, menhaden are filter-feeders, consuming phytoplankton and zooplankton. Consequently, variability in plankton concentrations in the coastal ocean and in the Chesapeake Bay could affect survival and growth, and be a significant factor controlling or regulating recruitment.

Since 1989, there has been a significant relationship between YOY recruitment of Atlantic menhaden and annual levels of primary production, especially chlorophyll-a biomass, in Chesapeake Bay (Houde and Harding 2009). Additionally, Love et al. (2006) found a positive correlation between YOY recruitment level and phosphorous loading in Maryland tributaries, suggesting that level of primary productivity may be related to menhaden recruitment.

3.0 Habitat Description

3.1 Overview

Atlantic menhaden occupy a wide variety of habitats during their life history. Adult Atlantic menhaden spawn primarily offshore in continental shelf waters. Larvae are carried by inshore currents to estuaries where they congregate in large concentrations near the upstream limits of the tidal zone and undergo metamorphosis into juveniles (June and Chamberlin 1959). As juvenile menhaden grow and develop, they form dense schools and range throughout the lower salinity portions of the estuary, eventually migrating to the ocean in late fall-winter.

The geographic range of Atlantic menhaden contains three large subregions. The northernmost region is the Gulf of Maine, a semi-enclosed sea bordered on the east, north, and west by the coasts of Nova Scotia, New Brunswick, and the New England states and bordered to the south by the open ocean of Georges Bank. The mid-Atlantic region extends from Cape Cod, MA to Cape Hatteras, NC. The south Atlantic region extends from Cape Hatteras south to Biscayne Bay and the Florida Keys.

Many factors in the estuarine environment affect the behavior and health of Atlantic menhaden. The combined influence of weather, tides, and river flow can expose estuarine fish to rapid changes in temperature and salinity. It has been reported that salinity affects menhaden temperature tolerance, activity and metabolic levels, and growth (Lewis 1966; Hettler 1976). Factors such as waves, currents, turbidity, and dissolved oxygen levels can impact the suitability of the habitat, as well as the distribution of fish and their feeding behavior (Reintjes and Pacheco 1966). However, the most important factors affecting natural mortality in Atlantic menhaden are considered to be predators, parasites, and fluctuating environmental conditions (Reish et al. 1985).

3.2 Spawning, Egg, and Larval Habitat

Spawning occurs in oceanic waters along the continental shelf as well as in sounds and bays in the northern extent of their range (Judy and Lewis 1983). The majority of ovigerous females have been observed in the south Atlantic, indicating spawning activity is highest in this region (Nelson et al. 1977). Specific spawning sites have not been directly observed, but are indicated by the presence of pelagic eggs.

Temperature, depth, and salinity at presumed spawning locations varies widely depending on latitude and distance from shore (Berrien and Sibunka 1999, Bourne and Govoni 1988, Checkley et al. 1999, Kendall and Reintjes 1975). Reported water temperatures are typically in the range of 13 to 24° C. Depths of approximately <10-20 m are most common. Salinity has been reported to be 29-36 ppt at offshore mid-Atlantic sites and 35.8-36.6 ppt at south-Atlantic sites. Inshore estuarine eggs have been found in waters with salinities of 18-28 ppt in Long Island Sound (Wheatland and Lewis 1956) and 10-22 ppt in Chesapeake Bay (Dovel 1971).

Larvae are carried by inshore currents to estuaries from November to May in the south Atlantic area (Hettler and Barker 1993, Warlen 1994), October to June in the mid-Atlantic area (Reintjes and Pacheco 1966), and May to October in the New England area (Reintjes and Pacheco 1966). Thus, New England larval production spans the end of one spawning season and the beginning of the next (Ahrenholz 1991). Mid-Atlantic larvae are produced during both the southerly fall spawning stock migration and the northerly spring migration. South Atlantic larvae are produced from spawning events during late fall to early spring.

Recorded depth of pelagic larval habitat varies widely from 5 m (Hettler and Hare 1998) to 200 m (Govoni 1993). In the mid-Atlantic, most larvae have been reported at temperatures of 15-20° C and salinities of 20-37 ppt (Kendall and Reintjes 1975). Larger, later-stage larvae being found at lower salinities (Hettler and Hare 1998).

3.3 Juvenile Habitat

Fall immigrants (e.g. larvae in the Chesapeake Bay and south-Atlantic region) begin transformation soon upon arrival in an estuary, but typically do not complete transformation until the following spring due to cool fall and winter water temperature (Ahrenholz et al. 2000). Larvae metamorphose to the juvenile stage in low salinity (<10 ppt) estuarine waters, whereas larger juveniles are found at higher salinities (Hettler and Barker 1993).

In the mid- and south-Atlantic nursery areas, bottom composition is "unconsolidated", consisting of sand mud, and organic material which may be important to juvenile consumption in some areas (Lewis and Peters 1984, Peters and Schaaf 1991). Northern nursery areas are typically found in rocky coves with cobble, rock, and sand bottoms. Temperatures and depth of juveniles vary depending on location and timing of transport to lower salinity areas of the estuary (Forward et al. 1999). Juvenile menhaden remain in their estuarine nursery areas throughout the summer. In fall, most juveniles emigrate southward in schools, however some overwinter in the Chesapeake Bay and south-Atlantic region estuaries.

3.4 Adult Habitat

The major source of information about adult habitat use is information collected from the purse-seine fishery and associated tagging studies (Nicholson 1978). Immature adult menhaden are found in largest numbers in inshore and estuarine areas from Chesapeake Bay southward. Adults make extensive north-south migrations in the near-shore ocean. Older, larger adult menhaden are typically found in colder, rockier northerly habitats during summer. Overwintering occurs somewhere off the coast of North Carolina. Adults appear to prefer temperatures of about 18° C, a potential cause of inshore-offshore migrations.

3.5 Habitat Areas of Particular Concern

Almost all of the estuarine and nearshore waters along the Atlantic coast from Florida to Nova Scotia serves as important habitat for egg, juvenile, and some spawning adult Atlantic menhaden. Pollution and habitat degradation threaten the coastal menhaden population, particularly during the estuarine residency of larvae and juveniles. Concern has been expressed that the outbreaks of ulcerative mycosis in the 1980s may have been symptomatic of deteriorating water quality in estuarine waters along the east coast (Ahrenholz et al. 1987a). Increasing coastal development and industrialization are expected to further reduce water quality unless steps are taken to ameliorate their effect on the environment (Cross et al. 1985). Estuarine and coastal habitats have been significantly reduced and continue to be adversely stressed by dredging, filling, coastal construction, energy plant development, pollution, waste disposal, and other human related activities (ASMFC 1999a). Other potential threats to the coastal menhaden population are posed by the offshore dumping of sewage. Warlen et al. (1977) showed that DDT was taken up by menhaden as a result of their feeding on plankton and detritus.

Estuaries of the mid-Atlantic and south Atlantic states provide most of the nursery areas utilized by Atlantic menhaden at the present time. Areas such as the Chesapeake Bay and the Albemarle-Pamlico system are especially susceptible to pollution because they are generally shallow, have a high total volume relative to freshwater inflow, low tidal exchange, and a long retention time. Most tributaries of these systems originate in the Coastal Plain and have relatively little freshwater flow to remove pollutants. Shorelines of most estuarine areas are becoming increasingly developed despite existing habitat protection programs. Thus, the specific habitats of greatest long-term importance to the menhaden stock and fishery are increasingly at risk.

4.0 Fishery-Dependent Data Sources

4.1 Commercial Reduction Fishery

Menhaden purse-seine vessels are called ‘steamers’, and carry crews of about 14 men. Each steamer also carries two purse boats which hold the net used to encircle a school of menhaden. Purse-seine nets are about 1,200 feet long and may be up to 10 fathoms deep; in Virginia, net meshes can be no smaller than 1-3/4” in stretched length. Airplane spotter pilots locate schools of fish and direct the setting of the net by the purse boat crews via radio. Catches are ‘hardened’ into one corner of the net, then hydraulically pumped into the hold of the steamer. Vessel trips generally last one to three days. Weather conditions permitting, vessels make on average four to five ‘sets’ of the net per fishing day. Smith (1999b) found that on average vessels made at least one set of the net on 76-83% of the available fishing days during May through December.

In Virginia the purse-seine season for menhaden begins on the first Monday of May and extends through the third Friday of November. After the close of ‘Bay Season’, Virginia permits purse-seine fishing in its ocean waters until the Friday before Christmas. Virginia menhaden vessels fish only Monday through Friday. Most menhaden fishing activity occurs in the Virginia portion of Chesapeake Bay from early June through mid-October. Smith (1999b) found that two statistical reporting areas near Smith Point and the Rappahannock River adjacent the fish factory at Reedville accounted for about 50% of the catch and effort by the purse-seine fleet within Chesapeake Bay. Historically, purse-seine fishing for menhaden has been prohibited in Maryland waters of Chesapeake Bay. North Carolina has numerous seasonal and temporal prohibitions on menhaden purse-seine fishing, as well as a minimum mesh size for netting. Beginning in 2006 and through 2010, the harvest of Atlantic menhaden for reduction in Chesapeake Bay was ‘capped’ by the Atlantic States Marine Fisheries Commission (Addendum III to Amendment 1 of the FMP) at 109,020 metric tons per year (with penalties for overages and credits for underages). The fishery has not exceeded the annual cap through 2009.

Each month, the menhaden factory at Reedville reports its daily vessel unloading figures to the NMFS in Beaufort, NC. Vessels maintain daily logbooks which itemize catch and location information for each purse-seine set. Logbook data are supplied to the NMFS at Beaufort on a weekly basis and are used to monitor the ‘Chesapeake Bay Cap’. The NMFS employs a full-time port agent at Reedville to sample catches at dockside throughout the fishing season for age and size composition of the catch.

4.1.1 Data Collection Methods

4.1.1.1 Survey Methods

Official commercial landings of Atlantic menhaden from the reduction purse-seine fleet have been maintained by the Beaufort Laboratory of the National Marine Fisheries Service since 1955. When the Menhaden Program began at the Beaufort Laboratory in the early 1950s, staff visited menhaden plants along the Atlantic coast, obtaining fishery landings for reduction back to 1940. Subsequently detailed landings data from the reduction fishery have been maintained on computer files from 1955 through the present. These reduction landings are maintained by fishing year (March 1 through February 28 of the following year). Landings of Atlantic menhaden for reduction are reported to the Beaufort Laboratory monthly during the fishing year. Daily vessel unloads are provided in thousands of standard fish (1,000 standard fish = 670 lbs), which are converted to kilograms. The biostatistical data, or port samples, for length and weight at-age are available from 1955 through 2008, and represent one of the longest and most complete time series of fishery data sets in the nation. The Captains Daily Fishing Reports (CDFRs, or daily logbooks) itemize purse-seine set locations and estimated catch; vessel compliance is 100%. CDFR data for the Atlantic menhaden fleet are available for 1985-2008.

4.1.1.2 Biological Sampling Methods and Intensity

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). The number of fish sampled in the second cluster was reduced during the early 1970s 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 scales are removed for ageing. June and Roithmayr (1960) performed detailed examinations (validation and verification) of Atlantic menhaden scales and determined that rings on the scales are reliable age marks (more discussion in S20DW04). Information on sample sizes can be found in the Life History section on growth.

4.1.1.3 Ageing methods

See Section 2.3 for a discussion on ageing.

4.1.2 Commercial Reduction Landings

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. The fish are 'hardened' into the bunt of the net, and then pumped onboard the steamer. The contemporary 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. By the 1990s, menhaden meal was being milled in greater quantities into aquaculture feeds. Historically, most menhaden oil was exported to Europe where it was processed into cooking oil or margarines. Since the late 1990s, greater quantities of menhaden oil, a high-grade source of omega-3 fatty acids, are being utilized by the pharmaceutical and processed-food industries of the U.S.

Landings at the menhaden reduction plants have been reported since 1940 and biostatistical samples of the catches have been continuously collected since 1955. A chronology of menhaden plant activity since 1955 is shown in **Table 4.1**. As the directed bait fishery for menhaden has grown in recent years, greater emphasis has been placed on acquiring more representative port samples and more accurate landings records from this segment of the fishery (**Figure 4.1**). Deck logbooks, or CDFRs, maintained by menhaden reduction vessels have helped reduce some sampling biases inherent in harvesting menhaden on distant fishing grounds.

Landings and nominal fishing effort (vessel-weeks, measured as number of weeks a vessel unloaded at least one time during the fishing year) are available since 1940 (**Table 4.2**). Landings rose during the 1940s (from 167,000 t to 376,000 t), peaked during the late 1950s (> 600,000 t for four of five years), and then declined to low levels during the 1960s (from 576,000 t in 1961 to 162,000 t in 1969). During the 1970s the stock rebuilt (landings rose from 250,000 t in 1971 to 376,000 t in 1979) and then maintained intermediate levels during the 1980s (varying between 238,000 t in 1986 when fish meal prices were extremely low to 418,600 mt in 1983). Landings during the 1990s declined from 401,200 t in 1990 to 171,200 t in 1999.

By 1998, the fishery had contracted to only two factories, one in VA and one in NC. Landings dipped to 167,200 t in 2000, rose to 233,700 t in 2001, and then varied annually from 174,000 t to 166,100 t to 183,400 t through 2004. Landings during 2000-04 when the fishery was relatively stable with two plants and about twelve vessels averaged 184,900 t. During 2005 to 2008 only the factory in Virginia operated and landings ranged 141,100 mt (2008) to 174,500 t (2007), and averaged 155,000 t. Reduction landings in 2008 accounted for 75% of total coastwide landings of Atlantic menhaden (bait and reduction combined); this is down from 80% in 2007 and 86% in 2006.

During the 1980s, the menhaden industry suggested that a "topping off" bias occurred in the NMFS' sampling routine. Virginia vessels, returning from more northerly waters with presumably larger and older fish, often made one final purse-seine set on relatively smaller and younger fish in Chesapeake Bay to "top off" the fish hold. Since port agents sample the top of the hold and hence the final set of the trip, larger and older fish could have been under-represented in the catch-at-age matrix. Annual CDFR data sets for 1985-2008 were used to better apportion weekly-plant catches by fishing area and to correct for this bias. Coastwide, only minor differences were found in catch-at-age estimates used for management. 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.

Smith (1999b) 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 t annually. Spotter aircraft assisted in 83% of the sets. Regionally, median catch per set was: 24 t off Rhode Island, New York, New Jersey and Delaware; 23 t off the ocean beaches of Virginia; 18 t in the Virginia portion of Chesapeake Bay; 26 t off North Carolina in summer; and 38 t off North Carolina in the fall fishery.

In recent years, median catches in Chesapeake Bay have been near equivalent at 21 mt in 2006, and 22 mt in 2007 and 23 mt in 2008. 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 t annually, a 28% decline versus 1990-99 when removals from the Bay averaged 145,700 t per year.

Commercial Catch Statistics from Historical Reports, 1879-2000

Atlantic menhaden commercial landings are available from a series of historical publications dating back to 1880. These include annual reports (*Fishery Industries of the United States*, 1920-1939, *Fishery Statistics of the United States*, 1939-1977, and *Fisheries of the United States*, 1966-2007). These data reported are available on excel spreadsheets, organized by state within region (New England, Middle Atlantic, Chesapeake Bay, and South Atlantic) for 1879-2000 (S20DW02). These data are summarized by calendar years 1879-1989 (Fisheries Statistics Division 1990), but they are not identified by gear, so these commercial landings are assumed to include both those for reduction and for other commercial uses (e.g., bait).

Landings are incomplete from 1879 to 1928, followed by occasional data gaps by region through 1949. In particular, the South Atlantic region provides no landings information for 1941-1944 and 1946-1949. This has also been noted for other South Atlantic species (e.g., Spanish mackerel and snapper-grouper species in other SEDAR assessments). With detailed reduction landings available beginning in 1940, we considered using the difference to help fill in for non-reduction landings from 1940 (or 1950) through 1984 Because of the gaps in the data, particularly by region, we have used a process of linear interpolation to fill these gaps on a regional basis. These interpolated values are highlighted in **Table 4.3**.

When comparing these catch statistics from Historical Reports (as interpolated) with the historical reduction landings maintained at the NOAA Fisheries Laboratory in Beaufort, NC, they compare fairly closely (**Figure 4.2**). Obviously there are some exceptions, including 1940 and interpolated value for 1942. There are more recent years when the deviations become more noticeable. It would be nice to ascribe these to bait landings (purse seines for bait and other gears), and this may be true for some years. However, there are other years when reduction landings exceed “Historical Records”. Regardless, these data do seem to provide a means of reconstructing menhaden landings back to 1880, with obviously some increased level of uncertainty, in part due to the interpolation process.

Menhaden Fishery, 1873-1964

We recently discovered an anonymous report titled, *Menhaden Fishery, 1873-1964.* This report, which can be found in USFWS (1966), contains a summary of landings in the menhaden fishery from 1873 – 1964 (a scanned pdf file is available). It was soon apparent that the landings presented include menhaden landings from both coasts: Atlantic and Gulf of Mexico. The landings data ("fish received") are in thousands of pounds, and then converted to thousands of metric tons (kmt) (**Table 4.4**). First we compared the historical commercial landings from the previous section for both Atlantic and gulf menhaden to confirm our suspicions. Then we computed the average percent (2.5%) of gulf menhaden landings to Atlantic menhaden landings for the period 1918-1940. This proportion was applied to the menhaden landings from 1873-1917 to separate landings between the two coasts (**Figure 4.3**).

In the back of this report, the author(s) indicate that this report was published in Statistical Digest No. 30 and revised and updated in Statistical Digest No. 57. These Statistical Digests are described as "Fisheries Statistics of the United States" with appropriate year. These results should be identical with those landings reported in the previous section. However, this report seems to contain landings (albeit not at the state level) for many years not otherwise available, and can thus be used to extend landings back to 1873, and may provide an alternate method for filling in missing years when available only from this source. Both data sources appear to be weak for the period 1899 to 1921. Generally these historical data sets agree reasonably well where they overlap as shown in **Figure 4.3**.

ACCSP Commercial Landings, 1950-2008

Atlantic menhaden commercial landings are also available through the Atlantic Coast Cooperative Statistical Program (ACCSP). Commercial landings are available by gear (purse seine, poundnet, and other) for calendar years from 1950-2008 (**Table 4.5**). These data were provided in final download by Julie Defilippi (Data Coordinator ACCSP) on 15 June 2009.

Historical commercial landings (1950 to present) for the Atlantic coast are maintained in the Atlantic Coastal Cooperative Statistics Program (ACCSP) Warehouse. The Warehouse was queried on 12 May 2009 for all menhaden landings (annual summaries by state and gear category) from 1950 to present for Florida (east coast), Georgia, South Carolina, North Carolina, Virginia, Maryland, Delaware, New Jersey, New York, Connecticut, Rhode Island, Massachusetts, New Hampshire and Maine. (ACCSP 2009). Data workshop gear categories were determined to be purse seine, pound net and other. The data were presented with specific ACCSP gear and gear category.

Purse-seine landings were the dominant gear (95.9%), but purse seine gears cannot be separated between that for reduction and bait. Pound nets of various types rank next with 3.3% over the 1950-2008 period. Other gears such as gill nets (0.17%), trawls (0.03%), not coded (0.12%) and combined gears (0.19%) were quite small, and in aggregate are 0.8% of total commercial landings. We compared collective (i.e., reduction and bait) purse-seine landings reported by ACCSP to the purse seine landings from the reduction fishery maintained by the NMFS in Beaufort, NC (**Figure 4.4**). The higher purse seine landings in recent years reflected the increase in bait landings by purse seine (predominantly in Virginia and New Jersey). However, there is no apparent explanation for why reduction landings exceed collective purse seine landings in other years (as recently as early the 1990s).

Menhaden landings for other than purse seine were available from this data set for 1950-2008. However, more detailed bait landings have been developed through the ASMFC (first AMAC and now AMTC) for 1985 to the present. Bait landings by purse seine were recorded for Maine, Massachusetts, Rhode Island, New Jersey, Virginia and North Carolina since 1985 (and only in 2003 for New York). However, it is difficult to consistently separate out purse-seine landings for bait from purse-seine reduction landings prior to 1985.

Reconstructed Historical Landings, 1873-2008

For purposes of historical perspective and use in the Stock Reduction Analysis, we reconstructed a time series of Atlantic menhaden landings for 1873-2008 as follows:

Years	Source
1873-1879	Menhaden Fishery, 1873-1964 (S20DW02)
1880-1939	Commercial Catch Statistics from Historical Reports, 1879-2000 (S20DW02)
1940-2008	Reduction Landings: official landings maintained at NMFS Beaufort (S20DW05)
1940-1949	Bait Landings: Average of poundnet & other gear for 1950-1984 (next)
1950-1984	Bait Landings: Poundnet & other gear from ACCSP (S20DW02)
1985-2008	Bait Landings: maintained by ASMFC Menhaden TC from state reporting (S20DW05)
1981-2008	Recreational Catches (MRFSS) (S20DW05)

These reconstructed menhaden landings for 1873-2008 are summarized in **Figure 4.5**. Discussions on recent bait landings can be found in Section 4.2.

4.1.3 Commercial Reduction Discards/Bycatch

Discard or bycatch information in the reduction fishery is undocumented. However, it is suspected that bycatch and discards of menhaden are trivial compared to total landings.

4.1.4 Commercial Reduction Catch Rates (CPUE)

Because of the lack of an adult abundance index, the last peer review panel (ASMFC 2004b) provided the following recommendations:

> • *Evaluate commercial purse seine fishery effort (vessel/weeks) series as a possible tuning index in the model. Evaluate any measure of effort contained in this or other data series.*
>
> • *Evaluate the data collected in the Captain's Daily Fishing Reports for an adult abundance index. If these data are not useful, explore the utility of a commercial fishery-based index, developed jointly with the fishermen, for future assessments.*

In general, fishery-dependent indices of abundance are viewed with suspicion, particularly for purse-seine fisheries (Clark and Mangel 1979; Condrey 1984). In particular, the catchability coefficient for menhaden fisheries has been demonstrated to be inversely related to population abundance (Vaughan 1987; Vaughan and Smith 1988; Vaughan et al. 1996, 2000). Any attempt to incorporate menhaden CPUE into the model structure will need to acknowledge this relationship. Recently, a special workshop of SEDAR was held to address the issue of time-varying catchability, and a report has been drafted. Recent papers by Wilberg and Bence (2006) and Wilberg et al. (2010) address this issue.

We summarize in the following sections estimates of nominal fishing effort estimated by three approaches: (1) the traditional vessel-week, (2) number of trips, and (3) number of sets.

Effort Based on Vessel-Week, 1940-2008

Historic catch summations and estimates of fishing effort in the menhaden purse-seine fishery for reduction are based on company records of individual vessel unloads. At dockside, menhaden are hydraulically pumped from the carrier vessel, or 'steamer', into a rotating hopper device. By convention and throughout the industry, each segment of the hopper volumetrically holds 1,000 'standard' fish. The actual number of fish of course varies with the size of the fish, but each measure of fish is estimated to weigh 670 pounds (June and Reintjes 1959). Companies report daily vessel unloads in terms of 1,000 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, or days when the catch was 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 1971a). 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 1940-2008 (**Table 4.6**). Similar trends in menhaden reduction landings and nominal effort (vessel-weeks) have been noted (**Figure 4.6**).

Effort Based on Trip, 1955-2008

Detailed catch data are available from the menhaden reduction fishery since 1955, representing almost 180,000 trips. In addition to landings, variables included in these files are offload date (year, month, and day), plant, and vessel. Location of fishing beyond plant location is not available on these records. To perform a more detailed analysis (e.g., general linear model) of these data, more detailed information on fishing location was thought useful. To accomplish this task, the landings record files were merged with the biostatistical sampling files at the trip level. Biostatistical samples are obtained from the top of the vessel hold, representing the location of the final set. These samples have been collected using a two-stage sampling framework since 1955 (Chester 1984). Information from this latter data set included not only fish length, weight and age, but also fishing location by general area (South Atlantic, Chesapeake Bay, Middle Atlantic, and New England) and by latitude (34^o to 44^o North in units of 10' arc). The merged data set contained almost 30,000 trips, or about 17% of all trips made between 1955 and 2008. Sample sizes are summarized by year and area in **Table 4.7**.

First, a simple annual landings per trip was calculated for both the complete landings file and for the merged subset file (**Figure 4.7**). Temporally, within-year factors were based on either month or season (Mar-May, Jun-Aug, Sep-Nov, and Dec-Feb) based on the fishing year of March 1 – February 28. Geographic area was based on either area or more finely on latitude. Separate GLMs were run using either the coarse level (area and season) or fine level (latitude and month). Furthermore, separate GLMS were run assuming either normal error (untransformed) or lognormal error (natural log transform). These analyses were run with PROC GLM in SAS and annual trends were obtained from the LSMEANS option. For the GLM runs on the lognormal catch per trip, the annual results from the LSMEANS option were retransformed back to normal space by applying the exp of LSMEANS plus bias corrections (RMSE/2). The results using "coarse" input data were compared to the averages (**Figure 4.7**). All factors were found to be highly significant. Overall, variance explained by the various GLMs ranged between 34% and 47%, with higher R^2 values for the finer input data.

Estimates of nominal fishing effort for Atlantic menhaden reduction fleet for 1955-2008 were compared (**Figure 4.8**). Measures of nominal effort for this comparison included: (1) vessel-week, (2) trips (all landings data), and (3) GLM LSMEANS (additive model) based on subset of trips. All effort estimates were standardized by dividing by respective value in 1955. The trends noted included a rapid decline in effort during the 1960s, a period of poor recruitment and low stock abundance. Effort temporarily stabilized during the 1970s, as the stock was rebuilding.

Declines in the 1980s were associated with low meal prices, and in 1986 one of the Reedville, VA, plants did not operate for economic reasons.

Effort Based on Sets, 1985-2008 (CDFRs)

Beginning in the late 1970s, the menhaden industry, state fisheries agencies, and the NMFS entered into a joint program called the Captains Daily Fishing Reports 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 catch, and distance from shore. Since the mid-1980s, compliance by menhaden fleets in Virginia and North Carolina has been almost 100%. CDFR data sets for fishing years 1985 through 2008 have been computerized at the NMFS Beaufort Laboratory. Smith (1999) summarized CDFR catch and effort information for fishing years 1985-1996.

CDFR catch records for fishing years 1985-2008 were concatenated into one large data set containing over 190,000 records of purse-seine sets by the Virginia and North Carolina menhaden fleets. Variables in the file include plant, vessel, set date (year, month, and day), set start and set finish times, fishing location, and an at-sea estimate of catch in metric tons. Analyses of catch per set were calculated in various ways. First, mean annual catch per set was calculated for all sets (**Table 4.8**). A pair of GLM analyses were also conducted assuming either normal or lognormal error. The GLMs used the following class variables as factors: year, plant, month, area, duration, and vessel. An index of annual catch per set was obtained using LSMEANS as in the analyses for catch per trip. All results show a peak in 1986 when one of the two plants in Chesapeake Bay did not operate because of low fish meal prices.

We scaled the different CPUE indices by dividing by their respective time series means for 1985-2008. We compared the observed CPUEs in **Figure 4.9.** In general, similar patterns were obtained from the different approaches to estimating fishery-dependent catch per effort from the menhaden reduction fishery. Finally, we compared the nominal effort obtained from these approaches (**Figure 4.10**) for the period 1985-2008. All three approaches for estimating nominal effort (vessel-week, trips, sets) showed similar patterns for this recent period. Following a period of low effort and low meal prices during the mid-1980s, effort peaked about 1990-1991, and has subsequently declined since then. Although we do not suggest that declining effort since 1990 implies declining fishing mortality, we note that the decline in fishing mortality found in past assessments can be explained in part by this decline in effort.

In general, we are wary about using fishery dependent CPUE as a measure of population abundance and effort as a measure of fishing mortality. This is particularly true for a purse-seine fishery such as for Atlantic menhaden.

4.1.5 Commercial Reduction Catch-at-Age

Detailed sampling of the reduction fishery permits landings in biomass to be converted to landings in numbers at age. For each port/week/area caught, biostatistical sampling provided 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 allowed the numbers of fish landed to be estimated. The age proportion then allowed numbers at age to be estimated. Adjustments in these estimates (using CDFRs) were made to account for potential bias resulting from "topping off" by vessels returning to Chesapeake Bay from outside and taking a final set before offloading (Chester 1984; Smith 1999). Developing the catch matrix at the port/week/area caught level of stratification provides for considerably greater precision than is typical for most assessments.

About 2,650 Atlantic menhaden from the reduction fishery have been processed annually for size and age composition over the past three fishing seasons, 2006-08 (**Table 4.9**). In comparing menhaden sampling intensity to the rule-of-thumb criteria used by the Northeast Fisheries Science Center (e.g. <200 t/100n), this sampling level might be considered low, although the results of Chester (1984) suggest this sampling level is relatively high.

In two of the past three years, age-2 Atlantic menhaden have comprised 60% or more of the total numbers of fish landed (**Table 4.10**). In 2006 the age composition of the coastwide landings for reduction was 1% age-0's, 40% age-1's, 40% age-2's, and 19% age-3+'s; in 2007, it was <1% age-0's, 26% age-1's, 65% age-2's, and 8% age-3+'s; and in 2008, it was 1% age-0's, 9% age-1's, 68% age-2's, and 22% age-3+'s. Overall mean weights of Atlantic menhaden for reduction in port samples for 2006 through 2008 were 225 g, 196 g, and 246 g, respectively.

4.1.6 Potential Biases, Uncertainty, and Measures of Precision

When the menhaden program began in the early 1950s at Beaufort, staff visited all menhaden plants along the Atlantic coast to obtain detailed information back to 1940. These landings and those subsequently collected are thought to be quite accurate. A study[1] 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 holds). Landings from earlier years, particularly those reconstructed through either linear interpolation for missing year data or through proportion of landings of Atlantic menhaden vs gulf menhaden are clearly subject to greater uncertainty. Reduction landings since 1940 are believed to be both accurate and precise compared to most other fisheries.

Development of catch matrices depended 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[2]. The catch matrix was built from samples by port, week and area fished as noted in section 4.1.5. Concerns about bias related to "topping off" by vessels from Reedville fishing outside its fishing area have been addressed through post stratification using the Captain's Daily Fishing Reports.

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[1] "Verification of menhaden conversion factor", prepared by Joseph Kutkuhn (JHK), 1-26-66. PDF available.
[2] "Instructions for menhaden sampling program", revised May 1995 by Joseph Smith. PDF available.

Uncertainty associated with ageing: During the early decades of the Menhaden Program at NOAA's 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. EAH was instructed to re-assign estimated ages, but not to make measurements to successive annuli (as per protocols for general menhaden ageing at the Beaufort Laboratory). Both sets of age estimates were stored in dBase files and analyzed in SAS.

A total of 3,711 fish were re-aged from the 2008 fishing season; samples from the reduction and bait fisheries were pooled. Ages ranged from age-0 to age-5. Overall, 80.3% (n = 2,978) of the paired readings agreed. Within age classes, younger ages (ages-0 through age-3) showed the best agreement versus older specimens (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). Agreement for age-4's was considerably less at 51.9% (n = 111), while agreement for age-5's was poor at 19.1% (n = 4). Most disagreements for ages-1, -2, and -3 were +/- one year (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 0.041, suggesting generally good agreement between readings.

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 crab pots, lobster pots, and hook and line fisheries (both sport and commercial, often as ground chum). A specialized use involves live menhaden as bait for coastal pelagic fishes (ASMFC 2001); however, no data are available to quantify these landings, which are usually taken by cast net or beach seine for personal bait or supplied to tournaments. Information on the harvest and use of menhaden for bait is often difficult to obtain because of the nature of the bait fisheries and the various data collection systems. Bait harvest comes from directed fisheries, primarily small purse seines, pound nets, and gill nets, and by-catch in various food-fish fisheries, such as pound nets, haul seines, and trawls.

Since the mid-1990s the Atlantic Menhaden Technical Committee (AMTC), and its predecessor the Atlantic Menhaden Advisory Committee (AMAC), recognized the increasing importance of landings of Atlantic menhaden for bait. Consequently, the AMTC has strived to better quantify bait landings through better reporting and to characterize bait landings through better port sampling information. The AMTC has determined that accurate bait landings are only available since 1985. The AMTC continues to develop and update the reported annual coastal bait landings for all gear types.

Commercial landings of menhaden for bait occur in almost every Atlantic coast state. The bait fishery utilizes a wide variety of gear and fishing techniques. Landings come from both directed menhaden fisheries, which make up the majority of the bait landings, and from non-directed, by-catch fisheries.

As mentioned earlier, the presumed growth of the Atlantic coast bait fishery must be tempered by the knowledge that systems for reporting bait landings have historically been incomplete, particularly for Atlantic menhaden. In most cases, recent landings estimates are more accurate, although for some states bait landings may still be underestimated. The nature of the fishery and its unregulated marketing are causes of the under-reporting problem. There are some well-documented, large-scale, directed bait fisheries for menhaden using gears such as purse seines, pound nets, and gill nets. There are also many small-scale bait fisheries and by-catch fisheries whose catch may be under-reported. Menhaden taken as by-catch in other commercial fisheries is often reported as "bait" together with other fish species. Some "over-the-side" sale of menhaden for bait by commercial fishermen may go unreported. Common practices such as utilizing menhaden for bait or chum in sport fishing tournaments is difficult to estimate when quantity sales are made to individual marinas and fishing clubs (ASMFC 2001).

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. Catch-per-unit-effort (CPUE) data, pounds caught per hour set, and pounds caught per yard of net set are also reported for directed gill net fisheries in some states.

In New England, purse-seine landings in Maine, Massachusetts, and Rhode Island account for the majority of the recorded bait landings. An ocean trap 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 utilized 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 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. 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).

4.2.1.1 Survey Methods

Prior to about 2006, biological sampling of bait landings had mostly been focused on directed-bait, purse-seine vessels in North Carolina, Virginia, and New Jersey. As adult menhaden have returned to more northern waters in recent years, additional effort has been made to acquire port samples from bait purse seines and pound nets in Narragansett Bay and purse seines in southern Maine (**Table 4.11**). Protocols for acquiring size-at-age data from the bait fisheries are similar to sampling procedures for the reduction fishery. In Virginia, a federal port agent meets bait vessels at dockside and then processes samples for size and age composition; samples from pound nets are made at dockside. In New Jersey most menhaden bait samples are acquired and frozen by the bait companies. New Jersey Fish and Wildlife personnel batch process the bait samples for length and weight; scale samples are aged at the Beaufort Laboratory. Likewise in Rhode Island, Massachusetts, and Maine, state fisheries personnel acquire bait port samples at dockside, process specimens for length and weight, then they ship scale samples to the Beaufort Laboratory. Sampling for bait has been at a similar level to that of the reduction fleet for North Carolina, Virginia, and New Jersey. Sampling intensity has increased recently in Massachusetts, Rhode Island, and Maine.

4.2.1.2 Biological Sampling Methods and Intensity

Sampling of the bait fishery for size and age has generally improved since 1988, especially beginning in 1994 when the AMAC emphasized greater biological sampling of the bait fishery (**Table 4.11**). 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. 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 million pounds of Atlantic menhaden was recommended. When fewer than two collections were suggested, then at least two to three collections were recommended. Bait landings were so low in New Hampshire, Connecticut, South Carolina and Georgia that no samples were recommended. In 1993, most of the recommended samples targeted Maine (10-20 collections), Rhode Island (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.

4.2.1.3 Ageing Methods

Same procedure as for reduction fishery samples, see Life History section on ageing.

4.2.2 Commercial Bait Landings

The commercial fisheries for Atlantic menhaden consist primarily of directed purse-seine fisheries for reduction and bait, and are nearly the exclusive sources of fishery-dependent data for the stock. As reduction landings have declined in recent years, menhaden landings for bait have become relatively more important to the coastwide total landings of menhaden. A mixed species aggregate by-catch of menhaden from pound nets, gill nets, and trawls also exists in several states; however, the landings are minor compared to the purse-seine fisheries.

Coastwide bait landings of Atlantic menhaden have gradually increased from 1985 to present (**Table 4.2**). During 1985 to 1989 bait landings averaged 30,485 mt, and landings peaked at 36,257 mt in 1988. During the 1990s bait landings averaged 32,425 mt, with peak landings of 39,194 mt in 1998. Between 2000 to present average bait landings for the coast increased again to 35,967 mt. After falling to 26,768 mt in 2006, bait landings rebounded to 44,563 mt in 2007, and rose further to peak landings for the time series of 46,674 mt in 2008.

In recent years (2006-2008) bait landings have averaged 20% of the total coastwide Atlantic menhaden landings (including landings for reduction) (**Figure 4.1**). This is up from an average of 11% of total landings for the period 1985-2000. The relative increase of 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, and the decline in coastal reduction landings because of plant closures.

Bait landings during 1985 to 1993 were widely distributed along the coast with major contributions from Maine, Massachusetts, Rhode Island, New Jersey, the PRFC, Virginia, North Carolina, and Florida (**Figure 4.11**). 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 about Long Island Sound and north after 1993; the decline in landings in Florida was no doubt due to the state's 'net ban' in 1995. From about 1998 to present coastwide bait landings have been dominated by contributions from two areas, namely, New Jersey and Chesapeake Bay; within the latter area, landings in Virginia dominate over those from Maryland and the PRFC. Thus, bait landings in Chesapeake Bay (all gears combined) beginning in 1998 accounted for on average 63% of coastwide bait landings. Bait landings in New Jersey for the same time period accounted on average for 32% of coastwide bait landings.

In terms of gear, on average purse seines accounted for 78% of all coastwide bait landings in recent years (2001-2008). Purse-seine fisheries for bait operate predominately in New Jersey and Virginia, with recent contributions from Narragansett Bay (Rhode Island and Massachusetts) and Maine (2008). A small purse-seine fishery for bait existed in North Carolina, but it ceased operation after 2003. Within Virginia in recent years (2000-2008), purse seines on average accounted for 87% of the bait landings by gear; likewise in New Jersey, on average purse seines accounted for 97% of that state's bait landings by gear (2000-2008).

Pound net and small scale directed gill net fisheries for menhaden as bait exist in many states. These fisheries account for the majority of the remaining bait landings coastwide. Additionally, menhaden for bait are taken as an aggregate by-catch in other coastal states by a variety of gears such as trawls, haul seines, traps, and cast nets.

To better document menhaden bait landings by purse seines in Virginia (snapper rigs), the AMAC requested that Virginia bait vessels voluntarily complete CDFRs during 1995-2001. With the adoption of Amendment 1 to the FMP, Virginia snapper rigs, beginning in 2002, were required to report their daily catches on CDFR forms, which are compiled at the Beaufort Laboratory. Bait vessels in New Jersey comply with Amendment 1 by completing daily logs documenting the amount and location of menhaden harvested to the NJ Division of Fish and Wildlife. The former bait purse-seine fishery in North Carolina reported daily catch activity on a state trip ticket to the NC Division of Marine Fisheries. Purse-seine vessels operating Narragansett Bay, RI report their daily catches to the RI Department of Environmental Management; similarly, purse-seine vessels operating in Maine waters report catches to the ME Department of Marine Resources. Recently, bait landings are again expanding in the New England area.

In the 2006 Atlantic Menhaden Assessment Update, concern was raised about unreported landings from Virginia bait purse seines during 1993-1997. As an alternate data input for subsequent model runs, Virginia bait landings for 1993-1997 were linearly interpolated from estimated values for 1992 and 1998. Thus, a second set of bait landings (alternate) was developed for analysis.

Staff at the Beaufort Laboratory recently 'discovered' daily catch records (= CDFRs) which were completed by two of the three or four Virginia 'snapper rigs' operating in 1995-1997. The data were probably overlooked because the entire 'snapper rig' fleet had not yet (not until 1998) enrolled in the voluntary CDFR reporting program to document their daily landings. For this assessment a preferred set of Virginia bait landings for 1995, 1996, and 1997 incorporates:

- reported landings by two vessels for all three years,
- average landings of a third vessel for 1999 and 2000, years when it joined the voluntary reporting system for all three years, and
- estimated landings for a fourth vessel, which only operated in 1995, based on reported landings of a similar-sized vessel which did report in 1995.

Landings for 1993 and 1994 were linearly interpolated from estimated values in 1992 and 1995.

Menhaden landings for gear other than purse seine are available for 1950-2008 (**Figure 4.12**). These are recommended for use in developing historical bait landings for 1940-1984. It is difficult to consistently separate out purse-seine landings for bait from purse-seine reduction landings prior to 1985.

4.2.3 Commercial Bait Discards/Bycatch

Discard or bycatch information in the bait fishery is undocumented. However, it is suspected that bycatch and discards of menhaden are trivial compared to total landings.

4.2.4 Commercial Bait Catch Rates (CPUE)

Pound net landings collected by the Potomac River Fisheries Commission (PRFC) were used to develop two fishery-dependent indices of relative abundance for adult menhaden. The pound net is a stationary presumably nonselective fishing gear that is used to harvest fishes in the Potomac River of Chesapeake Bay, including menhaden primarily aged-1 through 3 years. Other than the reduction landings, these data represent the only other available information that can be used to infer changes in relative abundance of adult menhaden along the east coast of the U.S.

The first catch-per-unit-effort (CPUE) index was calculated as annual ratios of total pounds landed to total pound net days fished. Raw catch and effort data were available for the years 1976-1980 and 1988-2008. Recently, the PRFC was able to obtain and computerize more detailed data on pound net landings and effort, which allowed index values to be calculated for 1964-1975 and 1981-1987 (Carpenter 2005). To generate estimates of pound net landings (PN) for the missing years, a linear regression was fitted to annual PN and published landings (PB):

$$PN = 219035.8 + 0.953 \cdot PB ,$$

which had an R^2 value of 0.996 and was highly significant ($p < 0.001$, $n = 26$). During 1964–1993, there were no restrictions on the number of licenses sold to fishers operating in the Potomac River, however after 1993, the number of licenses was capped at 100 (A. C. Carpenter, PRFC, personal communication). Therefore, to generate estimates of pound net days fished (DF) for the missing years, a second linear regression was fitted to DF as a function of the number of licenses (L):

$$DF = 3094.2 + 17.944 \cdot L ,$$

which had an R^2 value of 0.485 and was significant at an α-level of 0.104 ($n = 11$). The shorter period of overlap among DF and L and greater variability associated with the regression increases the uncertainty of the index for the reconstructed years, but not for the most recent years (1988–2008). This index was constructed in the same manner as those used for the 2003 and 2006 menhaden assessments, and it shows a variable trend over time with low values in the 1960s-1970s, peak values in the early 1980s, and intermediate values in recent years (**Figure 4.13**)

The second index was based on a generalized linear model (GLM). To identify the appropriate computational form of the index, four probability density/mass functions were fitted to the CPUE data (PN/DF) via the method of maximum likelihood: normal, lognormal, gamma, and negative binomial (Dick 2004). The distribution of the CPUE data were evaluated for each year separately; that is, the data were collapsed over months and areas to allow for sufficient sample sizes when fitting the density/mass functions. It was reasoned that pooling across months and areas would provide a better indication of the actual distribution of catches possible for a given year. All probability density/mass functions were fitted using the software package R, version 2.9.2 (R Development Core Team, 2009).

An information-theoretic approach was used to select from the set of candidate distributions fitted to the CPUE data (Burnham and Anderson 2002). Akaike's Information Criterion (AIC) was used to select the best of the competing distributions:

$$\mathrm{AIC} = -2 \cdot \ln(l(\theta)) + 2p$$

where $l(\theta)$ is the value of the maximized likelihood for the probability density/mass function of the fitted distribution and p is the number of estimated parameters. Models were compared using ΔAIC, where ΔAIC is the difference between the AIC values for each candidate distribution and the AIC value for the distribution with the smallest AIC. While AIC may be valuable for model selection, it may not necessarily permit identification of the true underlying distribution of the CPUE data (Burnham and Anderson 2002; Dick 2004)

The results of the distributional analysis suggested that the pound net CPUE data generally followed the negative binomial distribution. For the candidate distributions considered, 62% (16 out of 26 years) of the ΔAIC values associated with the negative binomial were zero, followed by 34% (9 out of 26 years) for the lognormal (**Figure 4.14**). The gamma distribution had a ΔAIC of zero for 4% (1 out of 26 years) and the normal distribution was not supported for any years. Given these results, four parameterizations of a negative binomial GLM were fitted to the CPUE data: Model 1 specified *year*, *month*, and *area* (location of the pound net in the Potomac River) as fixed factors; Model 2 included *year* and *month*; Model 3 contained *year* and *area*; and Model 4 specified only *year* effects. The aforementioned approach used to fill in missing years could not be utilized within the GLM framework because relationships among PN to PB and DF to L could not be constructed for all levels of the model parameterizations. Hence, this second index of abundance spans a restricted number of years when compared to the first index. Again AIC was used to discriminate among competing models, and fits were achieved using the software package R, version 2.9.2 (R Development Core Team, 2009).

AIC based evaluation of the negative binomial GLM analysis strongly suggested that Model 1 provided the best fit to the data (**Table 4.12**). It should be noted that the year 1988 had to be omitted from the analysis due to low sample size within the various levels of the factors for Model 1. The trend of the index is variable but decreasing from 1989 to 2003 followed by a fairly sharp increase in recent years (**Figure 4.15**)

4.2.5 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). Recently, landings have been primarily from the Mid-Atlantic and Chesapeake Bay regions (**Figure 4.16**). 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 and 1996-2006. Data for 1985 was kept separate because these were particularly small fish. For the Mid-Atlantic region, data for 1994-2008 were pooled and substituted for individual years 1985-1993 and 2004-2005. For the Chesapeake Bay region, data for 1992-2008 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) 1997-2008. Years within the respective temporal periods for which substitution was necessary were 1988-1990, 1992, 1996, 1999-2001, and 2003-2008. The resultant catch-at-age matrix for the bait fishery is shown in **Table 4.13**. So as not to completely ignore the small amount of recreational catches (see next section), the catch matrix was inflated to reflect these additional landings. The inflation was based on a regional basis.

From 1985-2000, 75% of the bait landings were age-2 and -3 menhaden (45% and 30%, respectively), with ages-1 and -4 significantly contributing to the landings (11% and 13%, respectively). Recently (2001-2008), age-2 and -3 menhaden comprised over 84% of the bait landings (54% and 31%, respectively), with age-1's comprising 8% and age-4's comprising 7%. Lower percentages for age-3 menhaden were obtained for the reduction fishery, ranging between 8% for 1985-2000 and 15% for 2001-2008.

4.2.6 Potential biases, Uncertainty, and Measures of Precision

Greater uncertainty is expected for the bait fishery as compared to the reduction fishery. Landings reconstructed for 1940-1984 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 aging.

4.3 Recreational Fishery

4.3.1 Data Collection Methods

It was brought to our attention recently that the Marine Recreational Fisheries Statistics Survey (MRFSS) contained estimated Atlantic menhaden catches. These were downloaded from

http://www.st.nmfs.noaa.gov/st1/recreational/queries/index.html

using the Custom Query option.

4.3.1.1 Survey Methods

See MRFSS online for discussion of methods:
http://www.st.nmfs.noaa.gov/st1/recreational/overview/overview.html#meth

4.3.1.2 Biological Sampling Methods and Intensity

Insufficient biological samples were available to develop a recreational catch at age matrix. See Section 4.3.5 for a discussion of the treatment of recreational landings.

4.3.2 Recreational Landings

Estimated recreational catches are reported as number of fish harvested (Type A+B1) and released alive (Type B2) (**Tables 4.14 and 4.15**, respectively). 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)], wave [six 2-month periods].

To put these removals into perspective, reduction landings have been on the order of 200,000 mt, bait landings around 30,000 to 40,000 mt, and recreational landings on the order of 300-400 mt. In general, the recreational landings represent less than about 1% of the combined bait and reduction landings, and at most 3% in 2006.

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 was by castnet, the judgment of the data workshop participants was that 50% 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 4.16**.

4.3.4 Recreational Catch Rates (CPUE)

Available recreational data was insufficient to calculate recreational catch rates.

4.3.5 Recreational Catch-at-Age

There are additional complications for estimating total biomass of fish dying due to recreational fishing. Because observed fish weights at this basic cell level are not always available for converting landings in numbers to landings in weight, or sample sizes are very small resulting in spurious estimates, reporting harvest (A+B1) in weight typically underestimates the actual harvest weight. Also, catches of released alive (B2) fish are only available in numbers. To provide estimates of harvest (Type A+B1) in weight, the catch records are retained at the basic cell level for which both harvest in numbers and harvest in weights are available. These landings were then pooled by region (NE, MA, SA) and the ratio used to obtain an average weight by region. Because it is remarkable that anglers would release menhaden, we make the assumption that the size (mean weight) of the B2 caught fish is similar to that of the A+B1 fish and combine them in calculating our harvest in weight. Thus, the average weight was applied by region to total harvest (A+B1+0.5*B2) in numbers to obtain harvest in weight (**Table 4.17**).

For handling this source of mortality in our models, the decision of the data workshop participants was to combine the recreational landings with bait landings. Specifically, the bait catch-at-age matrix will be expanded to reflect these additional landings in numbers applied regionally and then combined.

4.3.6 Potential biases, Uncertainty, and Measures of Precision

Uncertainty associated with recreational landings (MRFSS) is substantial, but probably no worse than for bait. The MRFSS provides estimates of PSE (proportional standard error) as a measure of precision in **Table 4.16**. With few exceptions, these values range between 15% and 30% and none exceed 50%. It can be noted that values under 20% are considered to be “good”. Potential biases are unknown.

5.0 Fishery-Independent Data – Juvenile Abundance Surveys

Data collected from seine surveys conducted within several states along the east coast of the U.S. were used to develop two indices of relative abundance for juvenile menhaden. The primary objective of these seine surveys was to measure the recruitment strength of species other than menhaden, that is, the underlying sampling protocols were designed to target juvenile striped bass, alosines, or other fishes and species complexes. Although menhaden are a bycatch species in these surveys, the seine catch-per-haul data represent the best available information for the construction of a menhaden juvenile abundance index (JAI).

The calculation of the menhaden JAI was based on data from the following state seine surveys:

- North Carolina alosine seine survey (1972-2008)
- Virginia striped bass seine survey (1968-1973, 1980-2008)
- Maryland striped bass seine survey (1959-2008)
- Connecticut seine survey (1987-2008)
- New Jersey seine survey (1980-2008)
- New York seine survey (1986-2008)
- Rhode Island seine survey (1988-2008)

5.1 Data Collection and Treatment

5.1.1 State Seine Survey Methods

The North Carolina Alosine seine survey (Program 100S) has operated continuously from 1972-present in the Albemarle Sound and surrounding estuarine areas. The survey targets juvenile alosine fishes and sampling is conducted monthly from June through October.

The Virginia striped bass seine survey was conducted from 1968-1973 and 1980-present. The survey targets juvenile striped bass following a fixed station design, with most sampling occurring monthly from July through September and occasional collections in October and November. In 1986 the bag seine dimensions were changed from 2 m x 30.5 m x 6.4 mm to the “Maryland” style seine with the dimensions 1.2 m x 30.5 m x 6.4 mm. Rivers sampled in the southern Chesapeake Bay system include the James, Mattaponi, Pamunkey, Rappahannock, and York.

The Maryland striped bass seine survey targets juvenile striped bass and has operated continuously from 1959-present. Survey stations are fixed and sampled in June and September with a beach seine of dimensions 1.2 m x 30.5 m x 6.4 mm. Permanent stations within the northern Chesapeake Bay system are sampled in four regions: Choptank River, Head of Bay, Nanticoke River, and Potomac River.

The New Jersey seine survey targets a variety of fishes and has operated continuously in the Delaware River from 1980-present. The sampling scheme has been modified over the years but the core survey area, sampling locations, and field time frame (June–November) have remained consistent. The current sampling protocol, which was established in 1998, consists of 32 fixed stations sampled twice a month from June through November within three distinct habitats: Area 1 – brackish tidal water; Area 2 – brackish to fresh tidal water; Area 3 – tidal freshwater. A beach seine with dimensions 1.8 m x 30.5 m x 6.4 mm is used for sampling.

The Connecticut seine survey targets juvenile alosines in the Connecticut River and has continuously operated from 1987-present. Sampling occurs monthly from July through October with a beach seine of dimensions 2.44 m x 15.2 m x 0.5 cm. Approximately 14 hauls are taken annually in the Deep, Essex, Glastonbury, and Salmon Rivers.

The Rhode Island seine survey targets a variety of fishes in Narragansett Bay and has operated continuously from 1988-present. A total of 18 fixed stations are sampled from June through October using a beach seine with dimensions 3.05 m x 61 m.

The New York seine survey targets a variety of fishes in western Long Island Sound and has operated continuously from 1984-present. Sampling occurs with a 61 m beach seine primarily from May through October within three areas: Jamaica Bay, Little Neck Bay, and Manhasset Bay.

5.1.2 Biological Sampling Methods

Length data (in mm) were available for the seine surveys conducted by North Carolina, Virginia, Maryland, and New Jersey; little or no length data are available for the seine surveys conducted by New York, Connecticut, and Rhode Island.

5.1.3 Ageing Methods

For state seine surveys (North Carolina, Virginia, Maryland, and New Jersey) with length data, catch-per-haul data were adjusted based on the convention cut-off sizes by month for juvenile menhaden adopted by the Atlantic menhaden Technical Committee in March 2003. Juvenile length cutoffs were defined as: June 1-June 30, 110 mm FL; July 1-August 15, 125 mm FL; and August 16-November 30, 150 mm FL.

5.2 Trends

5.2.1 Catch Rates (Numbers)

JAIs were based on generalized linear models (GLM). Examination of the raw catch-per-haul data for each state indicated that each data set contained a high proportion of zero catches, or alternatively, a low proportion of hauls where at least one juvenile menhaden was captured (**Figure 5.1**). Zero catches can arise for many reasons, and it was reasoned that the use of an active sampling gear combined with the schooling nature of menhaden was the likely cause (Maunder and Punt 2004). Although a variety of strategies can be used to deal with zero catches, a delta approach was adopted where the probability of obtaining a zero catch and the catch rate, given that the catch is non-zero, were modeled separately (Maunder and Punt 2004). The general form of a delta model is:

$$\Pr(Y = y) = \begin{cases} w & y = 0 \\ (1-w)f(y) & \text{otherwise} \end{cases}$$

The probability of obtaining a zero observation was modeled using the binomial distribution and the distribution used to model the non-zero catches was the identified in a manner similar to that used to identify the appropriate computational form of the second PRFC pound net index of relative abundance. That is, a variety of probability density/mass functions were fitted to the non-zero catches collapsed over months and sampling locations via maximum likelihood, and AIC was used to discriminate among competing distributions (see section 4.2.2.1 for more details). All probability density/mass functions were fitted using the software package R, version 2.9.2 (R Development Core Team, 2009).

The results of the distributional analysis strongly suggested that the non-zero juvenile catch data followed the lognormal distribution for all years of each state survey (**Figure 5.2**). Therefore, a delta-lognormal GLM was used as the computational form for both JAIs.

The first index developed was a single coastwide JAI based on the raw catch-per-haul data from all states combined, under the notion that each state's survey represented a component of a grand experiment to measure the relative abundance of juvenile menhaden coastally. Four parameterizations of a delta-lognormal GLM were fitted to the combined catch-per-haul data: Model 1 specified *year*, *month*, and *state* as fixed factors; Model 2 included *year* and *month*; Model 3 contained *year* and *state*; and Model 4 specified only *year* effects. Again AIC was used to discriminate among competing models, and fits were achieved using the software package R, version 2.9.2 (R Development Core Team, 2009).

AIC based evaluation of the delta-lognormal GLM analysis strongly suggested that Model 1 provided the best fit to the data (**Table 5.1**). The trend of the index is generally low during the 1960s, high from the mid 1970s to mid 1980s, and low to moderate from the mid 1980s to the present (**Figure 5.3**).

The second index developed was based on the creation of regional indices where the raw catch-per-haul data from particular groups of states were combined according to similarity among trends in state-specific JAIs. It was reasoned that regional indices would explicitly capture any spatial patterns in juvenile abundance, and that the creation of a single coastwide index could then be based on weights internally estimated by the age-structured assessment model. To determine the regional groupings, it was first necessary to develop state-specific indices. The same four parameterizations of the aforementioned delta-lognormal GLM were fitted to the catch-per-haul data of each state, with *station* as the spatial factor instead of *state*. Model 1 was strongly supported for all states except RI, where Model 4 provided the best fit to the data. These AIC selected state indices were introduced into a principle components analysis (PCA) for the years in which all state survey activities overlapped (1988-2008). The PCA was based on the correlation matrix of year by state index value, and a VARIMAX rotation was applied to the factors resulting from the PCA to simplify interpretation. Collinear variables load on the same composite factor during PCA, and VARIMAX rotation emphasizes the correlation of variables within a factor by maximizing the loadings of variables that correlate strongly with it while simultaneously reducing the loadings of variables with lesser correlation.

The results of the PCA suggested the following regional groupings: Region 1 included NC, VA, and MD; Region 2 included NY and RI; Region 3 was solely NJ, and Region 4 was solely CT (**Figure 5.4**). For each of these groupings, same four aforementioned parameterizations of the delta-lognormal GLM were fitted to the combined catch-per-haul data. Model comparisons using AIC strongly supported Model 1 for all regions. The trend in the JAI from Region 1 was generally similar to that of the single coastwide JAI (**Figure 5.5a**). The JAIs associated with Regions 2 and 4 were variable but higher in recent years (**Figures 5.5b, 5.5d**), and the JAI trend from Region 3 was generally low across the time series, although the true pattern is difficult to assess visually because of the influence of the 1981 index value (**Figure 5.5c**).

5.2.2 Catch-at-Age

See Section 6.2.1.2 for treatment of index of age-specific selectivity in the base model.

5.3 Potential Biases, Uncertainty, and Measures of Precision

Precision of indices in the form of CV's were calculated from jackknife-derived standard errors from the delta-lognormal GLM (**Figures 5.3 and 5.5)**. Because of the schooling nature of Atlantic menhaden combined with the fact that these seine surveys were originally designed to measure the abundance of other species, it is possible that the menhaden catch data are not truly representative of abundance.

5.4 Relationship Among Juvenile and Adult Abundance Indices

Pearson's product-moment correlation coefficient (r) was used to examine the strength of the relationship between the PRFC adult abundance index and the single coastwide YOY index. Estimation of r requires three assumptions: (i) the relative abundances of adult and juvenile menhaden are random variables; (ii) the observations of relative abundance for each component of the population are drawn from a bivariate normal distribution; and (iii) the relationship between the estimates of abundance is linear. YOY and PFRC adult index values were lagged two years (since the Potomac River pound nets collect adult menhaden primarily aged 1-3 years) and the correlation coefficient was estimated among YOY index values from 1962-2006 paired with PRFC index values from 1964-2008. The significance of r was determined using the t-distribution at an α level of 0.05. Forty-five years of data led to 43 degrees of freedom and corresponded to a t_{crit} ranging between 0.288 and 0.304 (taken from **Table 25**, Critical values correlation coefficients, Rohlf and Sokal 1969).

A linear regression among the two indices yielded an estimated correlation coefficient of $\hat{r} = 0.712$, which was highly significant (**Figure 5.6**). This result supports the use of the PRFC index in the stock assessment and it further suggests that the PRFC index adequately reflects coastwide fluctuations in menhaden recruitment despite being based on landings and effort data from one tributary in Chesapeake Bay.

6.0 Methods

6.1 Assessment Model Description

In this section, we identify five modeling approaches that were considered as potential base models during the Data and Assessment Workshops. These modeling approaches include: (1) Beaufort Assessment Model (BAM), (2) Stock Synthesis Model (SS3), (3) University of British Columbia (UBC) Model, (4) Multi-Species VPA (MSVPA-X), and (5) Stock Reduction Analysis (SRA). During the Assessment Workshop, **Table 6.1** was prepared for developing our recommendation of the base (preferred) assessment model.

We selected the Beaufort Assessment Model (BAM) as the base (preferred) model. Two other models, SS3 and UBC, are both statistical catch at age models similar in many respects to the BAM. However, given concerns identified below, we did not proceed further with either the SS3 or UBC approach. The MSVPA-X could serve as an alternative assessment model, but the committee decided that the use of BAM as the principal assessment model is preferable for a number of reasons outlined below. At the same time, MSVPA-X served as an important supplement in the assessment process by providing critical estimates of age- and year-varying natural mortality (M) as input to the Beaufort Assessment Model. Finally, as an alternate approach with quite different assumptions, we also proceeded with the Stock Reduction Model for exploration purposes to define the possible range of B_{msy} and F_{msy} given the history of stock exploitation. However, model results were not robust to the choices of current exploitation rate (*U*) and associated *cv* values, so the utility of stochastic SRA for this assessment was determined to be limited.

6.1.1 Beaufort Assessment Model (BAM)

The essence of forward-projecting age-structured models is to simulate a population that is projected forward in time like the population being assessed. Aspects of the fishing process (i.e. 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 fishery and year; observed age composition by gear and year; and observed indices of abundance. 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 Fournier and Archibald (1982) and Deriso et al. (1985) in their CAGEAN model and by Methot (1989) in his stock-synthesis model. 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), South Atlantic red porgy (SEDAR 1 - 2002), South Atlantic black sea bass (SEDAR 2 in 2003 and SEDAR Update 2005), South Atlantic snowy grouper and tilefish (SEDAR 4 - 2004), and South Atlantic red snapper (SEDAR 15 - 2008). Forward-projecting age-structured models share many attributes with ADAPT-style tuned and untuned VPAs. The BAM was the forward-projecting age-structured model used in the previous menhaden assessment and update (2003 and 2006, respectively). Updates to this model and subsequent analyses are found in Section 6.2.2.

6.1.2 Stock Synthesis Model (SS3)

"Stock Synthesis provides a statistical framework for calibration of a population dynamics model using a diversity of fishery and survey data. … The structure of Stock Synthesis allows for building of simple to complex models depending upon the data available" (NMFS Toolbox, SS3). Stock Synthesis was developed in the 1980s by Dr. Richard Methot and latest version (SS3) was added to the NMFS Toolbox in January 2009.

A modification to SS3 was made by Dr. Methot, specifically for menhaden, which allows direct input of observed size at age rather than estimating an underlying growth model. Input for added menhaden capability included (1) mean weight at age from 1955-2008 to represent both reduction and bait fisheries, (2) fecundity at age (adjusted for sex ratio and maturity schedule), and (3) expected weight at age on March 1 to represent spawning size at age and September 1 to represent catch size at age (sample size for SS3 was based on trips sampled, not number of fish sampled).

A working run had the following properties:

- Landings in metric tons, 1955-2008 for bait and reduction fisheries
- CVs [SE log(catch)] for both fisheries: 0.03 reduction, 0.1 bait
- Two surveys – JAI & Pound net (observations & se(log))
- Aging error – estimated by Punt's agemat.exe
- Age compositions (reduction 1955+, bait 1985+)
- Single time block for selectivity (tried multiple blocks for reduction selectivity)
    - ✓ Exponential logistic for reduction & bait (at Methot recommendation)
    - ✓ Age 0 only for JAI as in earlier assessments
    - ✓ Fixed for poundnet as in earlier assessments
- *M* which varied by age, but not annually
- Tried both Beverton-Holt and Ricker spawner-recruit curves
- Allowed autocorrelation in recruitment time series
- Tried modeling random walk in q for JAI and poundnet indices

We found implementing and parameterizing selectivity functions difficult. Before arriving at a potential base run, further exploration of selectivity will be necessary. Also, we did not attempt to incorporate the year-varying age-vectors of natural mortality (*M*) at this time.

With development of environmental forcing functions for menhaden growth, SS3 would be capable of using this information directly to estimate a time-varying underlying growth relationship and related fecundity estimates, rather than as data input as used in BAM and our exploration of SS3. BAM would also be capable of handling environmental forcing functions.

The SS3 is a relatively advanced model and was explored for use in the current menhaden assessment. SS3 has a steep learning curve. Although SS3 comes with a User's Manual, the need still existed for Dr. Methot to add a major data input component for analyzing menhaden (i.e., year varying size and fecundity at age). Because this model did not provide more options or insights (with the currently available data) than the Beaufort Assessment Model, we do not recommend its use as a base model for this assessment cycle. The assessment team acknowledged that much further development is needed with help from its author, Dr. Methot, before it can be given full consideration for use as the primary model. It is feasible that this could happen within the medium to long term.

6.1.3 University of British Columbia Model (UBC)

An additional statistical catch-at-age model developed by Dr. Steven Martell from the University of British Columbia (Martell et al. 2008) was evaluated for use in the 2010 Atlantic menhaden stock assessment. The goal of this evaluation was to explore and compare the performance of the UBC modeling approach with that of the ASMFC.

The major structural difference between the UBC and ASMFC modeling approaches is the way in which reference points are calculated. In recent ASMFC assessments, a statistical catch-at-age model was used to estimate population and fishery parameters (e.g. abundance-at-age, biomass, fishing mortality, selectivity). Outputs from the model were then used to calculate F_{med} and fecundity reference points.

In contrast, the UBC modeling approach involves internally estimating management parameters such as maximum sustainable yield (MSY) and the fishing mortality rate that would achieve MSY (F_{msy}). In other words, MSY-based reference points are estimated simultaneously with population and fishery parameters. To successfully estimate these reference points, the model requires informative priors (constraints) be placed on the estimates of MSY and F_{msy}. For comparison with the ASMFC modeling approach, F_{med} and fecundity reference points can be calculated using UBC model outputs, but the results are still conditioned on the internally estimated MSY-based reference points.

Given the overall similarity between these two modeling approaches, the SASC was interested in determining if the UBC approach would provide different management advice from that of the ASMFC approach if input data and model assumptions were similar.

Methods and results
UBC model code provided by Dr. Martell was modified to align F_{msy} and MSY prior equations with modeling efforts previously conducted for menhaden at UBC (pers. comm.). This model

configuration included the assumption that effective sample size for the reduction age composition data was equal to 1 (effectively assuming there is little to no information in the catch-at-age matrix). This model run predicted that the stock was overfished and that overfishing was occurring.

The assumption that there is no information in the catch-at-age matrix is unrealistic, so the UBC model was then reconfigured so that the effective sample size and landings error assumptions were similar to those made in the BAM model of ASMFC's 2010 assessment. Effective sample sizes for the reduction and bait age composition data were set at 1,500 and 100, respectively. These effective sample sizes were chosen because they were in the range of the number of trips from which age samples were taken. Standard deviations for the reduction and bait landings were assumed to be 0.03 and 0.15, respectively; these values were similar to CVs assumed in the base run of the BAM model. Despite different model structure and methods for calculating reference points, the UBC and ASMFC modeling approaches produced the same determination of stock status - not overfished and overfishing not occurring – when model assumptions were similar.

After examining UBC model performance relative to that of the ASMFC model, the SASC decided not to adopt the UBC modeling approach for several reasons. First, the UBC model code has not been as thoroughly vetted as the code used in ASMFC assessments. The SASC was particularly concerned that results previously reported by Dr. Martell (pers. comm.) could not be reproduced with the code provided. Second, the SASC was concerned that tight informative priors were required for the UBC model to perform well. The model could not estimate F_{msy} and MSY without strong constraints on the possible values of these reference points. Given that the values of F_{msy} and MSY are unknown, the SASC was uncomfortable using tightly constrained values for F_{msy} and MSY with strong priors on these parameters. Finally, the SASC did not feel that the MSY-based reference points provided by the UBC model were appropriate at this time given the lack of a detectable stock-recruitment relationship. The SASC preferred the BAM model approach which estimates initial recruitment and annual deviations without relying on the estimation of a stock-recruitment relationship.

6.1.4 MSVPA-X

The Multispecies Virtual Population Analysis (MSVPA) approach was developed within International Council for the Exploration of the Seas (ICES) as a multispecies extension of cohort analysis or virtual population analysis (VPA). The basic approach was initially described by Pope (1979) and Helgason and Gislason (1979), and later modified and described in Gislason and Helgason (1985). The approach can be viewed essentially as a series of single-species virtual population analysis (SSVPA) models that are linked by a simple feeding model to calculate predation mortality rates. The system of linked single-species models is run iteratively until the predation mortality (M2) rates converge. The basic model is therefore performed in two primary iteration loops. First, all single-species VPAs are run to calculate population size at all ages for predators and prey, then predation mortality rates are calculated for all age classes of each species based upon the simple feeding model. The single-species VPA for modeled prey is run again using the calculated M2 rates, and this iteration is repeated until convergence is achieved (reviewed in Magnusson 1995). The single-species VPAs for the ICES model employ the basic catch equation as described in Gulland (1983) using input values for terminal fishery mortality rates (F) that are generally derived from single-species assessments. A full detailed methodology for the modified version of MSVPA developed by the ASMFC can be found in ASMFC (2006).

In 2000, ASMFC configured an MSVPA similar to the configurations used in the North Sea. After extensive internal review, the output from this MSVPA was used in the 2003 SEDAR for Atlantic menhaden. In that assessment, the MSVPA-estimated vector of M at age was used as input in the single species menhaden model; the M at age vector was further modified within the assessment model by an estimated scalar parameter (see ASMFC 2004a). In 2005, the full MSVPA-X was peer reviewed in the SARC venue (NEFSC 2006b) and that configuration was used to provide the M at age vector in the most recent update for Atlantic menhaden (ASMFC 2006).

The MSVPA-X was updated in 2008 (ASMFC 2009) with data through 2006. This configuration was updated again in preparation for the 2010 menhaden assessment with data through 2008 using the most recent 2009 Atlantic striped bass update assessment (ASMFC 2009a), 2009 weakfish benchmark stock assessment (NEFSC 2009), 2009 bluefish update assessment (ASMFC 2009b), and 2009 Atlantic herring stock assessment (TRAC 2009). Not all information in the MSVPA-X could be updated through 2008, so the following assumptions and modifications to the 2008 model configuration were made for each major predator and some prey species:

For weakfish, 1) 2007 and 2008 size-at-age was assumed to be the same as that calculated for 2006; 2) 2008 weight-at-age and catch-at-age was assumed to be the same as that calculated for 2007; and 3) the MRFSS harvest-per-trip index was the only index used in the single species Extended Survivors Analysis (XSA). The MRFSS-only run of the weakfish XSA was an alternative configuration in the 2009 MSVPA-X update and is most similar to the weakfish benchmark assessment; it performed similarly to the weakfish XSA base run which included all available indices.

The menhaden catch-at-age was updated through 2008. Bluefish total biomass was also updated through 2008.

The Striped bass catch at age matrix was updated for 2007 and 2008 based on the 2009 stock assessment report of the ASMFC Atlantic Striped Bass Technical Committee. The following age structured indices were updated and used in the analysis: Massachusetts commercial age specific CPUE, New Jersey trawl age-specific CPUE, Delaware age specific spawning survey CPUE, and Maryland age specific spawning survey CPUE. Since 2007, indices from several surveys were calculated as age aggregated only and therefore could not be updated beyond 2006. These include NEFSC trawl, Connecticut trawl, and recreational catch per trip, as well as MRFSS catch per trip. In addition, New York Ocean Haul Seine Survey was terminated in 2007 and the time series ends in 2006. All age-structured indices are geometric means except for the Maryland Spawning Survey, which uses arithmetic means. Young of the year geometric mean indices of abundance were updated through 2008 for New York, New Jersey, Maryland and Virginia based on each states juvenile seine surveys and entered as age 1 on January 1 of the year following the survey year. Also, New York and Maryland Juvenile Surveys provided age 1 CPUEs which were entered as age 2 on January 1 of the year following the survey year.

A number of updates to the other prey items in the MSVPA-X were also made: 1) because Atlantic herring is an important alternate prey to Atlantic menhaden for many predators, and 2) because a recent update on the status of Atlantic herring substantially changed the overall stock biomass (TRAC 2009). Thus assessment results from this most recent update were used in the calculation of "Other Clupeid" biomass in the MSVPA-X. For all other prey, the 2007 and 2008 biomass at season was assumed to be the same as that of 2006.

Both the menhaden single species VPA (from the MSVPA-X) and BAM assessment methods for menhaden estimate similar patterns in menhaden population size, but not in fishing mortality. Abundance trends in recent years are similar, with some divergences in age 2+ abundance in less recent years (**Figure 6.1**). Both methods capture the recent declining trend in abundance as well as its magnitude. Fishing mortality estimates, however, differ widely between the two assessment methods in the first half of the time series then converge to similar values (**Figure 6.2**); note, however, that fishery selectivity is estimated differently between VPA and BAM methodologies. In general, the MSVPA shows less variability and some suggestion of increasing age 2+ F over the time series. In contrast, the BAM method shows higher but more variable age 2+ fishing mortality earlier in the time series. In general, MSVPA-X predator abundance and F estimates were similar in trend to that of recent (2009) single-species assessments; however, magnitude of those estimates varied during parts of the time series (A1-A2; **Appendix A.2**). One exception was weakfish F estimates which differed greatly due largely to different assumptions about natural mortality (A2).

After careful consideration of model function and structure, the menhaden single species VPA from the MSVPA-X was not chosen as the base model for this benchmark assessment. In comparison with the BAM statistical catch-at-age approach, the VPA has two major drawbacks. Unlike the BAM model, the single species VPA does not have the ability to incorporate error in catch-at-age or to estimate uncertainty in model output. Uncertainty estimates are particularly important because they allow managers and stakeholders to understand the variability around population estimates, and they allow the population to be projected forward in time if needed.

Although the menhaden VPA was not chosen as the final method for status determination, the MSVPA-X was determined to be the best available tool for synthesizing predator diet data and estimating changes in menhaden natural mortality at age over time. Age-structured assessment approaches like BAM are not designed to explicitly incorporate predator feeding ecology and therefore may not provide the most reliable estimates of time-varying, age-specific natural mortality of menhaden. This finding is consistent with the previous peer review of the MSVPA-X (NEFSC 2006b) which suggested that although the MSVPA-X cannot be used for stock status determination, it can be used to inform stock assessments with regard to natural morality.

6.1.5 Stock Reduction Analysis (SRA)

Stock reduction analysis (SRA) was used as an exploratory tool for evaluating likely estimates of important management parameters, e.g. U_{MSY} and MSY under an assumption that maximum sustainable yield is the reference point against which the Atlantic menhaden status is determined. The SRA uses long-term landings time series to predict what recruitment could have feasibly produced the landings history and the current stock status. We used the stochastic version of the SRA (stochastic SRA in visual basic) developed by Walters et al. (2006). Unlike earlier versions of the stochastic SRA that estimated uncertainty for recruitment compensation (*recK*) and unfished population recruitment (R_0), the new version estimates the uncertainty about population dynamic parameters that are of interest to managers, i.e. maximum sustainable yield (MSY) and the fishing mortality associated with this level of yield (F_{MSY} but expressed as an exploitation rate, U_{MSY}). The stochastic SRA is parameterized by taking U_{MSY} (annual exploitation rate producing MSY at equilibrium) and MSY as leading parameters, then calculating the Beverton-Holt stock-recruit parameters from these and from per-recruit fished and unfished eggs and vulnerable biomasses. Under this parameterization, the modeling approach assumes a uniform Bayes prior for U_{MSY} and MSY, rather than a uniform prior for the stock-recruitment parameters. The model randomly chooses values of *MSY* and U_{MSY} from the prior, and then calculates the parameters for the spawner-recruit equation.

Given a spawner-recruit relationship, an initial population age structure, and a lognormal set of recruitment anomalies, an age-structured population model in the SRA is used to project abundance of the population each year, given the observed catch is removed. This is repeated many times so that a set of U_{MSY} and *MSY* pairs are determined that do not lead the population to extinction over the course of the projection, while supporting the observed annual catches and fitting a series of recent abundance indices. The resulting sample of possible historical stock trajectories is resampled using sampling importance resampling (SIR), or a large sample is taken using MCMC. Summing frequencies of occurrence of different values of leading population parameter values over this sample amounts to solving the full state-space estimation problem for the leading parameters (i.e. find marginal probability distribution for the leading population parameters integrated over the probability distribution of historical state trajectories implied by recruitment process errors and by the likelihood of observed population trend indices).

Data and parameters input—Key data inputs to stochasticSRA were: landings time series, fisheries vulnerability at age, a tuning index, and various descriptors of growth and maturity. Historical landings for Atlantic menhaden were available for the period 1880-2008 (see section 4.1.2). The tuning index used in the SRA was the pound net catch rate (1964-2008, see section 5.2.1). The model fitted the catch rate data using a maximum likelihood function. The stochastic SRA requires a variety of life history information and assumptions about variability of recruitment and growth, and vulnerability to the fishery. The growth of Atlantic menhaden was assumed follow a von Bertalanffy growth equation with parameters (L_∞, K, and t_0): 40cm FL, 0.4 yr^{-1}, and -0.412 years. For the fishery vulnerability, we used the fixed vulnerability-at-age information generated from the 2009 BAM model. Other input parameters included: current estimates of exploitation rate and vulnerable biomass and associated coefficient of variation (*cv*) values; survival from natural mortality (e^{-M}), 0.65; the *cv* for length at age, 0.09; and maximum weight, 1.2 kg. We modeled recruitment variability using log-normally distributed error (σR) of 0.5 around the mean stock recruitment relationship. This is within the range of 0.3 to 0.6 typical of fish populations (Walters *et al.* 2006). We assumed no autocorrelation among recruitment estimates. For the SIR sampling, we used 50,000 model runs and allowed the SIR to sample priors over a wide range of values for MSY (100,000-1,000,000 mt), U_{MSY} (0.1- 0.8 yr^{-1}), and S (survival from natural mortality, 0.4-0.7).

We examined three base-run scenarios based on input values for current exploitation rate (U): base run1 (U=0.1,cv=0.1), base run2 (U=0.2,cv=0.1), and base run3 (U=0.3,cv=0.1). These reflected a range of fishing mortality rates estimated for the Atlantic menhaden fishery in recent years. Additional runs were made with *cv* values of 0.2 and 0.3.The sample distributions and likelihood profiles of MSY and U_{MSY} were estimated using MCMC sampling with the stochastic SRA population models for the three base-run scenarios. The uncertainty associated with current stock condition (B/B_0) and exploitation rate (U_{2008}/ U_{MSY}) was determined from the MCMC posterior distributions of these parameters.

Results- In general, model results were not robust to the choices of current exploitation rate (U) and associated *cv* values. The estimates of vulnerable biomass were significantly higher for base run1 (U=0.1) than the biomass estimates from base runs 2 (U=0.2) and 3 (U=0.3) (**Figure 6.3**). The vulnerable biomass estimates increased as the *cv* value associated with the current U increased (**Figure 6.4**). The SRA model results indicated wide uncertainty about U_{MSY} and somewhat lower uncertainty about MSY. The MCMC sample distributions and likelihood profiles for U_{MSY} and MSY varied for different values of current U and *cv* (**Figure 6.5**). The wide uncertainty associated U_{MSY} estimates could be due to a lack of contrast in the landings time series. The MCMC posterior distributions of the current stock condition (B/B_0) and exploitation rate (U_{2008}/U_{MSY}) were also sensitive to the *cv* values associated with the current exploitation rate (**Figure 6.6**). The current stock condition improved as the *cv* associated with current U increased.

The utility of stochastic SRA for this assessment is limited given the wide uncertainty associated with U_{MSY} estimates. Additionally, model sensitivities to the values of current U and associated *cvs* indicate that unless we have a good estimate of the current stock size (e.g., from survey) or current exploitation rate (e.g., from tagging) we could expect wider uncertainty about the current status of the stock.

6.2 Model Configuration for Base Approach

6.2.1 Base Assessment Model (BAM)

The Beaufort Assessment Model (BAM) used for this assessment is a statistical catch-at-age model (Quinn and Deriso 1999), implemented with the AD Model Builder software (Otter Research 2004).

6.2.1.1 Spatial and Temporal Coverage

The BAM model is not a spatially-explicit model and assumes one coastal population of Atlantic menhaden. Catches are reported by fishery and state, but are assumed to come from one population. During the1950s through the 1980s, reduction catches ranged from Maine to Florida. Recent catches by the reduction fishery range from North Carolina to New Jersey with a majority come from Virginia waters. Most catches by the menhaden bait fishery range from Virginia to Maine, with a majority harvested in Virginia and New Jersey waters. The abundance index data for Atlantic menhaden, which includes the PRFC pound net index and the state-specific juvenile abundance indices, are assumed to be measures of the coastwide population, as reflected by the age-specific selectivity vector applied to each survey. Little data are available reflecting explicit menhaden movements and patterns, limiting the modeling to the assumption of a single coastwide population, although recent genetic information supports the one stock hypothesis (See Section 2.1).

The BAM model for Atlantic menhaden employs annual time steps, modeling the years 1955-2008. The 1955 starting year reflects the first year of catch-at-age data. Landings data for Atlantic menhaden extend farther back in time, however, age compositions and abundance information is unavailable before 1955, limiting the value of modeling efforts prior to 1955. For longer-lived finfish species or species with a shorter time series of landings, improved model fits are sometimes achievable by extending the data back to the earliest data points; this is interpreted as possibly reflecting “virgin” conditions. However, that is not the case for Atlantic menhaden as this species has been exploited since the early 1800s.

6.2.1.2 Selection and Treatment of Indices

As mentioned above two sources of information were used for abundance indices in the BAM model. Fishery-dependent PRFC pound net data were used to develop a CPUE adult abundance index. The PRFC pound net fishery presumably catches age 1-3 Atlantic menhaden, with the majority of them presumed to be age 2. The index is derived for the area from the center of the stock distribution and was shown to have strong correlation with the two-year lagged age-0 JAI measured in the upper portion of Chesapeake Bay (MD DNR data). Although this index is from a single river in Chesapeake Bay, it was treated in the model as a representation of the coastwide stock, following the age-specific selectivity vector determined by the Data Workshop. This assumed age-specific selectivity schedule was as follows: 0.25 for age-1, 1.0 for age-2, 0.25 for age-3, and 0.0 for all other ages. The level of error in this index is uncertain, but for the base run, the coefficient of variation was assumed to be 0.5. Sensitivity runs (see below) explored alternate levels of error in this index, as well as alternate methods for deriving the index. In the BAM model the estimates of the product of total numbers of fish at the midpoint of the year, a single catchability parameter, and the selectivity schedule were fit to the PRFC pound net index value in that same year. The error in this abundance index was assumed to follow a lognormal distribution.

The other source of information used in the BAM model comes from a series of state-specific seine surveys. These surveys, ostensibly designed for other species and not designed for juvenile Atlantic menhaden, tend to capture primarily age-0 menhaden. Some older menhaden are captured, but based on size measurements these older fish are removed from the computation of the final CPUE index, leaving only age-0 menhaden upon which to base the index. 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 at the beginning of the year and a single catchability parameter to the computed index values. As was the case with the PRFC pound net index above, the error in the JAI index was assumed to follow a lognormal distribution. Sensitivity runs (see below) explored alternate methods for deriving the JAI, including the use of multiple indices with weighting parameters estimated by the BAM model.

6.2.1.3 Parameterization

The ADMB model code and input data file are attached as **Appendices A.3 and A.4**. A summary of the model equations may be found in **Table 6.2**. The formulation's major characteristics are summarized as follows:

Natural mortality: The age-specific natural mortality rate was assumed constant over time for early years 1955-1981, and was then based on estimates from the MSVPA-X analysis for years 1982-2008 (MSVPA-X discussed in Sections 2.7 and 6.1.4).

Stock dynamics: The standard Baranov catch equation was applied. This assumes exponential decay in population size because of fishing and natural mortality processes.

Growth/Maturity/Fecundity: Size, percent of females mature, and female fecundity-at-age for each year was fixed in the model.

Recruitment: Recruitment to age-0 was estimated in the assessment model for each year with a set of annual deviation parameters, conditioned about a mean and estimated in log-space.

Biological benchmarks: Biological benchmarks were calculated based on per recruit analysis following F_{MED}, as in the previous Atlantic menhaden stock assessment.

Fishing: Two fisheries were modeled individually: reduction and bait. Separate fishing mortality rates and selectivity-at-age patterns were estimated for each fishery.

Selectivity functions: Selectivity was fit parametrically, using a logistic model for both the reduction fishery and the bait fishery, rather than estimating independent selectivity values for each age. This approach reduces the number of estimated parameters and imposes theoretical structure on the estimates. Selectivity was assumed constant for the entire time period in the assessment model.

In previous stock assessments for Atlantic menhaden a dome-shaped selectivity function was applied to the bait fishery. This assumption was discussed and examined during the assessment workshop. After comparison of age data between the reduction and bait fisheries, it was decided that the a priori assumption for the bait fishery should be a flat-topped or logistic selectivity function. This became the choice for the base BAM model.

Discards: Discards are believed to be negligible and were therefore ignored in the assessment model.

Abundance indices: The model used two indices of abundance that were modeled separately: a juvenile (age-0) index series (1959–2008) and a pound net CPUE index series (1964–2008).

Fitting criterion: The fitting criterion was a total likelihood approach in which total catch, the observed age compositions, and the patterns of the abundance indices were fit based on the assumed statistical error distribution and the level of assumed or measured error (see Section 6.2.1.4 below).

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). Additionally, the general model structure has passed several rounds of independent peer review. 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.

6.2.1.4 Weighting of Likelihoods

The likelihood components in the BAM model include separate bait and reduction landings, bait and reduction catch-at-age data, a PRFC CPUE pound net index, and a seine survey-derived JAI index. For each of these components a statistical error distribution was assumed as follows:

Likelihood Component	Error Distribution	Error Levels
Reduction Landings	Lognormal	Constant CV value equal to 0.03
Bait Landings	Lognormal	Constant CV value equal to 0.15 in early years and 0.05 in later years
Reduction Catch-at-Age	Multinomial	Annual number of trips sampled was 278 to 1178
Bait Catch-at-Age	Multinomial	Annual number of trips sampled was 1 to 98
PFRC Pound Net Index	Lognormal	Constant CV value equal to 0.5
Seine Survey JAI Index	Lognormal	Annual CV values from 0.13 to 0.62

No additional weights were applied to the likelihood components; the measured or assumed error levels formed the basis for the relative fit among the components. Because some components error levels were assumed, some sensitivity runs were performed with alternate levels of error (see below).

6.2.1.5 Estimating Precision

The BAM model was implemented in the AD Model Builder software, which allowed for easy calculation of the inverse Hessian approximated precision measures. 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 probably underestimates of the true precision. Instead, the BAM model employed a parametric bootstrap procedure in which the input data sources were resampled using the measured or assumed statistical distribution and error levels in the table above. All the data sources in the table above were re-sampled in 2,000 bootstrap iterations.

6.2.1.6 Sensitivity Analyses

A total of 18 sensitivity runs were completed with the BAM model. These sensitivity runs are represented by those involving input data and those involving changes to the model configuration.

6.2.1.6.1 Sensitivity to Input Data

Several sensitivity runs were conducted to examine various effects to changes in the input data. The following is a list of these sensitivity runs.

Run number	Sensitivity Examined
menhad023	Time-invariant natural mortality (single vector used for all years)
menhad025	PRFC pound net index CV assumed to be 0.2
menhad026	PRFC pound net index CV assumed to be 0.8
menhad028	Used four separate JAI indices with internally estimated weights
menhad032	Allow random walk parameters for PRFC pound net index
menhad033	Omit the JAI index data
menhad034	Omit the PRFC pound net index data
menhad035	Used GLM based PRFC pound net index
menhad036	Natural mortality scaled up by 25%
menhad037	Natural mortality scaled down by 25%

Natural mortality is almost always a source of uncertainty in stock assessments. To test the sensitivity of the model output to assumptions about natural mortality, sensitivity run numbers menhad023, menhad036 and menhad037 were completed. In these sensitivity runs, natural mortality values were assumed to be time-invariant using the overall average age-specific vector for all years (menhad023), and the age and year specific values in the base BAM model were scaled up and down by 25% (menhad036 and menhad037, respectively).

The CV value for the PRFC pound net index in the base BAM model was assumed to be 0.5. Runs menhad025 and menhad026 tested lower (0.2) and higher (0.8) CV values, respectively. Also, a sensitivity run was examined using an alternately computed PRFC pound net index based on a derived index using a Generalized Linear Model (GLM) (menhad035). Another sensitivity analysis explored the flexibility of allowing the catchability of the fishery-dependent PRFC pound net CPUE index to follow a random walk process (menhad032). Lastly, a sensitivity run with the PRFC pound net index data removed was also completed (menhad034).

The seine survey JAI index was the result of combining several state specific indices using dated estimates of water body productivity. A sensitivity run was completed in which four separate indices (based on multivariate clustering analyses) were input into the model and a set of combination weights were estimated parameters in the BAM model (menhad028). A sensitivity run with the JAI index data removed was also performed (menhad033).

6.2.1.6.2 Sensitivity to Model Configuration

Several sensitivity runs were conducted to examine various effects to changes in the model configuration. The following is a list of these sensitivity runs.

Run number	Sensitivity Examined
menhad024	Average over last eight years used for per-recruit and benchmark calculations
menhad027	Assumed no age reading error
menhad029	Assumed dome-shaped selectivity in last time period (1994-2008) for reduction fishery
menhad030	Started model in 1964 (base model starts in 1955)
menhad031	Average over last three years used for per-recruit and benchmark calculations
menhad038	Allowed model to estimate a natural mortality scalar parameter
menhad039	Estimated underlying Beverton-Holt stock and recruitment curve
menhad040	Estimated underlying Ricker stock and recruitment curve (needed strong prior on R_0)

The computations of the benchmarks require some averaging for components like fecundity and natural mortality, which in the case of Atlantic menhaden vary annually. Thus, the choice of years to use for this averaging can be important. The sensitivity of the BAM model to alternate choices of averaging was explored in runs menhad024 and menhad031, which used the most recent eight and three years of data for computing the averages, respectively.

A change from previous assessment models of Atlantic menhaden was the inclusion of an age reader error matrix. A sensitivity run was completed to examine the effects of omitting this age reader error matrix from the model (menhad027).

The reduction fishery has experienced major changes over its history, most notably a steady decline in number of fish plants and vessels and also geographic coverage. Currently, one reduction plant with ten vessels operates at Reedville, VA. This contraction of the fishery may have had some effects on the shape of the selectivity applied to this fishery in recent years. A sensitivity run was completed to allow for dome-shaped selectivity in the most recent time period (1994-2008) via the inclusion of a double-logistic selectivity function (menhad029).

The historical estimates of recruitment from the BAM model suggest that some exceptionally large year classes occurred during the earliest part of the time series, that is, the 1950s. A sensitivity run was completed to address effects of omitting these early years from the stock assessment; in other words, starting the model in 1964 (menhad030), as opposed to starting it in 1955 as in the base BAM model.

As another way of addressing the uncertainty in natural mortality, and to be consistent with some past practices involving Atlantic menhaden stock assessments, a sensitivity run was completed which allowed a scalar parameter for natural mortality to be estimated (menhad038).

Lastly, two sensitivity runs were completed with underlying stock-recruit curves. Runs menhad039 and menhad040 were fit with Beverton-Holt and Ricker stock-recruit curves, respectively.

6.2.1.7 Retrospective Analyses

Retrospective analyses were completed by running the BAM model in a series of runs sequentially omitting years 2008 to 2002, as indicated below:

Run number	Sensitivity Examined
menhad041	Retrospective analysis with modeling ending in 2007
menhad042	Retrospective analysis with modeling ending in 2006
menhad043	Retrospective analysis with modeling ending in 2005
menhad044	Retrospective analysis with modeling ending in 2004
menhad045	Retrospective analysis with modeling ending in 2003
menhad046	Retrospective analysis with modeling ending in 2002
menhad047	Retrospective analysis with modeling ending in 2001

6.2.1.8 Reference Point Estimation – Parameterization, Uncertainty, and Sensitivity Analysis

As was the case in previous Atlantic menhaden stock assessments, this stock assessment continues to use F_{MED} to represent F_{REP} as the F-threshold (fishing limit). F_{MED} was estimated using the 50th percentile (median) fecundity per recruit for all years in the model. The F-target is based on the 75th percentile of the fecundity per recruit, which is consistent with the approach used for the F-threshold. The equilibrium fecundity per recruit calculations were based upon average selectivity, M-at-age, weight-at-age, and fecundity-at-age for all years in the model. Sensitivity runs were conducted using averages for these age-specific vectors from the last 3 and 8 years (see section 6.2.1.6.1).

As was also the case in previous Atlantic menhaden stock assessments, population fecundity (FEC, number of maturing or ripe eggs) was used as the measure of reproductive capacity. The target for FEC was determined by calculating fecundity-per-recruit value in yield per recruit model corresponding to the F_{MED} value, then multiplying this fecundity-per-recruit value times the median recruitment from all years. The FEC threshold (limit) was then simply assumed to be 50% of this value. Uncertainty estimates for these benchmarks are derived from the bootstrap method mentioned in section 6.2.1.5. Sensitivity analysis consisted of computing different types of benchmarks for comparison and using different time periods for computing averages and medians in the computation of the F_{MED}-based benchmarks (see section 6.2.1.6.1). Lastly, per-recruit calculations were used to compute alternate reference points.

7.0 Base Model Results

7.1 Results of Base BAM Model

7.1.1 Goodness of Fit

Goodness-of-fit was governed in the BAM assessment model by the likelihood components in the objective function (**Table 6.2**). The relative fit among the likelihood components was governed by the error levels for each data source (see section 6.2.1.4). During the assessment workshop, goodness of fit was also judged for each data source through examination of the model residuals.

Observed and model-predicted landings for the reduction fishery (1955–2008; **Figure 7.1**) and the bait fishery (1985–2008; **Figure 7.2**) were compared for the base model run. Reduction fishery landings, which are known fairly precisely, fit very well. The more poorly estimated bait landings show some deviations, but overall represent a good fit. Patterns in the annual comparisons of observed and predicted proportion catch-at-age for the reduction fishery (**Figure 7.3**) indicate a good overall model fit to the observed data. The bubble plot for the reduction fishery (**Figure 7.4**) indicates that the model fit overestimates age-1 and underestimates ages-0 and -2 in recent years. Patterns in annual comparisons of observed and predicted proportion catch-at-age for the bait fishery and associated bubble plots (**Figures 7.5 and 7.6**) indicate a good overall model fit to the observed data.

Observed and predicted coastwide juvenile abundance indices were compared for the base model run (1959–2008; **Figure 7.7**). The residual pattern suggests that the JAI index data did not fit well in years prior to 1978 as compared to the most recent years. Visual examination of the fit suggests that the overall pattern fit reasonably well, with the BAM model capturing the observed index values for the low-high-low recruitment pattern suggested for the years 1959-1973, 1974-1986, and 1987-2008, respectively. The observed and predicted PRFC pound net CPUE index (1964–2008; **Figure 7.8**) values do not fit as well as the JAI index values. The pattern of fit is similar in that the general high-low patterns are captured, but the relative fit within the time series is better in the early years and worse in the most recent years. The model estimates smaller numbers of fish in the last five years compared to the relative index values.

7.1.2 Parameter Estimates

7.1.2.1 Selectivities and Catchability

Fishing mortality was related to an overall level of fishing and the selectivity (or availability) of menhaden to the two fisheries (reduction and bait). Model estimates of selectivity (availability) for these fisheries were compared graphically in **Figures 7.9 and 7.10**. The results for both fisheries suggest very similar estimates of selectivity, with age-4 almost fully selected and age-5 and older fully selected. The big differences are in the amount of age-1 and age-2 fish that are selected. The reduction fishery selectivity estimates a higher proportion of age-1 and -2 fish compared to the bait fishery.

The base BAM model estimates a single, constant catchability parameter for each of the abundance indices, reflecting the assumption that catchability for these CPUE indices is believed to be constant through time. This is certainly a good assumption for the fishery-independent JAI abundance index since it is based on consistent, scientific survey collections, albeit the surveys are at fixed shore stations and ostensibly target other species. For the fishery-dependent PRFC pound net index, a sensitivity run was completed to examine a random walk process in catchability (see section 7.1.3).

7.1.2.2 Exploitation Rates

Total fishing mortality rates on ages-2 to -8+ (referred to as *F* age *2+*) were calculated as the weighted average of age-specific *F*s for those ages and population number-at-age (**Figure 7.11**). Highly variable fishing mortalities were noted throughout the entire time series, with a slight decline in fishing mortality from the mid-1960s to the early 1980s. Since the mid-1980s the fishing mortality rate has been quite variable, ranging between some of the highest and lowest values in the entire time series. In the most recent decade, the weighted average fishing mortality rate on ages 2-8+ has generally been below 1.0 (**Table 7.1**). The estimate of fishing mortality rate for 2008 of 0.86 is at the 39th percentile of the historical estimates (**Table 7.2**).

The fishery-specific fishing mortality rates are shown in **Figures 7.12 and 7.13**. The estimates suggest a high degree of variability, but in general the reduction fishery has experienced declining fishing mortality rates since the mid-1960s, while the bait fishery has experienced increasing fishing mortality rates since the 1980s (**Table 7.3**). The annual trend in full F by age classes is analogous to the one described for the average weighted F, as one would expect when time invariant selectivity at age is used (**Figure 7.14**). However, F rates can vary substantially among age groups (**Table 7.4**). Selectivity on age-1 is small, greater on age-2, almost fully selected at age-3, and generally fully selected at older ages.

Average exploitation rate, defined as the proportion of the population removed annually by the fishery ($\hat{C}_{ij}/\hat{N}_{ij}$, where i=age, j=year), over the last decade was 3% for age-1, 18% for age-2, and 22-23% for age-3 and older. Average exploitation rate, defined as the proportion of total mortality due to fishing ($\frac{\hat{C}_{ij}}{\hat{N}_{ij}} = \frac{\hat{F}_{ij}}{\hat{F}_{ij}+M_{ij}}(1-e^{-(\hat{F}_{ij}+M_{ij})})$, where i=age, j=year) over the last decade was 5% for age-1, 34% for age-2, 65% for age-3 and 69% for age 4 and older.

7.1.2.3 Abundance, Fecundity, and Recruitment Estimates

The base BAM model estimated population numbers-at-age (ages 0-8) for 1955–2008 (**Figure 7.15** and **Table 7.5**). From these estimates, along with growth and reproductive data (Section 2), different estimates of reproductive capacity were computed. Addendum 1 (ASMFC 2004b) adopted population fecundity as the preferred measure of reproductive output. Population fecundity (FEC, number of maturing ova) was high in the late 1950s and early 1960s, low in the late 1960s, and generally increasing since then (**Figure 7.16** and **Table 7.6**). The largest values of population fecundity were present in 1955 and 1961, resulting from two very strong recruitment events in 1951 and 1958 as noted in earlier stock assessments (Ahrenholz et al. 1987b; Vaughan and Smith 1988; Vaughan et al. 2002b; ASMFC 2004a). The time period 1955-2008 produced a median population fecundity of 69.0 x 10^{12} ova with an interquartile range between 47.0 x 10^{12} and 99.6 x 10^{12} (**Table 7.2**). The estimate for population fecundity in 2008 was 59.5 x 10^{12}, which was between the 25th and 50th percentile. Throughout the time series, the age-3 fish produced most of the total estimated number of eggs spawned annually (**Figure 7.17)**.

Age-0 recruits of Atlantic menhaden (**Figure 7.18** and **Table 7.7**) were high during the late 1950s, especially the 1958 year-class. Median and interquartile values for age-0 recruits are summarized in **Table 7.2**. The annual estimated recruitment values relative to the median are shown in **Figure 7.19**. Recruitment was generally poor during the 1960s, with values below the 25th percentile (20.5 billion) for the recruitment time series. High recruitment occurred during the late 1970s and early 1980s to levels above the 75th percentile (59.6 billion). These values are comparable to the late 1950s (with the exception of the extraordinary 1958 year-class). Generally low recruitment has occurred since the early 1990s. There is a hint of a potential long-term cycle from this historical pattern of recruitment, but not enough data are present to draw any conclusions regarding the underlying cause at this point (**Figure 7.18 and 7.19**). The most recent estimate for 2008 is quite low and likely to be modified in the future as more data from the cohort (age-1 in 2009, age-2 in 2010, etc.) are added to the analysis. The current estimate of recruits to age-0 in 2008 (11.4 billion) is below the 25th percentile (20.5 billion).

A plot of the fecundity (mature ova) to the recruits at age-0 indicated a weak relationship, suggesting Atlantic menhaden recruitment was only marginally governed by population fecundity (**Figure 7.20**). Additional discussion on dynamics of recruit per egg is presented in section 8.2.3. **Figure 7.20** also shows the median recruitment and fecundity-per-recruit estimates which were used to determine the benchmarks for Atlantic menhaden (see Section 6.2.1.8 for more details).

7.1.3 Sensitivity Analyses

The results of the 18 sensitivity runs suggest that the base BAM model is fairly robust to many of the induced changes (**Figures 7.21-7.23**). The largest changes in population estimates relative to base model estimates resulted from sensitivity runs which affected natural mortality. This included four of the sensitivity runs which used a constant natural mortality vector over time (menhad023), allowed for an estimated scalar on natural mortality (menhad038), increased natural mortality by 25% (menhad036), and decreased natural mortality by 25% (menhad037). These changes were greatest for the fishing mortality and recruitment estimates (**Figure 7.21 and 7.22**). The fecundity estimates were very robust to these sensitivity runs (**Figure 7.23**). The resulting recruitment, N-weighted fishing mortality rates (*F* age 2+), fecundity, benchmarks, and stock status indicators appear to be largely robust to the explored sensitivity runs with the exception of natural mortality effects (**Table 7.8**).

7.1.4 Retrospective Analyses

Patterns and biases in the results of a retrospective analysis over time are unclear (**Figures 7.24-7.26**). Regardless, the results indicate that the terminal N-weighted fishing mortality rate (F2+) is highly variable (**Figure 7.24**). The resulting recruitment, fecundity, benchmarks, and stock status indicators do not show consistent biases or patterns (**Figures 7.25 and 7.26; Table 7.8**). However, the magnitude of stock status outcomes vary considerably in this set of retrospective model runs. In particular, the ratio of N-weighted fishing mortality ($F2+/F_{MED}$) in terminal year to F_{MED} ranges from 0.45 to 2.77 within this range of retrospective runs and shows some large year-to-year variations (**Table 7.8**).

7.1.5 Uncertainty Analysis

The parametric bootstrap procedure was run for 2,000 iterations. The resulting estimates from these runs have been summarized in **Figures 7.11, 7.16 & 7.18** and **Tables 7.3, 7.6-7.7**, showing the 90% confidence region. In general the bootstrap results suggest fairly symmetrical error distributions about the base run results.

7.1.6 Reference Point Results – Parameter Estimates and Sensitivity

Fecundity-per-recruit and yield-per-recruit (mt) estimates as a function of total N-weighted fishing mortality rates (F2+) are shown in **Figures 7.27 and 7.28**. These plots are offered as a reference for other fishing mortality rates. For example, the terminal year fishing mortality rate estimate (F_{2008}) of 0.86 is equivalent to an $F_{14\%}$ mortality rate, and the F_{MED} estimate of 0.93 from the base BAM model is equivalent to an $F_{13\%}$ mortality rate (**Figure 7.27**).

The base BAM model estimates for the benchmarks and terminal year values are indicated in **Table 7.9**. This table also indicates the values for some per-recruit-based benchmarks of $F_{30\%}$, $F_{25\%}$, and $F_{20\%}$. The base BAM model estimated the stock status based on the F_{MED} estimators. The results suggest that the current stock status is not overfished ($FEC_{2008}/FEC_{threshold} > 1.0$) and overfishing is not occurring ($F_{2008}/F_{MED} < 1.0$). However, the fishing mortality rate is close to the F_{MED} threshold (limit) (**Table 7.8**).

The entire time series of relative estimates of N-weighted fishing mortality (F2+) and fecundity are shown in **Figures 7.29 and 7.30** and a phase plot of the last ten years of estimates is shown in **Figure 7.31**. The history of fishing mortality rates in **Figures 7.29 and 7.31** suggests that overfishing may have occurred 32 out of 54 years in the past. However, this plot can be deceptive and not entirely accurate since F_{MED} benchmark estimates may change every year. A more accurate method to examine this scenario would be with a retrospective analysis which re-estimates the benchmark annually (**Table 7.8**). This retrospective analysis suggested a high degree of variability in terminal fishing mortality rates, with very small differences in estimated F_{MED}.

The uncertainty in the terminal year stock status indicators is expressed using the results of the 2,000 bootstrap runs of the base BAM model. The results indicate that the fecundity estimates for the terminal year are well above the threshold (limit), with not a single bootstrap estimate falling below 1.0 (**Figures 7.32-7.34**). The results for the terminal year fishing mortality rate suggest that the base run estimate is just below the F_{MED} threshold (limit) with 36.8% of the bootstrap runs exceeding the F_{MED} threshold (**Figures 7.32-7.34**).

8.0 Stock Status

Limit reference points (limits) are the basis for determining stock status (i.e., whether overfishing is occurring or a stock is overfished). When the fishing mortality rate (*F*) exceeds the *F*-limit, then overfishing is occurring; the rate of removal of fish by the fishery exceeds the ability of the stock to replenish itself. When the reproductive output (measured as spawning stock biomass or population fecundity) falls below the biomass-limit, then the stock is overfished, meaning there is insufficient mature female biomass (SSB) or egg production (population fecundity) to replenish the stock.

The Magnuson-Stevens Reauthorization of 1997 (Restrepo et al. 1998) suggests that the target for spawning biomass (or population fecundity) be near B_{MSY} (or its proxy). The target level chosen for fishing mortality is less clear, other than the stipulation that F_{target} be sufficiently below the F_{limit}.

8.1 Current Overfishing, Overfished/Depleted Definitions

8.1.1 Amendment 1 Benchmarks

Ideally, *F*-based and SSB-based reference points should be based on an underlying population dynamics model (e.g., F_{MSY} and B_{MSY} from Ricker or Beverton-Holt spawner-recruit models). However, traditional methods of specifying these reference points perform poorly when applied to historical Atlantic menhaden data. There is considerable scatter in the spawner-recruit relationship and this stock's recruitment is suspected of being largely driven by environmental forces. Hence, the reference points in Amendment 1, adopted in 2001 (ASMFC 2001), were developed from the historic spawning stock per recruit (SSB/R) relationship. As such, F_{MED} was selected as F_{limit} (representing replacement level of stock, also known as F_{REP}) and was calculated by inverting the median value of R/SSB and comparing to the SSB/R curve following the method of Sissenwine and Shepherd (1987). The spawning stock biomass corresponding to F_{limit}, was calculated as a product of median recruitment and SSB/R at F_{MED}, from equilibrium YPR analysis, which became the SSB_{target}. The limit for SSB (SSB_{limit} or MSST) was calculated to account for natural mortality [(1-M)*SSB-target, where M=0.45]. In Amendment 1, the F_{target} was based on F_{MAX} (maximum fishing mortality before the process of recruitment overfishing begins). The values calculated for these reference points were 1.04 and 1.33 for the F_{target} and F_{limit}, respectively, while 37,400 mt and 20,570 mt were the SSB_{target} and SSB_{limit}, respectively (Table 13 in ASMFC 2001).

8.1.2 Addendum 1 Benchmarks

Based on the 2003 benchmark stock assessment for Atlantic menhaden, the benchmarks were modified by the ASMFC in Addendum 1 as recommended by the Technical Committee (ASMFC 2004a, 2004b). The TC recommended using population fecundity (number of maturing or ripe eggs) (FEC) as a more direct measure of reproductive output of the population compared to spawning stock biomass (the weight of mature females; SSB). For Atlantic menhaden, older menhaden release more eggs than younger menhaden per unit of female biomass. By using the number of eggs released, more reproductive importance is given to older fish in the population than accounted for simply by female biomass. They also recommended modifications to the fishing mortality (F) target and limit. The TC recommended continued use of F_{MED} to represent F_{REP} as the F_{limit}, but estimated it using fecundity per recruit rather the SSB per recruit. Because the analysis calculated an F_{MAX} (target) that was greater than F_{MED} (and may be infinite), they recommended instead that F_{target} be based on the 75th percentile. This approach was consistent with the approach used for the F_{limit}. For biomass (or egg) benchmarks, the TC recommended following the approach of Amendment 1. Benchmark and terminal year values for the F-based and EGG-based reference points are summarized in **Table 8.1** for the 2003 peer reviewed assessment (ASMFC 2004a, Table 9.1) and for the 2006 update assessment (ASMFC 2006, Table 7.1). Terminal years for these two assessments were 2002 and 2005, respectively. Because growth and fecundity at age vary annually, benchmarks may also vary annually. The changes in the biological reference points, while seemingly large for F, are a re-estimation of benchmarks based on updated population parameters, but using the same process defined in the 2003 peer-reviewed assessment (ASMFC 2004a). These changes primarily reflect annual growth patterns for the terminal year, and are neither more nor less conservative than the previous estimates.

8.2 Discussion of Alternate Reference Points

8.2.1 F_{MSY} Concept

On the federal level, preference has been given to managing US fisheries using MSY- (or Maximum Sustainable Yield) derived reference points such as B_{msy}, F_{msy}, etc, even though direct estimation of B_{msy} and F_{msy} is often not possible or reliable. Such reference points can be incorporated into control rules, which may then call for reductions in fishing effort or landings when a stock falls below an optimal population size (such as SSB_{msy}) or fishing mortality goes above what is sustainable in the long-term (such as F_{msy}). For many species setting harvest at some precautionary fraction of MSY allows managers to set long term sustainable harvest based on a long-term sustainable population size.

Implicit in that assumption of a long-term harvest being sustainable for a long-term population size (and vice versa), is that the stock recruitment relationship is well known and unchanging. For many species which exhibit a high degree of recruitment variability, setting reference points based around MSY may lead to rapid fluctuations in stock status. The greatest concern would be sharp population declines under MSY-level removals during periods of low recruitment, although the opposite is also possible. Such difficulties are more apparent when the species examined is short lived, as recruitment is a result of only a few age classes. In those cases, lower recruitment results in lower SSB within a few short years, further lowering the possibility for future recruitment. Management may not have time to react to such changes before complete stock collapse. Moreover, MSY-based reference points require equilibrium conditions, an assumption which is difficult to make for a forage species. As a result, many have called for the complete removal of MSY-based reference points all together (Larkin 1977; Gulland 1978, and Barber 1988).

In the case of menhaden the stock-recruitment relationship is poorly known. Menhaden are also relatively short lived, with a preponderance of the SSB residing in the younger age classes, and having a high but variable degree of natural mortality (predation) before recruitment to the SSB. As such, basing reference points on actual stock performance and long term medians is more appropriate than basing them on a variable and poorly understood stock recruitment relationship.

8.2.2. Equilibrium Yield per Recruit (YPR) and Spawner per Recruit- (SPR) Based Reference Points

There is a long history of YPR-based reference points used in fisheries management. Fmax and $F_{0.1}$ were widely used either as target or threshold levels of fishing mortality. These were often seen as proxy estimates to the F_{msy}. In the case of menhaden, the F_{max} =1.04 was used in Amendment 1 as a target fishing mortality (Section 8.1.1). However, recent updates in menhaden life history parameters resulted in a YPR curve with undefined maximum (asymptotic curve), primarily due to the new vector of natural mortality at age. The $F_{0.1}$ value can still be estimated and is equal to 1.37 (F for ages 2 and older weighted by numbers) or 0.93 (full F). The $F_{0.1}$ was generally seen as a precautionary or conservative value for a target (compared to F_{MAX}). However, $F_{0.1}$ does not reflect any compensatory effects of the underlying spawner–recruitment relationship or environmentally driven systematic changes in recruitment level.

The concept of F_{MED} was investigated by Mace and Sissenwine (1993) and compared to the percent of the maximum spawning potential (referred to as either %MSP and %SPR) that corresponds to F_{MED}, thus maintaining population replacement. Mace and Sissenewine (1993) reported that most of the stocks require at least 20-30% of maximum spawning potential to be maintained for population replacement. Among 83 populations analyzed, they estimated replacement %MSP for 19 stocks of clupeids, 9 of them being Atlantic herring (slower growing and larger maximum age). The percent corresponding to replacement ranged between 7% and 65%, with a median value of 37%. This variability in percent replacement may result from differences in the range of observed SSB values (if the stock is heavily exploited through the entire time series, the range of SSB is not as a large as that of a lightly exploited stock which is likely to affect the F_{MED} estimates). The %MSP appropriate for menhaden can only be selected arbitrarily based on the presumed population resilience. The current estimate of F_{MED} is equivalent to $F_{13\%}$ from the YPR/SPR equilibrium model.

8.2.3. Environmental Variability

Concern has arisen about the applicability of the current estimate of F_{med} to management of the stock in the most recent period. Following the underlying concept of $F_{rep,}$ or F_{med}, at any given level of the spawning stock the population should be able to produce variable recruitment, some of it below and some above the replacement line. An inspection of the time series plot of R/SSB (**Figure 8.1**) indicated that the menhaden stock experienced periods of high and low productivity, with high survivorship from egg to recruit in 1970s and 1980s and substantially lower (by 70%) survivorship in 1990s-2000s . While the actual reason for low survival in the recent period is unknown, Wood and Houde (2003) suggested the importance of the atmospheric circulation pattern of the Azore-Bermuda High on menhaden recruitment (Section 2.7). Regardless of the underlying reason, the population has been producing a lower number of recruits per unit of eggs during the last 20 years, compared to the earlier period as shown on **Figure 8.2**. The average R/SSB ratio during the last two decades was significantly lower than R/SSB for the entire series. The population was unable to achieve the median survivorship of the full time series and was not replacing itself on average. This raises concern over the appropriateness of using F_{MED} estimated for the full time series to manage the current stock. If the median line is drawn through the period 1991-2008, the slope of the replacement line is lower (**Figure 8.1**), the corresponding F_{MED} reduces to 0.526 (N-weighted age 2+) or 0.968 (full F). One may consider adjusting the limit and target reference points when the population is going through extended periods of higher or lower productivity as seems to be the case with menhaden. Should the population move in the future into another stanza of R/SSB values, the F reference point can be re-evaluated.

The historical pattern estimated by the BAM model suggests that Atlantic menhaden recruitment has varied from 8.8 to 156.2 billion fish annually, showing periods of high recruitment in the

1970s and 1980s, and periods of low recruitment in the 1960s, 1990s, and 2000s. The estimated population fecundity pattern shows very high levels in the 1950s, followed by some of the lowest values in the time series during the late 1960s. Since the 1970s, fecundity has varied between 40,000 and 140,000 billion mature ova. When age-0 recruitment is plotted with a one year lag against population fecundity estimates, no relationship appears (**Figure 8.3**). The cyclical pattern in recruitment seemingly has less to do with fecundity than it does outside forces (e.g. physical forcing, predation). The stock-recruit plot indicates that the fecundity levels which produced the highest recruitment values (above the 75th percentile) ranges from 42,000 to 102,000 billion mature ova, while most of the highest fecundity levels (100,000+ billion mature ova) produced recruitment values close to the historical median. It is often the case in other fisheries that the stock-recruit relationship is poor. However, in this case there is a complete absence of any high recruitment at the highest fecundity estimates, albeit there were few years in the time series with high fecundity estimates. The highest variability in recruitment occurs right around the median historical fecundity.

Past performance of Atlantic menhaden suggests it has gone from periods of low recruitment and fecundity to periods with high recruitment and fecundity, while sustaining moderate to high landings. In recent years the fishery has experienced some of the lowest landings on record, yet recruitment remains near the 25th percentile. This outcome may be indicative of a stock with an undefined production function (e.g. stock-recruitment curve), whose population fluctuations are almost entirely driven by non-fishery sources.

Menhaden spawning occurs for a very protracted period of time along the entire US Atlantic coast while fish schools undergo significant migratory movements. Simple estimation of total number of eggs potentially produced by the population does not account for specifics of stock structure (spatial and temporal distribution) of spawners along the coast, probability of "right" conditions for successful egg and larval survival and other potentially important factors. Identification of factors defining menhaden recruitment in the future may substantially improve our understanding of menhaden recruitment processes and offer possible modifications to our modeling that will account for more complex processes.

8.3 Stock Status Determination

8.3.1 Overfishing Status

F (N-weighted F for age 2+)/F_{med} for the terminal year was less than 1 (**Figure 7.29**). Hence, based on this criterion, overfishing is not occurring. However, several issues raise concern about the status of the stock relative to this benchmark. First, the terminal year value is close to the limit (ratio of 0.92). Second, there is relatively large variation in F among years. In recent years, overfishing was occurring in several years (1999, 2002, 2006). Third, as noted in a later section on uncertainty, about 40% of the bootstrapped values of F fall into the overfishing region. Fourth, numbers-weighted F is highly influenced by abundance of age 2 fish which are not fully recruited. A range of status determinations are shown based on the sensitivity runs (**Table 7.8**), several suggesting overfishing, although most do not. A corresponding figure for F based on Full F is presented with full F benchmarks for comparison in **Figure 8.4.**

8.3.2 Overfished Status

FEC/FEC_{limit} for the terminal year was greater than 1 (**Figure 8.5**). Hence, based on this criterion, the stock is not overfished. Furthermore, the terminal year value is close to the target (ratio of 1.9). Unlike estimates of F, there is a relatively small amount of variation in FEC between years. Also, the bootstrapped values of FEC fall completely in the region that is considered not to be overfished, although values do fluctuate around the target. None of the sensitivity runs suggest the stock is overfished (**Table 7.8**).

8.3.3 Control Rules

The phase plot shows the recent history of status variables relative to their benchmarks (**Figure 7.31**). Values of F in three years raise concern about occasional overfishing. But the stock was not overfished during this period since 1999. A phase plot for the terminal year based on 2000 bootstrapped experiments demonstrates the uncertainty relative to these control rules in the terminal year (**Figure 7.34**). With respect to the target F and fecundity, the stock has never been at or below target F, but has fluctuated around the fecundity target.

8.3.4 Uncertainty

Uncertainty of the status of stock relative to the two benchmarks was investigated using several approaches. First sensitivity runs were made to explore the effect on benchmarks from changes in assumptions from the base run (**Table 7.8**). Next sensitivity of the estimates was investigated based on a bootstrapped analysis within the BAM model. Alternatively, we had hoped to use the stochastic SRA model, based on a very different approach, to interpret the status of Atlantic menhaden. However, the sensitivity of this model to certain assumptions precluded that approach.

9.0 Research Recommendations

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.

<u>Annual Data Collection</u>
Long term:
1. [Highest Priority] Develop a coastwide fishery independent index of adult abundance at age to replace or augment the existing Potomac River pound net index in the model.
2. Work with industry to collect age structure data outside the range of the fishery.

Short term:
1. Continue current level of sampling from bait fisheries, particularly in the mid-Atlantic and New England, and continue recovery of historical tagging data from paper data sheets.
2. Request annual samples of menhaden from the PRFC pound net fishery to better characterize age and size structure of catch.

<u>Assessment Methodology</u>
Long term:
1. Develop multispecies statistical catch-at-age model to estimate menhaden natural mortality at age.
2. Develop spatially-explicit model, once sufficient age-specific data on movement rates of menhaden is available.

Short term:
1. Re-evaluate menhaden natural mortality-at-age and population response to changing predator populations by updating and augmenting the MSVPA (e.g. add additional predator, prey, and diet data when available).
2. Incorporate maturity at age variability in the assessment model.

<u>Future Research</u>
1. Evaluate productivity of different estuaries (e.g., replicate similar methodology to Ahrenholz et al. 1987).
2. Collect age-specific data on movement rates of menhaden to develop regional abundance trends.
3. Determine selectivity of PRFC pound nets.
4. Update information on maturity, fecundity, spatial and temporal patterns of spawning, and larval survivorship.
5. Investigate the effects of global climate change on distribution, movement, and behavior of menhaden.

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11.0 Tables

Table 2.1. Annual estimated parameters obtained from weight-length and length at age regressions from biological sampling of Atlantic menhaden, 1955-2008.

	Weight-Length				*Von Bertalanffy Curve*			
Year	**n**	**a**	**b**	**RMSE**	**n**	**L_∞**	**K**	**t_0**
1955	16037	-11.808	3.157	0.0097	15009	342.00	0.410	-0.446
1956	19873	-11.823	3.161	0.0152	17963	335.60	0.543	0.008
1957	19674	-12.262	3.242	0.0091	18389	337.20	0.440	-0.407
1958	15315	-12.348	3.263	0.0083	14303	334.00	0.493	-0.062
1959	17935	-12.359	3.262	0.0060	17938	357.70	0.319	-0.906
1960	13505	-12.736	3.332	0.0078	12783	348.90	0.384	-0.464
1961	13184	-12.688	3.323	0.0092	12898	355.10	0.316	-0.914
1962	15771	-11.378	3.083	0.0073	15458	355.00	0.332	-0.964
1963	13001	-11.959	3.194	0.0159	12716	365.10	0.314	-0.909
1964	10438	-11.830	3.169	0.0635	10286	367.30	0.322	-0.974
1965	19518	-11.970	3.193	0.0121	18955	379.70	0.314	-0.848
1966	15633	-11.541	3.110	0.0148	15486	353.50	0.314	-1.161
1967	15426	-12.232	3.238	0.0146	14653	327.60	0.451	-0.717
1968	26830	-11.869	3.176	0.0142	25888	336.50	0.361	-1.047
1969	15114	-11.797	3.167	0.1100	14858	454.30	0.195	-1.544
1970	8426	-11.651	3.139	0.0078	8239	449.10	0.221	-1.083
1971	8269	-11.364	3.079	0.0129	8118	334.80	0.511	-0.391
1972	6552	-11.673	3.130	0.0107	6198	361.80	0.548	0.067
1973	6351	-11.232	3.055	0.0103	6348	424.41	0.275	-0.671
1974	5421	-11.743	3.146	0.0122	5361	529.17	0.185	-0.735
1975	7278	-11.864	3.171	0.0130	7262	392.04	0.289	-0.465
1976	6725	-12.348	3.266	0.0141	6401	732.80	0.108	-0.778
1977	7276	-12.555	3.308	0.0138	7266	397.48	0.230	-0.660
1978	7094	-12.337	3.266	0.0097	7025	570.94	0.113	-1.303
1979	6365	-12.392	3.277	0.0161	6231	363.47	0.282	-0.593
1980	7291	-12.385	3.277	0.0183	7046	349.83	0.286	-0.592
1981	9201	-12.523	3.298	0.0142	8870	389.16	0.221	-0.759
1982	9066	-11.645	3.139	0.0113	8552	432.36	0.151	-1.483
1983	11533	-11.577	3.117	0.0093	11279	367.73	0.238	-0.903
1984	11689	-11.554	3.121	0.0164	11594	336.74	0.313	-0.516
1985	8498	-11.598	3.121	0.0093	8507	352.86	0.317	-0.458
1986	5828	-12.262	3.245	0.0071	5826	348.74	0.266	-0.767
1987	7618	-11.784	3.160	0.0097	7548	373.49	0.226	-1.014
1988	7349	-11.628	3.125	0.0141	7349	355.64	0.261	-0.703
1989	7027	-12.461	3.282	0.0092	6374	379.62	0.207	-1.328
1990	6838	-12.346	3.260	0.0091	6790	297.86	0.489	-0.526

Table 2.1. (*continued*)

	Weight-Length				Von Bertalanffy Curve			
Year	**n**	**a**	**b**	**RMSE**	**n**	**L_∞**	**K**	**t_0**
1991	7770	-11.754	3.147	0.0087	7614	318.90	0.352	-0.918
1992	5680	-12.139	3.215	0.0094	5440	299.93	0.532	-0.289
1993	5488	-11.941	3.182	0.0065	5348	312.55	0.391	-0.921
1994	5278	-12.251	3.238	0.0089	4862	318.19	0.452	-0.257
1995	4996	-11.781	3.145	0.0083	4504	311.74	0.556	-0.115
1996	4628	-12.279	3.247	0.0070	4275	322.35	0.569	0.037
1997	4465	-12.197	3.234	0.0070	3982	332.42	0.454	-0.256
1998	4558	-12.002	3.196	0.0083	3688	387.79	0.261	-1.065
1999	4279	-11.914	3.175	0.0092	3468	351.68	0.371	-0.523
2000	3669	-11.900	3.171	0.0074	3068	324.71	0.570	-0.031
2001	5012	-11.546	3.106	0.0082	4102	332.64	0.500	-0.473
2002	4370	-11.279	3.065	0.0093	3654	317.91	0.623	-0.065
2003	3945	-12.031	3.211	0.0052	3108	346.20	0.418	-0.556
2004	4600	-11.603	3.120	0.0049	3759	370.20	0.303	-0.609
2005	3940	-11.012	3.007	0.0041	3102	336.90	0.382	-0.412
2006	4209	-11.456	3.090	0.0054	3300	349.80	0.325	-0.880
2007	5320	-10.713	2.949	0.0070	3759	299.30	0.522	-0.514
2008	4438	-11.029	3.010	0.0072	3204	318.10	0.419	-0.826

Table 2.2. Annual estimated parameters obtained from weight-length and cohort estimated length at age regressions from biological sampling of Atlantic menhaden, 1955-2008.

	Weight-Length				Von Bertalanffy Curve			
Year	n	a	b	RMSE	n	L_{∞}	K	t0
1947					28	337.70	3.948	7.506
1948					101	335.50	2.764	5.836
1949					355	323.30	4.729	5.476
1950					1202	340.20	0.455	0.487
1951					6574	341.90	0.483	0.535
1952					3596	350.70	0.350	-1.015
1953					9362	340.30	0.514	-0.057
1954					9216	353.20	0.398	-0.498
1955	16037	-11.808	3.157	0.0097	18271	363.50	0.338	-0.572
1956	19873	-11.823	3.161	0.0152	20357	350.30	0.395	-0.274
1957	19674	-12.262	3.242	0.0091	9581	373.90	0.300	-0.786
1958	15315	-12.348	3.263	0.0083	34120	397.40	0.268	-0.522
1959	17935	-12.359	3.262	0.0060	6880	422.50	0.224	-1.299
1960	13505	-12.736	3.332	0.0078	9016	343.90	0.443	-0.317
1961	13184	-12.688	3.323	0.0092	8220	328.50	0.413	-0.675
1962	15771	-11.378	3.083	0.0073	11242	324.20	0.449	-0.647
1963	13001	-11.959	3.194	0.0159	9324	345.70	0.373	-0.839
1964	10438	-11.830	3.169	0.0635	17597	389.70	0.291	-1.011
1965	19518	-11.970	3.193	0.0121	17274	469.50	0.196	-1.166
1966	15633	-11.541	3.110	0.0148	25575	362.60	0.378	-0.759
1967	15426	-12.232	3.238	0.0146	13397	706.30	0.093	-1.947
1968	26830	-11.869	3.176	0.0142	9459	563.00	0.128	-1.925
1969	15114	-11.797	3.167	0.1100	11442	386.20	0.350	-0.841
1970	8426	-11.651	3.139	0.0078	4373	343.70	0.515	-0.358
1971	8269	-11.364	3.079	0.0129	7721	385.30	0.310	-0.746
1972	6552	-11.673	3.130	0.0107	6292	304.40	0.662	0.026
1973	6351	-11.232	3.055	0.0103	6366	343.60	0.341	-0.718
1974	5421	-11.743	3.146	0.0122	6796	335.50	0.348	-0.537
1975	7278	-11.864	3.171	0.0130	8832	377.20	0.223	-0.952
1976	6725	-12.348	3.266	0.0141	6814	333.60	0.342	-0.353
1977	7276	-12.555	3.308	0.0138	7168	347.10	0.310	-0.483
1978	7094	-12.337	3.266	0.0097	5200	374.90	0.214	-1.081
1979	6365	-12.392	3.277	0.0161	9437	510.90	0.117	-1.471
1980	7291	-12.385	3.277	0.0183	7302	333.20	0.328	-0.493
1981	9201	-12.523	3.298	0.0142	13566	330.80	0.363	-0.359
1982	9066	-11.645	3.139	0.0113	6564	361.50	0.268	-0.695
1983	11533	-11.577	3.117	0.0093	9446	416.40	0.172	-1.306
1984	11689	-11.554	3.121	0.0164	10173	333.80	0.303	-0.632
1985	8498	-11.598	3.121	0.0093	8361	328.10	0.321	-0.542
1986	5828	-12.262	3.245	0.0071	6350	316.30	0.355	-0.549
1987	7618	-11.784	3.160	0.0097	4215	349.50	0.270	-0.764
1988	7349	-11.628	3.125	0.0141	9608	314.20	0.458	-0.295
1989	7027	-12.461	3.282	0.0092	3806	307.00	0.483	-0.461
1990	6838	-12.346	3.260	0.0091	5668	342.90	0.315	-0.792

Table 2.2. (*continued*)

	Weight-Length				Von Bertalanffy Curve			
Year	**n**	**a**	**b**	**RMSE**	**n**	**L_∞**	**K**	**t0**
1991	7770	-11.754	3.147	0.0087	7743	329.00	0.407	-0.704
1992	5680	-12.139	3.215	0.0094	5775	357.00	0.351	-0.457
1993	5488	-11.941	3.182	0.0065	3567	353.60	0.337	-0.822
1994	5278	-12.251	3.238	0.0089	5693	335.20	0.546	-0.032
1995	4996	-11.781	3.145	0.0083	3201	344.60	0.443	-0.157
1996	4628	-12.279	3.247	0.0070	3329	331.90	0.476	-0.050
1997	4465	-12.197	3.234	0.0070	3364	363.80	0.340	-0.460
1998	4558	-12.002	3.196	0.0083	4574	392.00	0.271	-1.093
1999	4279	-11.914	3.175	0.0092	3797	331.90	0.518	-0.258
2000	3669	-11.900	3.171	0.0074	2182	316.50	0.633	-0.008
2001	5012	-11.546	3.106	0.0082	3377	291.80	0.627	-0.394
2002	4370	-11.279	3.065	0.0093	4238	312.90	0.503	-0.344
2003	3945	-12.031	3.211	0.0052	3326	339.90	0.345	-0.829
2004	4600	-11.603	3.120	0.0049	2281	388.50	0.272	-0.588
2005	3940	-11.012	3.007	0.0041	4188	303.20	0.532	-0.300
2006	4209	-11.456	3.090	0.0054	2866	378.10	0.326	-0.669
2007	5320	-10.713	2.949	0.0070	205			
2008	4438	-11.029	3.010	0.0072	46			

Table 2.3. Weighted mean fork length (mm) at age, with weightings based on annual catch in numbers by season and area.

[Shaded areas had no or insufficient (n<10) samples and are either averaged with pre- and post year values or averaged across all available years.]

Year	0	1	2	3	4	5	6	7	8
1955	126.8	187.5	242.5	275.4	288.8	304.0	319.2	330.9	327.5
1956	118.4	179.2	248.6	284.3	298.9	312.6	318.9	327.0	337.2
1957	129.8	181.9	234.2	278.8	307.9	314.9	319.7	324.4	324.7
1958	116.6	183.3	229.3	263.2	305.5	321.0	325.0	328.2	329.9
1959	153.6	164.7	229.5	261.0	309.2	320.3	326.5	333.0	338.3
1960	122.4	185.2	222.5	280.3	303.9	316.4	326.7	332.9	336.8
1961	131.9	180.1	240.5	255.4	290.1	310.1	324.6	333.2	336.8
1962	141.4	192.4	238.1	276.2	286.3	317.1	326.4	338.0	335.2
1963	144.5	186.2	223.5	282.8	306.6	314.7	327.0	329.9	338.6
1964	147.6	202.3	236.4	278.4	297.4	327.2	333.7	340.3	342.3
1965	144.9	198.5	235.3	284.4	300.1	325.1	345.0	352.0	334.2
1966	156.0	187.9	248.4	281.6	290.7	288.3	320.6	333.6	334.2
1967	157.1	192.4	236.2	296.6	304.0	313.9	320.6	333.6	334.2
1968	161.9	180.8	243.1	278.8	291.8	306.6	320.6	333.6	334.2
1969	163.9	194.1	226.9	306.2	318.0	330.6	320.6	333.6	334.2
1970	145.7	198.7	224.2	294.9	326.6	322.1	320.6	333.6	334.2
1971	140.1	202.2	251.1	293.3	311.1	313.6	320.6	333.6	334.2
1972	118.1	195.9	264.2	308.0	318.2	300.2	320.6	333.6	334.2
1973	130.9	204.8	220.2	294.0	333.3	300.2	320.6	333.6	334.2
1974	122.7	183.1	224.2	290.3	325.5	300.2	320.6	333.6	334.2
1975	120.6	163.2	206.2	277.1	302.7	300.2	320.6	333.6	334.2
1976	108.8	159.8	205.7	285.5	298.4	300.2	320.6	333.6	334.2
1977	116.4	155.2	189.9	256.9	280.1	286.7	320.6	333.6	334.2
1978	120.3	157.2	193.3	227.0	289.6	297.3	320.6	333.6	334.2
1979	116.2	170.9	201.9	251.1	281.1	295.9	320.6	333.6	334.2
1980	117.6	153.6	196.8	239.6	277.9	291.3	296.1	333.6	334.2
1981	107.7	159.4	192.2	218.4	280.8	294.4	300.1	333.6	334.2
1982	118.3	165.7	193.8	208.1	265.1	296.3	303.7	333.6	334.2
1983	121.8	159.5	197.6	245.4	271.9	295.5	303.7	333.6	334.2
1984	111.1	159.4	198.9	247.8	279.0	286.2	303.7	333.6	334.2
1985	109.3	166.9	203.7	245.3	289.5	300.6	307.2	333.6	334.2
1986	116.4	156.2	195.4	217.8	283.3	292.6	287.2	333.6	334.2
1987	117.3	158.9	199.1	234.6	275.6	289.2	287.3	333.6	334.2
1988	111.8	147.8	205.8	235.5	267.9	285.7	287.3	333.6	334.2
1989	126.2	176.7	195.1	236.6	270.5	283.6	287.3	333.6	334.2
1990	129.2	195.2	223.0	252.9	273.5	281.6	287.3	333.6	334.2

Table 2.3. (*continued*)

Year	0	1	2	3	4	5	6	7	8
1991	137.3	174.8	223.8	258.5	271.3	281.9	287.3	333.6	334.2
1992	123.1	195.9	216.8	258.3	277.1	285.4	284.8	333.6	334.2
1993	137.0	182.4	234.6	258.1	281.0	286.5	315.0	333.6	334.2
1994	117.6	174.0	215.8	272.2	280.6	289.8	315.0	333.6	334.2
1995	114.3	184.9	232.5	274.4	286.3	297.3	315.0	333.6	334.2
1996	114.9	178.1	249.0	286.1	296.9	300.9	315.0	333.6	334.2
1997	128.3	167.6	239.0	285.9	301.3	308.5	315.0	333.6	334.2
1998	148.2	167.1	233.5	286.2	306.9	316.3	315.0	333.6	334.2
1999	138.9	180.0	229.1	280.0	301.0	327.3	315.0	333.6	334.2
2000	117.9	190.6	252.4	279.1	297.0	309.8	315.0	333.6	334.2
2001	143.3	204.3	260.6	288.5	304.5	309.5	315.0	333.6	334.2
2002	132.3	197.0	250.4	285.7	300.5	310.0	315.0	333.6	334.2
2003	142.4	200.9	241.9	287.5	303.2	301.0	315.0	333.6	334.2
2004	122.4	178.8	222.9	270.4	282.6	301.0	315.0	333.6	334.2
2005	122.9	160.3	234.2	271.0	287.5	292.0	315.0	333.6	334.2
2006	139.9	190.8	226.7	272.4	283.5	294.1	315.0	333.6	334.2
2007	142.6	188.7	222.0	270.3	285.3	296.1	315.0	333.6	334.2
2008	145.2	193.2	238.8	264.5	280.1	295.5	315.0	333.6	334.2

Table 2.4. Weighted mean weight (g) at age, with weightings based on annual catch in numbers by season and area.

[Shaded areas had no or insufficient (n<10) samples and are either averaged with pre- and post-year values or averaged across all available years.]

Year	0	1	2	3	4	5	6	7	8
1955	35.6	118.7	250.6	387.7	445.6	527.2	611.7	688.0	669.9
1956	28.0	103.7	289.9	426.9	491.9	559.5	605.8	639.5	702.9
1957	36.9	104.9	234.4	416.0	568.0	588.9	622.1	656.1	652.7
1958	26.2	109.6	223.7	368.2	569.6	662.4	689.2	710.1	662.5
1959	64.4	74.8	216.4	335.6	568.1	619.2	672.0	700.0	744.7
1960	32.4	114.2	194.6	449.1	581.7	656.3	726.7	758.5	726.5
1961	43.0	103.8	252.3	309.1	484.8	593.1	652.5	715.2	726.5
1962	53.6	134.5	254.9	380.8	428.5	599.2	649.0	717.2	708.3
1963	55.0	123.4	222.2	426.6	562.0	606.2	667.4	711.2	757.0
1964	56.5	152.9	248.2	402.2	512.7	720.9	733.6	796.6	769.1
1965	56.4	145.6	251.1	447.4	549.5	706.1	790.5	875.6	708.4
1966	70.4	123.7	285.5	408.0	468.6	412.3	657.9	724.4	708.4
1967	66.9	136.1	253.9	489.8	535.7	629.6	657.9	724.4	708.4
1968	79.6	116.9	290.6	419.6	468.0	507.0	657.9	724.4	708.4
1969	85.1	147.6	235.6	566.5	642.7	722.0	657.9	724.4	708.4
1970	67.8	160.1	224.3	497.9	648.3	643.9	657.9	724.4	708.4
1971	45.5	166.1	311.7	465.0	561.6	565.8	657.9	724.4	708.4
1972	27.6	130.8	336.7	510.4	589.3	540.3	657.9	724.4	708.4
1973	39.7	162.0	190.2	499.8	640.0	540.3	657.9	724.4	708.4
1974	30.7	114.9	201.8	443.0	599.9	540.3	657.9	724.4	708.4
1975	29.9	76.5	156.2	398.7	507.6	540.3	657.9	724.4	708.4
1976	21.6	70.1	163.2	449.4	511.8	540.3	657.9	724.4	708.4
1977	25.8	66.9	123.3	343.2	456.4	514.7	657.9	724.4	708.4
1978	28.4	71.1	132.1	228.2	473.8	511.5	657.9	724.4	708.4
1979	23.3	88.6	156.4	311.2	426.0	494.1	657.9	724.4	708.4
1980	27.7	67.2	138.1	281.5	434.0	488.6	525.4	724.4	708.4
1981	21.0	70.2	128.8	200.9	429.7	492.0	475.3	724.4	708.4
1982	30.2	85.2	133.5	173.9	378.4	488.9	482.2	724.4	708.4
1983	30.9	72.6	136.5	286.4	387.7	513.7	482.2	724.4	708.4
1984	22.7	77.1	150.3	301.0	421.9	461.8	482.2	724.4	708.4
1985	21.1	83.8	150.4	280.5	429.8	482.0	489.1	724.4	708.4
1986	24.1	65.6	130.7	191.9	400.2	449.9	418.6	724.4	708.4
1987	26.4	72.5	149.7	242.9	371.7	429.2	406.0	724.4	708.4
1988	21.5	57.4	160.9	241.6	338.2	408.4	406.0	724.4	708.4
1989	34.4	94.5	132.6	249.4	367.8	409.8	406.0	724.4	708.4
1990	35.2	141.8	205.3	298.1	366.8	398.2	406.0	724.4	708.4

Table 2.4. (*continued*)

Year	0	1	2	3	4	5	6	7	8
1991	44.4	100.7	211.6	308.3	353.7	388.6	393.3	724.4	708.4
1992	28.2	132.4	185.0	311.6	361.9	396.9	389.4	724.4	708.4
1993	42.3	110.7	231.4	325.6	422.6	422.4	594.8	724.4	708.4
1994	24.7	94.9	176.1	355.3	387.3	457.5	594.8	724.4	708.4
1995	22.8	108.1	221.9	350.2	408.9	463.0	594.8	724.4	708.4
1996	23.3	103.1	291.1	436.2	483.3	512.1	594.8	724.4	708.4
1997	33.7	83.3	258.4	444.3	511.5	536.4	594.8	724.4	708.4
1998	56.6	83.6	233.8	434.0	548.5	592.7	594.8	724.4	708.4
1999	43.2	106.5	213.7	378.6	472.6	632.3	594.8	724.4	708.4
2000	26.0	131.0	286.8	386.3	469.6	530.6	594.8	724.4	708.4
2001	49.9	155.8	306.0	418.0	503.3	525.0	594.8	724.4	708.4
2002	39.7	147.4	293.8	425.9	504.1	554.1	594.8	724.4	708.4
2003	48.7	163.4	281.4	474.9	540.9	483.7	594.8	724.4	708.4
2004	30.1	103.9	198.2	356.0	403.6	483.7	594.8	724.4	708.4
2005	32.3	77.0	227.8	337.0	391.6	413.2	594.8	724.4	708.4
2006	44.3	122.6	208.3	353.3	396.6	427.0	594.8	724.4	708.4
2007	48.4	117.6	186.1	327.8	378.5	440.7	594.8	724.4	708.4
2008	52.6	129.5	230.8	323.3	381.2	437.4	594.8	724.4	708.4

Table 2.5. Correlation analysis (Pearson correlation coefficients) of Atlantic menhaden weighted mean fork length-at-age (L0-L4) and weighted mean weight-at-age (W0-W4). [Cohort correlations are lagged to line up lengths and weight by year class, while annual (year) correlations are unlagged.]

Correlations by cohort

	L0	L1	L2	L3	L4	W0	W1	W2	W3	W4
L0	1.00	0.62	0.61	0.68	0.69	0.98	0.65	0.64	0.68	0.63
L1		1.00	0.73	0.72	0.58	0.60	0.98	0.73	0.70	0.53
L2			1.00	0.81	0.71	0.58	0.70	0.98	0.78	0.62
L3				1.00	0.78	0.66	0.70	0.81	0.97	0.69
L4					1.00	0.73	0.58	0.74	0.80	0.95
W0						1.00	0.65	0.63	0.68	0.66
W1							1.00	0.71	0.69	0.52
W2								1.00	0.80	0.65
W3									1.00	0.74
W4										1.00

Correlations by year

	L0	L1	L2	L3	L4	W0	W1	W2	W3	W4
L0	1.00	0.56	0.49	0.49	0.36	0.98	0.58	0.51	0.49	0.36
L1		1.00	0.70	0.66	0.49	0.50	0.98	0.69	0.63	0.42
L2			1.00	0.75	0.49	0.44	0.67	0.98	0.66	0.39
L3				1.00	0.77	0.48	0.66	0.75	0.97	0.68
L4					1.00	0.38	0.51	0.50	0.82	0.95
W0						1.00	0.55	0.47	0.50	0.41
W1							1.00	0.68	0.65	0.45
W2								1.00	0.69	0.43
W3									1.00	0.79
W4										1.00

Correlation Differences (cohort-year)

	L0	L1	L2	L3	L4	W0	W1	W2	W3	W4
L0	0.00	0.06	0.12	0.18	0.34	0.00	0.06	0.13	0.19	0.27
L1		0.00	0.03	0.06	0.09	0.09	0.00	0.04	0.07	0.12
L2			0.00	0.06	0.22	0.14	0.03	0.00	0.12	0.23
L3				0.00	0.01	0.18	0.04	0.06	0.00	0.01
L4					0.00	0.34	0.07	0.24	-0.03	0.00
W0						0.00	0.10	0.16	0.18	0.25
W1							0.00	0.03	0.04	0.06
W2								0.00	0.11	0.22
W3									0.00	-0.05
W4										0.00

Table 2.6. Estimated fork lengths and weights for Atlantic menhaden calculated at middle of fishing year averaged over 2001-2008 (annual estimates), and female maturity at age.

[As summarized from Higham and Nicholson (1964), Dietrich (1979), and Lewis et al. (1987).]

Age	Fork Length (mm)	Weight (g)	Maturity (% Female Mature)
0	139	46	0
1	192	124	0
2	240	247	11.8
3	271	359	86.4
4	292	448	100
5	305	516	100
6	314	565	100

Table 2.7. Fork length (mm) at age on March 1 (start of fishing year) estimated from annual von Bertalanffy growth parameters presented in Table 2.1.

Year	0	1	2	3	4	5	6	7	8
1955	109.9	152.9	216.5	258.7	286.7	305.3	317.6	325.8	331.3
1956	78.6	139.7	221.8	269.4	297.2	313.3	322.6	328.1	331.2
1957	111.0	155.6	220.3	261.9	288.7	306.0	317.1	324.2	328.8
1958	80.8	136.2	213.2	260.2	288.9	306.5	317.2	323.7	327.7
1959	129.2	162.8	216.0	254.7	282.8	303.2	318.1	328.9	336.7
1960	107.9	150.0	213.5	256.7	286.1	306.1	319.8	329.1	335.4
1961	127.9	161.0	213.6	251.9	279.8	300.2	315.1	325.9	333.8
1962	136.5	169.9	222.1	259.6	286.5	305.9	319.7	329.7	336.8
1963	130.7	164.8	218.8	258.3	287.1	308.1	323.5	334.7	342.9
1964	138.7	172.7	226.2	265.1	293.2	313.6	328.4	339.1	346.8
1965	130.8	166.9	224.2	266.0	296.6	319.0	335.3	347.3	356.0
1966	143.7	174.2	222.6	257.9	283.7	302.5	316.3	326.3	333.6
1967	138.3	176.5	231.3	266.2	288.5	302.7	311.7	317.5	321.2
1968	144.0	175.8	224.5	258.4	282.1	298.6	310.0	318.1	323.6
1969	149.3	177.6	226.6	266.9	300.1	327.4	349.9	368.4	383.6
1970	132.6	165.8	222.0	267.1	303.2	332.1	355.4	374.0	388.9
1971	122.3	170.2	236.0	275.5	299.2	313.4	322.0	327.1	330.2
1972	76.4	144.7	236.3	289.2	319.8	337.5	347.8	353.7	357.1
1973	116.8	156.4	220.8	269.8	306.9	335.2	356.6	372.9	385.3
1974	108.1	145.3	210.1	264.0	308.8	346.0	376.9	402.7	424.0
1975	95.4	135.3	199.8	248.0	284.2	311.2	331.5	346.7	358.1
1976	94.5	128.0	189.9	245.5	295.4	340.2	380.4	416.5	448.8
1977	93.1	126.1	181.9	226.2	261.4	289.3	311.6	329.2	343.2
1978	105.2	130.8	177.8	219.8	257.4	290.9	320.8	347.5	371.4
1979	96.4	131.5	188.5	231.5	263.9	288.4	306.8	320.8	331.3
1980	93.8	128.0	183.1	224.6	255.8	279.2	296.7	309.9	319.9
1981	94.5	125.3	177.7	219.6	253.2	280.2	301.8	319.1	333.0
1982	111.9	135.2	176.8	212.6	243.4	269.9	292.7	312.3	329.1
1983	104.4	133.9	183.5	222.5	253.2	277.5	296.6	311.7	323.5
1984	91.7	127.2	183.5	224.7	254.8	276.8	292.9	304.7	313.3
1985	92.4	130.6	191.0	235.0	267.0	290.3	307.3	319.7	328.7
1986	99.8	130.8	181.7	220.7	250.6	273.5	291.1	304.6	314.9
1987	108.2	136.6	184.5	222.7	253.2	277.5	297.0	312.4	324.8
1988	95.8	127.6	180.0	220.3	251.4	275.4	293.8	308.0	319.0
1989	119.6	145.2	189.0	224.6	253.6	277.2	296.3	311.9	324.6
1990	117.5	156.6	211.3	244.7	265.3	277.9	285.6	290.3	293.3

Table 2.7. (*continued*)

Year	0	1	2	3	4	5	6	7	8
1991	125.3	156.6	204.7	238.6	262.4	279.2	291.0	299.3	305.1
1992	102.8	148.9	211.2	247.8	269.3	281.9	289.4	293.7	296.3
1993	133.2	165.1	212.8	245.1	266.9	281.7	291.7	298.4	303.0
1994	92.2	137.9	203.5	245.2	271.7	288.6	299.4	306.2	310.6
1995	90.3	144.0	215.6	256.6	280.1	293.6	301.3	305.8	308.3
1996	74.7	136.0	216.9	262.6	288.5	303.2	311.5	316.2	318.9
1997	96.6	144.5	213.1	256.6	284.3	301.8	313.0	320.1	324.6
1998	130.0	161.6	213.5	253.6	284.4	308.2	326.4	340.5	351.4
1999	111.1	151.8	213.8	256.5	286.0	306.4	320.4	330.1	336.8
2000	84.8	144.3	222.7	267.0	292.1	306.3	314.3	318.8	321.4
2001	128.1	173.4	236.0	274.1	297.1	311.1	319.6	324.7	327.8
2002	94.3	154.2	230.1	270.8	292.6	304.4	310.6	314.0	315.8
2003	123.5	165.5	227.2	267.9	294.6	312.3	323.9	331.5	336.5
2004	105.5	142.7	202.1	246.0	278.4	302.4	320.1	333.2	342.8
2005	99.1	140.5	202.9	245.5	274.5	294.3	307.8	317.1	323.4
2006	126.3	159.8	212.5	250.6	278.1	298.0	312.3	322.7	330.2
2007	123.1	163.6	218.8	251.5	271.0	282.5	289.3	293.4	295.8
2008	135.4	169.9	220.6	253.9	275.9	290.3	299.8	306.1	310.2

Table 2.8. Fork length (mm) at age on March 1 (beginning of fishing year) estimated from year class von Bertalanffy growth parameters.

Year	0	1	2	3	4	5	6	7	8
1955	110.6	158.6	222.1	264.5	277.7	296.5	296.1	322.1	289.7
1956	92.3	149.9	222.5	269.6	289.9	302.3	312.5	323.1	334.7
1957	119.7	138.5	211.2	265.4	298.0	307.9	317.4	322.6	323.3
1958	95.1	155.1	207.6	254.9	294.2	315.0	320.5	326.8	329.0
1959	140.0	132.9	211.8	254.2	286.1	313.6	325.2	329.4	332.6
1960	104.4	169.9	195.0	253.8	285.5	308.3	326.6	331.3	335.7
1961	126.2	151.9	220.5	242.5	284.9	306.7	324.2	335.3	334.9
1962	130.5	163.9	220.6	261.0	278.9	308.0	320.9	335.4	341.2
1963	136.0	169.4	219.5	264.7	293.4	306.7	325.0	330.5	343.5
1964	138.5	171.7	225.4	256.4	293.1	319.2	328.0	337.7	337.0
1965	130.8	172.4	225.9	261.1	280.7	311.3	339.9	344.3	347.1
1966	137.2	162.4	227.2	263.2	283.9	296.9	322.9	356.5	356.8
1967	143.2	176.0	217.1	268.2	288.9	298.5	307.6	330.4	369.7
1968	149.9	168.7	234.7	262.1	298.8	306.6	307.8	314.6	335.3
1969	144.5	175.5	216.2	274.9	299.0	321.7	318.8	313.7	319.3
1970	122.8	183.2	221.9	259.6	302.5	329.4	338.9	327.2	317.5
1971	123.5	173.0	243.1	262.8	299.1	321.4	354.3	351.7	332.9
1972	82.0	161.1	241.7	285.3	298.8	335.1	334.4	374.8	361.3
1973	116.7	144.6	220.9	282.8	315.1	330.5	367.9	343.2	391.7
1974	101.7	152.2	221.9	264.7	307.3	336.0	358.3	397.9	349.3
1975	104.3	139.1	207.5	261.8	296.9	322.0	350.8	382.9	425.1
1976	84.3	133.1	196.8	246.8	282.4	320.5	330.7	361.3	404.5
1977	91.1	123.4	181.9	237.6	274.7	293.1	337.7	335.9	368.6
1978	107.6	127.9	184.2	220.9	266.4	294.6	298.6	350.4	339.1
1979	104.9	134.8	186.3	227.4	252.1	286.7	308.7	301.4	359.7
1980	92.7	127.9	181.0	229.1	258.2	277.1	301.1	318.8	302.8
1981	88.5	129.1	170.1	218.4	260.6	280.0	297.1	311.2	326.0
1982	99.0	128.6	186.2	207.6	248.5	283.6	295.5	313.1	318.3
1983	110.9	131.9	190.1	227.4	241.0	272.9	300.5	306.5	325.9
1984	97.0	136.0	185.9	232.9	257.0	270.7	292.5	312.9	314.4
1985	93.3	130.3	180.2	227.1	262.7	278.3	297.1	308.4	322.0
1986	98.3	128.1	183.5	217.4	258.7	283.4	293.7	320.6	321.2
1987	101.2	133.7	183.0	222.8	248.8	282.8	297.8	304.7	341.6
1988	95.8	132.6	188.2	222.9	251.9	275.2	301.3	307.8	312.7
1989	114.0	140.4	184.0	226.5	251.7	273.3	297.5	315.5	314.8
1990	114.7	155.4	204.2	223.2	253.3	272.7	289.1	316.2	326.3

Table 2.8. (*continued*)

Year	0	1	2	3	4	5	6	7	8
1991	127.3	148.0	213.5	244.6	253.1	272.1	287.9	300.8	332.0
1992	101.8	164.4	200.7	249.3	270.2	276.0	285.3	299.0	309.4
1993	127.2	142.8	219.4	239.2	271.4	286.3	293.4	294.5	307.0
1994	84.5	162.3	206.1	256.0	267.2	285.0	296.6	306.7	301.0
1995	86.9	144.3	217.1	250.7	280.4	287.7	293.5	303.0	316.8
1996	76.3	138.1	224.6	256.1	282.2	296.6	302.6	298.6	307.1
1997	101.2	130.4	211.9	271.1	284.0	304.3	307.4	313.5	301.8
1998	137.3	142.3	206.7	259.4	298.1	304.0	319.9	314.6	321.5
1999	107.8	169.5	206.1	254.0	289.9	313.7	318.2	330.8	319.4
2000	87.0	158.9	222.3	251.5	283.5	309.4	322.7	328.3	338.6
2001	125.1	149.2	228.9	262.5	283.8	301.8	322.0	328.0	335.5
2002	108.2	170.0	227.6	270.5	293.2	306.9	313.2	330.1	331.0
2003	125.0	153.7	226.7	269.3	295.3	316.7	323.3	320.3	335.3
2004	99.4	159.1	216.6	257.0	291.4	310.1	334.5	334.9	324.7
2005	105.1	136.1	211.9	254.6	273.2	303.2	318.9	348.2	343.3
2006	119.6	151.4	196.2	249.3	277.6	281.9	309.4	324.2	358.6
2007		158.5	214.1	241.9	275.7	291.6	286.5	312.7	327.3
2008			219.5	250.9	276.8	294.5	300.0	289.0	314.5

Table 2.9. Weight (g) at age on September 1 (middle of fishing year) estimated from annual weight-length parameters presented in Table 2.1 and annual lengths at age in Table 2.5.

Year	0	1	2	3	4	5	6	7	8
1955	20.8	58.9	176.6	309.9	428.7	522.7	592.4	642.0	676.4
1956	7.3	44.6	192.3	355.9	485.0	573.1	628.9	663.1	683.5
1957	20.3	60.7	187.2	328.2	450.1	543.4	610.1	655.9	686.7
1958	7.3	40.1	172.9	331.5	466.4	565.3	632.4	675.9	703.5
1959	33.1	70.5	177.3	303.4	427.0	536.2	626.8	699.0	755.0
1960	17.6	52.7	170.5	315.1	452.4	566.9	655.5	721.2	768.5
1961	31.1	66.9	170.9	295.7	419.5	529.8	622.1	696.1	753.8
1962	43.9	86.2	197.1	318.9	432.2	528.5	605.9	666.0	711.5
1963	37.1	77.7	192.3	326.5	457.8	573.8	670.3	747.5	807.5
1964	46.2	92.5	217.6	359.4	494.8	612.4	708.6	784.5	842.9
1965	36.5	79.6	204.0	352.4	498.8	629.0	737.8	825.0	893.1
1966	50.2	91.4	195.8	309.5	416.2	508.3	583.7	643.3	689.3
1967	42.0	92.4	221.9	349.9	453.8	530.0	583.0	618.6	642.1
1968	50.5	95.1	206.8	323.5	427.3	511.8	577.1	625.8	661.4
1969	61.0	105.8	228.9	384.4	557.2	734.1	905.9	1066.4	1212.3
1970	40.3	81.1	202.7	362.1	539.3	718.1	887.7	1041.9	1177.9
1971	31.3	86.4	236.5	380.8	491.0	566.5	615.3	646.0	664.9
1972	6.7	49.6	230.0	433.0	593.2	702.2	771.0	812.8	837.7
1973	27.6	67.2	192.8	355.5	527.5	690.2	834.2	956.2	1056.5
1974	20.0	50.7	161.9	332.0	543.5	777.5	1017.9	1252.7	1474.0
1975	13.4	40.6	139.7	277.5	427.2	570.1	696.4	802.8	889.3
1976	12.4	33.3	120.9	279.5	511.4	810.9	1167.8	1570.0	2005.0
1977	11.6	31.6	106.2	218.3	352.2	493.0	629.6	755.6	867.4
1978	17.7	36.1	98.4	196.6	328.9	490.5	675.4	877.1	1089.7
1979	13.3	36.8	119.7	234.7	360.6	482.1	590.7	683.1	759.1
1980	12.3	33.9	109.7	214.2	327.8	436.8	533.6	615.4	682.3
1981	12.0	30.5	96.3	193.7	309.8	432.5	552.6	664.3	764.6
1982	23.8	43.1	100.0	178.5	272.9	377.3	486.5	596.2	703.0
1983	18.5	40.2	107.1	195.3	292.4	388.9	478.6	558.5	627.6
1984	12.9	35.8	112.4	211.4	313.0	405.4	483.6	546.9	596.6
1985	12.6	37.1	121.3	231.7	345.3	448.4	535.5	605.8	660.7
1986	14.6	35.0	101.8	191.4	289.0	384.0	469.9	544.2	606.3
1987	20.6	42.9	110.9	201.1	301.6	403.0	499.0	585.9	662.3
1988	14.0	34.2	100.2	188.5	284.7	378.3	463.2	536.9	598.7
1989	25.7	48.5	115.2	203.2	302.5	404.9	504.2	596.5	679.8
1990	24.5	62.4	165.6	267.5	347.9	404.7	442.6	467.0	482.4

Table 2.9. (*continued*)

Year	0	1	2	3	4	5	6	7	8
1991	31.6	63.6	148.1	239.7	323.5	393.0	447.6	489.0	519.6
1992	15.8	51.9	159.9	267.4	349.4	404.9	440.2	461.9	475.0
1993	37.7	74.5	167.2	262.0	343.7	408.0	455.8	490.3	514.6
1994	11.0	40.7	143.3	262.2	365.7	444.6	500.5	538.5	563.7
1995	10.9	47.2	167.7	290.0	382.1	443.1	480.8	503.5	516.7
1996	5.6	39.5	179.6	334.5	454.1	533.4	582.3	611.3	628.2
1997	13.3	48.9	171.7	313.4	436.3	529.7	595.7	640.4	670.0
1998	35.2	70.4	171.6	297.1	428.7	554.0	666.1	762.4	842.9
1999	21.0	56.7	168.0	299.7	423.5	526.8	607.3	667.6	711.5
2000	8.9	47.9	189.7	337.3	448.3	521.0	565.5	591.8	607.1
2001	34.2	87.4	228.0	362.5	465.9	537.4	584.2	613.9	632.4
2002	14.3	64.5	220.2	362.9	460.2	519.0	552.6	571.2	581.3
2003	31.0	79.4	219.8	372.8	506.1	609.8	685.5	738.8	775.3
2004	18.8	48.3	143.3	264.6	389.4	503.9	601.8	681.9	745.6
2005	16.6	47.4	143.0	253.5	354.9	437.6	500.9	547.4	580.8
2006	33.1	68.5	165.1	274.8	379.2	469.4	542.9	600.7	644.9
2007	32.5	75.3	177.6	267.9	333.7	377.3	404.9	421.9	432.2
2008	42.5	84.2	184.6	282.0	361.9	421.9	464.9	494.7	515.0

Table 2.10. Weight (g) at age on September 1 (middle of fishing year) estimated from annual weight-length parameters presented in Table 2.1 and annual lengths at age in Table 2.6.

Year	0	1	2	3	4	5	6	7	8
1955	36.2	124.3	274.3	390.3	451.5	523.3	610.8	681.9	674.8
1956	25.2	105.1	267.1	428.1	498.1	558.8	601.7	633.0	710.4
1957	41.2	91.3	230.8	413.4	553.1	595.6	645.8	668.9	649.8
1958	22.8	109.9	231.7	382.2	555.5	655.8	686.9	719.8	728.9
1959	60.5	75.2	231.4	373.5	507.5	643.9	697.1	726.6	739.2
1960	32.2	129.6	189.6	375.4	513.3	636.2	738.3	752.7	789.3
1961	48.3	116.0	258.4	336.7	512.9	618.3	727.6	789.9	771.3
1962	60.1	131.0	267.1	394.1	466.5	591.0	644.3	731.1	754.8
1963	63.5	145.6	257.7	424.9	567.3	635.0	727.1	742.6	835.6
1964	67.1	150.4	281.1	380.3	550.2	721.1	767.2	811.7	786.5
1965	53.0	145.8	275.5	386.3	462.2	621.2	835.8	853.3	852.3
1966	66.8	121.9	278.1	387.7	455.6	509.7	648.2	899.7	887.3
1967	62.1	157.6	252.4	434.2	507.2	535.7	581.5	722.8	1063.5
1968	74.7	128.1	316.8	424.3	583.3	596.3	583.3	620.6	751.8
1969	83.3	152.8	268.9	500.0	649.2	759.4	705.9	655.1	689.9
1970	58.7	185.4	269.3	419.1	595.1	790.4	814.4	705.8	631.7
1971	50.6	169.4	341.9	406.3	589.4	654.5	905.8	844.3	695.9
1972	24.7	122.7	328.9	493.1	566.4	800.0	713.2	1048.6	897.8
1973	43.1	121.1	263.3	475.2	636.9	752.9	1039.3	764.4	1175.1
1974	28.7	103.4	263.0	408.7	582.0	764.0	968.3	1344.6	817.8
1975	27.1	84.5	214.8	379.8	560.5	666.2	877.0	1204.4	1682.8
1976	17.3	67.4	192.4	345.3	474.1	732.6	761.3	1023.0	1543.4
1977	20.2	64.4	151.3	317.3	471.6	533.0	878.5	821.9	1126.2
1978	28.4	68.7	163.2	252.6	420.4	556.1	543.8	944.0	817.6
1979	24.8	68.7	168.8	279.1	366.8	516.4	638.4	562.1	1028.2
1980	21.7	56.6	148.1	288.8	391.6	482.0	593.8	702.3	573.1
1981	19.5	68.2	118.8	239.7	396.9	475.8	575.8	637.1	732.7
1982	26.7	76.2	167.7	212.4	341.0	486.7	533.9	643.0	650.7
1983	31.4	70.8	171.6	258.4	303.4	414.5	534.0	553.5	675.8
1984	25.6	71.9	165.8	291.7	368.6	440.4	525.8	623.9	621.0
1985	22.6	68.4	139.3	260.6	374.2	430.8	546.0	579.3	641.6
1986	24.3	64.4	149.8	230.7	375.2	470.7	516.2	715.8	683.0
1987	26.6	75.5	153.6	249.4	338.2	476.8	533.3	566.0	847.6
1988	27.8	69.4	159.9	241.3	329.2	429.6	541.5	556.9	580.4
1989	39.1	91.1	150.3	256.1	341.1	427.5	567.7	657.1	632.2
1990	35.8	113.1	208.5	248.2	340.4	419.4	494.0	670.6	713.7

Table 2.10. (*continued*)

Year	0	1	2	3	4	5	6	7	8
1991	52.0	92.8	224.1	309.7	334.8	393.4	461.9	521.5	723.5
1992	28.3	123.1	186.4	318.7	392.3	420.5	445.0	512.0	565.8
1993	49.8	93.4	243.6	294.7	396.0	457.6	501.1	488.5	553.9
1994	23.5	118.8	214.3	355.7	395.0	450.3	504.8	572.6	523.3
1995	22.6	112.6	229.7	331.8	423.1	453.4	456.3	501.1	586.3
1996	17.0	96.5	288.8	371.6	483.5	529.8	564.3	517.7	564.7
1997	28.8	87.6	246.6	447.0	491.0	594.2	585.9	625.8	536.0
1998	60.3	93.9	227.2	390.9	547.0	574.4	662.1	608.2	654.1
1999	39.1	131.1	214.0	354.9	496.6	597.8	627.1	699.9	612.1
2000	27.1	131.5	252.7	345.5	456.5	577.9	633.4	674.5	736.3
2001	55.0	125.1	280.6	382.9	462.1	522.0	624.5	643.7	697.6
2002	40.4	149.4	290.1	422.1	526.3	581.0	588.9	683.6	677.6
2003	49.5	121.7	277.0	440.1	557.5	701.6	725.3	678.0	779.9
2004	27.0	113.9	238.6	339.2	482.6	572.9	738.6	722.8	638.4
2005	37.3	81.3	214.5	328.6	369.5	495.8	572.7	760.5	714.6
2006	45.3	111.1	185.4	321.5	411.2	407.1	537.6	619.3	862.4
2007	50.2	119.8	219.0	297.3	390.9	434.4	399.2	514.3	588.0
2008	52.4	123.8	247.9	313.7	424.9	473.5	479.2	419.4	539.6

Table 2.11. Annual estimates of fecundity (no. of maturing or ripe ova in billions) at age on March 1 (start of fishing year) by applying Eq. (4) to fork lengths at age on March 1 in Table 2.5.

Year	2	3	4	5	6	7	8
1955	65949.3	124197.1	189046.2	249843.2	300637.5	339930.3	368805.1
1956	71350.8	145893.6	221082.0	281485.0	323903.6	351431.8	368491.4
1957	69755.9	130231.2	194694.2	252253.7	298049.8	331859.9	355641.4
1958	62742.6	127047.7	195469.1	254297.0	298619.5	329403.9	349743.6
1959	65429.2	116854.9	178156.9	242095.8	302576.0	355843.2	400376.6
1960	62993.1	120421.0	187223.2	252866.1	310306.2	356727.7	392258.9
1961	63108.8	112118.2	170487.9	231438.3	289228.2	340281.9	383110.9
1962	71738.6	125907.4	188539.5	251921.3	310174.4	360122.5	400861.1
1963	68266.4	123392.5	190115.2	260675.8	328248.8	388419.2	439216.3
1964	76304.0	136584.7	208296.4	282833.5	353041.4	414595.2	465819.1
1965	74006.1	138638.3	219348.0	306734.5	391922.9	468807.4	534383.2
1966	72242.9	122686.2	180619.5	239570.0	294453.5	342326.2	382136.8
1967	82336.0	139039.8	194152.9	240185.9	275062.4	299885.0	316859.3
1968	74287.6	123609.2	176275.6	225754.4	268244.0	302506.4	328945.3
1969	76710.2	140455.0	231049.2	348010.3	487504.9	643343.8	808304.8
1970	71604.5	140774.6	242018.5	373657.9	529258.9	699614.4	874983.4
1971	88365.5	159805.9	228041.3	282284.4	320851.1	346482.3	362837.4
1972	88728.3	196295.5	310676.5	405139.4	472357.8	516201.3	543385.8
1973	70335.3	146577.5	256029.5	391089.0	539542.8	688932.1	829478.9
1974	59921.8	134467.6	263246.2	460078.9	731729.1	1076050.9	1482614.4
1975	51290.4	105786.3	181934.0	273083.1	370174.3	464899.7	551412.2
1976	44269.7	101891.2	215330.4	421508.4	770273.3	1323361.4	2151052.9
1977	39237.7	76253.5	129278.7	196647.3	274423.1	357615.1	441350.2
1978	36925.0	69332.6	121707.7	201181.0	315162.1	470598.9	673230.3
1979	43339.1	82589.6	134324.8	193857.3	255656.9	314994.2	368700.6
1980	39976.0	74456.1	118800.2	168756.6	219677.7	267808.6	310786.5
1981	36818.3	69066.1	114365.7	171354.7	236961.6	307287.6	378470.8
1982	36367.8	62232.2	98767.9	146927.2	206735.1	277293.6	356937.8
1983	40164.7	72126.8	114419.2	164610.1	219259.9	274847.9	328429.0
1984	40211.1	74572.2	117144.1	162986.1	207507.4	247588.0	281717.2
1985	44961.5	86963.9	140606.2	199518.0	257437.6	309949.5	354820.0
1986	39114.8	70228.3	109981.4	155105.5	201865.7	247041.6	288398.4
1987	40796.0	72388.1	114377.0	164748.9	220418.4	278035.1	334619.2
1988	38136.8	69853.3	111339.6	159442.0	210247.3	260173.2	306576.1
1989	43649.8	74502.2	115064.4	163838.7	218371.0	275830.6	333519.5
1990	60942.8	100724.9	137073.8	165583.4	185926.2	199618.7	208509.6

Table 2.11. (*continued*)

Year	2	3	4	5	6	7	8
1991	55259.4	91855.1	131315.3	168839.1	201484.3	228155.5	249000.8
1992	60880.2	105438.8	145585.1	175964.5	196686.9	209979.9	218203.7
1993	62377.1	101231.3	140459.4	175289.6	203623.3	225341.2	241329.3
1994	54230.6	101392.7	150988.4	194532.8	228572.0	253272.0	270362.0
1995	65011.7	120287.6	171189.3	209589.0	235382.6	251583.5	261372.9
1996	66284.8	131710.6	194282.2	242100.8	274216.6	294250.9	306234.3
1997	62616.1	120348.4	182241.7	237188.9	280399.6	311843.8	333620.3
1998	63070.8	114972.2	182580.8	260720.6	343046.8	423793.2	498730.8
1999	63278.6	120156.4	187032.6	253818.4	313348.1	362383.8	400626.2
2000	72340.6	140656.9	204867.5	253413.8	285798.9	305913.1	317908.6
2001	88394.0	156324.1	220904.5	272453.7	309414.3	334233.4	350246.9
2002	80846.3	148907.9	206625.7	246312.6	270651.3	284681.1	292503.0
2003	77468.7	142516.7	212892.6	277274.3	329956.0	369992.6	398967.8
2004	53106.2	102593.2	166887.1	239086.0	311830.7	379455.7	438678.4
2005	53759.4	101801.8	157389.1	211880.0	259533.1	298064.7	327591.3
2006	62088.5	109903.4	166054.9	223767.3	277603.3	324409.6	363078.9
2007	68215.4	111497.2	149230.4	177403.4	196571.1	208907.7	216589.6
2008	70113.7	115614.9	160674.2	199526.3	230086.4	252706.9	268791.9

Table 2.12. Annual estimates of fecundity (no. of maturing or ripe ova in billions) at age on March 1 (start of fishing year) by applying Eq. (4) to fork lengths at age on March 1 in Table 2.6.

Year	2	3	4	5	6	7	8
1955	71746.5	135469.3	165103.0	219032.1	217740.1	321214.8	197636.0
1956	72101.7	146295.9	198364.8	238714.9	278271.9	326058.9	387984.5
1957	60931.2	137238.2	224018.7	259559.1	299712.5	323917.3	327224.5
1958	57709.7	117363.6	211476.4	289036.4	313736.4	344903.3	356688.9
1959	61418.3	116011.4	187290.0	282759.0	336617.2	358599.7	376132.3
1960	47771.5	115336.1	185701.6	261358.4	343689.8	368737.1	394034.3
1961	70012.3	97434.6	183959.9	254960.3	331451.9	391833.4	389392.5
1962	70150.0	128511.8	168105.1	259983.0	315659.2	392634.8	427907.7
1963	68998.5	135948.5	208853.0	255173.2	335925.7	364506.9	443038.6
1964	75369.9	119891.7	207921.9	307939.1	351182.9	406165.6	401611.8
1965	75931.9	128807.6	172835.8	273147.7	420038.6	448401.7	467516.7
1966	77430.6	132904.1	181346.3	220185.2	325456.6	538379.7	540607.8
1967	66557.2	143143.8	195394.4	225602.4	258463.6	364216.3	656568.9
1968	86617.7	130603.6	226649.3	254766.3	259346.1	287396.6	391507.4
1969	65678.2	158388.4	227291.6	319609.4	305825.1	283479.5	308310.1
1970	71523.3	125825.5	239545.2	358395.7	413288.6	346808.1	300046.0
1971	98268.8	132073.9	227585.6	318079.5	521103.1	500891.0	378172.8
1972	96288.1	185087.5	226596.6	390623.1	386318.9	708822.3	578341.6
1973	70423.5	178247.8	289225.2	364405.4	639177.6	441371.0	912764.0
1974	71533.1	135920.3	257500.9	396200.1	553580.4	1001314.7	483572.6
1975	57577.3	130162.3	220146.2	320777.2	494627.6	799846.0	1507571.6
1976	49093.0	103811.8	177277.6	313544.5	365765.6	578387.4	1105787.7
1977	39217.1	90510.0	157887.4	207919.5	406384.1	395594.0	645832.0
1978	40638.0	70425.4	139390.9	212756.8	225750.7	491521.0	414559.3
1979	41903.8	77700.7	112507.8	189066.7	263043.8	235543.2	565096.5
1980	38722.3	79680.8	123163.9	163675.8	234455.7	305896.6	240761.9
1981	32854.9	67809.1	127673.3	170869.8	220931.7	272912.2	340565.5
1982	41866.7	57672.8	106595.3	180426.7	215632.6	280867.9	303797.8
1983	44385.3	77593.2	95158.3	153582.4	232534.3	254407.9	340343.7
1984	41641.0	84315.7	121001.4	148589.2	206248.0	280103.7	286134.6
1985	38259.9	77327.9	131778.5	166630.6	220915.9	261679.2	321082.5
1986	40211.0	66869.5	124164.0	179808.9	209811.6	314420.0	317126.5
1987	39899.6	72506.8	107027.8	178376.7	223223.1	247684.1	430450.4
1988	43139.6	72525.0	112059.2	159064.3	235350.1	259481.7	279124.6
1989	40485.7	76555.8	111879.1	154548.9	222090.4	290944.2	288136.5
1990	54851.7	72906.0	114475.2	153220.9	195959.8	294199.2	342190.6

Table 2.12. (*continued*)

Year	2	3	4	5	6	7	8
1991	63019.2	100508.4	114208.9	151802.4	192481.2	233508.3	372828.0
1992	52052.2	107864.2	147452.8	160861.0	185035.0	227120.4	265781.3
1993	68848.3	92672.9	150264.8	187929.0	208909.7	212599.2	256088.9
1994	56432.9	119239.0	141156.7	184363.1	219108.9	255019.7	234349.9
1995	66500.4	110186.9	171898.0	191874.1	209152.0	241463.1	296939.1
1996	74449.0	119510.8	176525.7	219312.3	240032.1	226078.4	256774.4
1997	61582.4	149569.4	181601.6	246019.9	257939.6	282627.8	237196.1
1998	56880.8	125461.7	224088.8	244804.8	310819.9	287368.7	318397.4
1999	56378.7	115805.7	198169.6	283247.6	302967.2	366459.5	308807.7
2000	71927.3	111448.6	180156.5	265804.7	324434.9	352754.9	411526.9
2001	79355.5	131543.7	181047.5	237106.0	320982.0	350990.4	393221.1
2002	77920.9	148231.0	208482.5	255752.8	281249.5	362327.9	367362.8
2003	76840.2	145559.5	215084.2	296236.4	327067.9	312738.2	391655.1
2004	65996.0	121074.9	202863.4	268488.9	387279.9	389663.9	334063.3
2005	61521.3	116790.2	154372.8	241982.8	306414.8	475127.0	441406.0
2006	48597.1	107765.5	164961.6	175773.6	265744.9	331510.3	555314.3
2007	63580.9	96542.4	160274.7	203292.5	188400.4	279302.4	347428.0
2008	68957.5	110407.6	162892.4	212288.9	230685.1	195515.4	286783.3

Table 2.13. Constant *M* from life history approaches, using K & L_∞ averaged across annual values, either full period of 1955-2008 or recent period of 2000-2008.

[Maximum age, t_{max}, is 10 years, and water temperature, T^oC, is 19. For comparison, we have included the average estimates of *M* from age-varying approaches for ages 1-10.[

Life History	Parameters	Recent (2000-2008)	Overall (1955-2008)
Fixed M Approaches:	$t_{max} = 10$ $T = 19^oC$	$L_\infty = 33.47$ cm, K = 0.455	$L_\infty = 36.75$ cm, K = 0.362
Alverson & Carney	K, t_{max}	0.30	0.37
Hoenig	t_{max}	0.42	0.42
Jensen	K	0.68	0.53
Pauly	K, L_∞, T^oC	0.86	0.72
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}	0.64	0.63
Boudreau & Dickie	W_a^{-1}	0.52	0.51
Lorenzen	W_a^{-1}	0.59	0.58
MSVPA-X (1982-2008)	MSVPA-X	0.50	0.50

Table 2.14. Summaries of various age-specific estimates of *M* including those as inverse function of size at age, and the predator-prey approach used in MSVPA-X.

[Petersen and Wroblewski (1984), Boudreau and Dickie (1989), and Lorenzen (1996)]

Age	Peterson & Wroblewski	Boudreau & Dickie	Lorenzen	MSVPA-X
0	1.187	1.173	1.257	1.140
1	0.904	0.819	0.902	0.897
2	0.745	0.633	0.711	0.673
3	0.665	0.546	0.620	0.559
4	0.620	0.497	0.569	0.508
5	0.591	0.467	0.537	0.483
6	0.573	0.448	0.516	0.468
7	0.560	0.435	0.502	0.468
8	0.551	0.426	0.493	0.468
9	0.544	0.419	0.486	0.468
10	0.540	0.414	0.481	0.468

Table 2.15. Year- and age-varying estimates of *M* from MSVPA-X for 1982-2008, and average of age-varying values for 1982-2008 repeated for 1955-1981.

[Average age-varying M from MSVPA-X for 1982-2008 also shown at bottom.]

Year	0	1	2	3	4	5	6+
1955	1.140	0.897	0.673	0.559	0.508	0.483	0.468
1956	1.140	0.897	0.673	0.559	0.508	0.483	0.468
1957	1.140	0.897	0.673	0.559	0.508	0.483	0.468
1958	1.140	0.897	0.673	0.559	0.508	0.483	0.468
1959	1.140	0.897	0.673	0.559	0.508	0.483	0.468
1960	1.140	0.897	0.673	0.559	0.508	0.483	0.468
1961	1.140	0.897	0.673	0.559	0.508	0.483	0.468
1962	1.140	0.897	0.673	0.559	0.508	0.483	0.468
1963	1.140	0.897	0.673	0.559	0.508	0.483	0.468
1964	1.140	0.897	0.673	0.559	0.508	0.483	0.468
1965	1.140	0.897	0.673	0.559	0.508	0.483	0.468
1966	1.140	0.897	0.673	0.559	0.508	0.483	0.468
1967	1.140	0.897	0.673	0.559	0.508	0.483	0.468
1968	1.140	0.897	0.673	0.559	0.508	0.483	0.468
1969	1.140	0.897	0.673	0.559	0.508	0.483	0.468
1970	1.140	0.897	0.673	0.559	0.508	0.483	0.468
1971	1.140	0.897	0.673	0.559	0.508	0.483	0.468
1972	1.140	0.897	0.673	0.559	0.508	0.483	0.468
1973	1.140	0.897	0.673	0.559	0.508	0.483	0.468
1974	1.140	0.897	0.673	0.559	0.508	0.483	0.468
1975	1.140	0.897	0.673	0.559	0.508	0.483	0.468
1976	1.140	0.897	0.673	0.559	0.508	0.483	0.468
1977	1.140	0.897	0.673	0.559	0.508	0.483	0.468
1978	1.140	0.897	0.673	0.559	0.508	0.483	0.468
1979	1.140	0.897	0.673	0.559	0.508	0.483	0.468
1980	1.140	0.897	0.673	0.559	0.508	0.483	0.468
1981	1.140	0.897	0.673	0.559	0.508	0.483	0.468

Table 2.15. (cont.)

Year	0	1	2	3	4	5	6
1982	1.624	1.350	0.993	0.826	0.597	0.527	0.506
1983	1.487	1.272	0.917	0.662	0.586	0.516	0.495
1984	1.313	1.123	0.845	0.595	0.524	0.506	0.468
1985	1.314	1.128	0.930	0.610	0.521	0.516	0.499
1986	1.279	1.106	0.863	0.675	0.525	0.516	0.532
1987	1.117	0.936	0.757	0.602	0.511	0.495	0.499
1988	1.044	0.940	0.711	0.581	0.516	0.493	0.489
1989	0.950	0.789	0.678	0.565	0.510	0.490	0.482
1990	0.981	0.736	0.603	0.537	0.500	0.486	0.476
1991	0.948	0.814	0.609	0.526	0.501	0.491	0.481
1992	0.900	0.670	0.588	0.503	0.481	0.451	0.452
1993	0.986	0.802	0.562	0.519	0.485	0.458	0.429
1994	0.993	0.783	0.596	0.504	0.483	0.460	0.432
1995	1.089	0.764	0.584	0.514	0.497	0.473	0.448
1996	1.038	0.778	0.540	0.482	0.467	0.459	0.442
1997	1.062	0.793	0.541	0.470	0.453	0.450	0.443
1998	1.118	0.853	0.564	0.478	0.445	0.448	0.450
1999	1.124	0.763	0.588	0.496	0.466	0.448	0.464
2000	1.096	0.732	0.548	0.495	0.475	0.461	0.454
2001	1.137	0.785	0.570	0.510	0.483	0.474	0.465
2002	1.143	0.842	0.591	0.516	0.504	0.479	0.471
2003	1.114	0.841	0.618	0.533	0.492	0.479	0.458
2004	1.241	0.895	0.673	0.557	0.535	0.487	0.465
2005	1.199	0.997	0.653	0.565	0.526	0.496	0.458
2006	1.212	0.962	0.696	0.572	0.538	0.500	0.463
2007	1.149	0.895	0.723	0.585	0.536	0.497	0.464
2008	1.130	0.863	0.639	0.605	0.550	0.498	0.463
Average (1982-2008)	1.140	0.897	0.673	0.559	0.508	0.483	0.468

Table 4.1. Years of activity for individual menhaden reduction plants along the U.S. Atlantic coast, 1955-2009.

	Plant																																			Total	Number
Year	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	12
2005										+																										1	11
2006										+																										1	10
2007										+																										1	10
2008										+																										1	10
2009										+																										1	10

Table 4.1. (*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, MA
		(Gloucester Marine Protein)	
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 4.2. Atlantic menhaden landings and effort (vessel-weeks) of from the reduction purse-seine fishery, 1940-2008, landings from the bait fisheries, 1985-2008, landings estimated from the recreational fishery (MRFSS), 1981-2008, and total landings for all fisheries.

[Recreational landings represent removals of A+B1+50%B2 by weight.]

	Reduction Fishery		Bait Fishery	Recreational Fishery	Total Landings
Year	Landings (1000 t)	Effort (v-w)	Landings (1000 t)	Catches (1000 t)	(1000 t)
1940	217.7	967			217.7
1941	277.9	1291			277.9
1942	167.2	991			167.2
1943	237.2	889			237.2
1944	257.9	1167			257.9
1945	295.9	1271			295.9
1946	362.4	1365			362.4
1947	378.3	1582			378.3
1948	346.5	1781			346.5
1949	363.8	2076			363.8
1950	297.2	1650			297.2
1951	361.4	1686			361.4
1952	409.9	1653			409.9
1953	593.2	1972			593.2
1954	608.1	2094			608.1
1955	641.4	2748			641.4
1956	712.1	2878			712.1
1957	602.8	2775			602.8
1958	510.0	2343			510.0
1959	659.1	2847			659.1
1960	529.8	2097			529.8
1961	575.9	2371			575.9
1962	537.7	2351			537.7
1963	346.9	2331			346.9
1964	269.2	1807			269.2
1965	273.4	1805			273.4
1966	219.6	1386			219.6
1967	193.5	1316			193.5
1968	234.8	1209			234.8
1969	161.6	995			161.6
1970	259.4	906			259.4
1971	250.3	897			250.3
1972	365.9	973			365.9
1973	346.9	1099			346.9
1974	292.2	1145			292.2
1975	250.2	1218			250.2

Table 4.2. (*continued*)

Year	Reduction Fishery		Bait Fishery	Recreational Fishery	Total Landings
	Landings (1000 t)	Effort (v-w)	Landings (1000 t)	Catches (1000 t)	(1000 t)
1976	340.5	1163			340.5
1977	341.1	1239			341.1
1978	344.1	1210			344.1
1979	375.7	1198			375.7
1980	401.5	1158			401.5
1981	381.3	1133		0.12	381.4
1982	382.4	948		0.13	382.5
1983	418.6	995		0.12	418.7
1984	326.3	892		0.15	326.4
1985	306.7	577	26.7	0.16	333.5
1986	238.0	377	28.0	0.35	266.3
1987	327.0	531	30.6	0.25	357.9
1988	309.3	604	36.3	0.31	345.9
1989	322.0	725	31.0	0.15	353.2
1990	401.2	826	30.8	0.17	432.2
1991	381.4	926	36.2	0.38	418.0
1992	297.6	794	39.0	0.52	337.2
1993	320.6	626	42.8	0.19	363.6
1994	260.0	573	39.1	0.12	299.3
1995	339.9	600	42.4	0.24	382.5
1996	292.9	528	35.3	0.09	328.3
1997	259.1	618	36.5	0.09	295.7
1998	245.9	437	39.4	0.08	285.3
1999	171.2	382	36.2	0.23	207.6
2000	167.2	311	35.3	0.07	202.6
2001	233.7	334	36.3	0.13	270.1
2002	174.0	318	37.1	0.19	211.2
2003	166.1	302	33.8	0.21	200.2
2004	183.4	345	35.5	0.36	219.2
2005	146.9	291	38.8	0.13	185.9
2006	157.4	322	26.5	0.40	184.3
2007	174.5	333	42.8	0.34	217.6
2008	141.1	262	47.4	0.37	188.8

Table 4.3. Historical catch statistics (in 1000 pounds) for menhaden with interpolated values by region, 1880-2000.

[Linearly interpolated values by region are highlighted in red.]

Year	NE Total	MA Total	CB Total	SA Total	Total
1880	133,786	318,519	92,117	0	544,422
1881	125,721	285,207	91,134	0	502,061
1882	117,655	251,895	90,150	0	459,700
1883	109,590	218,583	89,167	0	417,339
1884	101,525	185,270	88,183	0	374,979
1885	93,460	151,958	87,200	0	332,618
1886	85,394	118,646	86,216	0	290,257
1887	77,329	85,334	85,233	14,756	262,652
1888	130,350	144,136	84,610	13,844	372,940
1889	173,803	137,754	109,961	8,753	430,271
1890	127,217	159,185	135,312	12,410	434,124
1891	80,631	125,598	136,932	12,253	355,414
1892	34,045	119,858	143,945	12,096	309,944
1893	27,507	114,118	150,958	11,939	304,522
1894	20,969	108,379	157,971	11,781	299,099
1895	14,431	102,639	164,983	11,624	293,677
1896	7,893	96,899	171,996	11,467	288,255
1897	1,355	91,159	179,009	11,310	282,833
1898	23,680	91,159	179,009	11,310	305,158
1899	22,379	121,700	204,411	13,198	361,687
1900	21,078	152,240	229,813	15,086	418,216
1901	19,776	213,321	280,616	18,862	532,575
1902	18,475	226,884	273,000	24,369	542,728
1903	22,911	240,447	265,384	29,876	558,619
1904	27,348	254,010	257,768	35,383	574,509
1905	31,784	211,756	243,922	40,891	528,352
1906	27,256	169,502	230,075	46,398	473,231
1907	22,728	127,248	216,229	51,905	418,109
1908	18,200	84,994	202,382	57,412	362,988
1909	19,130	95,989	216,049	77,447	408,616
1910	20,061	106,985	229,716	97,481	454,243
1911	20,991	117,980	243,383	117,516	499,871
1912	21,921	128,976	257,050	137,551	545,498
1913	22,852	139,971	270,717	157,586	591,126
1914	23,782	150,967	284,385	177,620	636,754
1915	24,713	161,962	298,052	197,655	682,381
1916	25,643	172,958	311,719	217,690	728,009
1917	26,573	183,953	325,386	237,724	773,636
1918	27,504	194,949	339,053	257,759	819,264
1919	28,434	205,944	352,720	235,843	822,941
1920	24,254	216,940	366,387	213,928	821,509

Table 4.3. (cont.)

1921	20,075	227,935	323,208	192,012	763,230
1922	15,895	190,319	280,029	170,097	656,340
1923	11,716	152,703	236,851	148,181	549,450
1924	7,536	115,087	193,672	150,627	466,922
1925	6,946	77,471	150,493	153,073	387,983
1926	6,356	39,855	137,677	155,519	339,407
1927	5,765	40,077	124,861	157,965	328,668
1928	5,175	40,298	112,045	150,844	308,362
1929	395	40,520	99,229	234,420	374,564
1930	1,708	52,397	115,842	192,994	362,941
1931	5	40,567	112,920	72,456	225,948
1932	54	43,194	195,486	77,176	315,910
1933	1,030	79,575	115,990	115,992	312,586
1934	0	0	143,879	154,807	298,686
1935	4,284	179,603	121,088	192,439	497,414
1936	0	0	167,558	230,070	397,628
1937	294	148,505	121,980	205,108	475,887
1938	328	86,941	95,083	302,769	485,121
1939	122	148,584	127,681	287,243	563,630
1940	88	245,369	143,227	224,882	613,566
1941	82	224,943	182,223	231,161	638,409
1942	75	204,517	64,115	237,441	506,148
1943	132	196,259	71,043	243,720	511,154
1944	70	304,314	77,970	250,000	632,354
1945	200	368,122	89,357	256,279	713,958
1946	204	74,830	149,339	234,448	458,821
1947	222	508,727	178,248	212,617	899,814
1948	1,216	389,188	151,932	190,787	733,123
1949	12,566	392,410	137,812	168,956	711,744
1950	9,304	372,946	170,912	147,125	700,287
1951	11,761	441,825	127,425	188,090	769,101
1952	36,088	480,305	92,374	314,841	923,608
1953	39,875	857,584	162,227	199,345	1,259,031
1954	59,685	781,761	288,816	206,262	1,336,524
1955	79,794	763,827	315,359	227,811	1,386,791
1956	78,767	953,568	190,422	314,646	1,537,403
1957	41,788	821,554	267,852	196,401	1,327,595
1958	13,853	525,516	322,786	244,117	1,106,272
1959	52,851	653,024	414,505	330,516	1,450,896
1960	42,629	670,799	248,905	215,023	1,177,356
1961	26,011	715,049	298,679	254,505	1,294,244
1962	23,753	782,487	327,910	157,169	1,291,319
1963	353	372,851	259,015	215,886	848,105
1964	6	139,258	336,414	190,146	665,824
1965	20	151,011	359,946	192,275	703,252

Table 4.3. (cont.)

1966	14	22,016	277,895	215,114	515,039
1967	36	46,538	223,268	193,778	463,620
1968	23	86,262	274,077	191,382	551,744
1969	46	43,755	181,651	164,874	390,326
1970	10,506	31,470	449,797	136,253	628,026
1971	25,893	61,562	400,103	99,289	586,847
1972	30,692	140,280	556,501	105,951	833,424
1973	66,647	156,250	505,620	85,223	813,740
1974	78,442	107,896	384,775	133,837	704,950
1975	50,866	67,030	321,889	166,895	606,680
1976	59,013	151,487	446,141	145,033	801,674
1977	30,878	98,385	509,955	158,656	797,874
1978	20,326	82,698	427,929	205,359	736,312
1979	66,535	104,041	460,968	259,366	890,910
1980	62,302	120,900	545,938	218,226	947,366
1981	47,836	103,814	411,409	324,871	887,929
1982	78,153	2,090	607,577	197,374	885,194
1983	42,698	1,839	651,319	186,259	882,115
1984	17,993	3,194	491,199	166,146	678,531
1985	33,428	3,958	644,889	103,517	785,792
1986	22,869	2,873	451,124	73,968	550,834
1987	19,980	2,792	621,317	58,278	702,367
1988	19,885	2,616	556,987	74,750	654,238
1989	534	3,394	618,328	68,128	690,384
1990	7,468	9,832	707,199	74,867	799,366
1991	22,734	17,528	604,728	113,025	758,014
1992	21,581	28,708	577,122	60,263	687,674
1993	21,056	29,510	642,410	67,296	760,272
1994	100	39,370	516,782	76,982	633,233
1995	317	37,768	704,447	61,458	803,990
1996	91	35,629	584,296	54,135	674,151
1997	2,909	38,728	502,060	98,136	641,833
1998	2,358	33,375	513,192	62,677	611,602
1999	937	31,127	383,879	42,639	458,582
2000	334	31,319	372,002	53,031	456,687

Regional definitions are: New England (ME, NH, MA, RI, CT), Middle Atlantic (NY, NJ, DE), Chesapeake Bay (MD, VA), and South Atlantic (NC, SC, GA, east coast of FL).

Table 4.4. Historical menhaden plants and landings (Atlantic and gulf menhaden) from the report *Menhaden Fishery, 1873-1964*.

[Fish received is in thousands of pounds, and 'Landings' is converted to 1000 metric tons (kmt).]

Year	Plants	Fish Received	Landings
1873	62	266459	120.9
1874	64	330228	149.8
1875	60	377429	171.2
1876	64	343342	155.7
1877	56	393720	178.6
1878	56	514412	233.3
1879	60	426833	193.6
1880	79	520506	236.1
1881	97	304309	138.0
1882	97	232248	105.3
1883	78	411019	186.4
1884	52	575257	260.9
1885	50	321074	145.6
1886	26	189681	86.0
1887	28	223488	101.4
1888	24	294391	133.5
1889	29	372064	168.8
1890	28	357570	162.2
1891	27	237943	107.9
1892	29	149828	68.0
1893	33	245492	111.4
1894	44	357352	162.1
1895	42	309370	140.3
1896	35	268955	122.0
1897	41	391483	177.6
1898	40	363475	164.9
1899	*		
1900	*		
1901	36	609744	276.6
1902	*		
1903	*		
1904	*		
1905	*		
1906	*		
1907	*		
1908	*		
1909	*		
1910	*		
1911	*		
1912	48	711435	322.7
1913	*		
1914	*		
1915	*		
1916	*		
1917	*	306146	138.9
1918	*	259292	117.6
1919	*	438520	198.9
1920	*		

Table 4.4. (cont.)

1921	40	691132	313.5
1922	45	812342	368.5
1923	50	743895	337.4
1924	45	344284	156.2
1925	43	532118	241.4
1926	41	382781	173.6
1927	39	392763	178.2
1928	34	362213	164.3
1929	37	442443	200.7
1930	33	409513	185.8
1931	27	236432	107.2
1932	24	375479	170.3
1933	30	357726	162.3
1934	27	517403	234.7
1935	27	434386	197.0
1936	29	516104	234.1
1937	32	529202	240.0
1938	32	517530	234.7
1939	33	574825	260.7
1940	30	634589	287.8
1941	29	775087	351.6
1942	30	482644	218.9
1943	25	615554	279.2
1944	27	685980	311.2
1945	24	759074	344.3
1946	28	916013	415.5
1947	31	948156	430.1
1948	31	1007889	457.2
1949	31	1072630	486.5
1950	35	1000498	453.8
1951	35	1103915	500.7
1952	40	1386281	628.8
1953	36	1683406	763.6
1954	34	1740600	789.5
1955	35	1848299	838.4
1956	38	2076588	941.9
1957	41	1681580	762.8
1958	38	1544683	700.7
1959	40	2193864	995.1
1960	38	1999036	906.7
1961	35	2290936	1039.2
1962	33	2227316	1010.3
1963	32	1787638	810.9
1964	31	1530631	694.3

Table 4.5. Historical landings (1,000 metric tons) by gear available from ACCSP, 1950-2008.

Year	Purse Seine	Pound Net	Other	Total
1950	306.4	8.7	2.6	317.6
1951	328.4	18.0	2.4	348.9
1952	404.8	11.7	2.4	418.9
1953	545.3	25.0	0.8	571.1
1954	587.0	18.2	1.1	606.2
1955	614.4	13.8	0.8	629.0
1956	674.1	22.2	1.1	697.4
1957	577.5	22.9	1.8	602.2
1958	487.1	12.9	1.8	501.8
1959	637.5	18.4	2.2	658.1
1960	514.6	16.8	2.7	534.0
1961	562.0	18.0	7.0	587.1
1962	559.2	24.2	2.4	585.7
1963	360.3	20.5	3.9	384.7
1964	281.8	18.9	1.3	302.0
1965	295.4	19.0	4.7	319.0
1966	219.9	10.6	3.2	233.6
1967	198.7	10.5	1.1	210.3
1968	240.8	8.6	0.9	250.3
1969	166.4	9.8	0.8	177.0
1970	263.2	20.3	1.3	284.9
1971	252.7	12.5	0.9	266.2
1972	367.7	8.8	1.5	378.0
1973	354.3	13.5	1.3	369.1
1974	305.2	13.2	1.4	319.8
1975	253.5	20.4	1.3	275.2
1976	344.0	18.5	1.1	363.6
1977	344.2	21.7	1.4	367.3
1978	330.3	19.2	6.7	356.2
1979	391.1	10.4	2.6	404.1
1980	403.6	16.0	10.1	429.7
1981	380.3	14.9	7.5	402.8
1982	381.7	14.6	5.3	401.5
1983	401.9	14.3	4.7	421.0
1984	322.2	9.6	4.7	336.6
1985	346.8	11.3	3.5	361.6
1986	244.4	7.7	4.3	256.3
1987	314.3	9.9	2.1	326.3
1988	296.5	9.3	1.7	307.5
1989	311.7	9.4	1.3	322.4

Table 4.5. (cont.)

Year	Purse Seine	Pound Net	Other	Total
1990	363.3	4.6	2.5	370.3
1991	339.2	4.7	2.0	345.9
1992	306.3	4.7	2.2	313.2
1993	340.6	5.3	1.9	347.8
1994	280.2	4.5	1.7	286.5
1995	361.4	4.0	3.4	368.9
1996	303.0	2.6	3.1	308.7
1997	285.1	3.3	2.7	291.1
1998	270.5	2.7	2.2	275.4
1999	202.3	4.9	1.0	208.2
2000	203.0	5.0	0.9	208.9
2001	255.6	4.0	1.5	261.1
2002	206.5	4.0	1.0	211.5
2003	198.9	3.1	1.2	203.3
2004	207.3	4.1	2.7	214.1
2005	176.7	9.1	8.4	194.2
2006	173.7	4.3	6.0	183.9
2007	200.8	9.5	6.7	217.0
2008	172.2	6.3	9.2	187.7

Table 4.6. Menhaden reduction landings (1,000 mt), nominal effort (vessel-week), and LPUE (landings per vessel-week), 1940-2008.

	Reduction Fishery		
Year	Landings (1000 t)	Effort (v-w)	LPUE
1940	217.7	967	0.225
1941	277.9	1,291	0.215
1942	167.2	991	0.169
1943	237.2	889	0.267
1944	257.9	1,167	0.221
1945	295.9	1,271	0.233
1946	362.4	1,365	0.265
1947	378.3	1,582	0.239
1948	346.5	1,781	0.195
1949	363.8	2,076	0.175
1950	297.2	1,650	0.180
1951	361.4	1,686	0.214
1952	409.9	1,653	0.248
1953	593.2	1,972	0.301
1954	608.1	2,094	0.290
1955	641.4	2,748	0.233
1956	712.1	2,878	0.247
1957	602.8	2,775	0.217
1958	510.0	2,343	0.218
1959	659.1	2,847	0.232
1960	529.8	2,097	0.253
1961	575.9	2,371	0.243
1962	537.7	2,351	0.229
1963	346.9	2,331	0.149
1964	269.2	1,807	0.149
1965	273.4	1,805	0.151
1966	219.6	1,386	0.158
1967	193.5	1,316	0.147
1968	234.8	1,209	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	1,099	0.316
1974	292.2	1,145	0.255
1975	250.2	1,218	0.205

Table 4.6. (*continued*)

Year	Reduction Fishery		LPUE
	Landings (1000 t)	Effort (v-w)	
1976	340.5	1,163	0.293
1977	341.1	1,239	0.275
1978	344.1	1,210	0.284
1979	375.7	1,198	0.314
1980	401.5	1,158	0.347
1981	381.3	1,133	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

Table 4.7. Number of fishing trips by the Atlantic menhaden reduction fleet, 1955-2008.

[Approximately 17% of all trips (179,891) were matched with corresponding biostatistical samples (29,626), and hence fishing location was available.]

	All Data			Subsetted Data			Sampling
Year	N	Catch (mt)	SE (C MT)	N	Catch (mt)	SE (Catch)	Fraction
1955	8978	160.6	1.39	668	179.9	5.67	0.074
1956	9912	161.5	1.38	806	178.4	5.23	0.081
1957	9403	144.1	1.24	809	161.2	4.55	0.086
1958	7828	146.5	1.36	706	158.6	5.04	0.090
1959	9969	148.6	1.17	874	167.3	4.26	0.088
1960	7611	156.5	1.36	635	179.6	5.57	0.083
1961	8428	153.6	1.38	605	173.4	5.59	0.072
1962	8015	151.0	1.43	736	162.8	5.12	0.092
1963	7232	107.8	1.20	598	110.8	4.46	0.083
1964	5742	105.4	1.37	482	112.9	5.34	0.084
1965	5659	108.6	1.39	898	104.5	3.22	0.159
1966	4525	109.1	1.84	708	108.3	4.49	0.156
1967	3968	109.6	1.90	661	111.3	4.54	0.167
1968	3729	141.5	2.25	885	152.0	4.77	0.237
1969	2837	128.0	2.59	701	111.2	5.06	0.247
1970	3099	187.3	2.70	415	223.6	7.63	0.134
1971	3016	185.7	2.78	385	208.4	8.41	0.128
1972	3181	257.4	3.32	631	271.3	6.93	0.198
1973	3652	212.6	3.08	577	223.4	8.30	0.158
1974	3338	195.9	3.31	479	199.4	9.93	0.143
1975	3500	160.0	2.79	648	187.5	8.29	0.185
1976	3450	220.9	3.85	574	279.8	12.07	0.166
1977	3416	223.5	3.61	635	248.6	9.28	0.186
1978	3365	228.8	3.92	664	263.1	10.12	0.197
1979	3266	257.4	4.30	582	300.7	12.27	0.178
1980	3198	281.0	4.48	656	309.7	11.77	0.205
1981	2970	287.3	5.18	811	270.5	10.12	0.273
1982	2933	291.8	4.90	829	306.5	9.66	0.283
1983	2666	351.4	5.84	952	298.6	9.06	0.357
1984	2349	310.8	6.13	982	273.9	8.77	0.418
1985	1261	544.2	9.36	505	503.2	14.47	0.400
1986	933	570.8	11.00	379	387.4	18.03	0.406
1987	1252	584.3	9.24	574	543.4	13.69	0.458
1988	1525	453.8	8.17	567	434.1	11.55	0.372
1989	1775	406.0	7.35	587	424.8	11.33	0.331

Table 4.7. (*continued*)

	All Data			Subsetted Data			Sampling
Year	N	Catch (mt)	SE (C MT)	N	Catch (mt)	SE (Catch)	Fraction
1990	2201	407.9	6.77	624	389.4	11.06	0.284
1991	2250	379.3	6.23	660	415.0	11.41	0.293
1992	1716	388.1	7.34	445	435.0	14.33	0.259
1993	1489	481.8	8.53	423	506.7	16.04	0.284
1994	1339	434.5	8.65	377	518.3	17.22	0.282
1995	1431	531.6	9.43	361	600.8	19.42	0.252
1996	1399	468.5	9.04	350	578.8	19.17	0.250
1997	1499	386.9	8.11	347	487.0	18.73	0.231
1998	999	550.9	11.09	282	599.7	19.62	0.282
1999	895	428.0	10.27	297	528.6	18.68	0.332
2000	690	542.4	13.76	209	560.2	24.87	0.303
2001	836	625.7	12.69	285	644.4	20.40	0.341
2002	783	497.5	12.09	247	531.1	21.02	0.315
2003	777	478.4	11.62	282	508.9	18.78	0.363
2004	807	508.5	11.34	318	498.2	17.05	0.394
2005	745	441.1	9.80	295	463.8	15.10	0.396
2006	684	514.9	12.21	208	445.4	18.88	0.304
2007	803	486.2	10.48	279	452.8	14.48	0.347
2008	567	557.0	12.37	133	468.9	21.89	0.235

Table 4.8. Sample size (number of sets), mean catch per set (mt), and standard error of mean catch per set made by the Virginia and North Carolina reduction fleet, 1985-2008.

Year	N	Catch (mt)	Std Err
1985	10,587	26.25	0.26
1986	5,313	41.09	0.53
1987	9,208	32.59	0.32
1988	9,523	26.70	0.28
1989	10,925	25.67	0.26
1990	12,061	26.81	0.26
1991	13,113	23.95	0.24
1992	11,590	22.98	0.24
1993	9,620	31.27	0.33
1994	10,850	24.19	0.27
1995	11,158	31.12	0.33
1996	9,612	30.38	0.32
1997	10,548	26.10	0.32
1998	7,491	32.97	0.44
1999	6,400	27.27	0.39
2000	4,739	36.34	0.57
2001	5,665	41.01	0.56
2002	4,910	36.37	0.59
2003	4,565	36.93	0.61
2004	5,551	33.36	0.44
2005	5,103	29.16	0.35
2006	3,953	41.71	0.66
2007	4,698	38.99	0.56
2008	3,467	42.68	0.75

Table 4.9. 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, 1955-2005.

Year	Sample Size (n)	Landings (millions)	Landings (1000 mt)	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 4.9. (*continued*)

Year	Sample Size (n)	Landings (millions)	Landings (1000 mt)	Intensity (C/100n)	Mean 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

Table 4.10. Estimated reduction landings of Atlantic menhaden in numbers by age (in millions), 1955-2005.

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 4.10. (*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

Table 4.11. Number of fish sampled from Atlantic menhaden landed for bait, 1985-2008.

	Purse Seine				Poundnet				Totals		
Year	NE	MA	CB	SA	NE	MA	CB	SA	Purse Seine	Poundnet	Grand
1985	600	0	0	170	0	0	0	30	770	30	800
1986	40	0	0	340	0	0	0	40	380	40	420
1987	0	0	0	220	0	0	0	0	220	0	220
1988	0	0	0	10	0	0	0	0	10	0	10
1989	20	0	0	10	0	0	0	0	30	0	30
1990	0	0	0	10	0	0	10	0	10	10	20
1991	0	0	0	78	0	0	0	0	78	0	78
1992	0	0	30	40	0	0	0	0	70	0	70
1993	29	0	10	130	0	0	0	0	169	0	169
1994	80	320	0	139	0	0	10	0	539	10	549
1995	130	59	96	77	0	0	0	0	362	0	362
1996	15	187	137	18	0	0	0	0	357	0	357
1997	0	110	136	67	0	0	100	0	313	100	413
1998	0	225	295	106	0	0	0	10	626	10	636
1999	0	192	299	47	0	0	0	0	538	0	538
2000	0	273	231	39	0	0	0	0	543	0	543
2001	0	677	275	10	0	0	0	0	962	0	962
2002	0	155	471	76	0	0	0	0	702	0	702
2003	0	108	309	10	0	0	0	0	427	0	427
2004	0	28	326	0	0	0	0	0	354	0	354
2005	0	4	318	0	0	0	0	0	322	0	322
2006	28	223	203	0	0	10	20	0	454	30	484
2007	122	477	374	0	190	10	80	0	973	280	1253
2008	199	329	314	0	140	50	80	0	842	270	1112
Total	663	3367	3824	1597	330	70	300	80	10051	780	10831

Table 4.12. AIC based evaluation of model fits to the PRFC pound net CPUE data.

Model parameterization	*-log(l(θ))*	*# parameters*	*AIC*	**ΔAIC**
1	189236.6	44	378561.3	0.0
2	189890.1	36	379852.2	1290.9
3	189847.3	34	379762.6	1201.3
4	190444.9	26	380941.8	2380.5

Table 4.13. Atlantic menhaden catch in numbers (in millions) at age from the bait fishery, 1985-2008.

[Includes adjustment to include recreational landings (MRFSS).]

Year	0	1	2	3	4	5	6	Total
1985	0.3	8.8	67.6	19.4	6.4	1.1	0.2	103.8
1986	0.2	5.1	40.9	34.8	12.8	1.2	0.2	95.2
1987	0.2	5.0	50.5	34.9	13.0	1.2	0.2	104.9
1988	0.2	6.1	49.6	45.4	17.4	1.6	0.2	120.6
1989	0.3	7.8	59.9	32.8	10.9	1.1	0.1	112.8
1990	0.4	23.6	47.3	34.1	12.4	1.3	0.2	119.3
1991	0.2	15.9	53.2	43.8	16.5	1.7	0.2	131.6
1992	0.4	20.6	48.6	47.3	17.6	1.9	0.3	136.7
1993	0.8	23.9	43.9	49.7	17.9	1.9	0.3	138.4
1994	0.3	12.5	60.2	36.7	17.8	2.4	0.2	130.1
1995	0.0	41.6	44.9	50.7	26.1	0.1	0.0	163.5
1996	0.0	2.9	61.7	28.6	6.8	0.2	0.0	100.4
1997	0.0	5.1	39.0	31.6	20.4	5.5	1.1	102.6
1998	3.2	5.0	44.9	31.5	21.2	3.5	0.7	110.0
1999	0.2	5.2	75.3	30.9	14.1	1.8	0.3	127.8
2000	0.6	18.8	65.5	20.6	8.1	1.0	0.3	114.9
2001	0.2	4.7	55.4	37.4	4.5	0.6	0.1	103.0
2002	0.0	2.5	16.8	44.5	18.7	2.6	0.1	85.3
2003	0.5	9.1	69.8	24.0	4.8	0.2	0.0	108.4
2004	0.0	7.8	88.2	31.0	8.0	0.9	0.1	136.0
2005	0.0	1.6	55.7	53.2	7.0	0.9	0.1	118.4
2006	0.0	18.4	39.8	29.7	5.7	0.2	0.0	93.8
2007	0.0	36.5	116.1	34.1	8.1	0.5	0.1	195.3
2008	0.0	3.5	96.1	53.2	11.1	1.3	0.0	165.3

Table 4.14. Recreational harvest (Type A+B1) in numbers of Atlantic menhaden in the recreational fishery by region (New England, Middle Atlantic, and South Atlantic states), 1981-2008.

Year	MA	NE	SA	Overall
1981	117,956	248,063	77,841	443,860
1982	3,362	218,032	546,378	767,772
1983	26,032	175,877	382,532	584,441
1984	315,659	101,280	259,740	676,679
1985	266,892	227,163	101,708	595,763
1986	736,270	557,216	13,463	1,306,949
1987	365,505	463,769	142,009	971,283
1988	892,561	252,017	280,734	1,425,312
1989	192,874	258,202	182,656	633,732
1990	234,233	250,854	343,572	828,659
1991	856,362	374,939	390,179	1,621,480
1992	288,409	1,098,239	1,266,056	2,652,704
1993	268,991	354,035	84,018	707,044
1994	222,664	133,236	279,251	635,151
1995	777,497	142,589	85,271	1,005,357
1996	50,411	181,925	297,758	530,094
1997	227,652	98,780	135,071	461,503
1998	54,784	187,576	78,272	320,632
1999	742,075	54,578	289,447	1,086,100
2000	47,275	131,385	99,969	278,629
2001	147,773	17,388	985,208	1,150,369
2002	200,812	233,814	515,634	950,260
2003	217,044	21,153	1,669,518	1,907,715
2004	88,731	44,850	1,138,636	1,272,217
2005	144,656	42,526	952,714	1,139,896
2006	821,451	58,421	1,582,632	2,462,504
2007	322,704	329,903	1,407,367	2,059,974
2008	921,417	345,909	571,790	1,839,116

Table 4.15. Recreational released alive (Type B2) in numbers of Atlantic menhaden in the recreational fishery by region (New England, Middle Atlantic, and South Atlantic states), 1981-2008.

Year	MA	NE	SA	Overall
1981	0	14,269	71,401	85,670
1982	9,314	0	378,801	388,115
1983	539	5,314	805,522	811,375
1984	44,583	5,435	534,244	584,262
1985	46,767	8,020	338,916	393,703
1986	30,881	3,372	97,582	131,835
1987	36,935	6,102	58,806	101,843
1988	29,642	22,082	41,840	93,564
1989	11,980	10,676	162,419	185,075
1990	43,490	27,470	108,289	179,249
1991	265,965	66,990	22,600	355,555
1992	697	96,997	22,737	120,431
1993	13,642	27,527	177,890	219,059
1994	12,424	18,771	4,116	35,311
1995	99,622	17,829	9,124	126,575
1996	2,082	3,139	391	5,612
1997	1,458	861	6,164	8,483
1998	3,208	3,628	10,219	17,055
1999	1,119	51,974	369,179	422,272
2000	57,935	0	81,725	139,660
2001	714	1,276	413,751	415,741
2002	91,224	18,222	387,997	497,443
2003	17,352	0	613,070	630,422
2004	2,040,891	5,569	316,253	2,362,713
2005	8,557	5,943	351,737	366,237
2006	321,391	71,738	773,188	1,166,317
2007	331,594	9,447	325,870	666,911
2008	29,723	19,262	20,124	69,109

Table 4.16. Total catch (A+B1+0.5*B2) in numbers of Atlantic menhaden in the recreational fishery (MRFSS) by region (New England, Middle Atlantic, and South Atlantic states), 1981-2008.

[Proportional standard error (PSE), analogous to CV, is also provided by MRFSS. The estimate shown here is adjusted for 0.5*B2.]

Year	MA	NE	SA	Overall	PSE
1981	117,956	255,198	113,542	486,695	27.26
1982	8,019	218,032	735,779	961,830	35.60
1983	26,302	178,534	785,293	990,129	38.80
1984	337,951	103,998	526,862	968,810	35.20
1985	290,276	231,173	271,166	792,615	36.00
1986	751,711	558,902	62,254	1,372,867	33.59
1987	383,973	466,820	171,412	1,022,205	15.82
1988	907,382	263,058	301,654	1,472,094	31.19
1989	198,864	263,540	263,866	726,270	18.63
1990	255,978	264,589	397,717	918,284	14.47
1991	989,345	408,434	401,479	1,799,258	20.07
1992	288,758	1,146,738	1,277,425	2,712,920	31.12
1993	275,812	367,799	172,963	816,574	20.48
1994	228,876	142,622	281,309	652,807	18.88
1995	827,308	151,504	89,833	1,068,645	28.28
1996	51,452	183,495	297,954	532,900	48.94
1997	228,381	99,211	138,153	465,745	31.62
1998	56,388	189,390	83,382	329,160	28.82
1999	742,635	80,565	474,037	1,297,236	57.96
2000	76,243	131,385	140,832	348,459	27.95
2001	148,130	18,026	1,192,084	1,358,240	26.96
2002	246,424	242,925	709,633	1,198,982	21.27
2003	225,720	21,153	1,976,053	2,222,926	16.03
2004	1,109,177	47,635	1,296,763	2,453,574	65.13
2005	148,935	45,498	1,128,583	1,323,015	20.03
2006	982,147	94,290	1,969,226	3,045,663	12.00
2007	488,501	334,627	1,570,302	2,393,430	18.01
2008	936,279	355,540	581,852	1,873,671	16.67

Table 4.17. Total catch (A+B1+0.5*B2) in weight (1000 metric tons) of Atlantic menhaden in the recreational fishery (MRFSS) by region (New England, Middle Atlantic, and South Atlantic states), 1981-2008.

Year	MA	NE	SA	Total
1981	0.0265	0.0798	0.0088	0.1150
1982	0.0018	0.0682	0.0567	0.1267
1983	0.0059	0.0558	0.0605	0.1223
1984	0.0759	0.0325	0.0406	0.1491
1985	0.0652	0.0723	0.0209	0.1584
1986	0.1689	0.1747	0.0048	0.3484
1987	0.0863	0.1459	0.0132	0.2454
1988	0.2039	0.0822	0.0233	0.3094
1989	0.0447	0.0824	0.0203	0.1474
1990	0.0575	0.0827	0.0307	0.1709
1991	0.2223	0.1277	0.0309	0.3809
1992	0.0649	0.3585	0.0985	0.5218
1993	0.0620	0.1150	0.0133	0.1903
1994	0.0514	0.0446	0.0217	0.1177
1995	0.1859	0.0474	0.0069	0.2402
1996	0.0116	0.0574	0.0230	0.0919
1997	0.0513	0.0310	0.0106	0.0930
1998	0.0127	0.0592	0.0064	0.0783
1999	0.1669	0.0252	0.0365	0.2286
2000	0.0171	0.0411	0.0109	0.0691
2001	0.0333	0.0056	0.0919	0.1308
2002	0.0554	0.0759	0.0547	0.1860
2003	0.0507	0.0066	0.1523	0.2097
2004	0.2492	0.0149	0.1000	0.3641
2005	0.0335	0.0142	0.0870	0.1347
2006	0.2207	0.0295	0.1518	0.4019
2007	0.1098	0.1046	0.1210	0.3354
2008	0.2104	0.1112	0.0449	0.3664

Table 5.1. AIC based evaluation of delta-lognormal fits to the combined catch-per-haul data used for the construction of first JAI.

Model parameterization	*AIC Binomial*	*ΔAIC Binomial*	*AIC Lognormal*	**ΔAIC Lognormal**
1	38041.3	0	80513.2	0
2	39679.2	1637.9	81300.2	787
3	39391.3	1350	80605.4	92.2
4	41166.4	3125.1	81402.3	889.1

Table 6.1. Evaluation of potential assessment models for the menhaden stock assessment.

Criteria	BAM	MSVPA	SS3	UBC	SRA
Applicability to management (benchmarks)	Multiple options for benchmark computation	Externally estimated benchmarks	Multiple options for benchmark computation	Conditioned on MSY benchmarks	Limited to MSY benchmarks
Used in other stock assessments	Peer reviewed for menhaden and other species	Approach only peer reviewed	Peer reviewed for other species	Published but not peer reviewed as an assessment	Peer reviewed for other species
Data requirements	All available menhaden data	Much more data required (e.g., other species diet data)	All available menhaden data	All available menhaden data; need prior distributions	Less data required (limited to landings and indices); need prior distributions
Model complexity	Moderate	High	Potentially high; limited by data	Moderate	Low
Measures of uncertainty	Bootstrap and sensitivity runs	Sensitivity runs	MCMC, bootstrap, and sensitivity runs	MCMC and sensitivity runs	MCMC and sensitivity runs
Understanding model properties and operation	Familiar among committee	Familiar among committee	Least familiar among committee	Less familiar among committee	Less familiar among committee
Appropriateness of model assumptions for menhaden	Very appropriate	Less appropriate because of VPA-like assumptions	Very Appropriate	Less appropriate because of MSY benchmarks and strong priors	Less appropriate because of MSY benchmarks
Model diagnostics	Many	None in direct output; can be done externally	Many	Many possible but currently not coded	Few

Table 6.2 General definitions, input data, population model, and negative log-likelihood components of the BAM forward-projecting statistical age-structured model used for Atlantic menhaden.

General Definitions	Symbol	Description/Definition
Year index: y = {1955,..,2008}	y	
Age index: a = {0,...,8+}	a	
Fishery index: f = {1 reduction, 2 bait}	f	
Input Data	**Symbol**	**Description/Definition**
Fishery Weight-at-age	w_a^f	Computed from size at age from fishery samples
Population Weight-at-age	w_a^p	Computed from size at age back-calculated to beginning of year
Maturity-at-age	m_a	From data workshop with recent added samples
Fecundity-at-age	γ_a	From data workshop
Observed age-0 CPUE y = {1959,...,2008}	$U_{1,y}$	Based on numbers of age-0 fish from various seine samples (selected/combined Assessment Workshop)
Observed pound net CPUE y = {1964,...,2008}	$U_{2,y}$	Based on pound net landings of menhaden per set from the Potomac River Fisheries Commission
Selectivity for U_2	s'_a	Fixed at 0.25 for a = {1, 3}, 1.0 for a = {2}, and 0 for a = {0,4,...,8+} (from Assessment Workshop)
Coefficient of variation for U	c_U	Based on annual estimates from samples for U_1, fixed at 0.5 for U_2
Observed age compositions	$p_{f,a,y}$	Computed as percent age composition at age (a) for each year (y) and fishery (f)
Age composition sample sizes	$n_{f,y}$	Number of trips sampled in each year (y) from each fishery (f)
Observed fishery landings	$L_{f,y}$	Reported landings in weight for each year (y) from each fishery (f)
Coefficient of variation for L_f	c_{L_f}	Fixed at 0.03 for L_1 and 0.15 (early years) and 0.05 (recent years) for L_2
Observed natural mortality	$M_{a,y}$	From MSVPA-X model, constant in years 1955-1981

Table 6.2 (*continued*)

Population Model	Symbol	Description/Definition
Fishery selectivity	$s_{f,a}$	Assumed constant for all years (y) $s_a = \frac{1}{1+\exp(-\eta_1[a-\alpha_1])}$ $s_a = \left[\frac{1}{1+\exp(-\eta_{1,2}[a-\alpha_{1,2}])}\right]\left[1-\frac{1}{1+\exp(-\eta_{2,2}[a-\alpha_{2,2}])}\right]\left[\frac{1}{\max(s_{2,a})}\right]$ where η's and α's are estimated parameters. The base BAM model assumed logistic selectivity for both reduction and bait fisheries.
Fishing mortality (fully selected)	$F_{f,a,y}$	$F_{f,a,y} = s_a F_{f,y}$ where $F_{f,y}$s are estimated parameters
Total mortality	$Z_{a,y}$	$Z_{a,y} = M_{a,y} + \sum_{f=1}^{2} F_{f,a,y}$
Fecundity per recruit at $F = 0$	ϕ_y	$\phi_y = \sum_{a=0}^{8+} N_{a,y} m_a \gamma_a 0.5 \Big/ N_{0,y}$ where $N_{a+1,y} = N_{a,y}\exp(-Z_{a,y})$ and $N_{8+,y} = N_{7,y}\exp(-Z_{7,y})/[1-\exp(-Z_{8+,y})]$
Population numbers Population fecundity	$N_{a,y}$ ε_y	$N_{a+1,1955} = N_{a,1955}\exp(-Z_{a,1955})$ $N_{8+,1955} = N_{7,1955}\exp(-Z_{7,1955})/[1-\exp(-Z_{8+,1955})]$ $\varepsilon_y = \sum_{a=0}^{8+} N_{a,y} m_a \gamma_a 0.5$ $N_{0,y} = R_y$ $N_{a+1,y+1} = N_{a,y}\exp(-Z_{a,y})$ $N_{A,y} = N_{A-1,y-1}\exp(-Z_{A-1,y-1}) + N_{A,y-1}\exp(-Z_{A,y-1})$ where R_y are annual recruitment parameters.

Table 6.2 (*continued*)

Population Model (*cont.*)	**Symbol**	**Description/Definition**
Population biomass	B_y	$B_y = \sum_{a=0}^{8+} N_{a,y} w_a^p$
Predicted catch-at-age	$\hat{C}_{f,a,y}$	$\hat{C}_{f,a,y} = \frac{F_{f,a,y}}{Z_{a,y}} N_{a,y} \left[1 - \exp\left(-Z_{a,y}\right)\right]$
Predicted landings	$\hat{L}_{f,y}$	$\hat{L}_{f,y} = \sum_{a=0}^{8+} \hat{C}_{f,a,y} w_a^f$
Predicted age composition	$\hat{p}_{f,a,y}$	$\hat{p}_{f,a,y} = \hat{C}_{f,a,y} \Big/ \sum_{a=0}^{8+} \hat{C}_{f,a,y}$
Predicted age-0 CPUE	$\hat{U}_{1,y}$	$\hat{U}_{1,y} = N_{0,y} q_1$ where q_1 is a catchability parameter
Predicted pound net CPUE	$\hat{U}_{2,y}$	$\hat{U}_{2,y} = \sum_{a=0}^{8+} N_{a,y} s'_a q_2$ where q_2 is a catchability parameter
Negative Log-Likelihood	**Symbol**	**Description/Definition**
Multinomial age composition	Λ_f	$\Lambda_f = -\lambda_f n_{f,y} \sum_{a=0}^{8+} \left(p_{f,a,y} + x\right) \log\left(\hat{p}_{f,a,y} + x\right) - \left(p_{f,a,y} + x\right) \log\left(p_{f,a,y} + x\right)$ where λ_f is a preset weighting factor and x is fixed at an arbitrary value of 0.001
Lognormal indices	Λ_f	$\Lambda_f = \lambda_f \sum_y \frac{\left[\log\left(U_{f,y} + x\right) - \log\left(\hat{U}_{f,y} + x\right)\right]^2}{2c_U^2}$ where λ_f is a preset weighting factor and x is fixed at an arbitrary value of 0.001
Lognormal landings	Λ_f	$\Lambda_f = \lambda_f \sum_y \frac{\left[\log\left(L_{f,y} + x\right) - \log\left(\hat{L}_{f,y} + x\right)\right]^2}{2c_{L_f}^2}$ where λ_f is a preset weighting factor and x is fixed at an arbitrary value of 0.001

Table 7.1 Estimated annual total fishing mortality rates, *F* (N-weighted over ages 2+) from the base BAM model.

Year	Reduction Fishery F	Bait Fishery F	Total F
1955	0.79	0.02	0.81
1956	1.37	0.06	1.43
1957	1.45	0.08	1.54
1958	0.66	0.02	0.68
1959	1.55	0.08	1.64
1960	0.39	0.01	0.40
1961	0.66	0.03	0.70
1962	0.81	0.04	0.85
1963	1.61	0.18	1.78
1964	1.25	0.15	1.40
1965	1.83	0.25	2.07
1966	1.97	0.21	2.18
1967	1.16	0.11	1.26
1968	1.62	0.09	1.71
1969	1.08	0.12	1.21
1970	1.19	0.19	1.38
1971	0.48	0.03	0.51
1972	1.60	0.07	1.67
1973	1.03	0.06	1.09
1974	1.35	0.12	1.47
1975	0.85	0.10	0.95
1976	1.31	0.13	1.44
1977	0.99	0.09	1.08
1978	1.00	0.10	1.10
1979	1.13	0.06	1.18
1980	0.99	0.08	1.06
1981	0.97	0.09	1.05
1982	0.75	0.05	0.81
1983	1.04	0.06	1.10
1984	1.37	0.09	1.45
1985	1.09	0.16	1.25
1986	0.49	0.07	0.55
1987	0.73	0.07	0.80
1988	0.80	0.11	0.92
1989	1.15	0.20	1.35
1990	0.56	0.05	0.62
1991	1.99	0.36	2.35
1992	1.10	0.24	1.34
1993	0.72	0.12	0.84
1994	0.42	0.06	0.48
1995	1.22	0.21	1.43
1996	0.59	0.08	0.67
1997	0.60	0.09	0.69
1998	0.88	0.16	1.04
1999	1.00	0.33	1.33
2000	0.48	0.13	0.61
2001	0.62	0.11	0.73
2002	1.07	0.33	1.40
2003	0.58	0.16	0.73
2004	0.56	0.13	0.70
2005	0.48	0.14	0.61
2006	0.83	0.19	1.03
2007	0.62	0.20	0.82
2008	0.60	0.26	0.86

Table 7.2 Historical performance based on percentiles (median and interquartile range) for output variables from the base BAM model, 1955–2008.

Output Variables	Current Year Value (2008)	Percentiles		
		25th	50th	75th
Fishing Mortality, F (ages 2+)	0.86	0.75	1.07	1.40
Population Fecundity (billions)	59544	47042	68975	99640
Recruits to Age-0 (billions)	11.4	20.5	29.5	59.6

Table 7.3 Estimated annual total N-weighted fishing mortality rates, *F* (ages 2+) from the base BAM model and percentiles from the bootstrap runs.

Year	Base BAM Model	5th Percentile	50th Percentile	95th Percentile
1955	0.81	0.57	0.82	1.33
1956	1.43	0.92	1.42	2.28
1957	1.54	1.00	1.60	2.32
1958	0.68	0.44	0.68	1.12
1959	1.64	1.21	1.73	2.62
1960	0.40	0.33	0.40	0.48
1961	0.70	0.53	0.69	0.96
1962	0.85	0.56	0.84	1.14
1963	1.78	1.30	1.82	2.71
1964	1.40	1.04	1.43	2.06
1965	2.07	1.60	2.10	2.89
1966	2.18	1.58	2.28	3.21
1967	1.26	0.84	1.30	2.10
1968	1.71	1.36	1.71	2.25
1969	1.21	1.05	1.24	1.48
1970	1.38	1.12	1.42	1.93
1971	0.51	0.41	0.50	0.62
1972	1.67	1.30	1.73	2.27
1973	1.09	0.76	1.09	1.50
1974	1.47	1.04	1.51	2.44
1975	0.95	0.69	0.97	1.45
1976	1.44	1.15	1.48	2.01
1977	1.08	0.79	1.08	1.50
1978	1.10	0.72	1.09	1.80
1979	1.18	0.70	1.20	2.84
1980	1.06	0.68	1.03	1.44
1981	1.05	0.57	1.06	2.63
1982	0.81	0.53	0.80	1.43
1983	1.10	0.72	1.12	2.26
1984	1.45	0.95	1.49	2.75
1985	1.25	0.87	1.29	1.94
1986	0.55	0.38	0.55	0.87
1987	0.80	0.56	0.79	1.75
1988	0.92	0.66	0.91	1.37
1989	1.35	0.93	1.40	2.13
1990	0.62	0.37	0.60	0.96
1991	2.35	1.52	2.53	4.35
1992	1.34	1.01	1.37	1.98
1993	0.84	0.64	0.85	1.12
1994	0.48	0.34	0.48	0.62
1995	1.43	1.24	1.47	1.92
1996	0.67	0.62	0.68	0.76
1997	0.69	0.61	0.69	0.79
1998	1.04	0.84	1.03	1.22
1999	1.33	1.00	1.41	2.07
2000	0.61	0.48	0.61	0.79
2001	0.73	0.43	0.70	0.87
2002	1.40	0.88	1.52	2.81
2003	0.73	0.55	0.74	1.08
2004	0.70	0.58	0.71	0.95
2005	0.61	0.51	0.61	0.74
2006	1.03	0.83	1.06	1.48
2007	0.82	0.67	0.83	1.03
2008	0.86	0.62	0.89	1.37

Table 7.4. Estimated full fishing mortality rates at age from the base BAM model.

	Age								
Year	0	1	2	3	4	5	6	7	8
1955	0.01	0.08	0.53	1.14	1.27	1.29	1.29	1.29	1.29
1956	0.02	0.15	0.99	2.14	2.40	2.43	2.43	2.43	2.43
1957	0.02	0.21	1.34	3.01	3.39	3.43	3.43	3.43	3.43
1958	0.01	0.09	0.59	1.28	1.43	1.45	1.45	1.45	1.45
1959	0.02	0.18	1.19	2.61	2.93	2.96	2.96	2.96	2.96
1960	0.01	0.06	0.37	0.83	0.93	0.94	0.94	0.94	0.94
1961	0.01	0.06	0.38	0.81	0.91	0.92	0.92	0.92	0.92
1962	0.01	0.09	0.60	1.31	1.47	1.48	1.49	1.49	1.49
1963	0.02	0.18	1.20	2.74	3.09	3.12	3.13	3.13	3.13
1964	0.02	0.17	1.14	2.70	3.04	3.08	3.08	3.08	3.08
1965	0.03	0.25	1.69	4.08	4.62	4.66	4.67	4.67	4.67
1966	0.03	0.29	1.96	4.68	5.29	5.35	5.35	5.35	5.35
1967	0.02	0.17	1.11	2.61	2.94	2.98	2.98	2.98	2.98
1968	0.02	0.23	1.53	3.43	3.85	3.90	3.90	3.90	3.90
1969	0.01	0.14	0.94	2.20	2.48	2.51	2.51	2.51	2.51
1970	0.02	0.17	1.19	2.96	3.36	3.39	3.39	3.40	3.40
1971	0.01	0.07	0.46	1.04	1.17	1.18	1.19	1.19	1.19
1972	0.02	0.18	1.16	2.53	2.84	2.87	2.88	2.88	2.88
1973	0.02	0.15	0.99	2.24	2.53	2.55	2.56	2.56	2.56
1974	0.02	0.17	1.13	2.57	2.89	2.93	2.93	2.93	2.93
1975	0.01	0.12	0.80	1.92	2.17	2.19	2.19	2.19	2.19
1976	0.02	0.18	1.21	2.83	3.19	3.22	3.23	3.23	3.23
1977	0.01	0.14	0.96	2.24	2.53	2.56	2.56	2.56	2.56
1978	0.01	0.13	0.87	2.02	2.28	2.31	2.31	2.31	2.31
1979	0.02	0.15	0.97	2.13	2.40	2.43	2.43	2.43	2.43
1980	0.01	0.13	0.87	1.98	2.23	2.25	2.26	2.26	2.26
1981	0.01	0.14	0.91	2.11	2.38	2.41	2.41	2.41	2.41
1982	0.01	0.09	0.62	1.39	1.57	1.59	1.59	1.59	1.59
1983	0.01	0.14	0.93	2.08	2.34	2.36	2.37	2.37	2.37
1984	0.02	0.16	1.03	2.27	2.55	2.58	2.58	2.58	2.58
1985	0.02	0.16	1.10	2.73	3.09	3.12	3.13	3.13	3.13
1986	0.01	0.07	0.49	1.20	1.36	1.38	1.38	1.38	1.38
1987	0.01	0.09	0.60	1.39	1.57	1.59	1.59	1.59	1.59
1988	0.01	0.10	0.65	1.55	1.75	1.77	1.77	1.77	1.77
1989	0.01	0.14	0.94	2.26	2.55	2.58	2.58	2.58	2.58
1990	0.01	0.08	0.54	1.27	1.44	1.45	1.45	1.46	1.46
1991	0.02	0.21	1.44	3.43	3.88	3.92	3.92	3.92	3.92
1992	0.02	0.16	1.14	3.02	3.43	3.46	3.47	3.47	3.47
1993	0.01	0.10	0.70	1.75	1.98	2.00	2.00	2.00	2.00
1994	0.01	0.05	0.36	0.86	0.98	0.99	0.99	0.99	0.99
1995	0.01	0.13	0.89	2.11	2.38	2.41	2.41	2.41	2.41
1996	0.01	0.08	0.53	1.27	1.44	1.45	1.45	1.45	1.45
1997	0.01	0.07	0.45	1.05	1.18	1.19	1.19	1.19	1.19
1998	0.01	0.11	0.72	1.75	1.98	2.00	2.00	2.00	2.00
1999	0.01	0.12	0.86	2.30	2.62	2.64	2.64	2.64	2.64
2000	0.01	0.07	0.48	1.27	1.45	1.47	1.47	1.47	1.47
2001	0.01	0.08	0.53	1.28	1.45	1.46	1.46	1.46	1.46
2002	0.01	0.11	0.79	2.01	2.28	2.30	2.30	2.30	2.30
2003	0.01	0.08	0.58	1.55	1.77	1.79	1.79	1.79	1.79
2004	0.01	0.08	0.54	1.41	1.60	1.61	1.61	1.61	1.61
2005	0.01	0.06	0.42	1.10	1.25	1.26	1.26	1.26	1.26
2006	0.01	0.09	0.63	1.57	1.78	1.80	1.80	1.80	1.80
2007	0.01	0.09	0.66	1.84	2.10	2.12	2.12	2.12	2.12
2008	0.01	0.07	0.55	1.54	1.76	1.77	1.77	1.77	1.77

Table 7.5 Estimated numbers of Atlantic menhaden (billions) at the start of the fishing year from the base BAM model.

	Age								
Year	0	1	2	3	4	5	6	7	8
1955	83.8	13.7	6.9	1.02	3.44	7.49E-02	4.80E-02	3.36E-03	2.52E-04
1956	77.2	26.6	5.1	2.08	0.19	5.78E-01	1.27E-02	8.27E-03	6.22E-04
1957	47.7	24.3	9.3	0.98	0.14	1.01E-02	3.14E-02	7.00E-04	4.89E-04
1958	156.2	14.9	8.1	1.24	0.03	2.83E-03	2.03E-04	6.35E-04	2.40E-05
1959	18.8	49.5	5.6	2.29	0.20	3.95E-03	4.11E-04	2.98E-05	9.69E-05
1960	42.5	5.9	16.8	0.87	0.10	6.37E-03	1.26E-04	1.33E-05	4.09E-06
1961	26.6	13.5	2.3	5.89	0.22	2.30E-02	1.54E-03	3.09E-05	4.25E-06
1962	26.6	8.4	5.2	0.80	1.50	5.26E-02	5.67E-03	3.84E-04	8.78E-06
1963	24.3	8.4	3.1	1.46	0.12	2.08E-01	7.35E-03	8.03E-04	5.56E-05
1964	28.0	7.6	2.9	0.48	0.05	3.38E-03	5.64E-03	2.02E-04	2.36E-05
1965	19.2	8.8	2.6	0.47	0.02	1.54E-03	9.61E-05	1.63E-04	6.50E-06
1966	28.1	6.0	2.8	0.25	0.00	1.11E-04	8.98E-06	5.65E-07	9.94E-07
1967	12.6	8.7	1.8	0.20	0.00	1.37E-05	3.27E-07	2.66E-08	4.62E-09
1968	20.5	4.0	3.0	0.31	0.01	4.12E-05	4.29E-07	1.04E-08	9.95E-10
1969	34.0	6.4	1.3	0.33	0.01	1.08E-04	5.16E-07	5.44E-09	1.44E-10
1970	18.2	10.7	2.3	0.26	0.02	2.86E-04	5.43E-06	2.62E-08	2.84E-10
1971	45.0	5.7	3.7	0.35	0.01	4.44E-04	5.94E-06	1.14E-07	5.57E-10
1972	28.0	14.3	2.2	1.19	0.07	1.41E-03	8.37E-05	1.14E-06	2.19E-08
1973	33.8	8.8	4.9	0.35	0.05	2.51E-03	4.91E-05	2.96E-06	4.09E-08
1974	46.6	10.6	3.1	0.92	0.02	2.60E-03	1.20E-04	2.39E-06	1.46E-07
1975	73.4	14.7	3.7	0.51	0.04	6.99E-04	8.60E-05	4.03E-06	8.47E-08
1976	57.7	23.2	5.3	0.84	0.04	2.76E-03	4.81E-05	6.00E-06	2.87E-07
1977	59.1	18.1	7.9	0.81	0.03	1.06E-03	6.79E-05	1.20E-06	1.56E-07
1978	61.8	18.6	6.4	1.54	0.05	1.36E-03	5.06E-05	3.29E-06	6.56E-08
1979	104.4	19.5	6.7	1.37	0.12	3.02E-03	8.37E-05	3.15E-06	2.09E-07
1980	72.2	32.9	6.9	1.29	0.09	6.38E-03	1.65E-04	4.63E-06	1.86E-07
1981	150.1	22.8	11.8	1.46	0.10	5.98E-03	4.13E-04	1.08E-05	3.15E-07
1982	77.4	47.3	8.1	2.41	0.10	5.67E-03	3.33E-04	2.33E-05	6.26E-07
1983	110.5	15.1	11.2	1.61	0.26	1.16E-02	6.85E-04	4.10E-05	2.94E-06
1984	128.5	24.6	3.7	1.77	0.10	1.41E-02	6.53E-04	3.92E-05	2.51E-06
1985	95.6	34.0	6.8	0.57	0.10	4.81E-03	6.44E-04	3.09E-05	1.97E-06
1986	59.8	25.3	9.4	0.90	0.02	2.72E-03	1.26E-04	1.72E-05	8.77E-07
1987	35.5	16.5	7.8	2.43	0.14	3.04E-03	4.10E-04	1.87E-05	2.67E-06
1988	63.9	11.5	5.9	2.00	0.33	1.72E-02	3.80E-04	5.09E-05	2.66E-06
1989	21.2	22.3	4.1	1.51	0.24	3.43E-02	1.79E-03	3.97E-05	5.59E-06
1990	34.1	8.1	8.8	0.81	0.09	1.11E-02	1.59E-03	8.37E-05	2.12E-06
1991	32.3	12.7	3.6	2.80	0.13	1.29E-02	1.60E-03	2.31E-04	1.24E-05
1992	30.9	12.2	4.5	0.46	0.05	1.67E-03	1.58E-04	1.96E-05	2.98E-06
1993	19.5	12.3	5.3	0.80	0.01	1.07E-03	3.33E-05	3.13E-06	4.48E-07
1994	26.9	7.2	5.0	1.51	0.08	1.16E-03	9.18E-05	2.93E-06	3.15E-07
1995	16.9	9.9	3.1	1.93	0.39	1.94E-02	2.74E-04	2.22E-05	7.85E-07
1996	19.2	5.6	4.0	0.72	0.14	2.16E-02	1.09E-03	1.57E-05	1.32E-06
1997	15.4	6.8	2.4	1.39	0.12	2.09E-02	3.21E-03	1.64E-04	2.56E-06
1998	20.9	5.3	2.9	0.89	0.31	2.43E-02	4.04E-03	6.24E-04	3.24E-05
1999	20.4	6.8	2.0	0.80	0.10	2.71E-02	2.11E-03	3.49E-04	5.67E-05
2000	8.8	6.6	2.8	0.47	0.05	4.41E-03	1.23E-03	9.41E-05	1.81E-05
2001	18.4	2.9	3.0	1.00	0.08	7.08E-03	6.42E-04	1.81E-04	1.64E-05
2002	26.8	5.9	1.2	0.99	0.17	1.17E-02	1.02E-03	9.33E-05	2.87E-05
2003	22.5	8.4	2.3	0.31	0.08	1.03E-02	7.26E-04	6.37E-05	7.60E-06
2004	17.3	7.3	3.4	0.68	0.04	8.25E-03	1.07E-03	7.67E-05	7.54E-06
2005	36.9	5.0	2.8	1.00	0.10	4.56E-03	1.01E-03	1.34E-04	1.05E-05
2006	20.6	11.0	1.7	0.95	0.19	1.63E-02	7.89E-04	1.81E-04	2.59E-05
2007	11.1	6.1	3.8	0.46	0.11	1.86E-02	1.63E-03	8.19E-05	2.15E-05
2008	11.4	3.5	2.3	0.97	0.04	7.98E-03	1.36E-03	1.23E-04	7.79E-06

Table 7.6 Estimated annual fecundity (billions of eggs) from the base BAM model and percentiles from the bootstrap runs.

Year	Base BAM Model	5th Percentile	50th Percentile	95th Percentile
1955	387220	222931	404422	586301
1956	243424	153231	249996	354261
1957	114513	78879	118612	178541
1958	94384	65513	93565	142904
1959	153677	95561	156038	241272
1960	102465	77048	100797	132267
1961	277319	236708	279859	331891
1962	200152	153214	204839	257225
1963	138718	106843	141515	210283
1964	45342	34995	46325	60286
1965	39917	29983	40590	55096
1966	27819	21432	28392	37941
1967	20003	13659	19689	29697
1968	34292	23659	34145	51489
1969	28469	22385	28849	36493
1970	26425	23096	26676	31007
1971	43405	35213	44214	54481
1972	114895	96372	117806	145711
1973	55977	45644	56727	71218
1974	70130	53017	72146	103720
1975	45832	33079	46562	64925
1976	57476	42508	58112	79349
1977	52764	42827	53570	66219
1978	66064	51929	68108	88912
1979	69463	49493	72823	103450
1980	66599	32682	67997	112006
1981	73410	60176	77631	119513
1982	86397	49276	88774	147682
1983	97613	70983	101331	148979
1984	80333	44766	81229	120687
1985	42055	25428	42569	65316
1986	50673	36727	51015	73781
1987	101928	72553	103464	148036
1988	97550	60121	98400	132517
1989	75698	56227	76973	103151
1990	61610	47632	63407	86359
1991	142434	96619	148739	238371
1992	40015	26165	39936	62371
1993	55738	42856	56469	73797
1994	100316	81942	101464	132436
1995	138295	113206	141701	190913
1996	70122	61301	70542	78134
1997	111874	103575	112217	121394
1998	95505	87205	96200	106781
1999	60086	53253	62877	76858
2000	40179	31979	40621	51734
2001	78875	66313	81845	100379
2002	87359	76322	92622	146618
2003	40219	26598	39418	60119
2004	54178	41023	55513	71328
2005	68488	56028	69139	82212
2006	66136	57515	67605	79913
2007	45045	37500	45349	54476
2008	59544	51795	61257	74622

Table 7.7 Estimated annual recruitment of age-0 (billions) fish from the base BAM model and percentiles from the bootstrap runs.

Year	Base BAM Model	5th Percentile	50th Percentile	95th Percentile
1955	83.8	69.5	85.8	106.1
1956	77.2	61.9	78.4	99.3
1957	47.7	31.2	48.8	68.0
1958	156.2	135.8	158.6	182.8
1959	18.8	7.8	19.0	32.8
1960	42.5	30.3	43.7	61.4
1961	26.6	21.1	27.4	33.7
1962	26.6	23.2	27.2	31.3
1963	24.3	20.6	24.6	28.9
1964	28.0	24.9	28.6	34.0
1965	19.2	15.9	19.7	23.6
1966	28.1	25.1	28.3	31.9
1967	12.6	11.4	12.9	14.6
1968	20.5	18.6	21.0	23.6
1969	34.0	30.3	34.5	39.5
1970	18.2	14.8	18.6	22.3
1971	45.0	40.7	46.0	53.0
1972	28.0	23.4	28.9	34.4
1973	33.8	27.2	34.7	43.1
1974	46.6	39.7	47.7	56.6
1975	73.4	65.7	75.1	86.0
1976	57.7	48.2	60.0	72.3
1977	59.1	46.4	61.3	78.1
1978	61.8	46.9	65.1	87.7
1979	104.4	83.4	110.4	168.9
1980	72.2	51.4	76.4	106.6
1981	150.1	122.3	156.1	192.2
1982	77.4	43.2	81.1	121.7
1983	110.5	82.4	115.1	149.1
1984	128.5	98.6	130.3	173.0
1985	95.6	73.4	99.2	127.6
1986	59.8	44.5	61.8	85.2
1987	35.5	26.0	36.9	48.0
1988	63.9	52.3	65.3	86.6
1989	21.2	14.7	22.8	31.3
1990	34.1	27.3	34.8	43.8
1991	32.3	27.7	32.9	38.8
1992	30.9	26.2	31.8	39.0
1993	19.5	16.9	20.0	23.3
1994	26.9	25.4	27.0	29.0
1995	16.9	15.4	17.2	19.0
1996	19.2	17.7	20.0	22.6
1997	15.4	13.2	15.9	18.5
1998	20.9	17.8	21.3	25.4
1999	20.4	17.5	21.4	27.5
2000	8.8	7.1	9.0	11.8
2001	18.4	14.7	19.0	23.3
2002	26.8	22.4	27.0	32.3
2003	22.5	18.6	23.2	27.9
2004	17.3	14.2	17.8	22.2
2005	36.9	33.8	38.0	43.0
2006	20.6	17.8	21.0	24.4
2007	11.1	8.8	11.6	15.9
2008	11.4	9.4	11.8	15.9

Table 7.8 Results from base BAM model, sensitivity runs, and retrospective analysis.

[Median recruitment to age-0 (billions) is labeled as R, total N-weighted fishing mortality (F) is for age 2+, and population fecundity (FEC) is in billions of mature ova.]

BAM Model Run	Median R	F_{MED}	F_{target}	FEC_{MED}	FEC_{thresh}	$F_{(2008)}/F_{MED}$	$FEC_{(2008)}/FEC_{thresh}$
Base run	29.5	0.93	0.44	62777	31389	0.92	1.90
Time invariant natural mortality (M)	32.3	1.00	0.54	63554	31777	0.87	1.88
Eight year average used for benchmark calculations	29.5	1.03	0.48	62777	31389	0.83	1.90
Pound net index coefficient of variation (CV)=0.2	29.4	0.93	0.45	62844	31422	0.82	1.93
Pound net index coefficient of variation (CV)=0.8	29.5	0.93	0.44	62839	31419	0.93	1.89
No ageing reader error	28.0	0.88	0.46	61849	30925	0.88	1.88
Four separate juvenile abundance indices (JAIs) with estimated weights	29.3	0.94	0.44	61847	30923	0.85	1.90
Dome-shaped selectivity in last period (1994-2008) for the reduction fishery	29.9	1.11	0.50	59375	29687	0.91	2.20
Start model in 1964	28.8	1.09	0.51	52645	26322	0.85	2.37
Three year average used for benchmark calculations	29.5	0.86	0.37	62777	31389	0.99	1.90
Random walk on pound net index catchability (q)	29.5	0.93	0.44	62893	31447	0.94	1.89
Leave out juvenile abundance index (JAI)	29.5	0.94	0.42	62334	31167	1.15	1.85
Leave out pound net (PN) index	29.6	0.93	0.44	62890	31445	0.94	1.89
GLM based pound net (PN) index	29.5	0.93	0.44	62771	31385	0.91	1.90
Natural mortality (M) re-scaled +25%	54.6	0.81	0.32	67975	33987	0.98	1.92
Natural mortality (M) re-scaled -25%	16.4	1.07	0.58	58517	29258	0.86	1.86
Estimate natural mortality (M) scalar	151.9	0.62	0.16	76346	38173	1.13	2.01
Estimate MSY based on Beverton-Holt curve	29.5	0.93	0.44	62921	31460	0.92	1.89
Estimate MSY based on Ricker curve	27.7	0.91	0.48	59585	29793	0.95	1.98
Retrospective to 2007	30.7	0.95	0.43	63870	31935	1.24	1.43
Retrospective to 2006	29.3	0.93	0.44	62927	31463	1.73	2.43
Retrospective to 2005	30.6	0.95	0.44	64191	32096	0.45	2.49
Retrospective to 2004	31.4	0.95	0.44	65973	32987	0.77	1.66
Retrospective to 2003	32.1	0.97	0.44	65393	32696	0.68	1.31
Retrospective to 2002	32.8	0.93	0.44	69074	34537	2.77	3.88
Retrospective to 2001	33.6	0.94	0.48	69444	34722	0.29	3.39

Table 7.9 Summary of benchmarks and terminal year (2008) values estimated for the base BAM model (F are N-weighted for ages 2+).

Benchmarks and Terminal Year Values	**Base BAM Model Estimates**
Median Age-0 Recruits (billions)	29.5
Threshold (Limit): F_{MED}	0.93
Target: F_{target}	0.44
F_{2008}	0.86
F_{2008}/F_{MED}	0.92
F30%	0.41
F25%	0.50
F20%	0.62
Target: FEC_{MED}	62777
Threshold (Limit): $FEC_{threshold}$	31389
FEC_{2008}	59544
$FEC_{2008}/FEC_{threshold}$	1.90

Table 8.1 Summary of benchmarks and terminal year value from previous stock assessments (ASMFC 2004, Table 9.1; and ASMFC 2006, Table 7.1).

[Terminal years are 2002 and 2005, respectively; F is average for ages 2+, and eggs (fecundity) are mature ova in trillions.]

Benchmarks	F-based	Egg-based
2003 Peer Review:		
Target	0.75	26.60
Limit	1.18	13.30
Terminal	0.79	40.60
2006 Update:		
Target	0.55	26.35
Limit	0.91	13.18
Terminal	0.50	41.74

12.0 Figures

Figure 1.1 VPA historical retrospective on fishing mortality (F), both as (a) fishing mortality F for terminal years 1992-2001, and (b) as proportional deviations from terminal year 2000 (1992-1999).

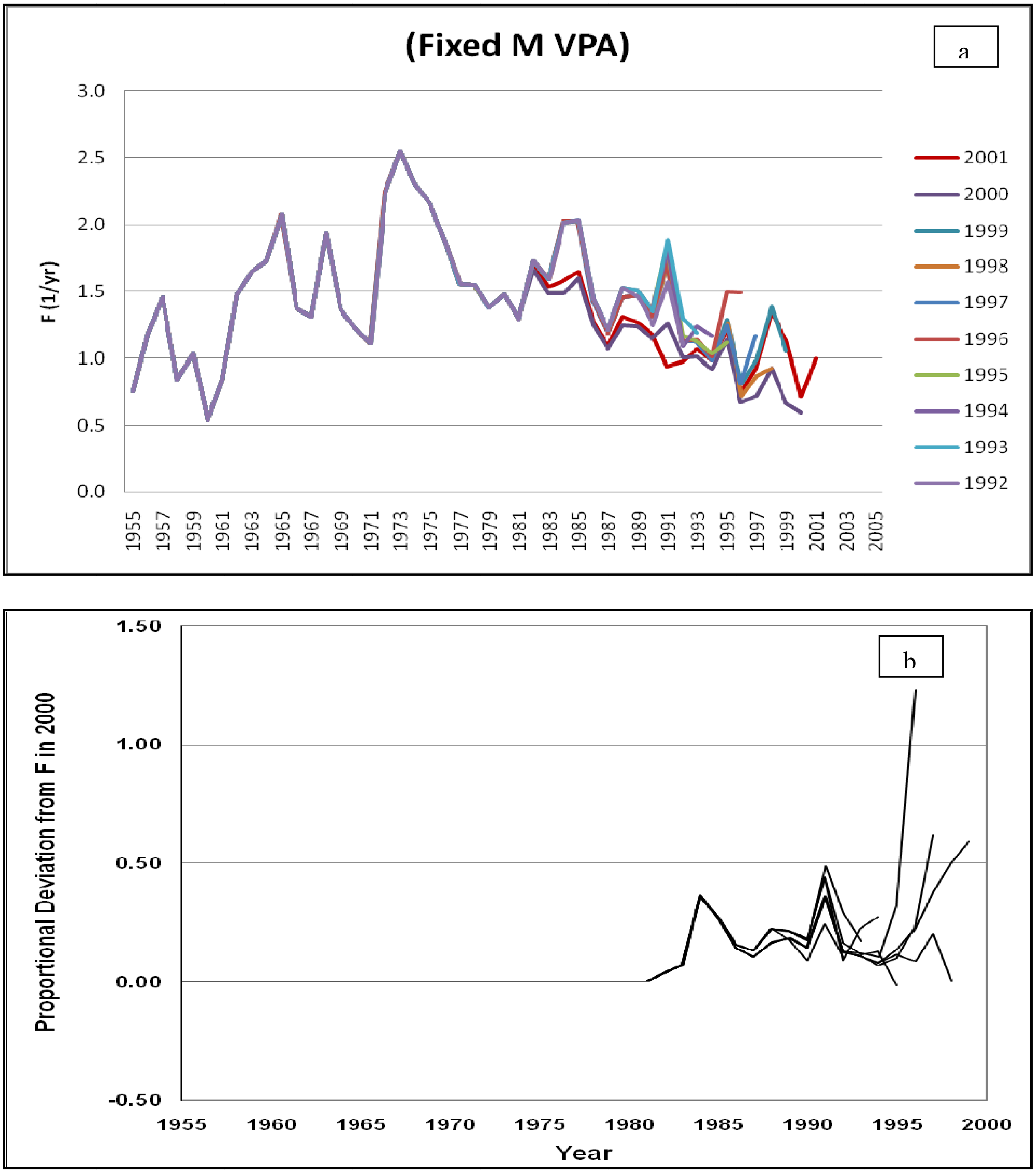


Figure 1.2 VPA historical retrospective on spawning stock biomass (SSB), both as (a) SSB for terminal years 1990, 1992-2001, and (b) as proportional deviations from terminal year 2000 (1992-1999).

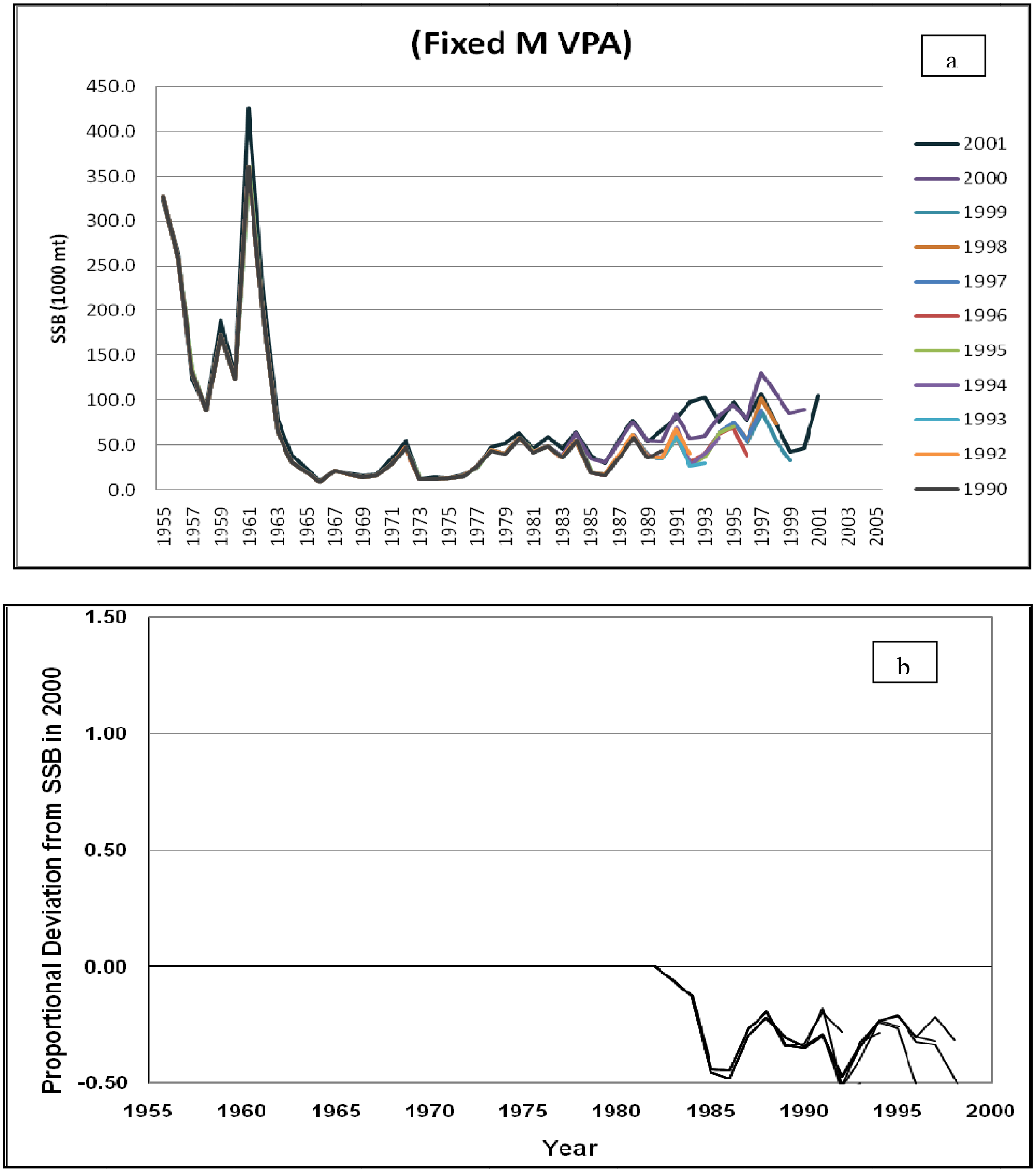
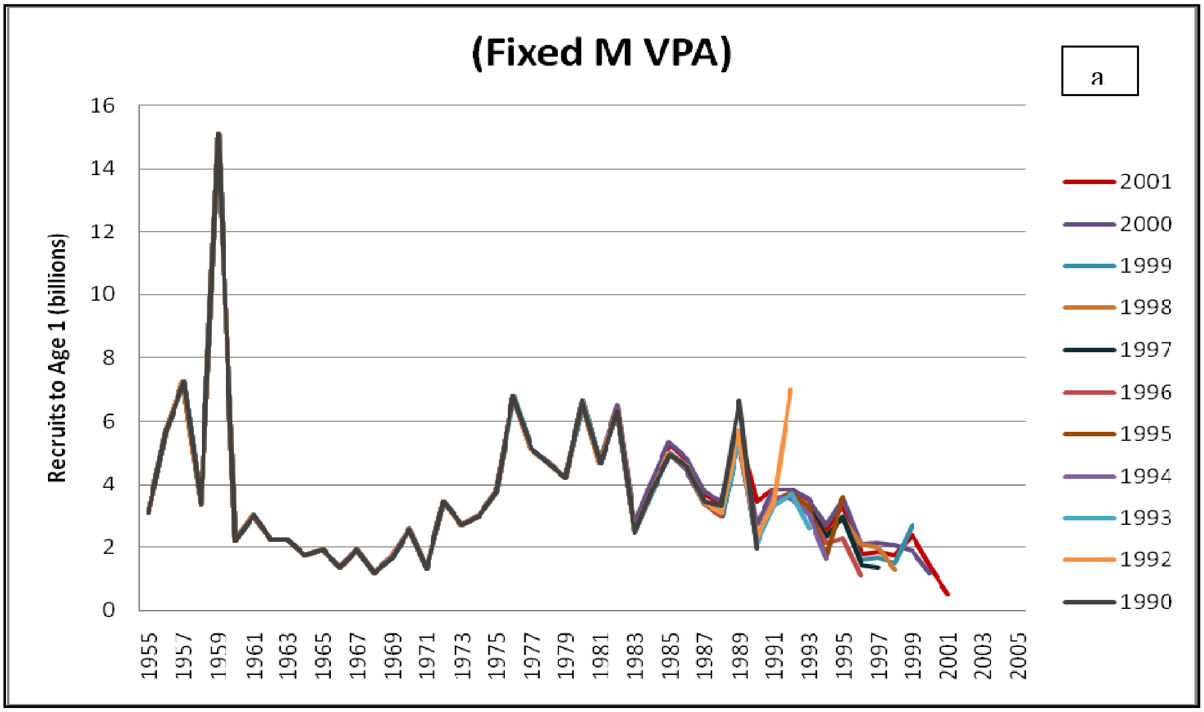


Figure 1.3 VPA historical retrospective on recruits to age 1 (R_1), both as (a) R_1 for terminal years 1990, 1992-2001, and (b) as proportional deviations from terminal year 2000 (1992-1999).



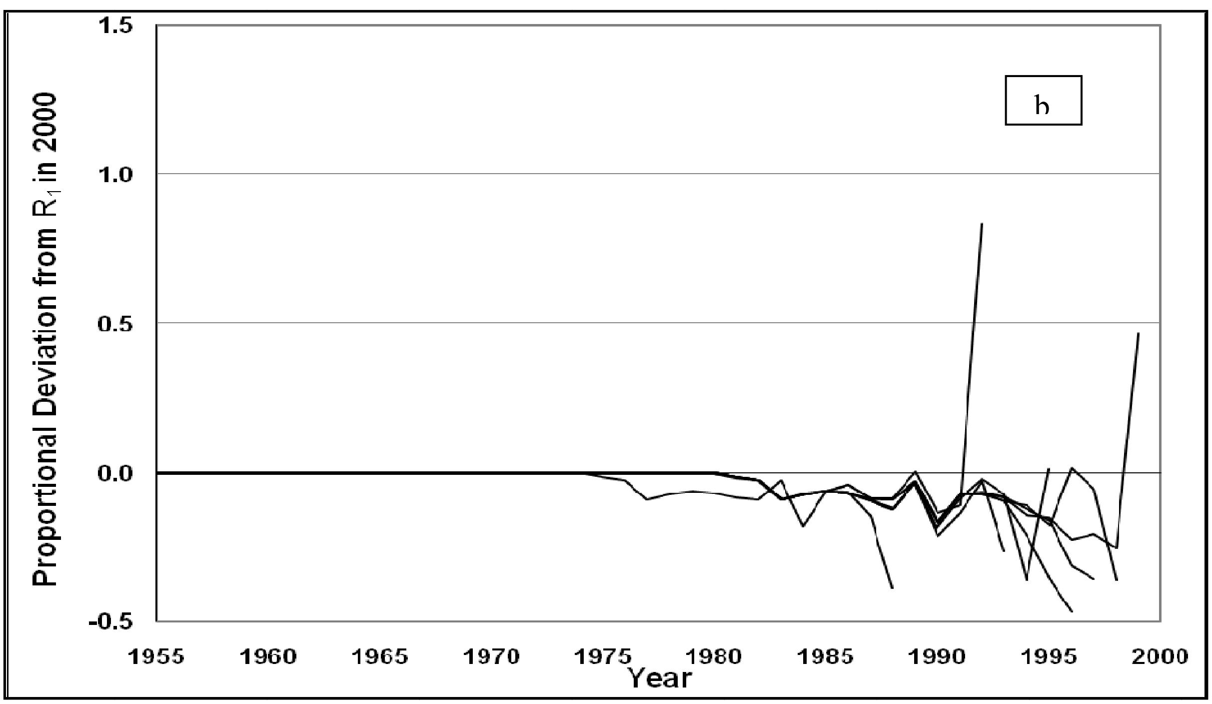


Figure 1.4 Comparison of fishing mortality, F, from “untuned” VPA with preliminary statistical catch model for terminal years 2000 and 2001.

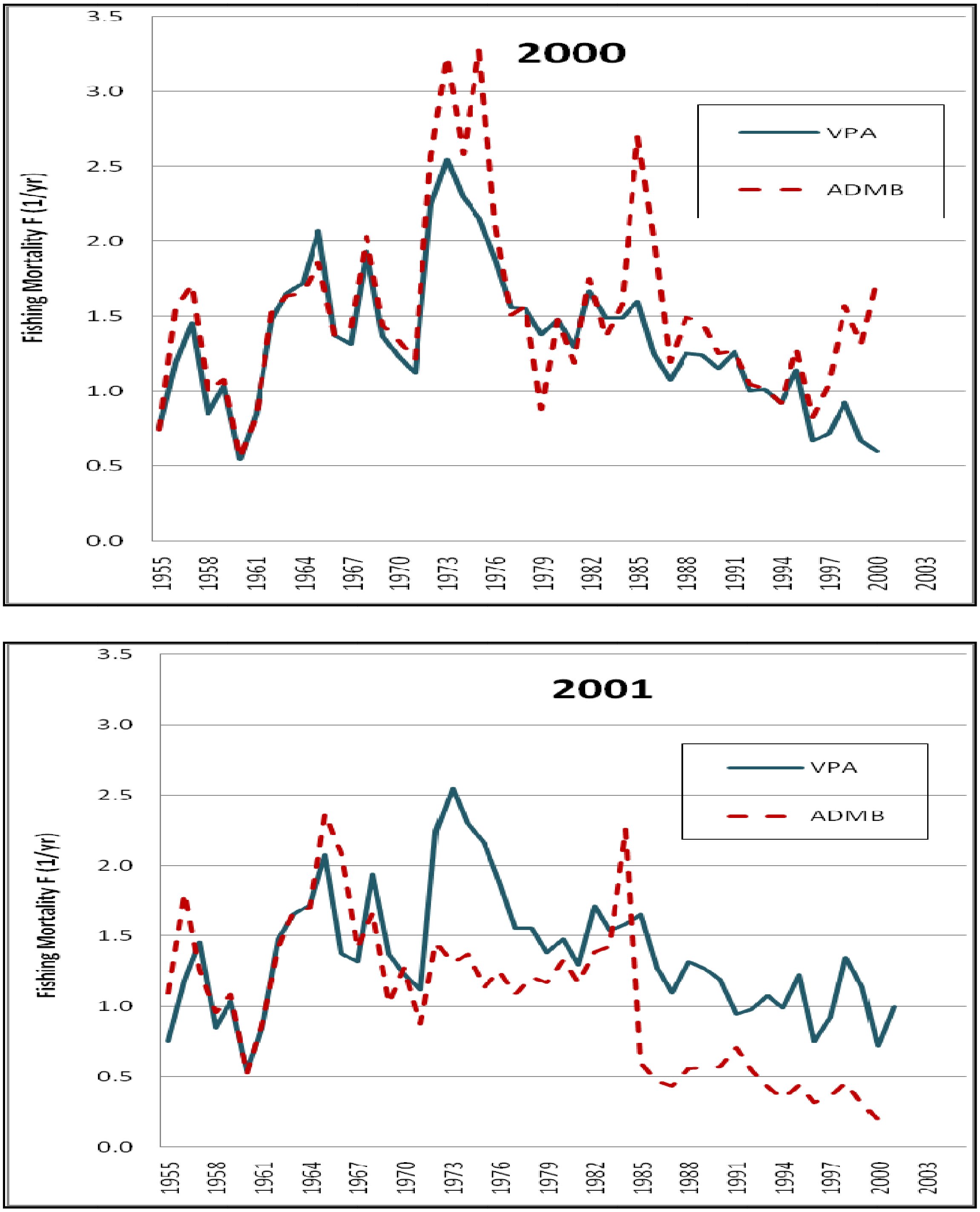
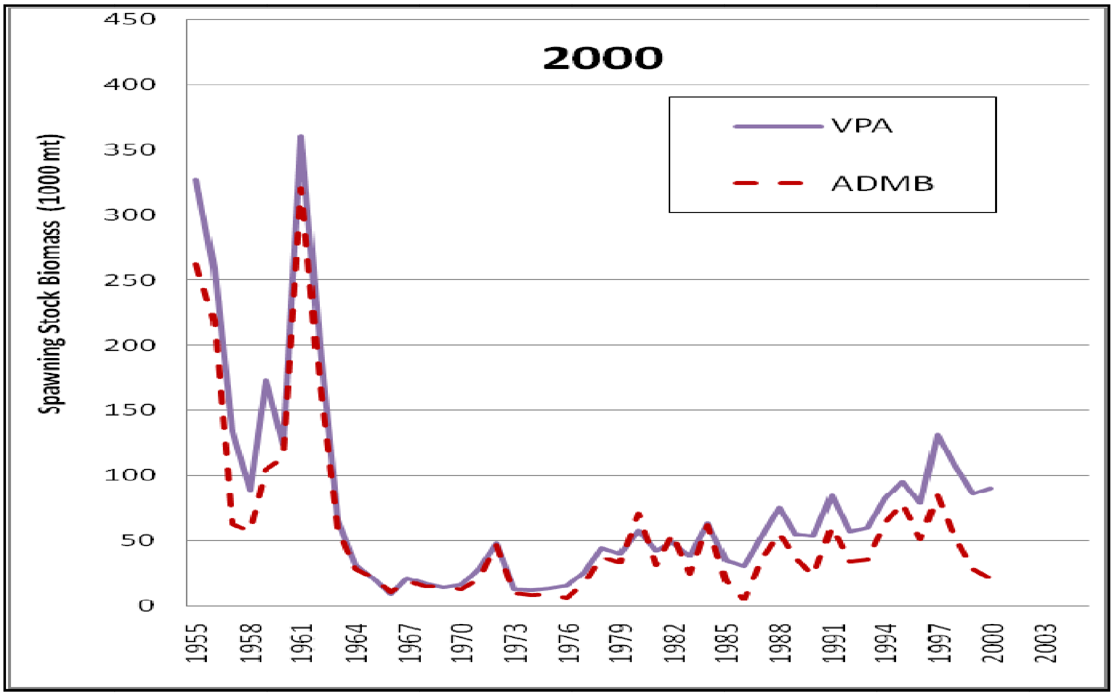


Figure 1.5 Comparison of spawning stock biomass, SSB, from "untuned" VPA with preliminary statistical catch model for terminal years 2000 and 2001.



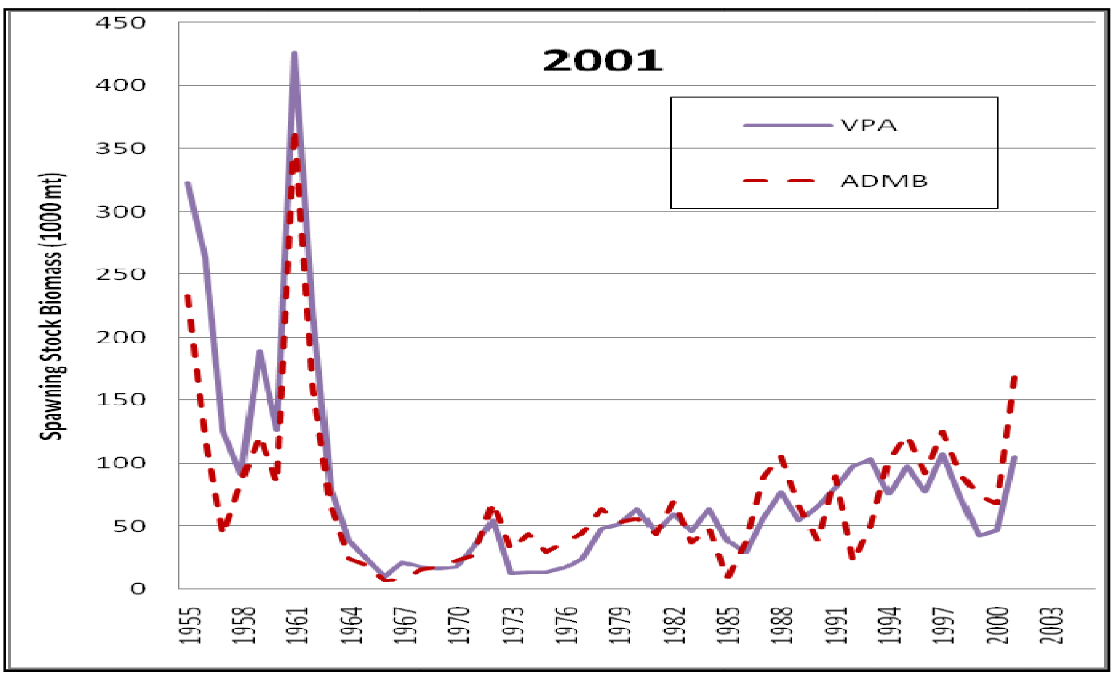
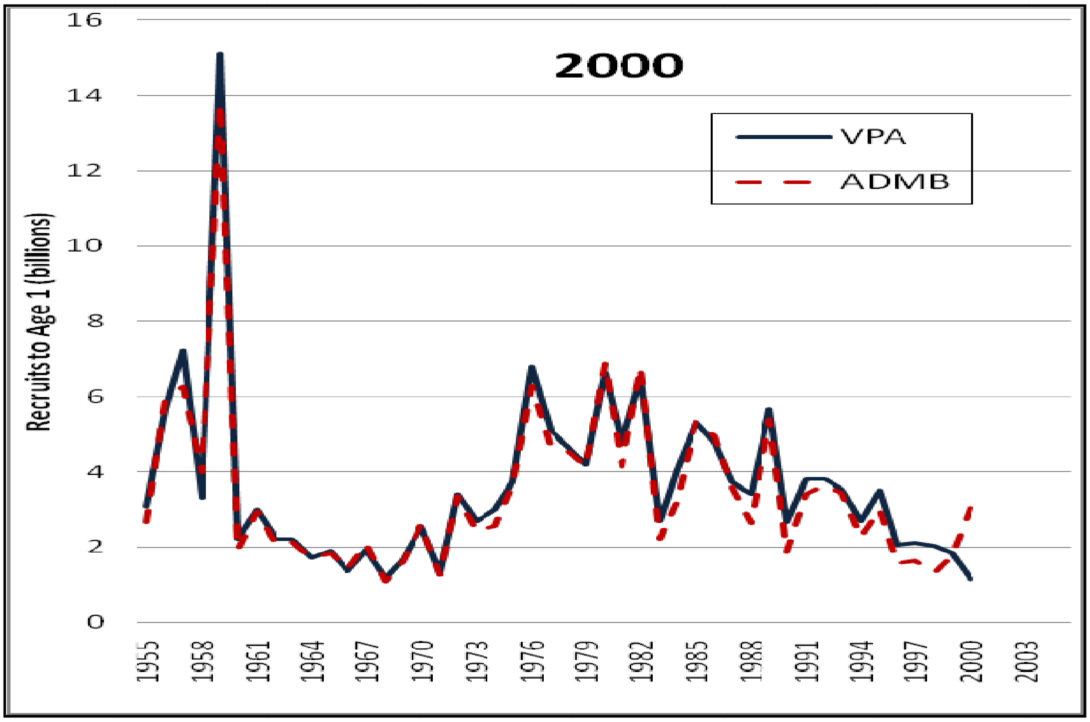


Figure 1.6 Comparison of recruits to age 1, R_1, from "untuned" VPA with preliminary statistical catch model for terminal years 2000 and 2001.



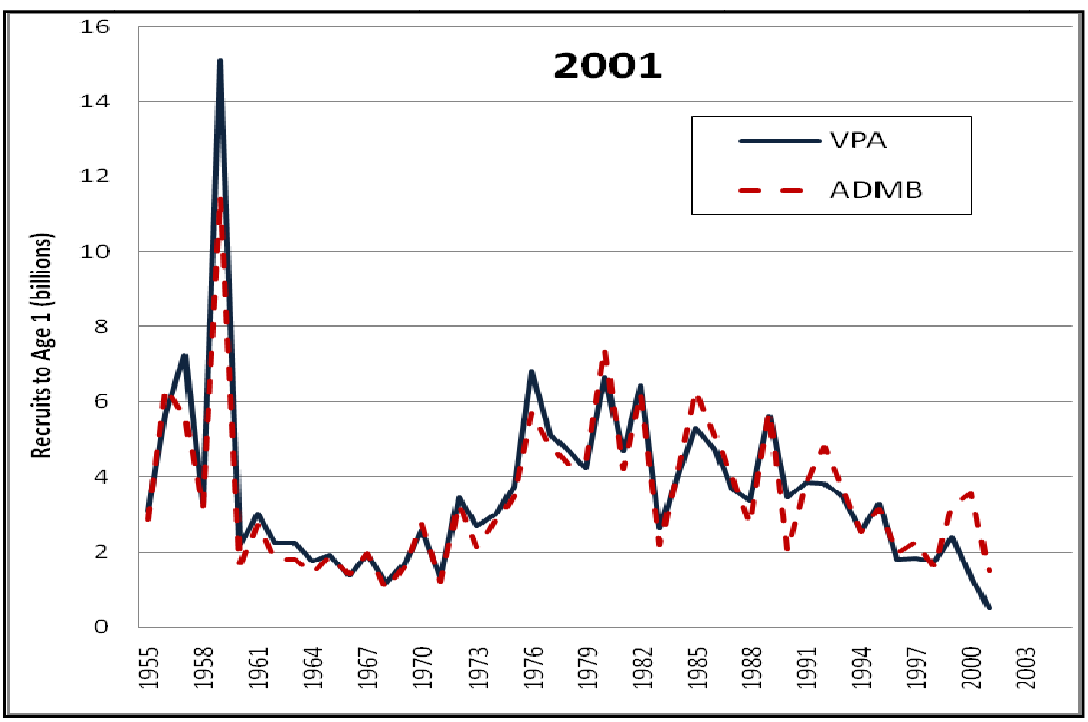


Figure 1.7 Comparison of fishing mortality, F, from statistical catch model for peer review (2003) and update (2006).

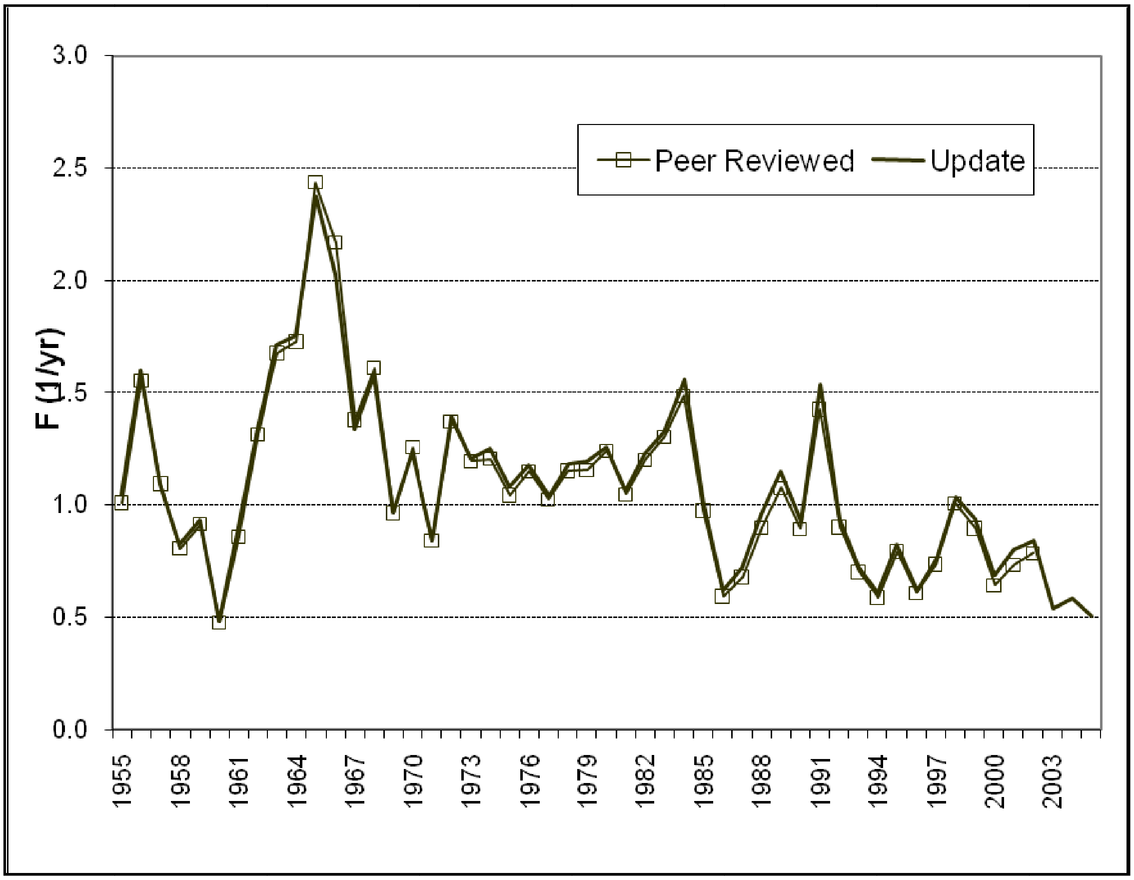


Figure 1.8 Comparison of spawning stock biomass, SSB, from statistical catch model for peer review (2003) and update (2006).

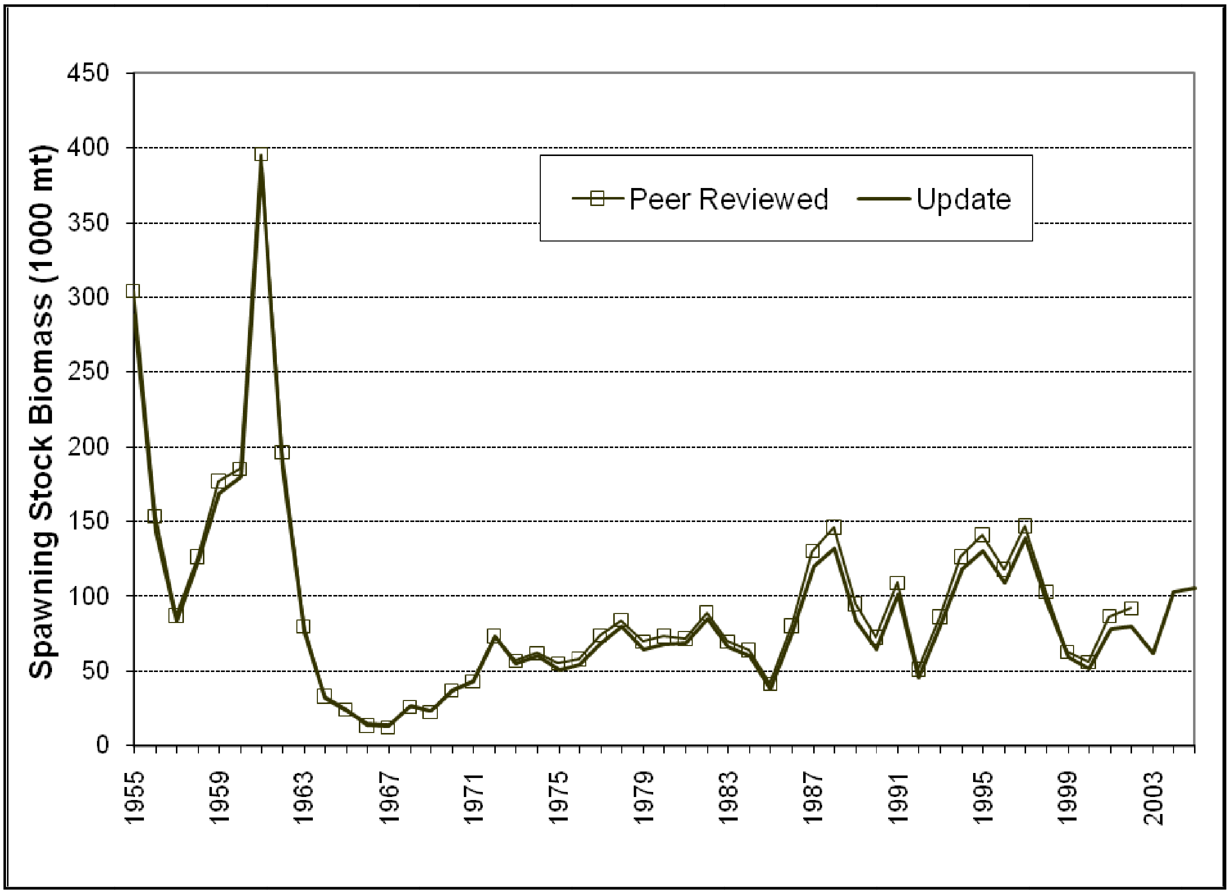


Figure 1.9 Comparison of recruits to age 1, R_1, from statistical catch model for peer review (2003) and update (2006).

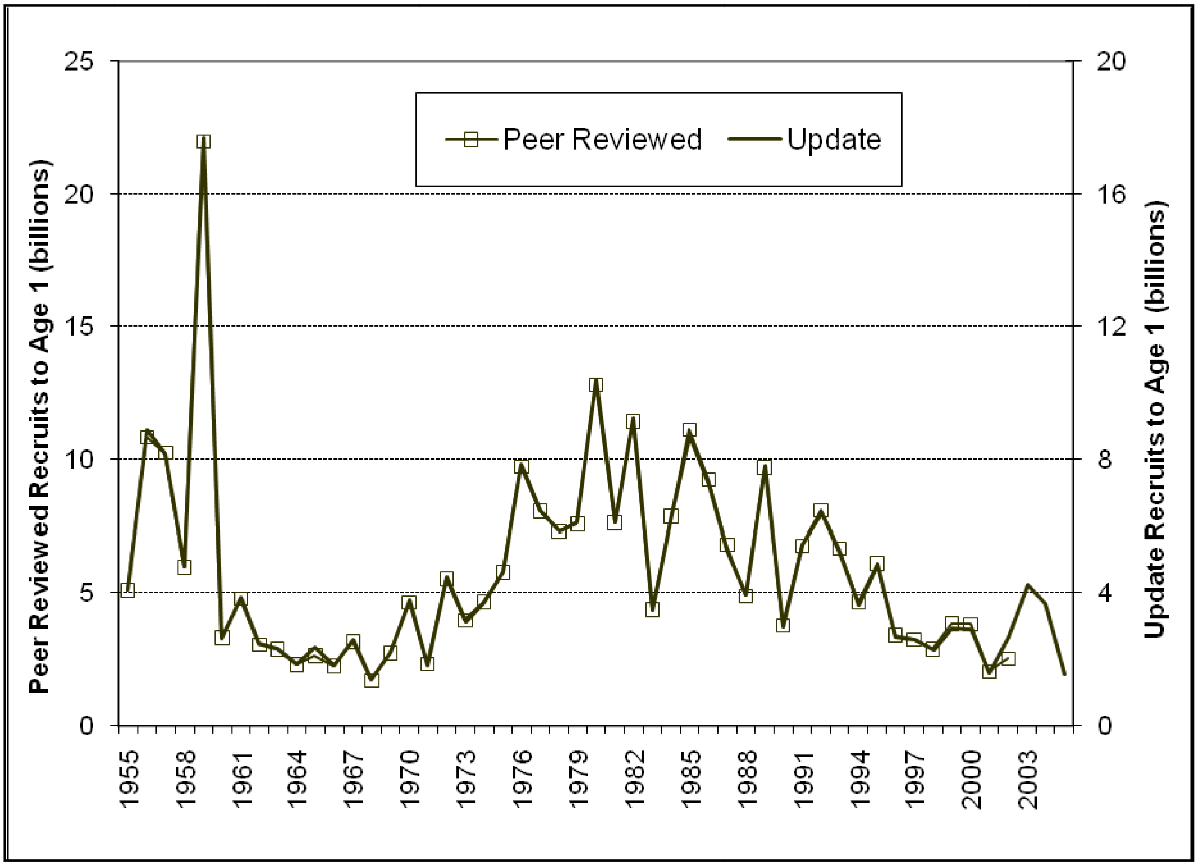


Figure 2.1. Matrix of paired age readings by scales for Atlantic menhaden from 2008.

First reading age (in yrs)

First reading age	0	1	2	3	4	5
5			2	9	6	4
4			4	90	111	9
3		1	157	821	115	9
2	6	59	1850	180	31	1
1	3	152	48	1		
0	40	2				

Second reading age (in yrs)

Figure 2.2. Weighted mean weight at age for Atlantic menhaden for ages 1 through 3.

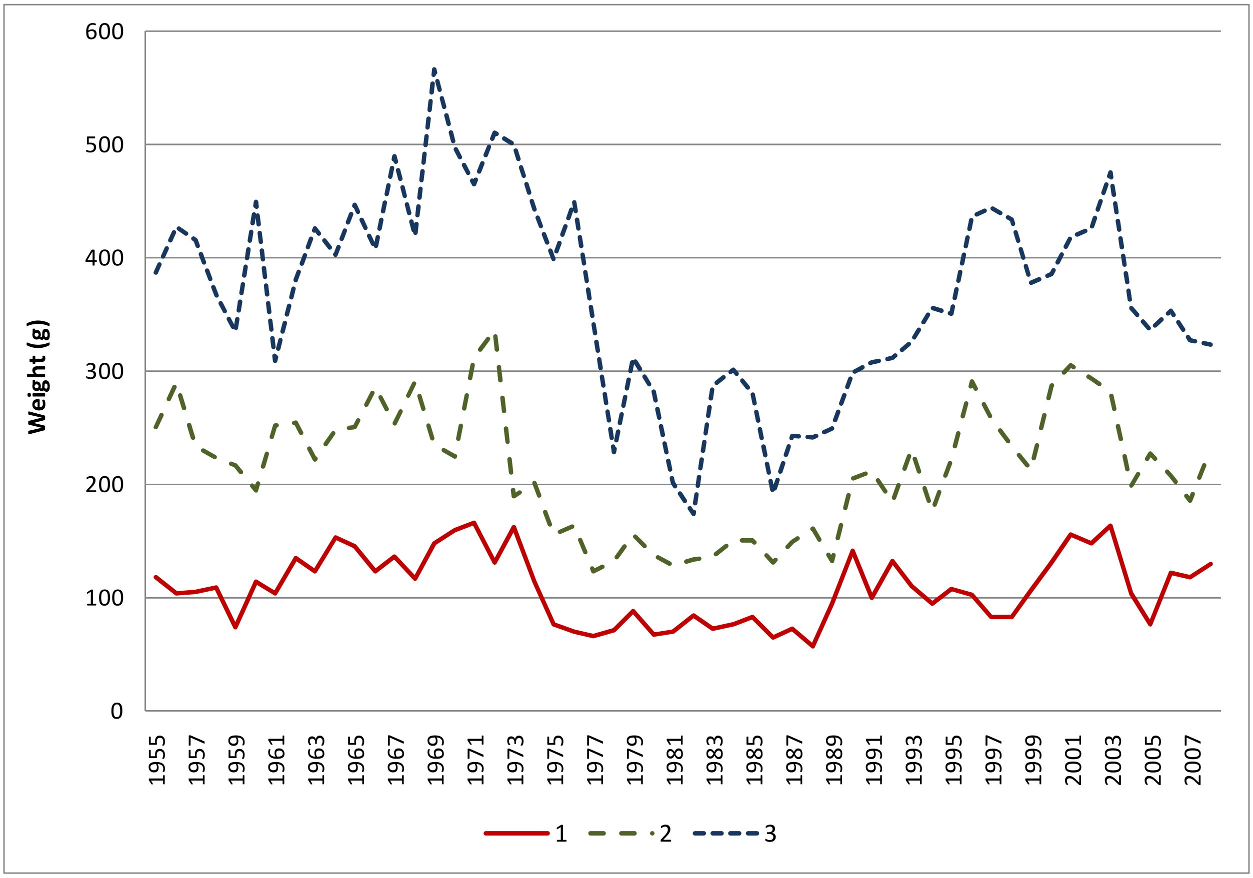


Figure 2.3. Weighted mean weight at age 0 plotted against recruits to age 0 obtained from latest Atlantic menhaden stock assessment (ASMFC 2006) for 1955-2005.

[A statistically significant forty nine percent ($R^2 = 0.49$) of the variability in mean weight is explained by variability in recruits to age 0.]

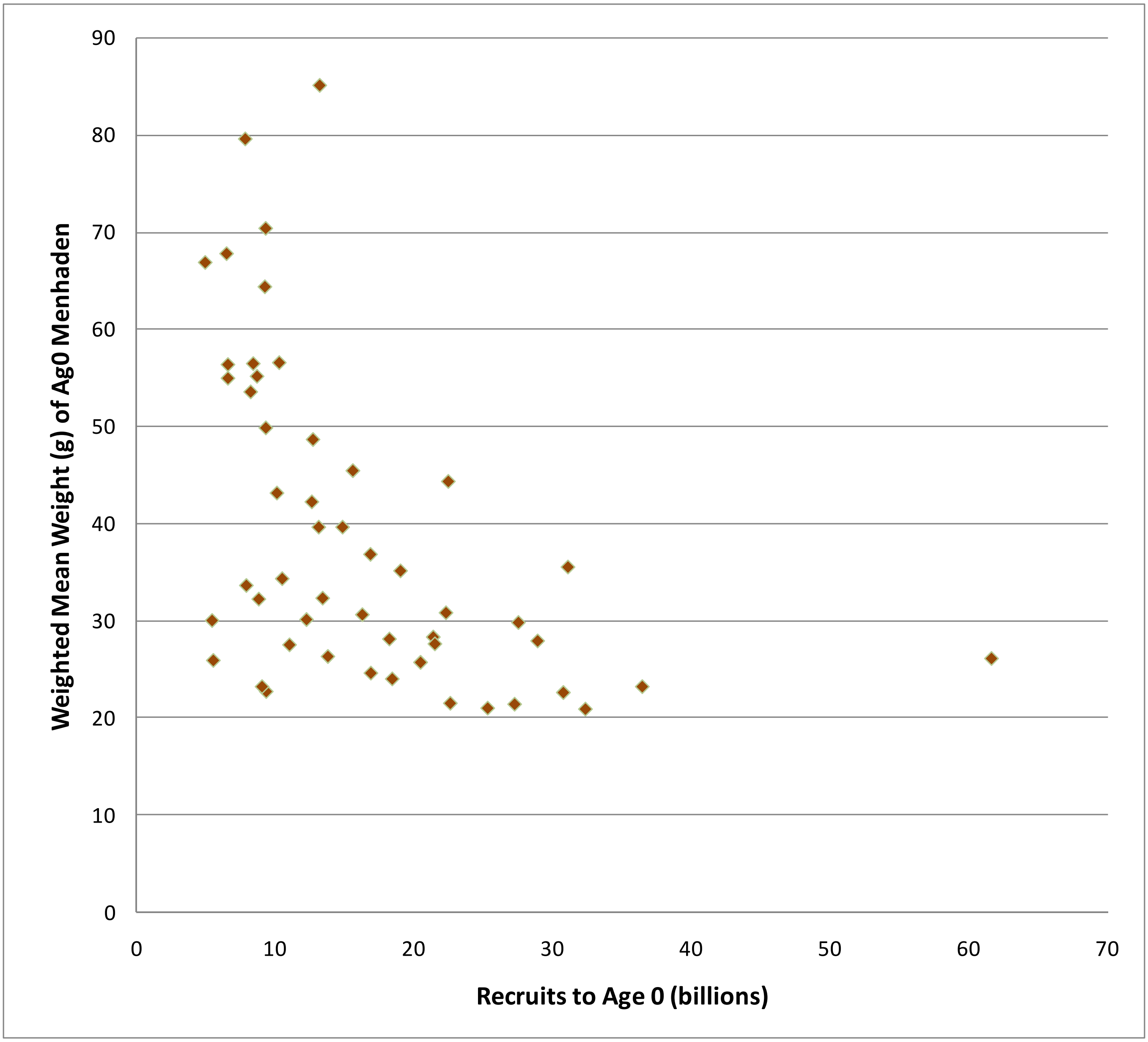
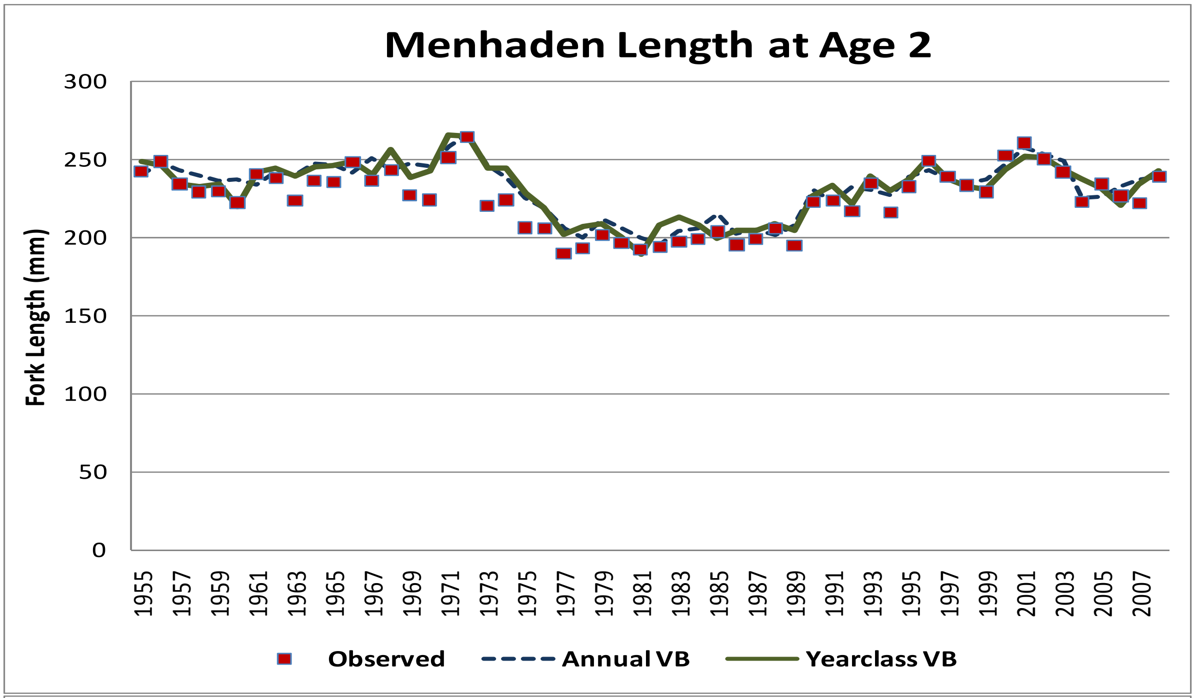


Figure 2.4. Comparison of observed weighted mean length at age (ages 2 and 3) with values estimated from the year and cohort based von Bertalanffy growth equation for mid-year (t+0.5).



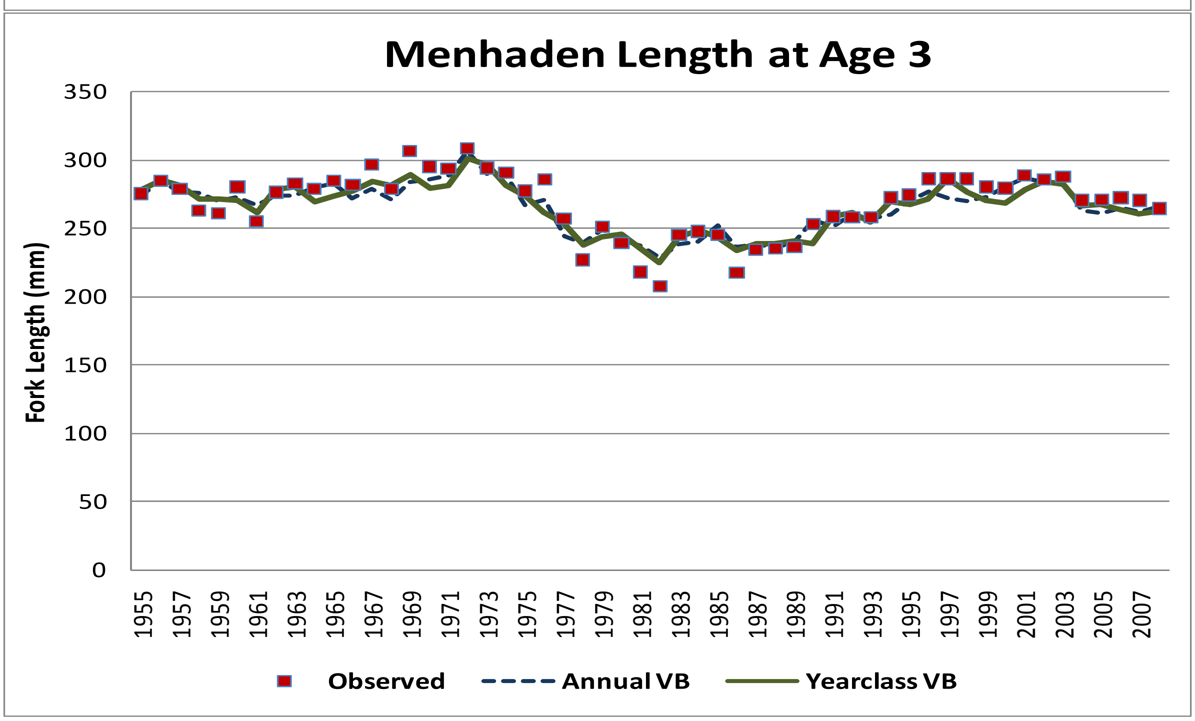


Figure 2.5. Fecundity (no. of maturing or ripe ova) as a function of fork length (mm) for Atlantic menhaden.

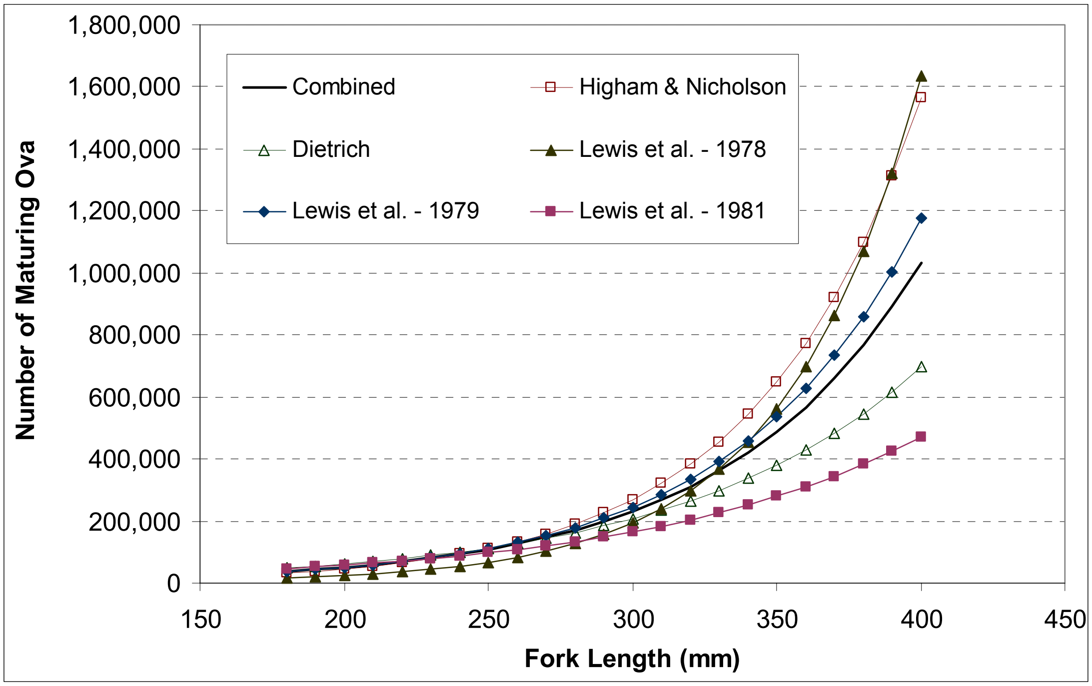


Figure 2.6. Proportion of age 2 (11.8% mature) and age 3 (86.4%) spawning (essentially first time spawners) to total female spawning stock as estimated in numbers and in biomass from the most recent stock assessment (ASMFC 2006), 1955-2005.

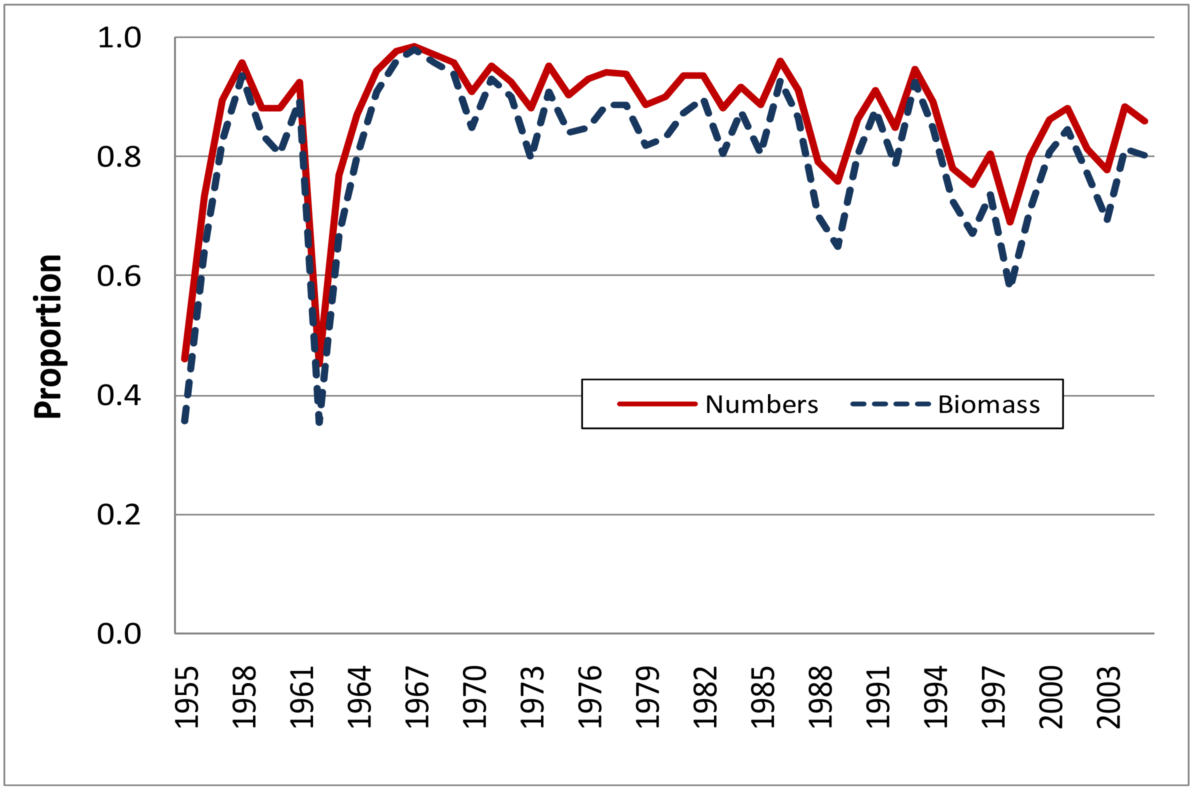


Figure 2.7. Annual calculated values of *M* from age-constant *M* approaches and average *M* across ages 1-10 (constant for 6+) of MSVPA-X.

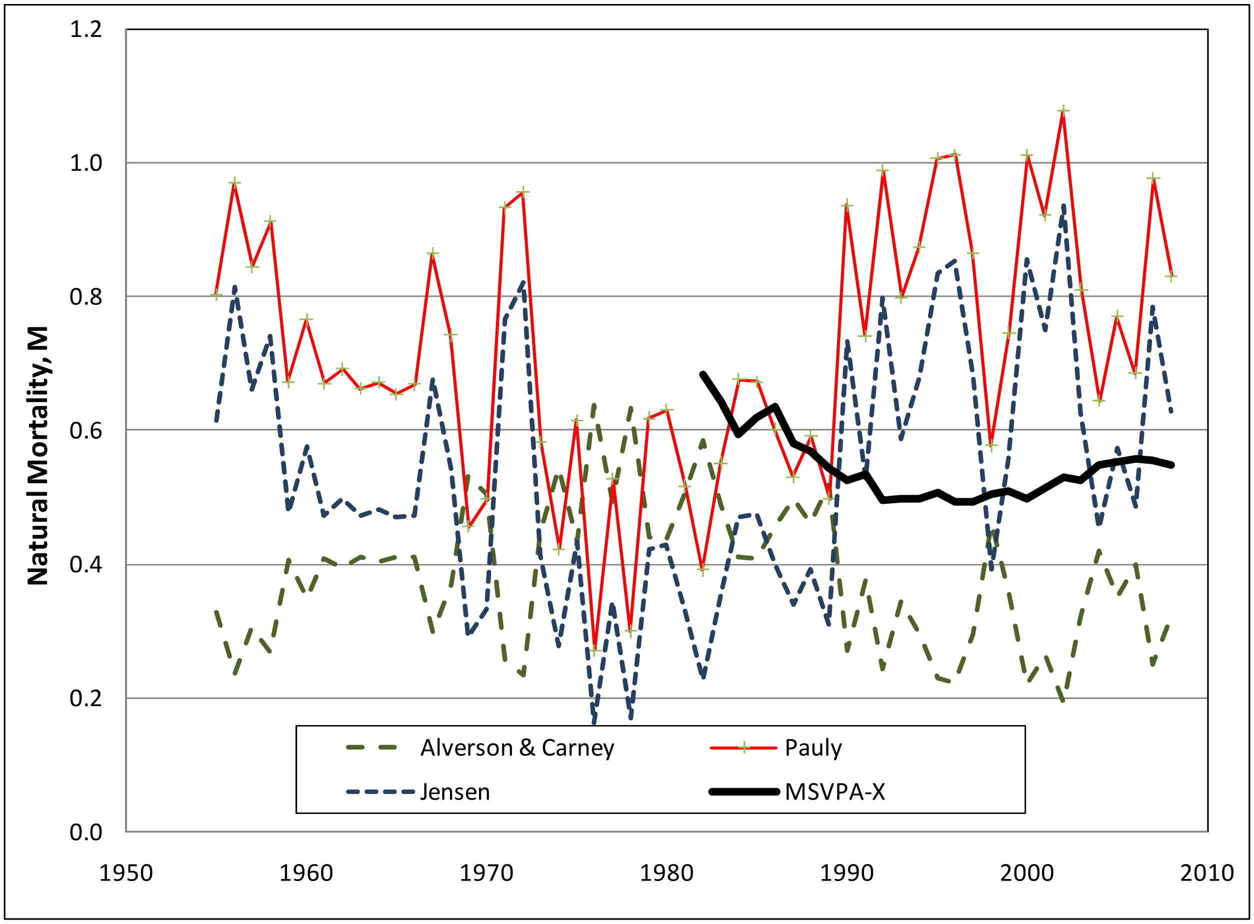


Figure 2.8. Age-varying estimates of *M* averaged across all available years for three age-varying methods based on weight at age (Boudreau & Dickie, Peterson & Wroblewski, and Lorenzen) and MSVPA-X.

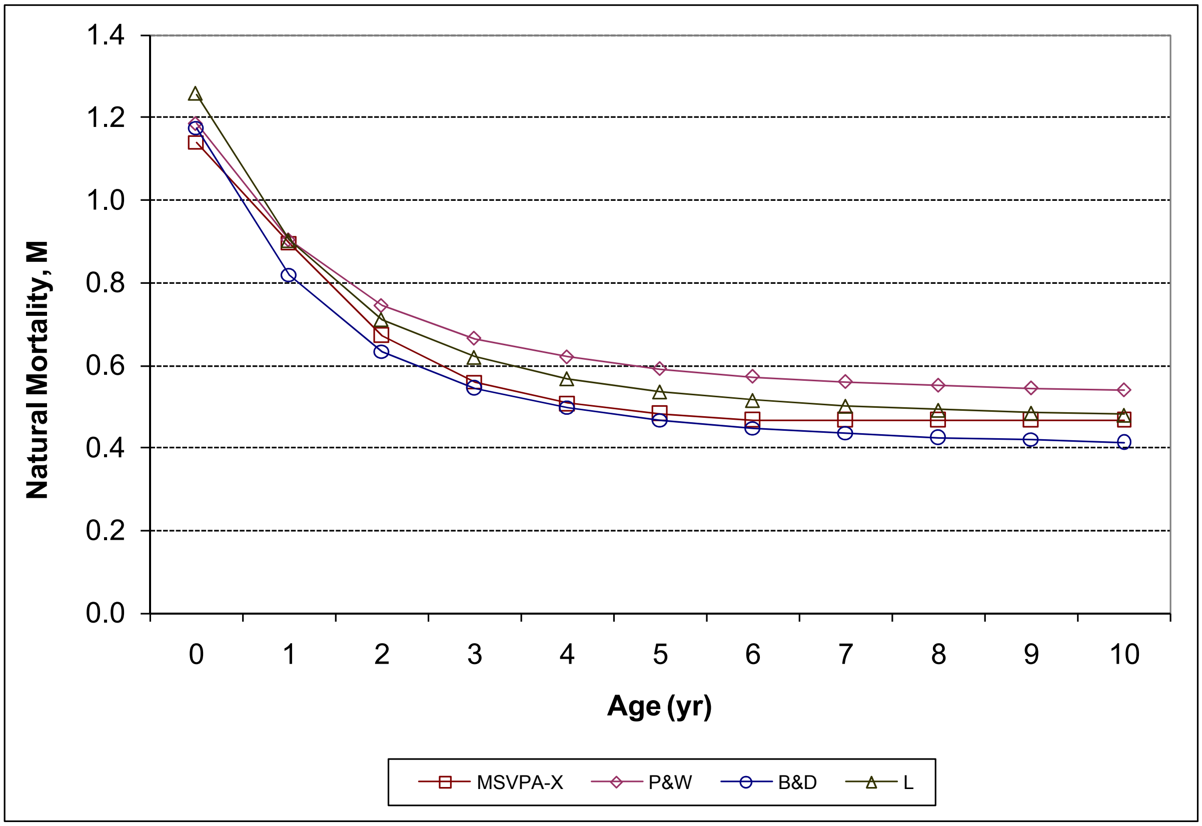


Figure 2.9. Comparison of several age-varying methods for estimating *M* scaled to average *M* over ages.

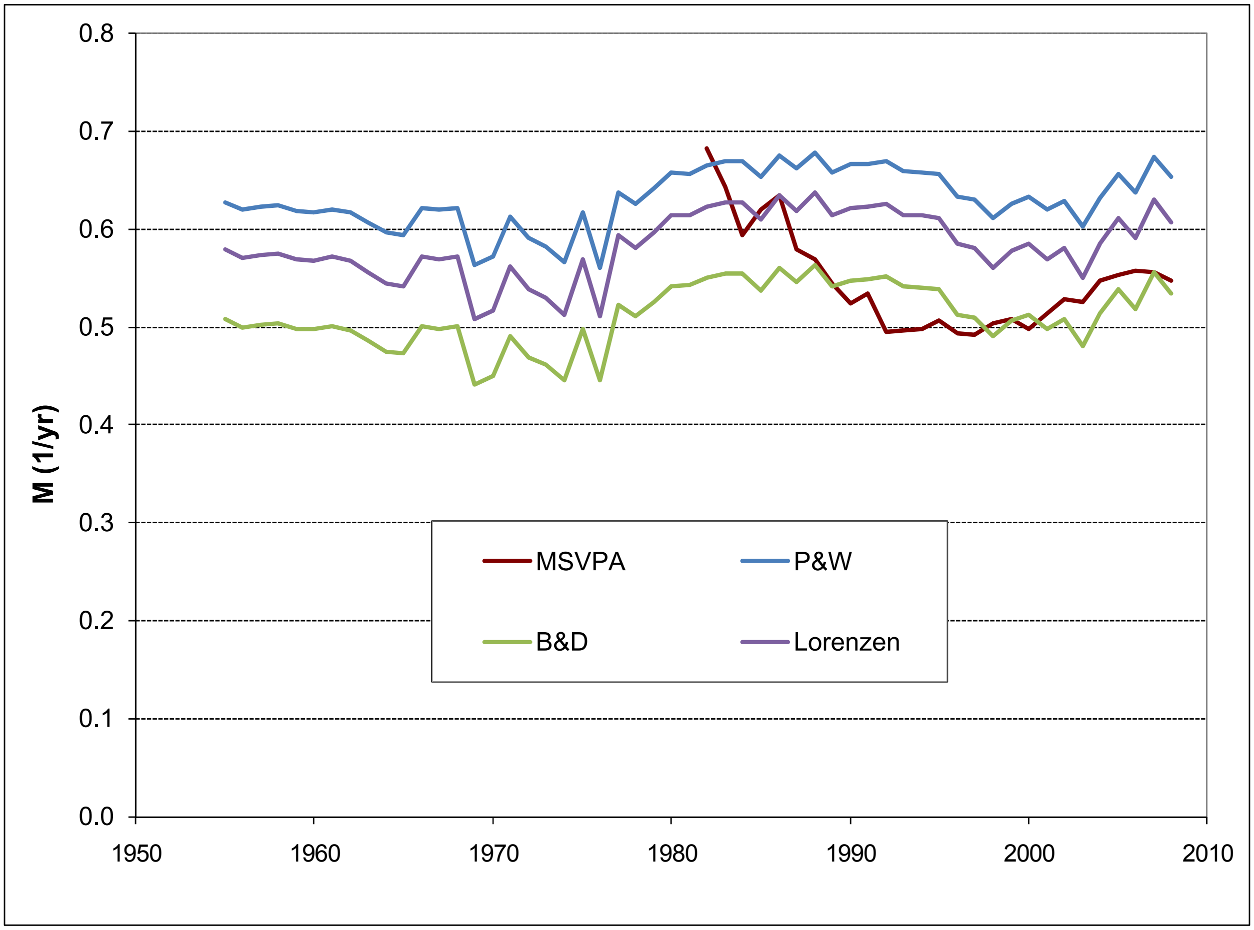


Figure 4.1. Landings from the reduction purse seine fishery (1940-2008) and bait fishery (1985-2008) for Atlantic menhaden.

[Recreational catches (1981-2008) are not included because they are two-orders of magnitude smaller than the bait landings.]

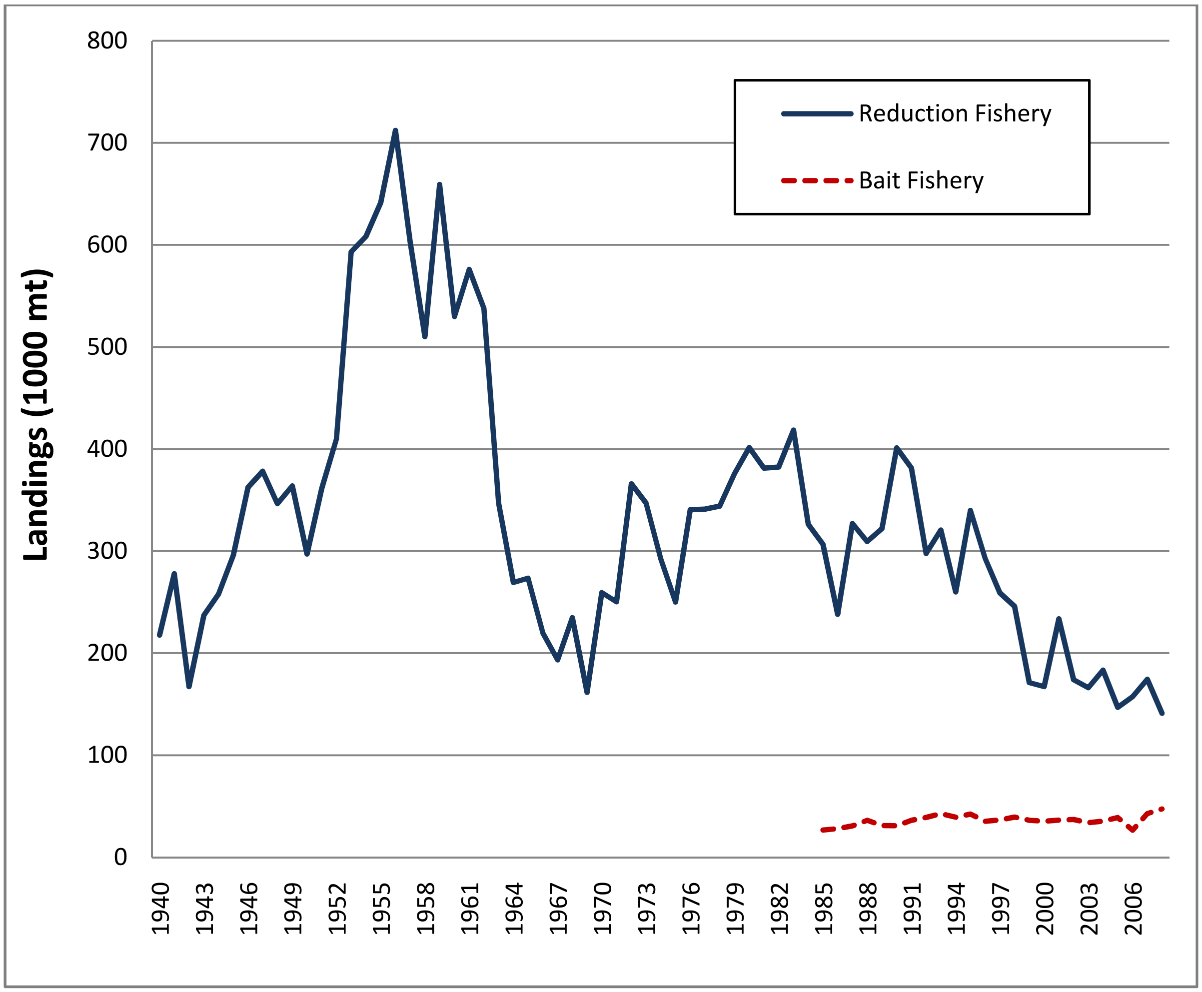


Figure 4.2. A comparison of commercial catch statistics taken from *Historical Reports* (linearly interpolated by region) with reduction landings statistics maintained at NOAA Fisheries at Beaufort, NC.

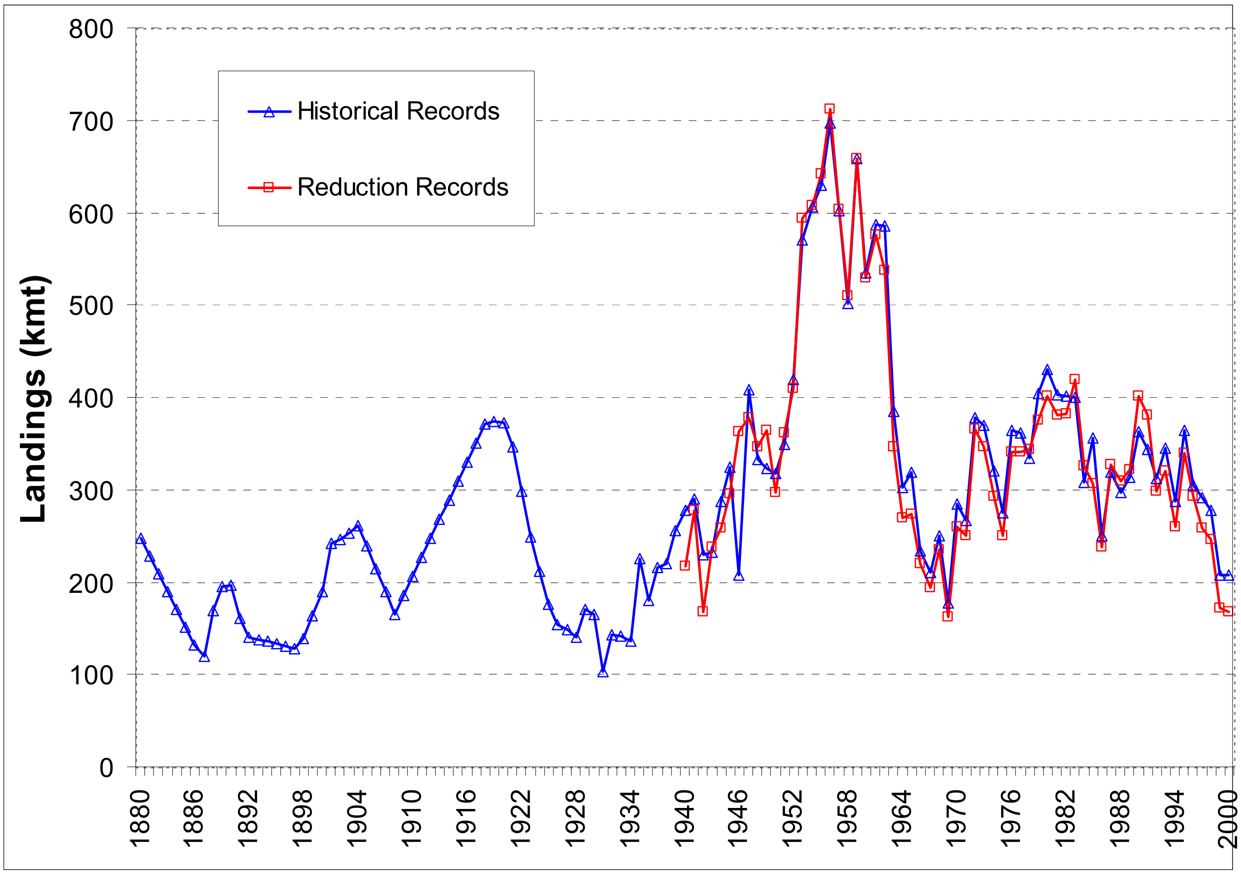


Figure 4.3. Comparison of menhaden landings (Atlantic and gulf menhaden combined) between two sources of historical data, 1873-1964.

[Reconstructed landings refer to the historical landings available on excel spreadsheets from annual historical reports, and Menhaden landings refers to those taken from the report *Menhaden Landings, 1873-1964*.]

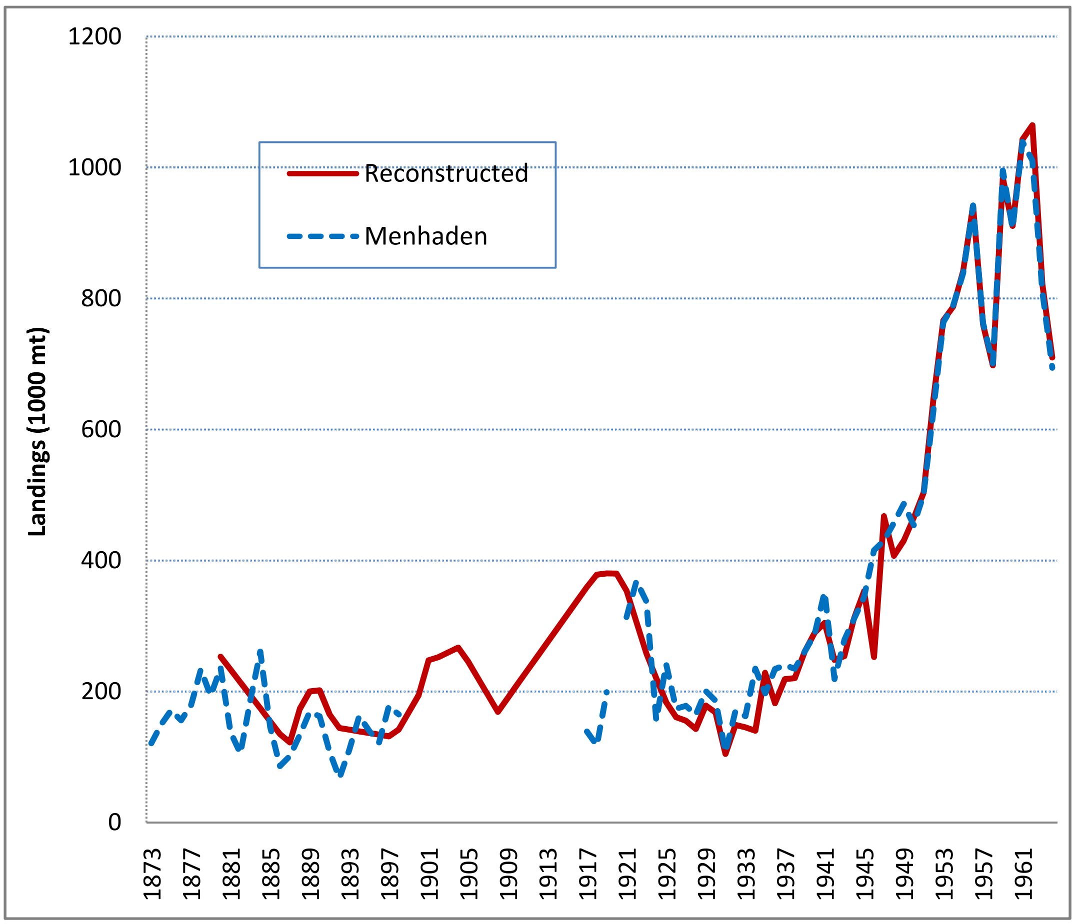


Figure 4.4. A comparison of purse seine landings obtained from the ACCSP Commercial Landings (Purse Seine) to purse-seine reduction landings (Reduction) maintained by NOAA Fisheries at Beaufort, NC.

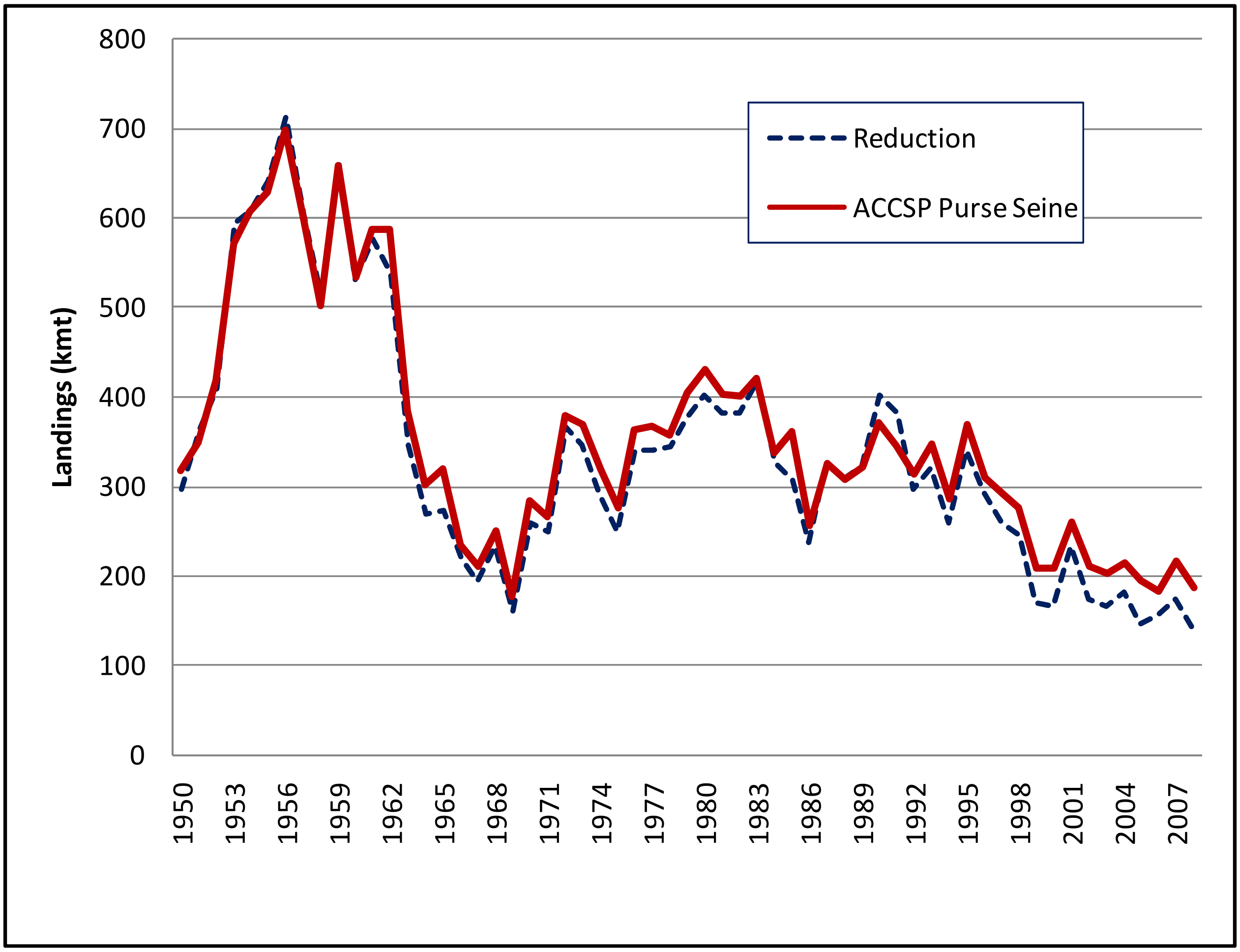


Figure 4.5. Reconstructed Atlantic menhaden landings along the coast of the U.S., 1873-2008.

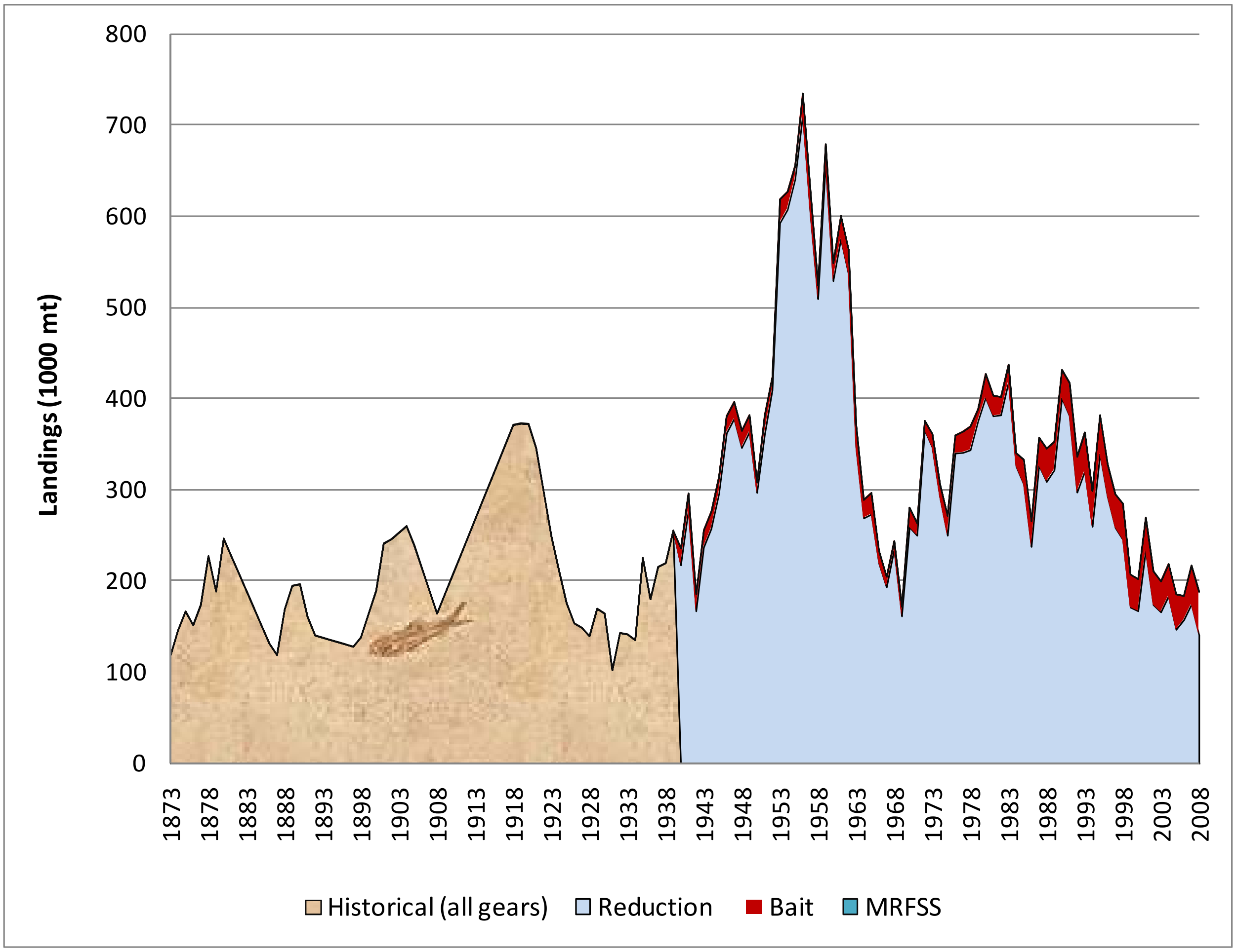


Figure 4.6. Annual values of menhaden reduction landings (1,000 mt) and nominal effort (vessel-week), 1940-2008.

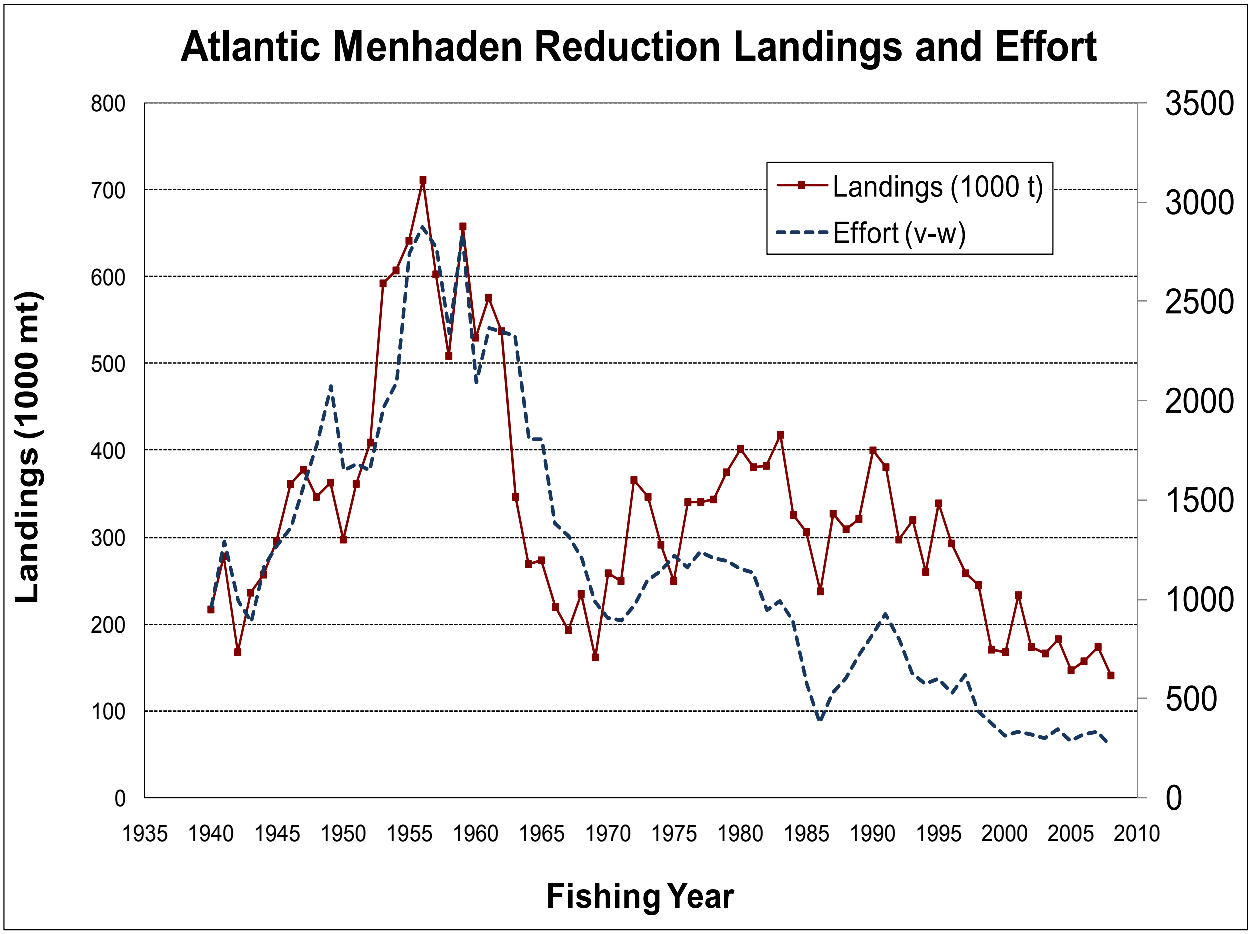


Figure 4.7. Comparison of catch per trip from all Atlantic menhaden reduction trips, subset sampled in biostatistical program (merged data), and LSMEANS from initial GLM runs based on coarse (area/season) input data with either normal or lognormal error structure.

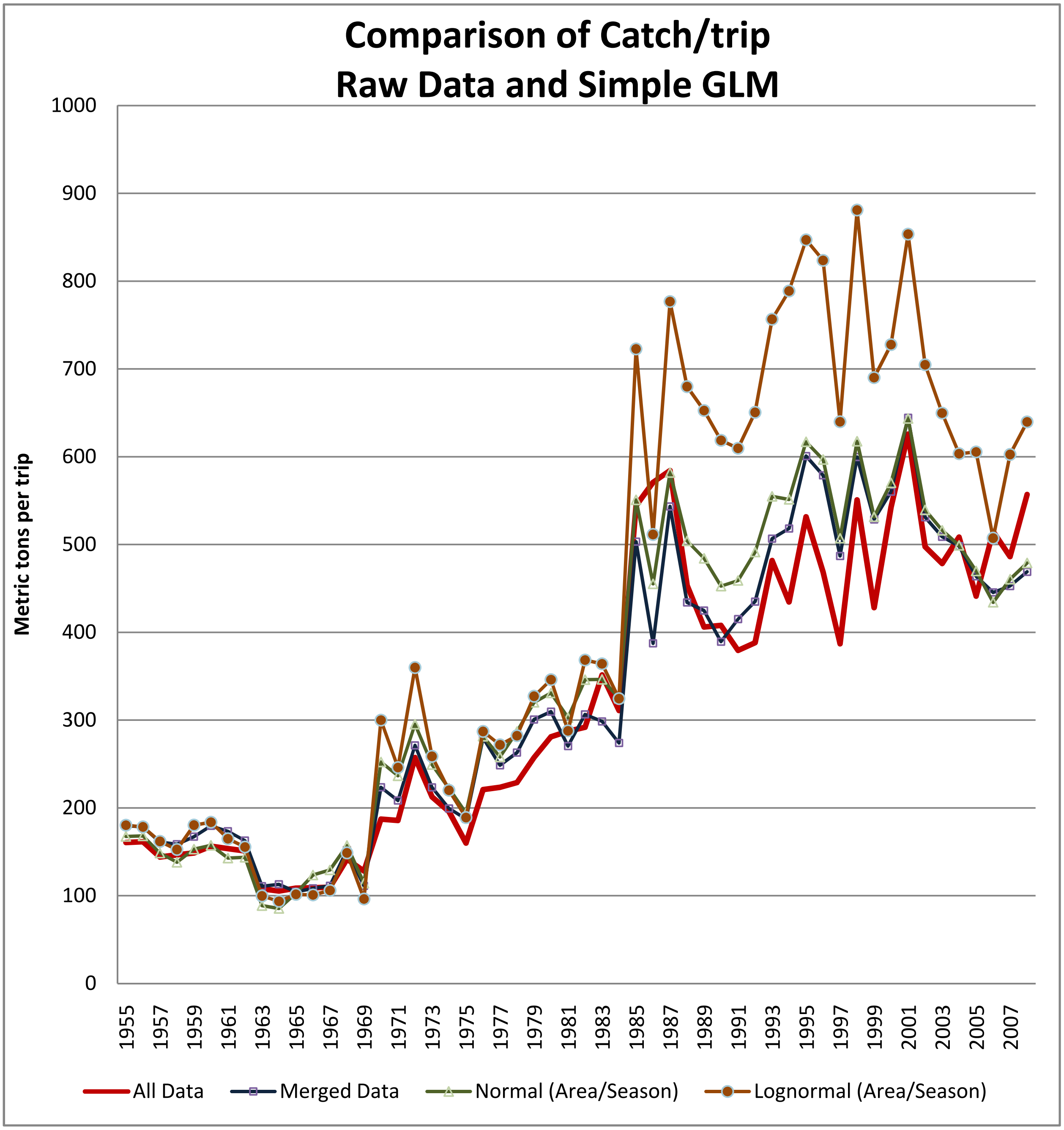


Figure 4.8. Comparison of nominal fishing effort for Atlantic menhaden reduction fleet, 1955-2008.

[Effort compared includes: (1) vessel-week, (2) trips (all landings data), and (3) GLM LSMEANS (additive model) based on subset of trips. All effort estimates are standardized by dividing by respective value in 1955.]

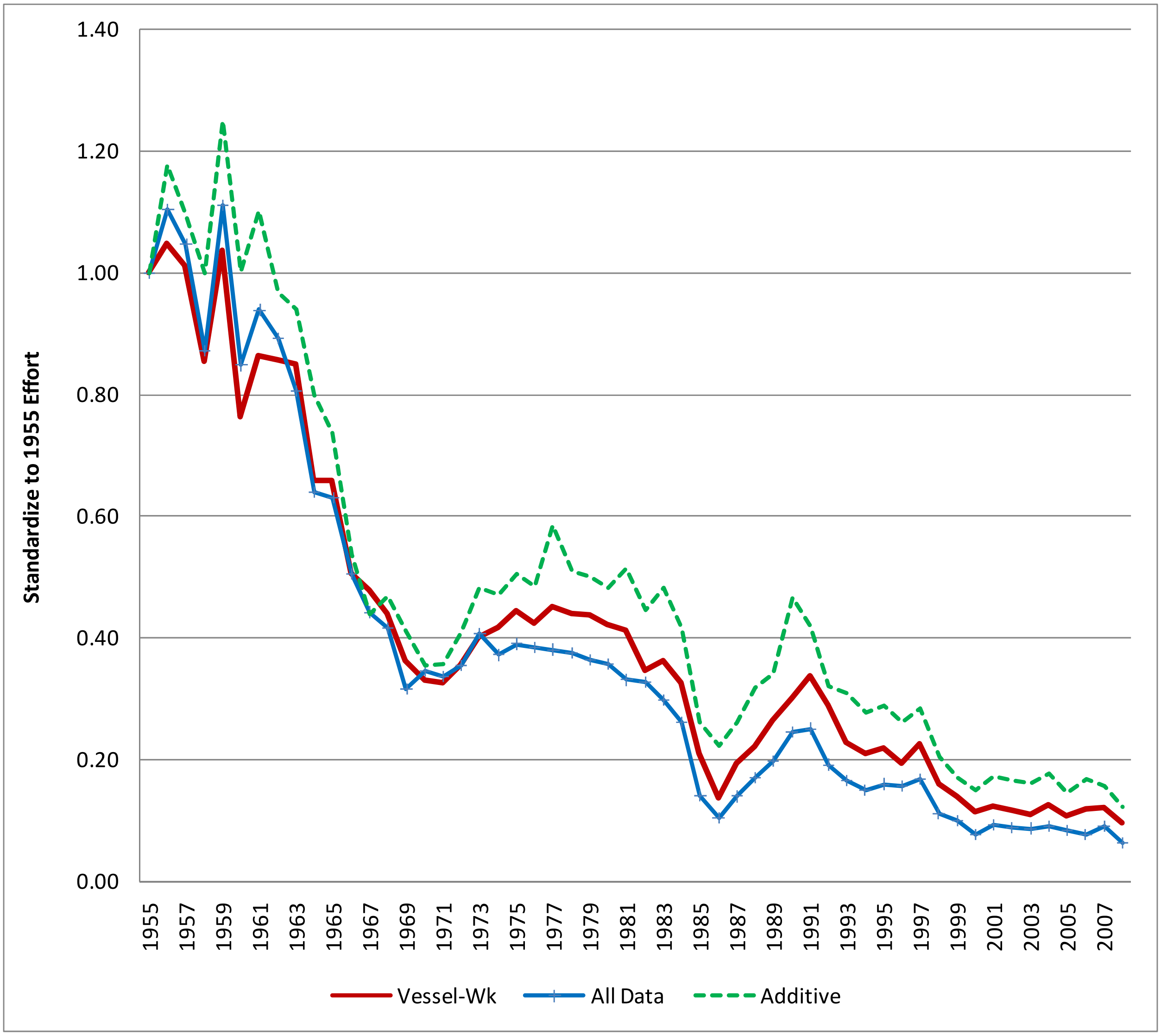


Figure 4.9. Comparison of calculated averages for CPUE across different measures of fishing effort, including landings per vessel week, landings per trip and catch per set.

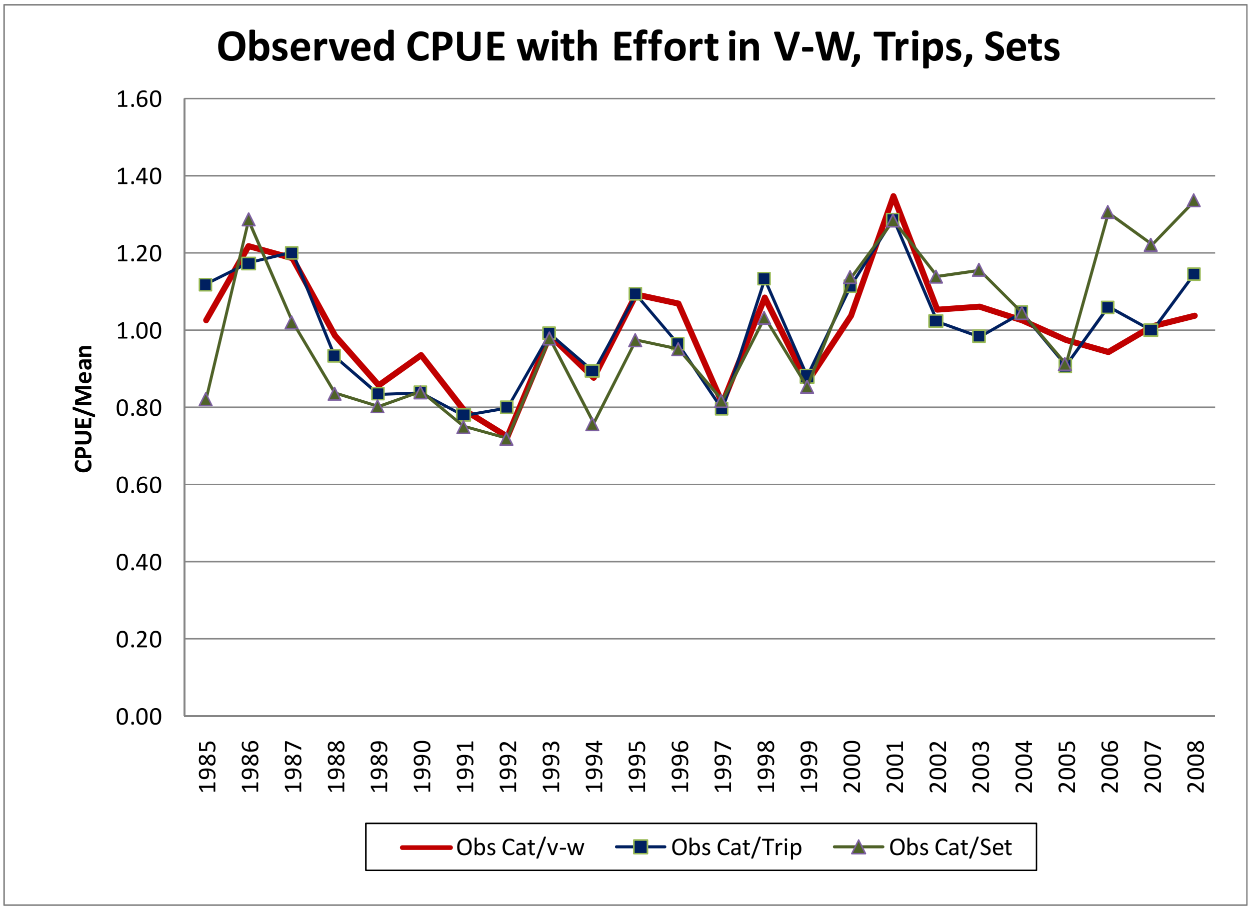


Figure 4.10. Comparison of nominal fishing effort for Atlantic menhaden reduction fleet, 1985-2008.

[Effort compared includes: (1) vessel-week, (2) trips (all landings data), and (3) purse-seine sets from VA and NC reduction plants. All effort estimates are standardized by dividing by respective value in 1985.]

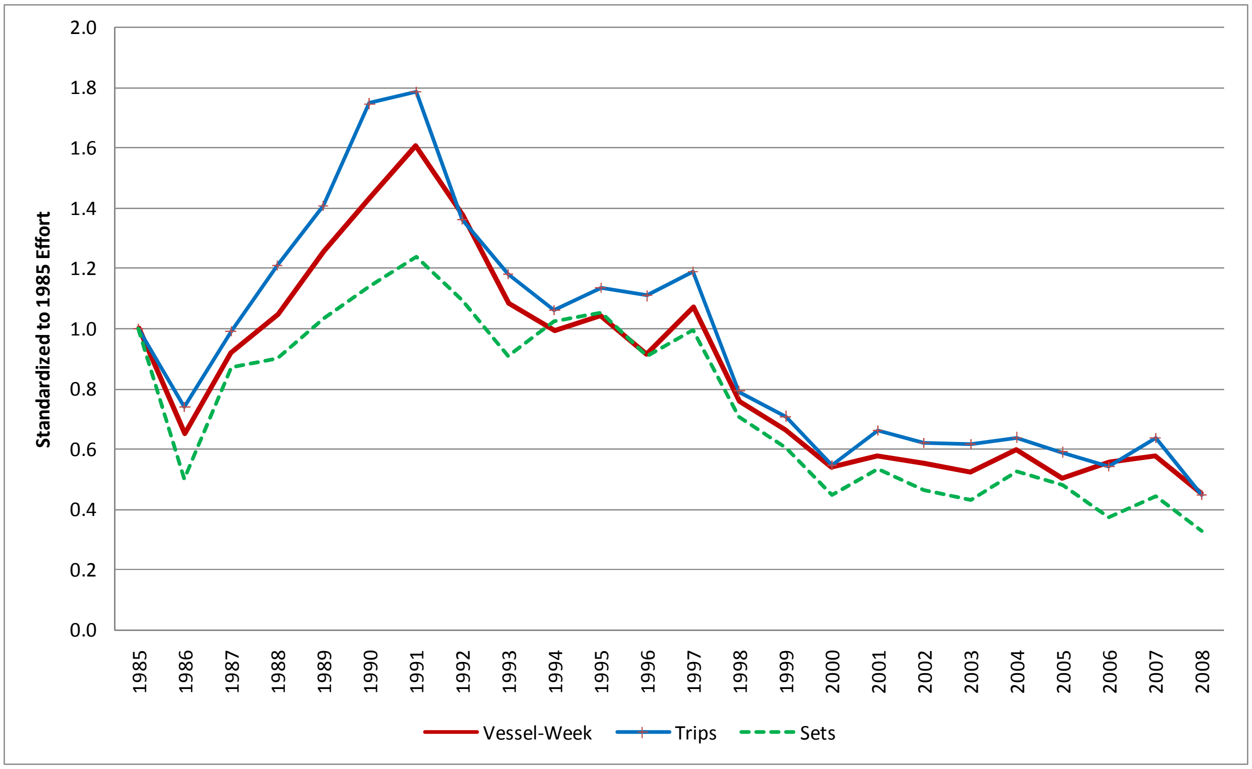


Figure 4.11. Comparison of mean landings by state from the bait fishery for Atlantic menhaden, 1985-2000 and 2001-2008.

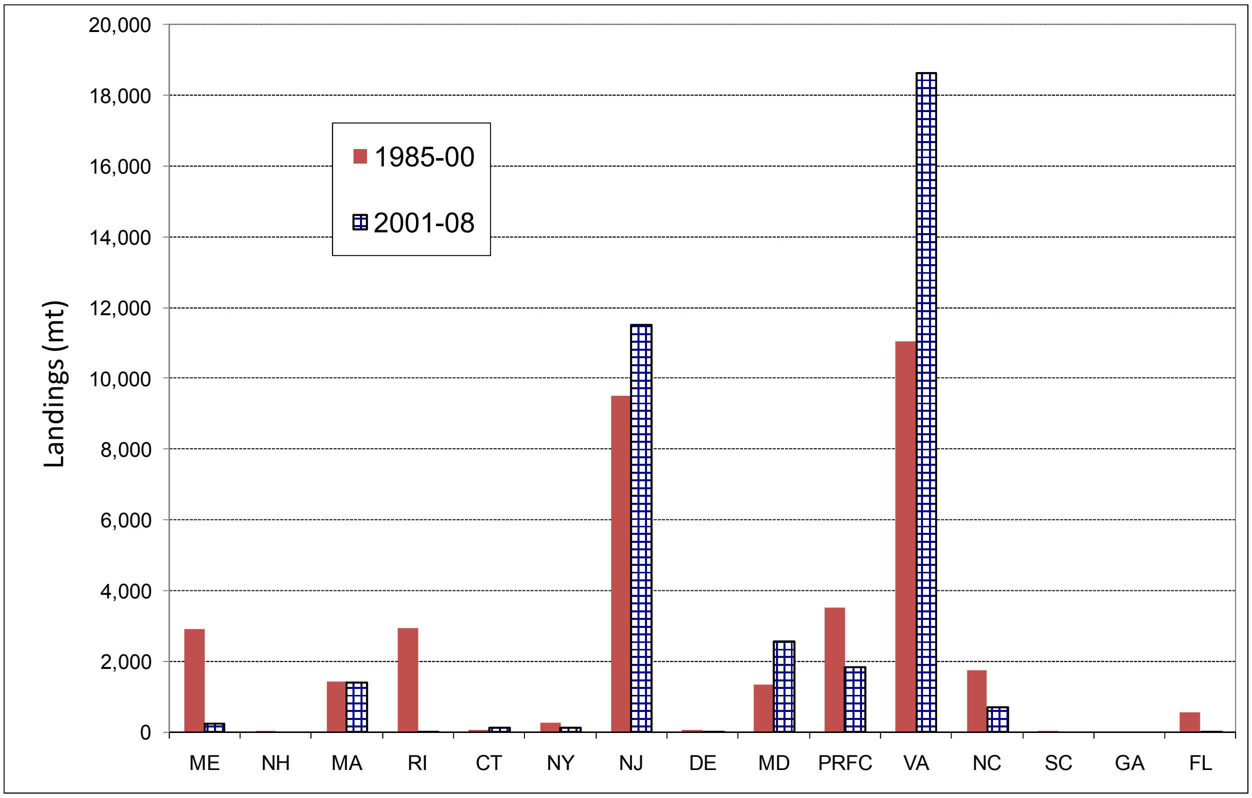


Figure 4.12. Non-purse seine landings obtained from the ACCSP Commercial Landings, 1950-2008.

[Primarily pound net and a mix of other gears (gill nets, haul seines, fyke and hoop nets, otter trawl, cast nets, etc.).]

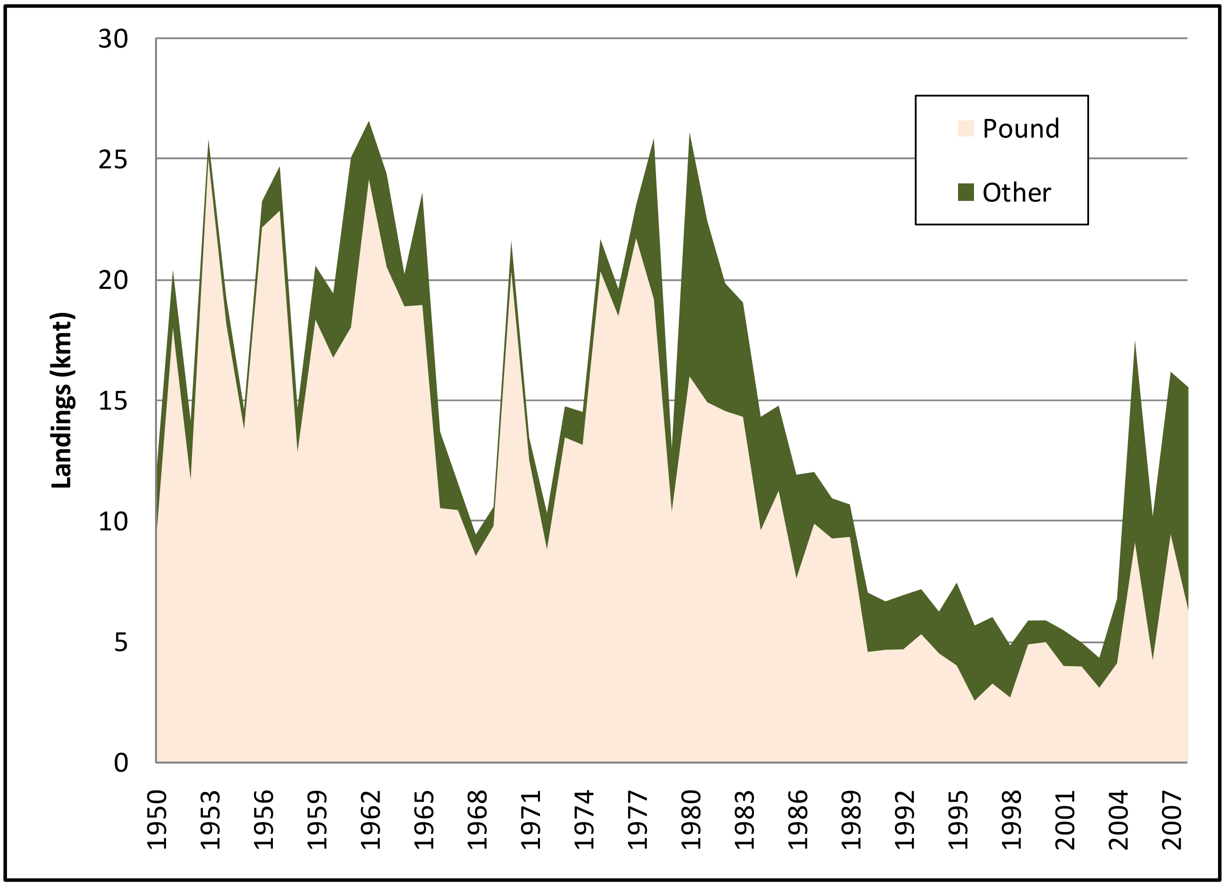


Figure 4.13. PRFC adult Atlantic menhaden (primarily ages-1 through 3) index of relative abundance calculated as the ratio of total annual landings to total annual pound net days fished.

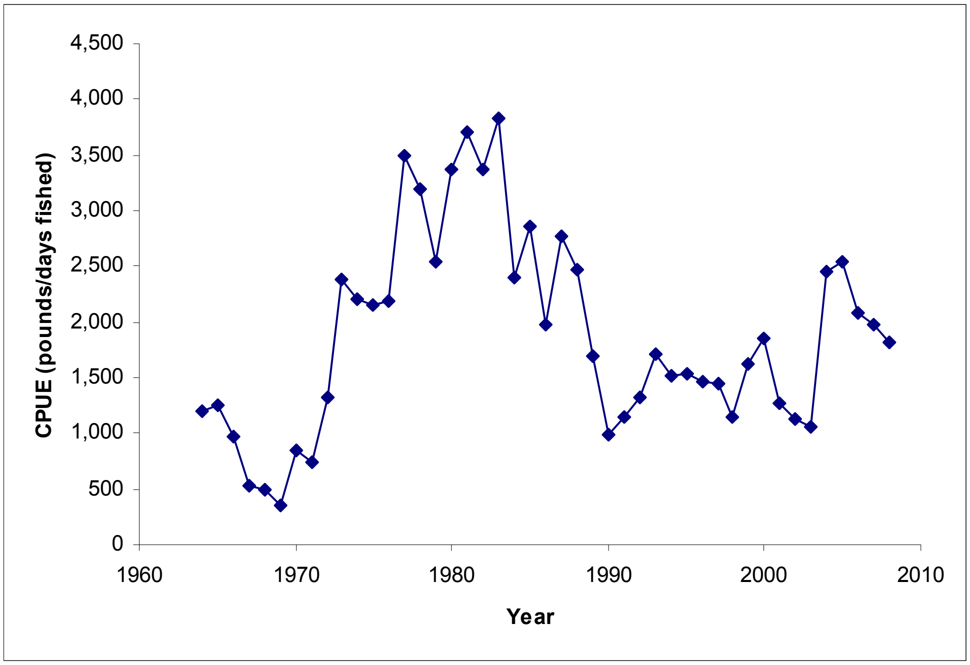


Figure 4.14. AIC based evaluation of the distribution of the PRFC adult Atlantic menhaden pound net CPUE data.

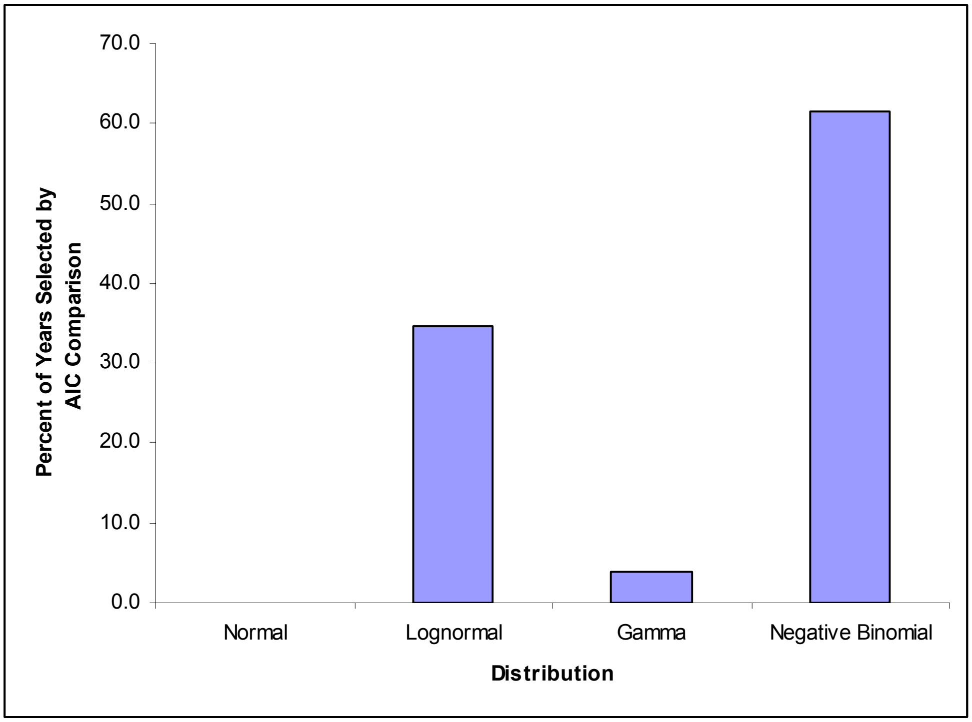


Figure 4.15. PRFC adult Atlantic menhaden (primarily ages-1 through 3) index of relative abundance based on a negative binomial GLM with *year*, *month*, and *area* as fixed factors.

[Coefficients of variation for all years exceeded 1.0.]

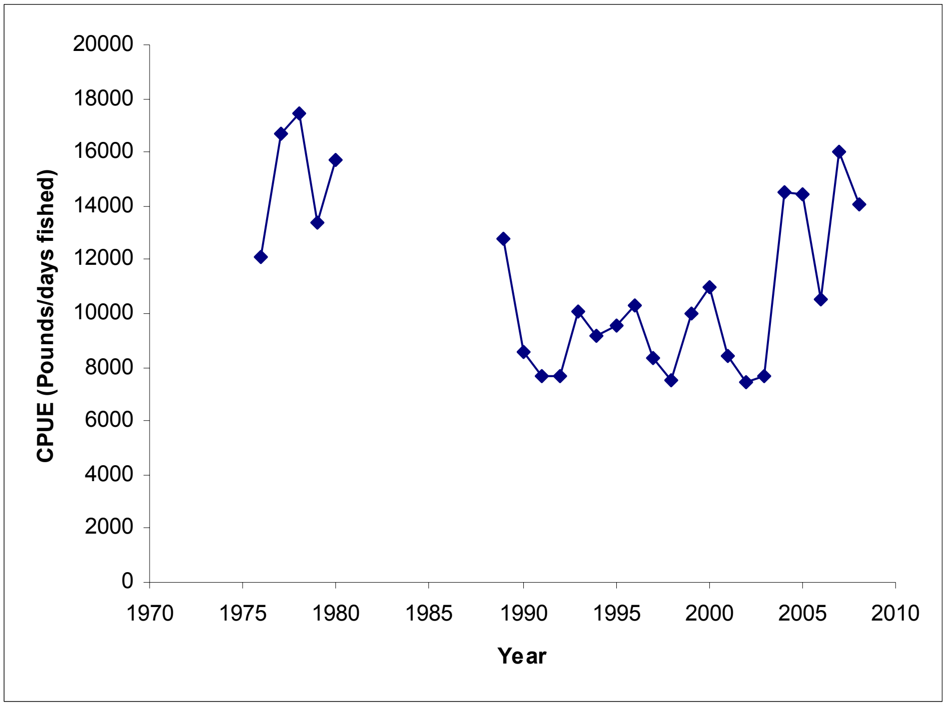


Figure 4.16. Atlantic menhaden bait landings (1,000 metric tons) by region, 1985-2008.

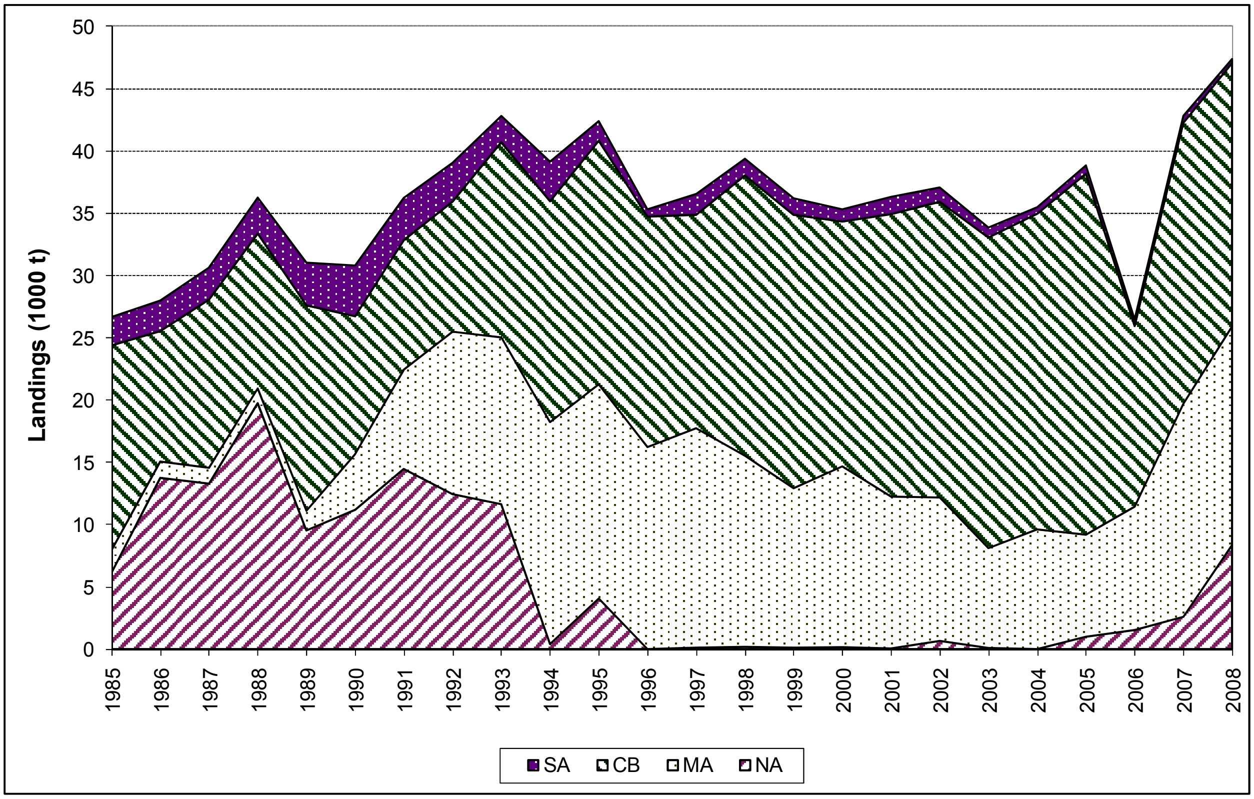


Figure 5.1. Proportion of seine hauls where at least one juvenile menhaden was captured by year for each state seine survey.

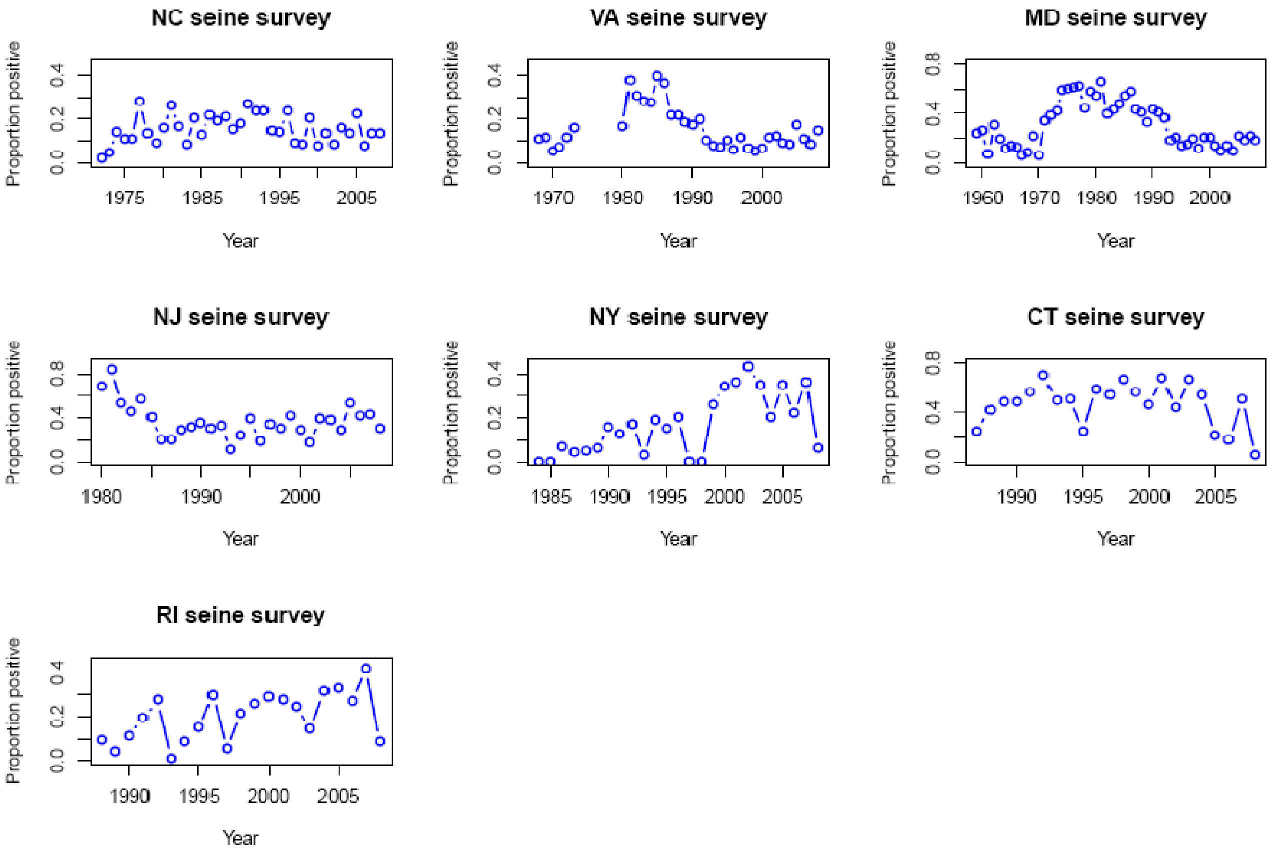


Figure 5.2. AIC based evaluation of the distribution of the juvenile catch-per-haul data for each state seine survey.

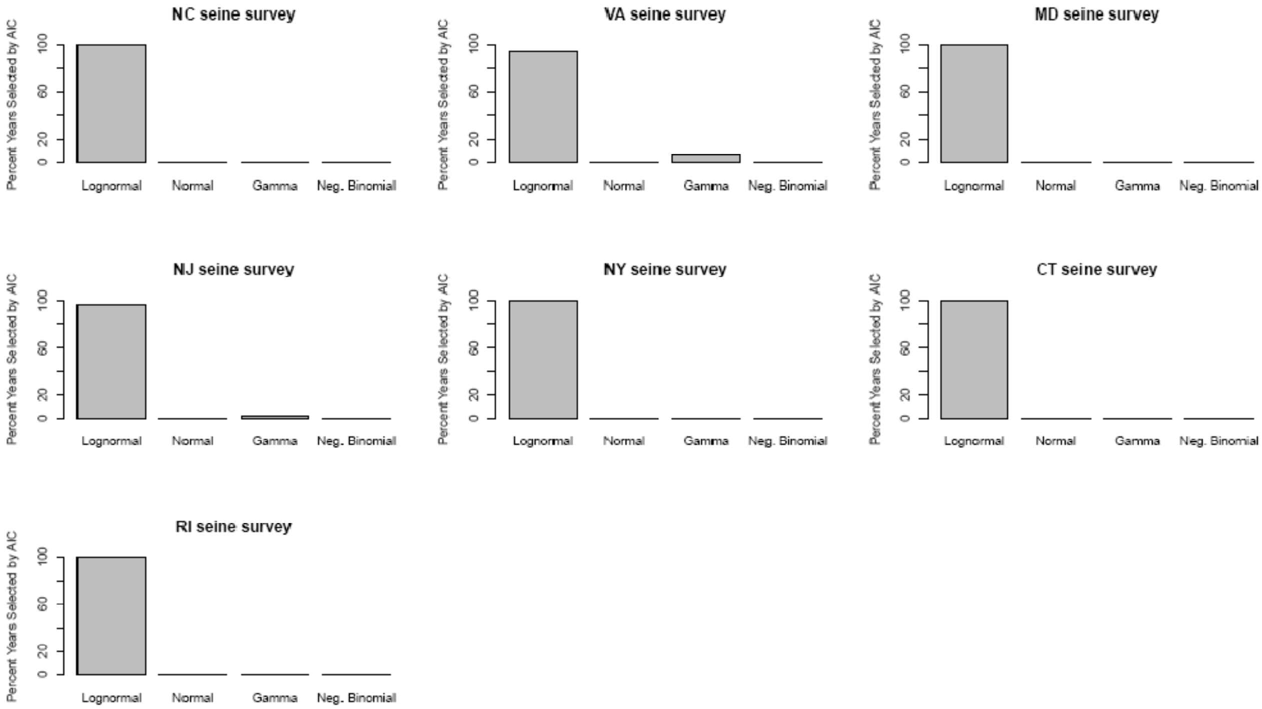


Figure 5.3. Coastwide juvenile abundance index based on the full delta-lognormal GLM fitted to seine catch-per-haul data from all states combined.

[CVs were calculated from jackknifed derived SEs.]

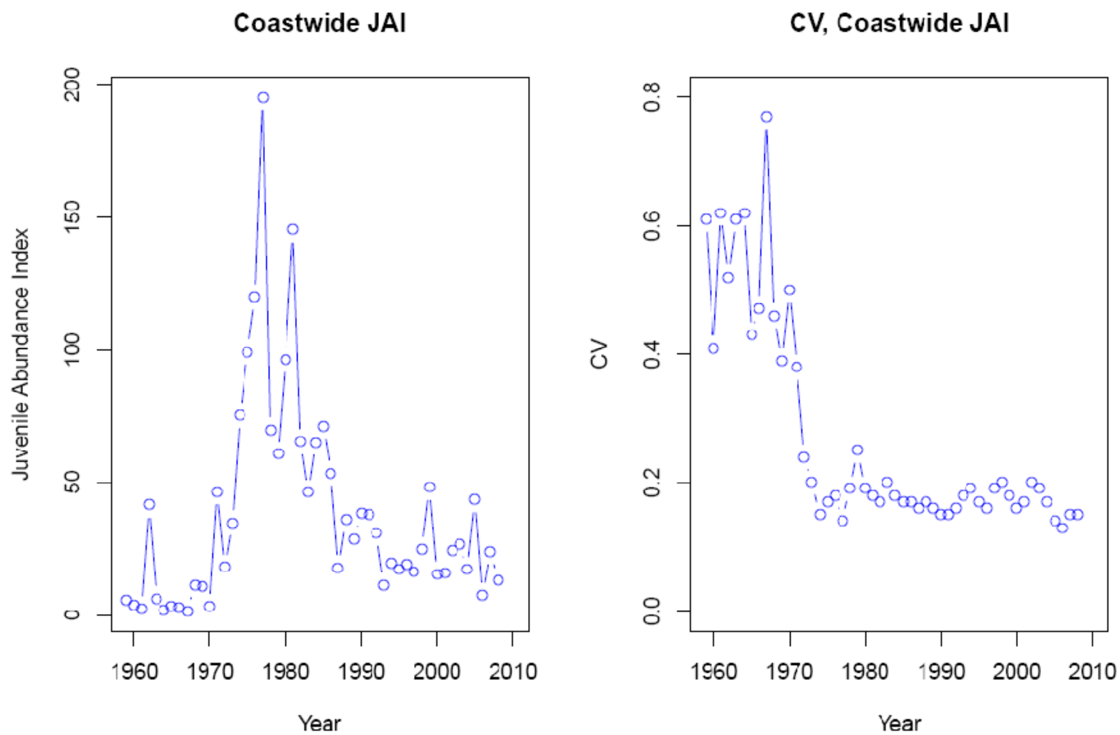


Figure 5.4. Principle components analysis biplot used to investigate potential groupings of Region 1 juvenile abundance index based on delta-lognormal GLM fitted to seine catch-per-haul data from NC, VA, and MD combined.

[CVs were calculated from jackknifed derived SEs.]

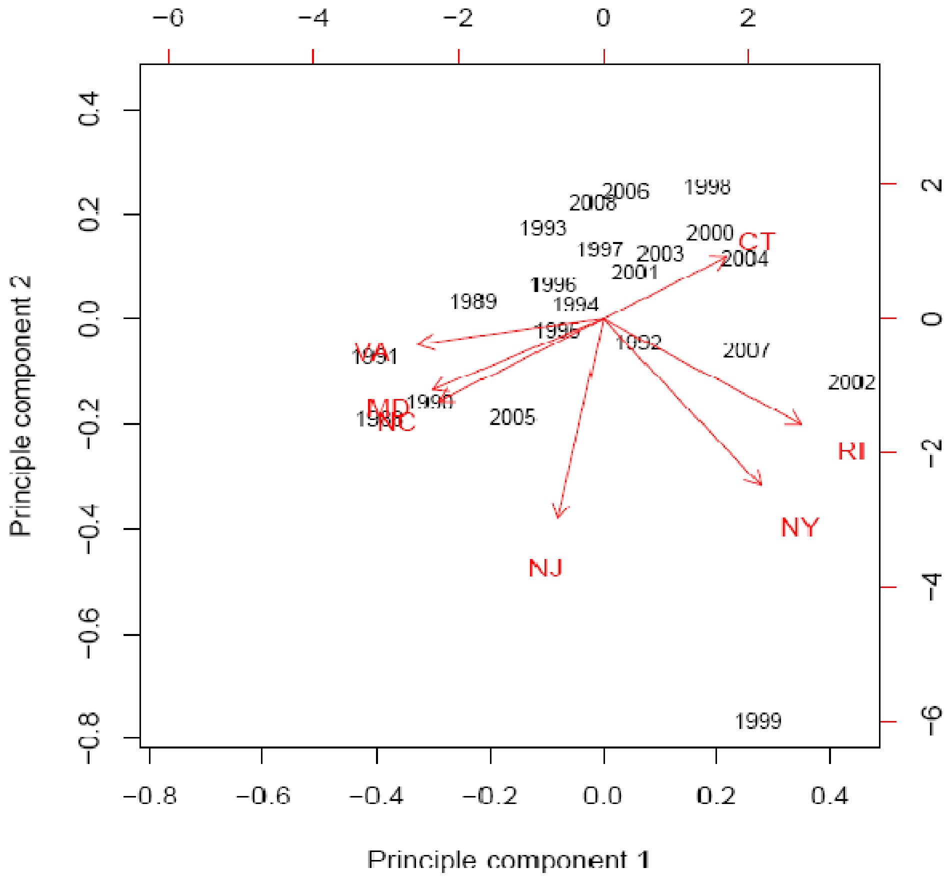


Figure 5.5a. Region 1 juvenile abundance index based on the full delta-lognormal GLM fitted to seine catch-per-haul data from NC, VA, and MD combined.
[CVs were calculated from jackknifed derived SEs.]

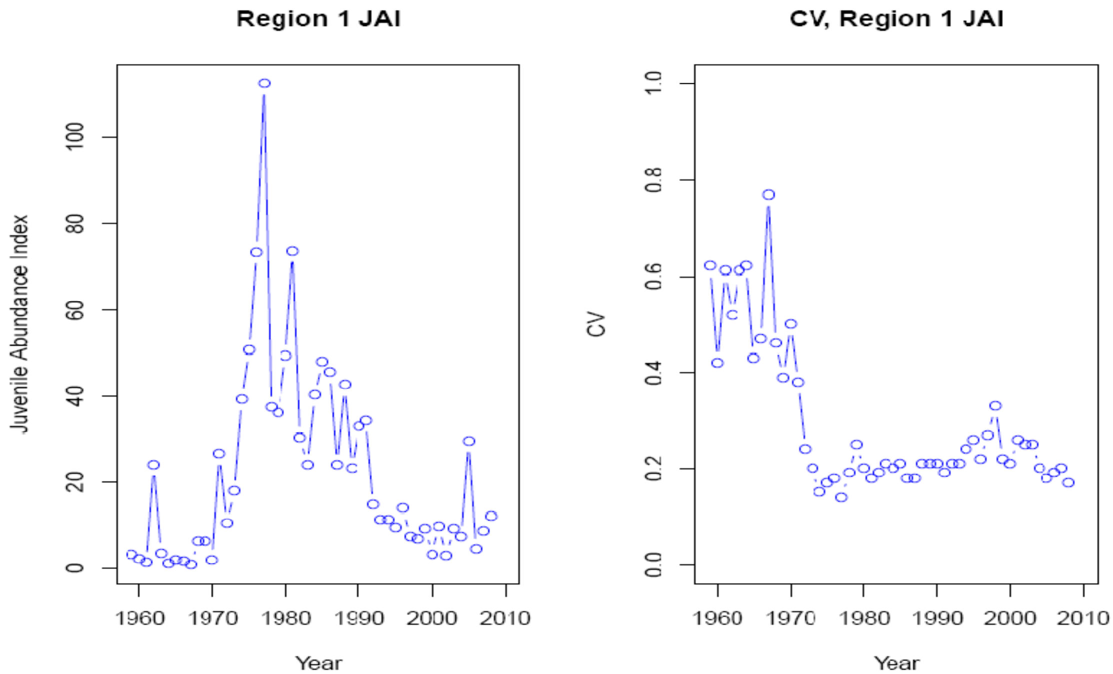


Figure 5.5b. Region 2 juvenile abundance index based on the full delta-lognormal GLM fitted to seine catch-per-haul data from NY and RI combined.
[CVs were calculated from jackknifed derived SEs.]

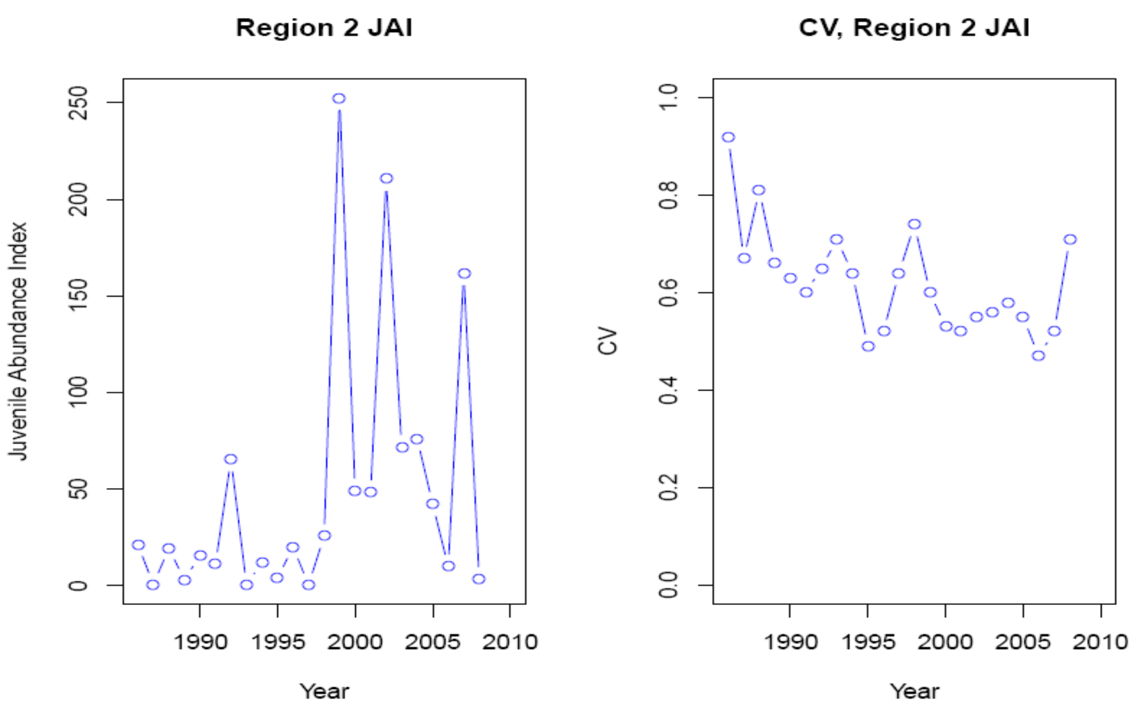


Figure 5.5c. Region 3 juvenile abundance index based on the full delta-lognormal GLM fitted to seine catch-per-haul data from NJ.
[CVs were calculated from jackknifed derived SEs.]

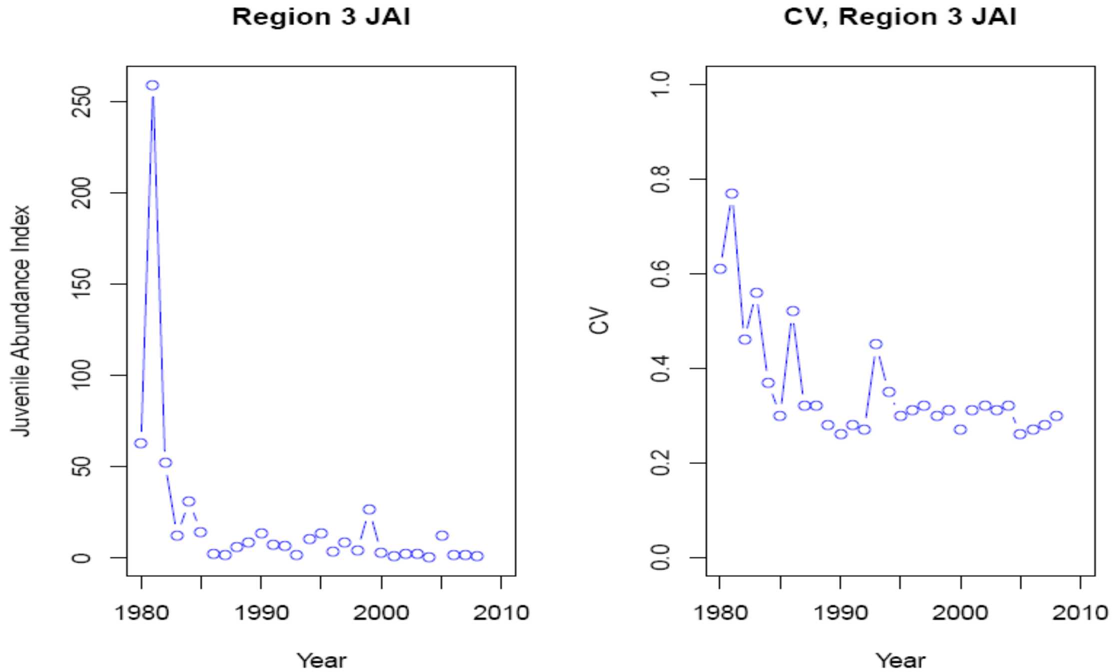


Figure 5.5d. Region 4 juvenile abundance index based on the full delta-lognormal GLM fitted to seine catch-per-haul data from CT.
[CVs were calculated from jackknifed derived SEs.]

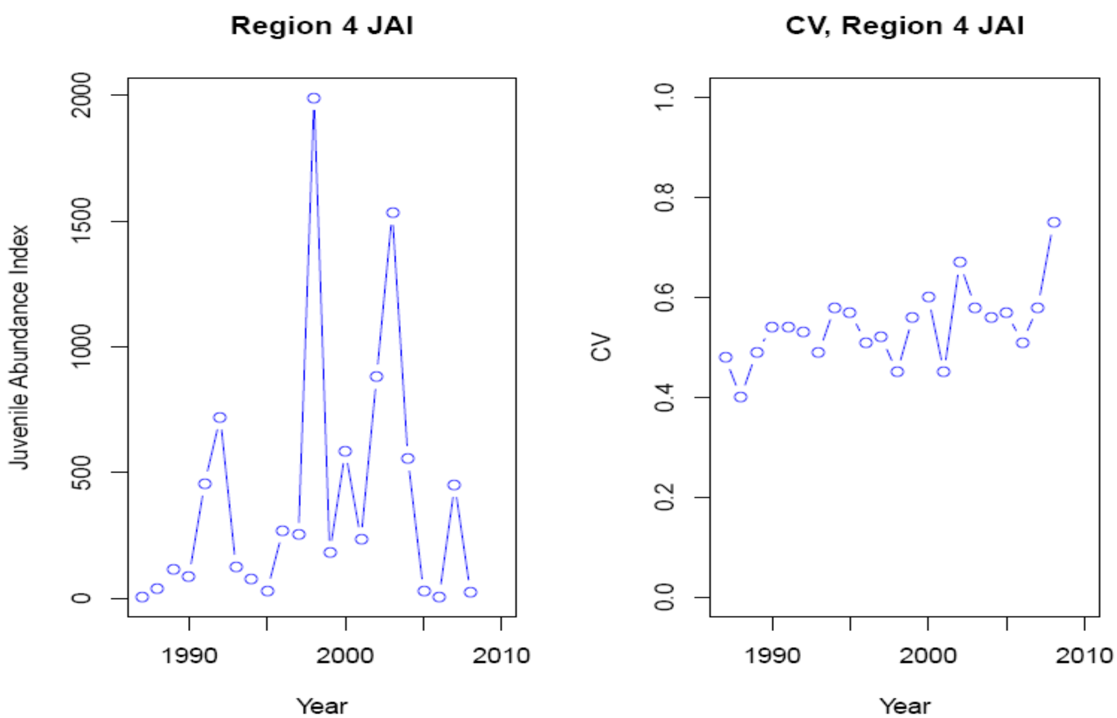


Figure 5.6. Linear regression fitted to the coastwide YOY and PRFC adult indices lagged by two years.

[Estimates of YOY relative abundance correspond to 1962-2006 while the PRFC index values represent 1964-2008. The estimate Peason's correlation coefficient was $\hat{r} = 0.712$.]

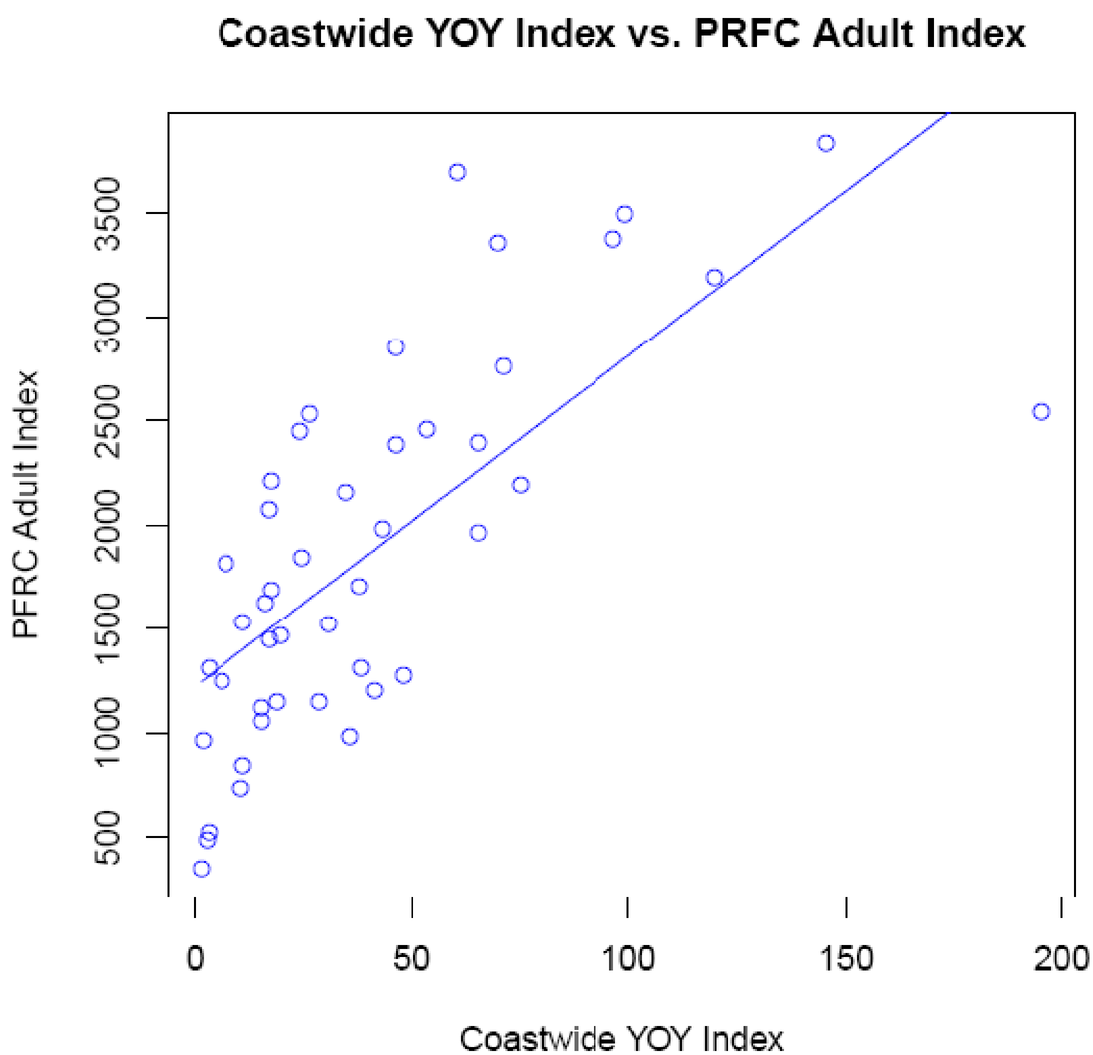


Figure 6.1. Comparison of age 2+ population size by year between Beaufort Assessment Model (BAM) and MSVPA-X.

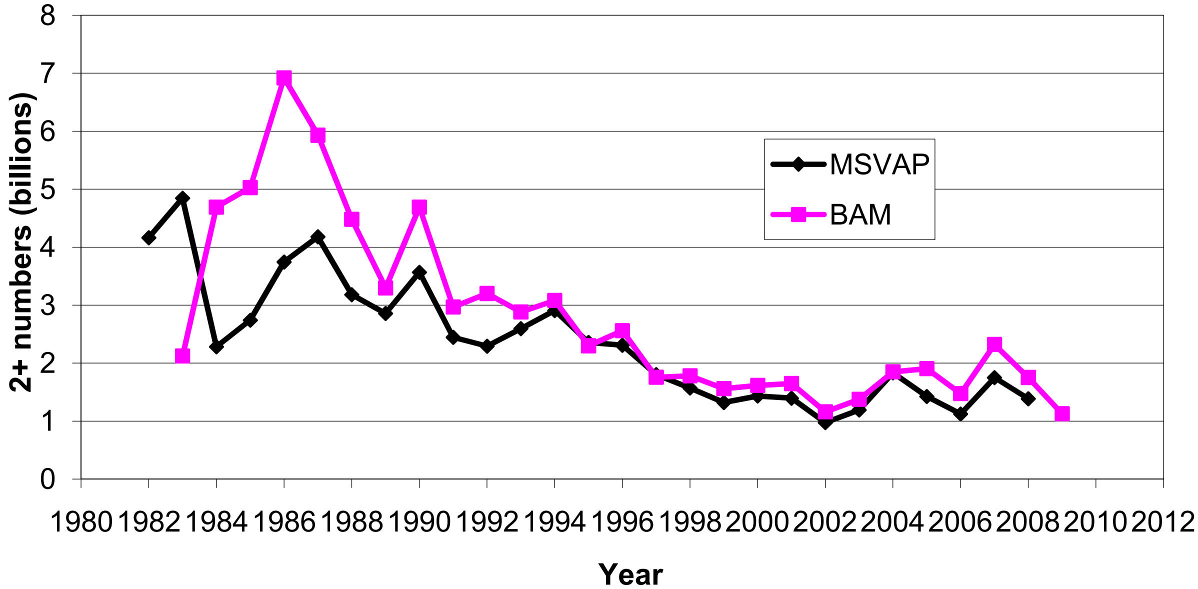


Figure 6.2. Comparison of unweighted average 2+ fishing mortality by year between Beaufort Assessment Model (BAM) and MSVPA-X.

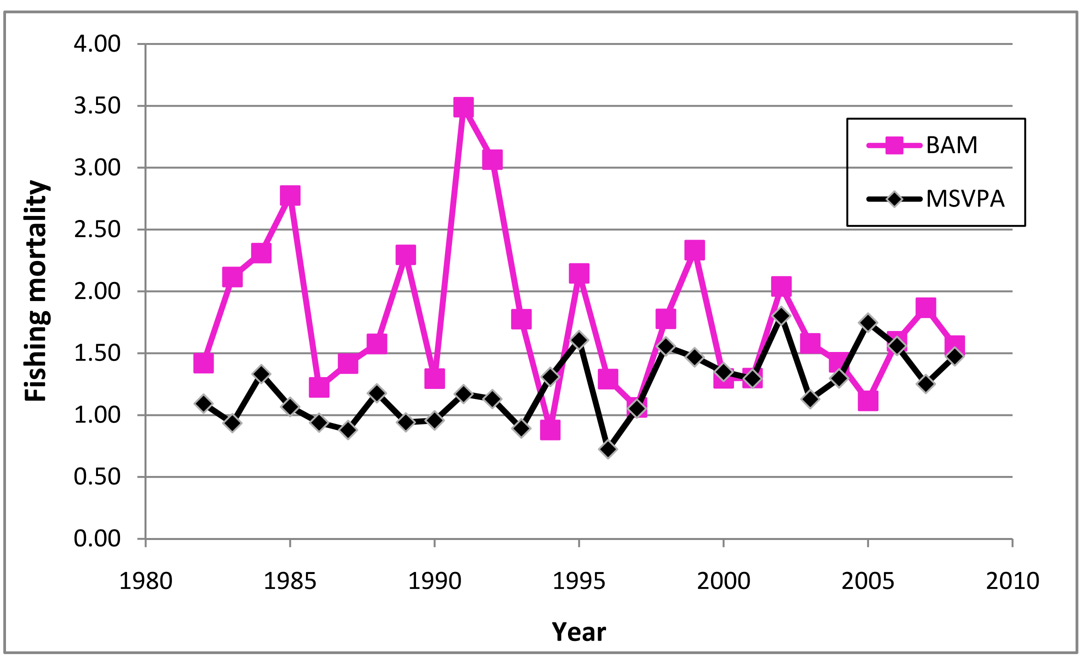


Figure 6.3. Estimates of vulnerable stock biomass generated from the stochastic SRA base runs with current exploitation rates (*U*) set at: *U*=0.1, *U*=0.2, *U*=0.3.

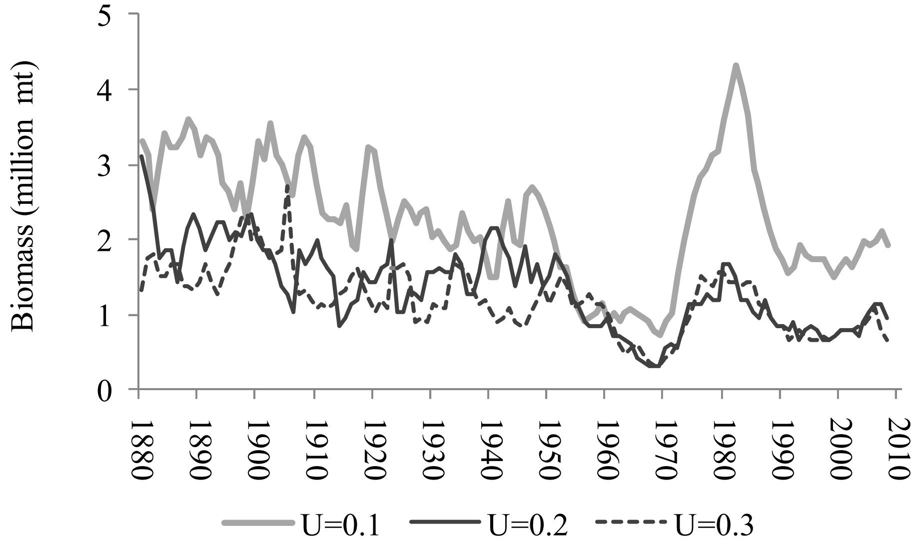


Figure 6.4. Estimates of vulnerable stock biomass generated from the stochastic SRA base run2 (*U*=0.2) with associated *cv* values set at 0.1, 0.2, and 0.3.

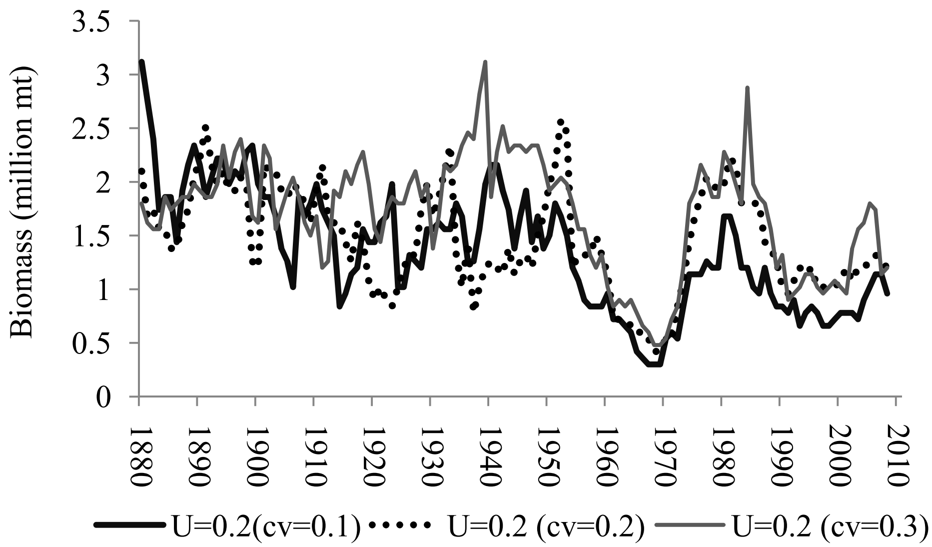


Figure 6.5. MCMC sample distributions and likelihood profiles of U_{MSY} and MSY generated from three simulation runs based on current exploitation rate (*U*)

[*U* = 0.1 (left column), 0.2 (center column), and 0.3 (right column) and associated *cv* values 0.1 (top row), 0.2 (center row), and 0.3 (bottom row).]

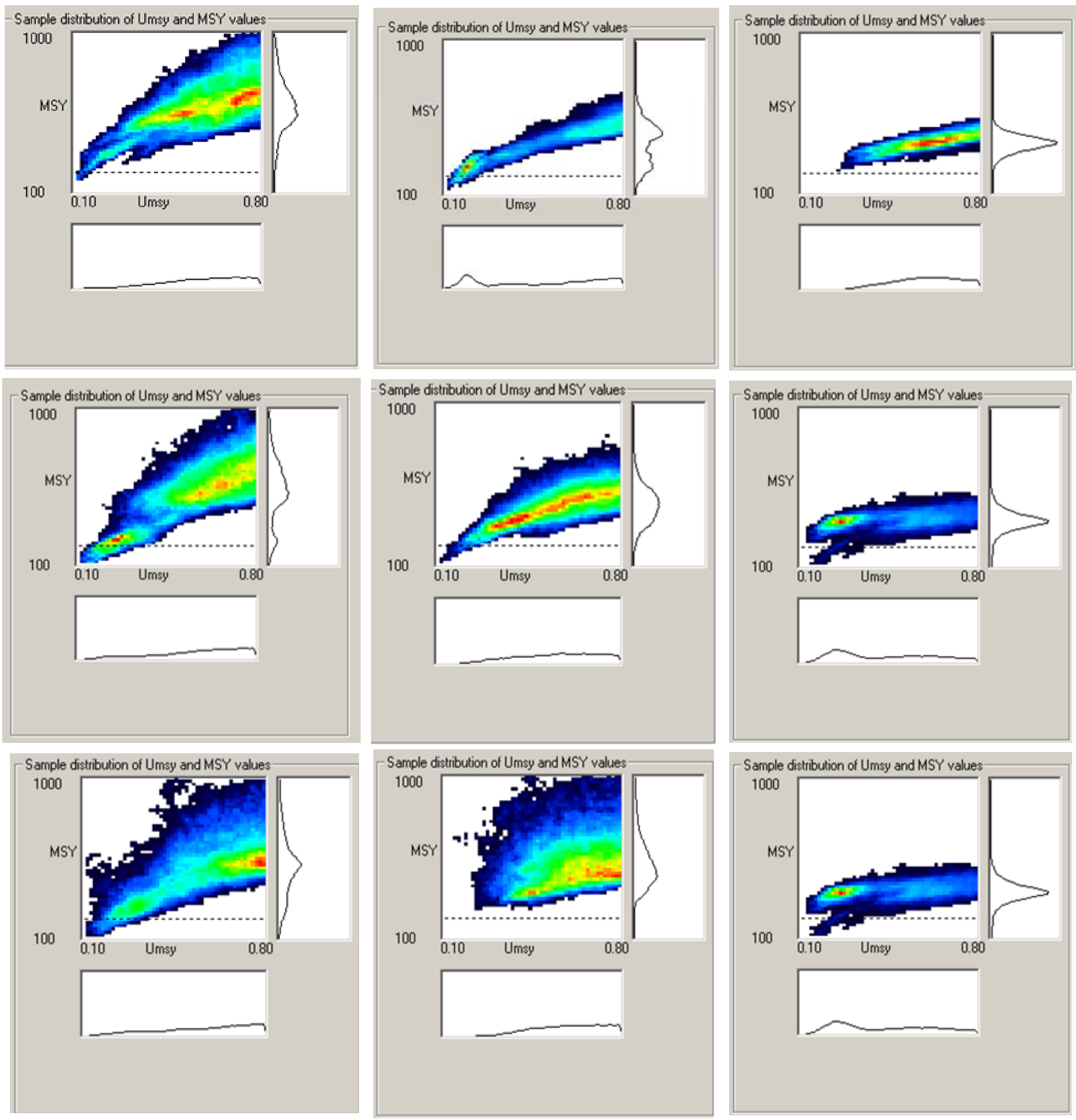


Figure 6.6. Posterior distributions of B/B_0 and U_{2008}/U_{MSY} generated from three simulation runs based on current exploitation rate (*U*).

[*U* = 0.1 (left column), 0.2 (center column), and 0.3 (right column) and associated *cv* values 0.1 (top row), 0.2 (center row), and 0.3 (bottom row).]

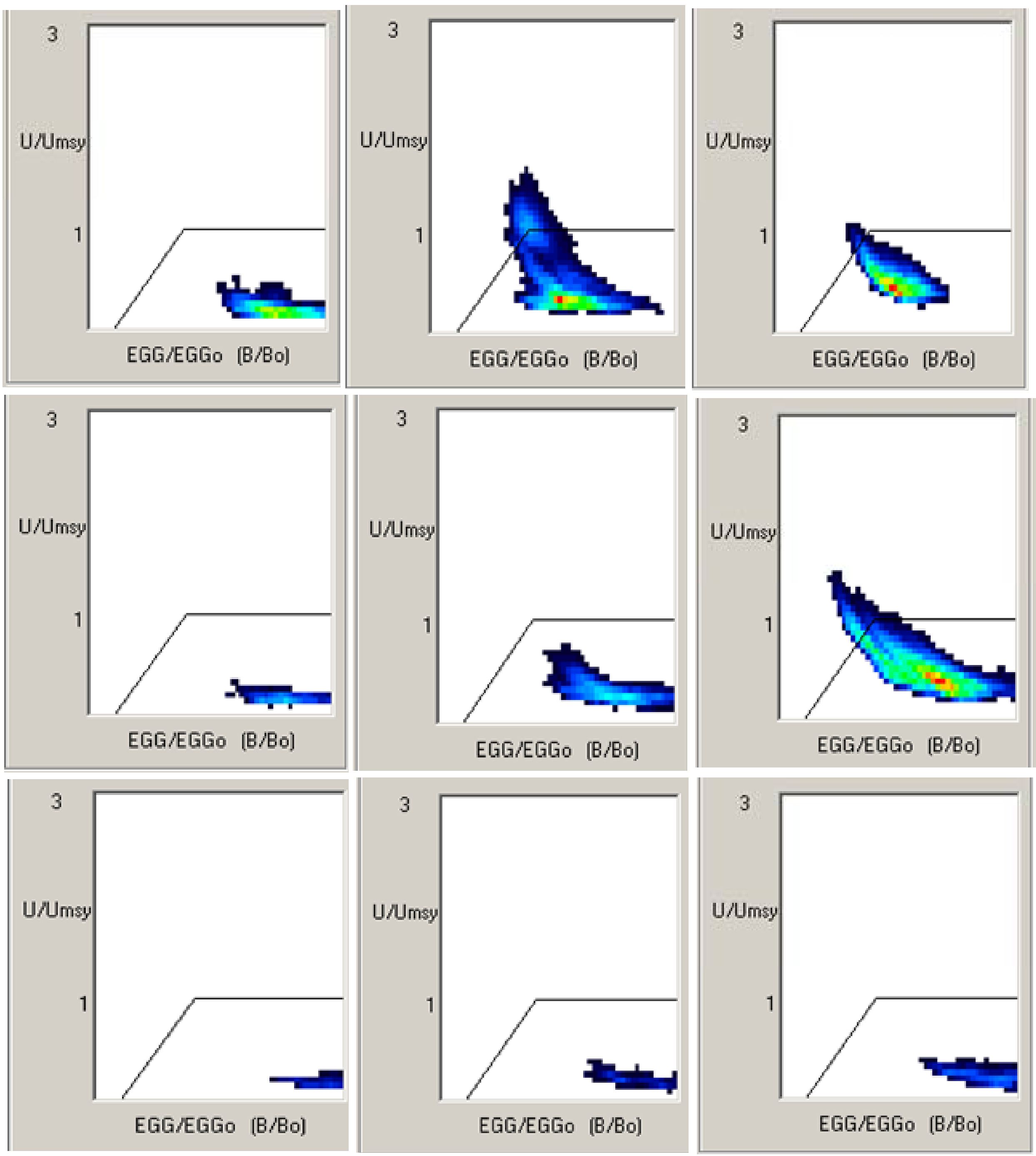


Figure 7.1 Observed (open circles) and predicted (connected points) landings in 1000 metric tons of Atlantic menhaden by the commercial reduction fishery from the base BAM model.

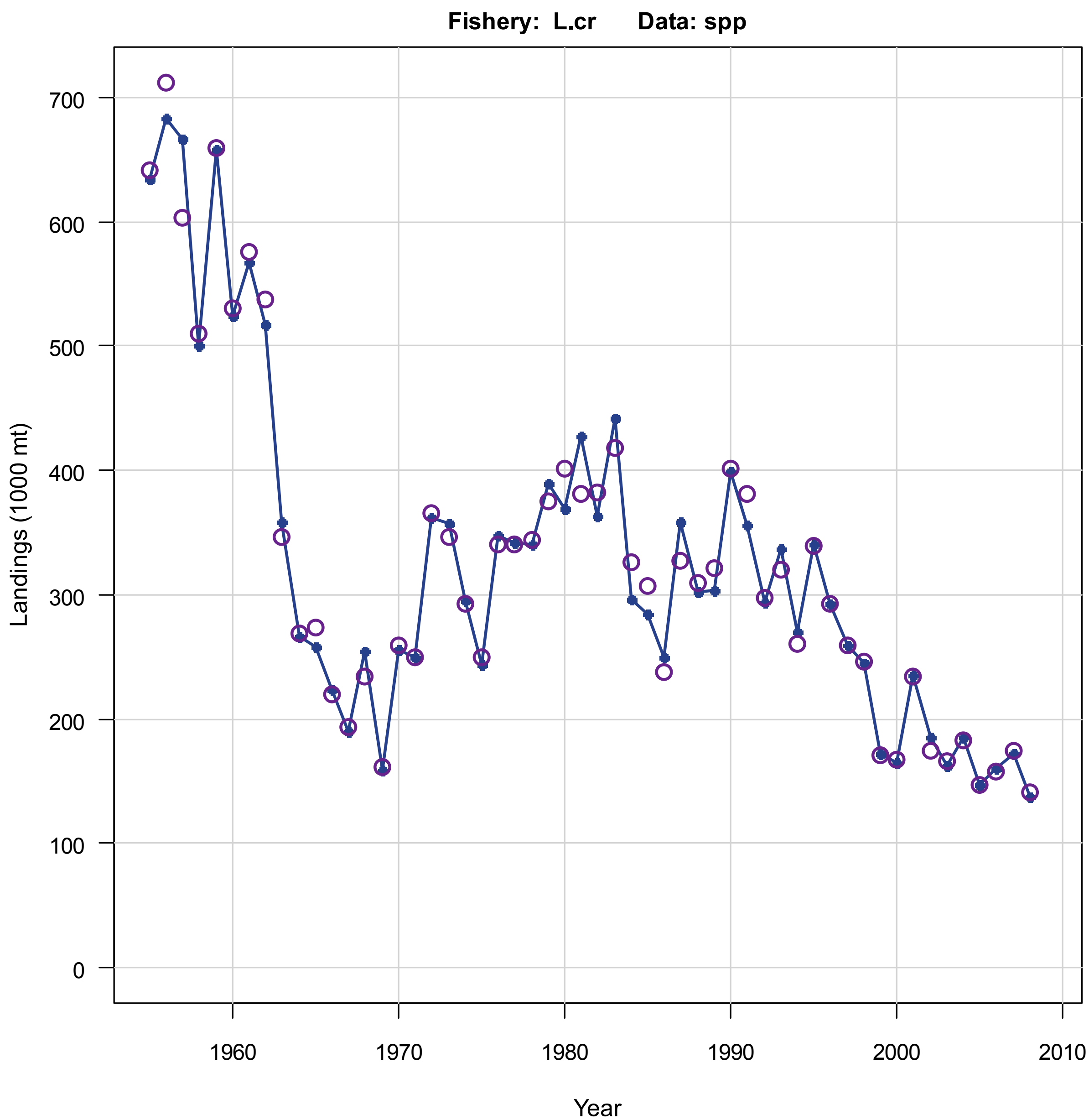


Figure 7.2 Observed (open circles) and predicted (connected points) landings in 1000 metric tons of Atlantic menhaden by the bait fishery from the base BAM model.

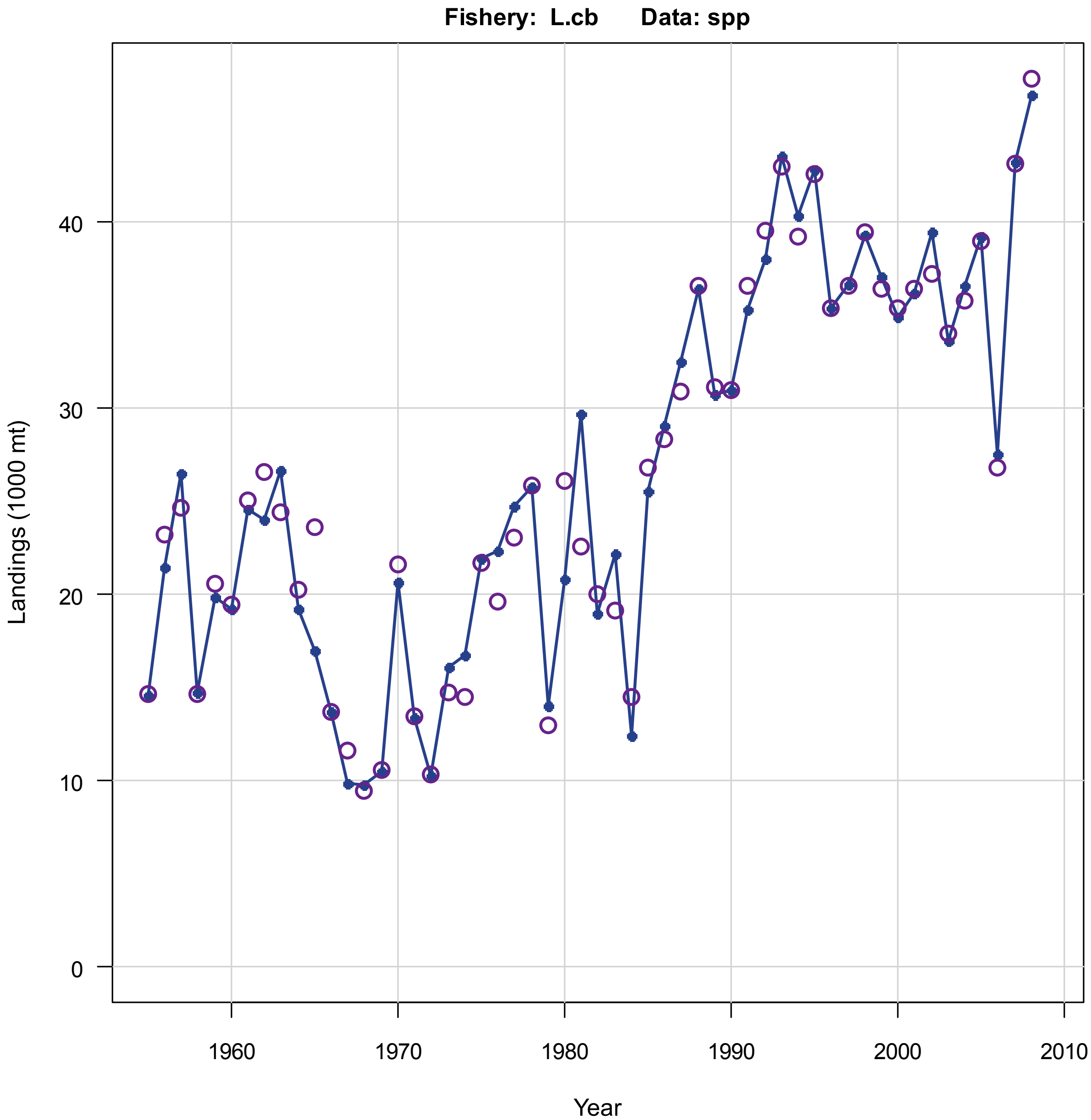


Figure 7.3 Annual observed (open circles) and predicted (connected points) proportions at age for Atlantic menhaden from the commercial reduction fishery from the base BAM model.

[The number of trips sampled (*N*) is indicated for each year.]

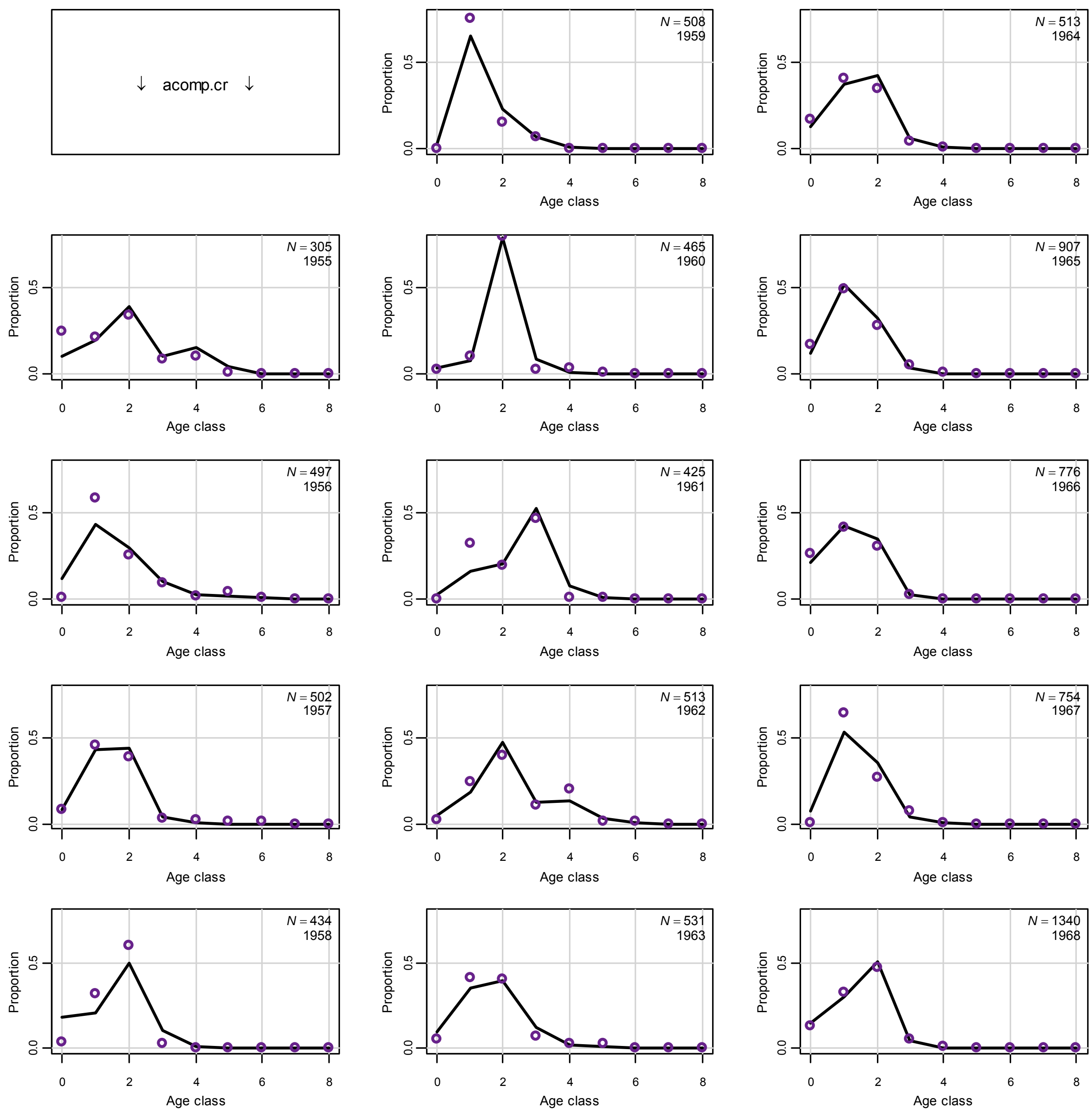


Figure 7.3 (*continued*)

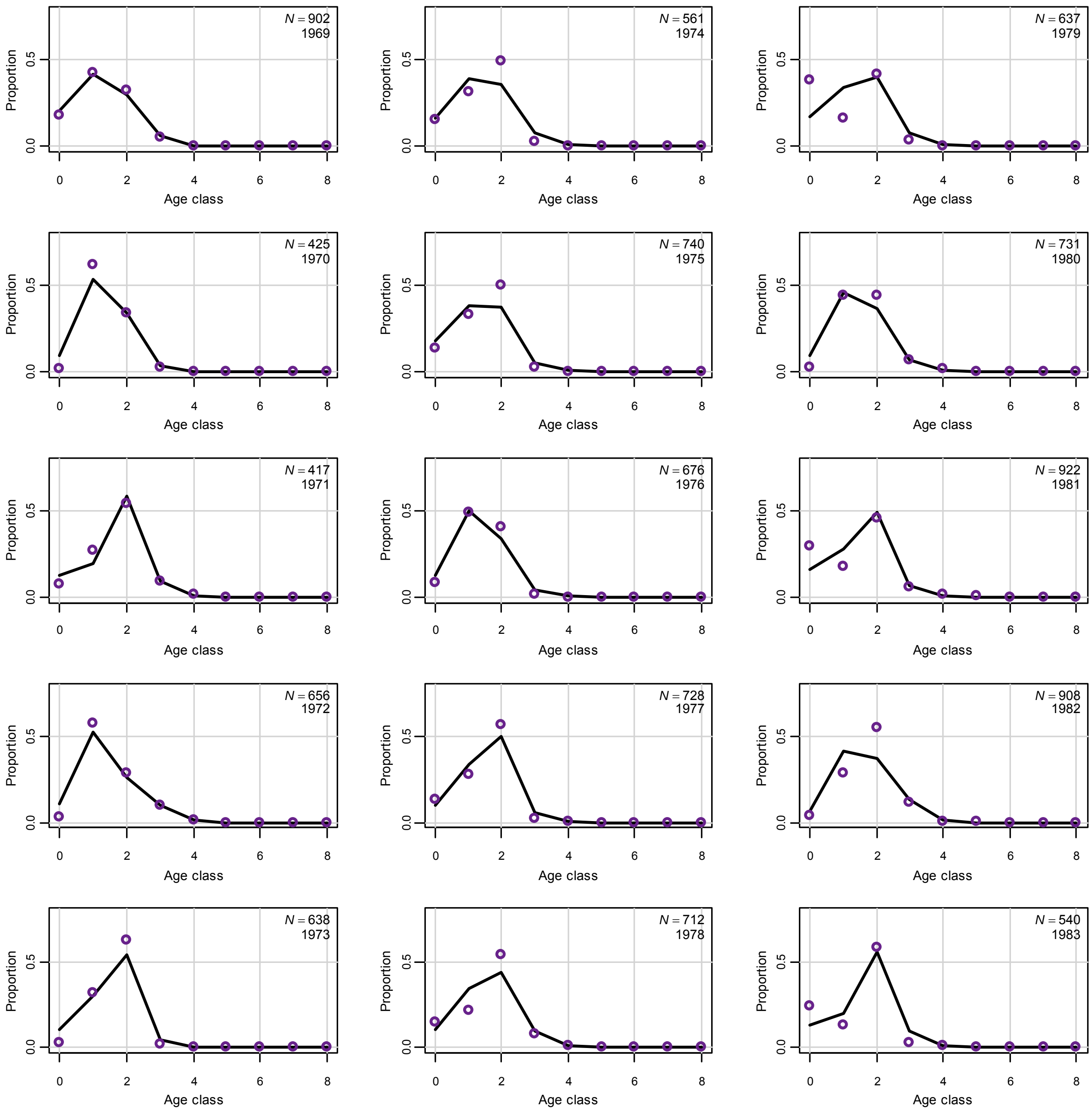


Figure 7.3 (*continued*)

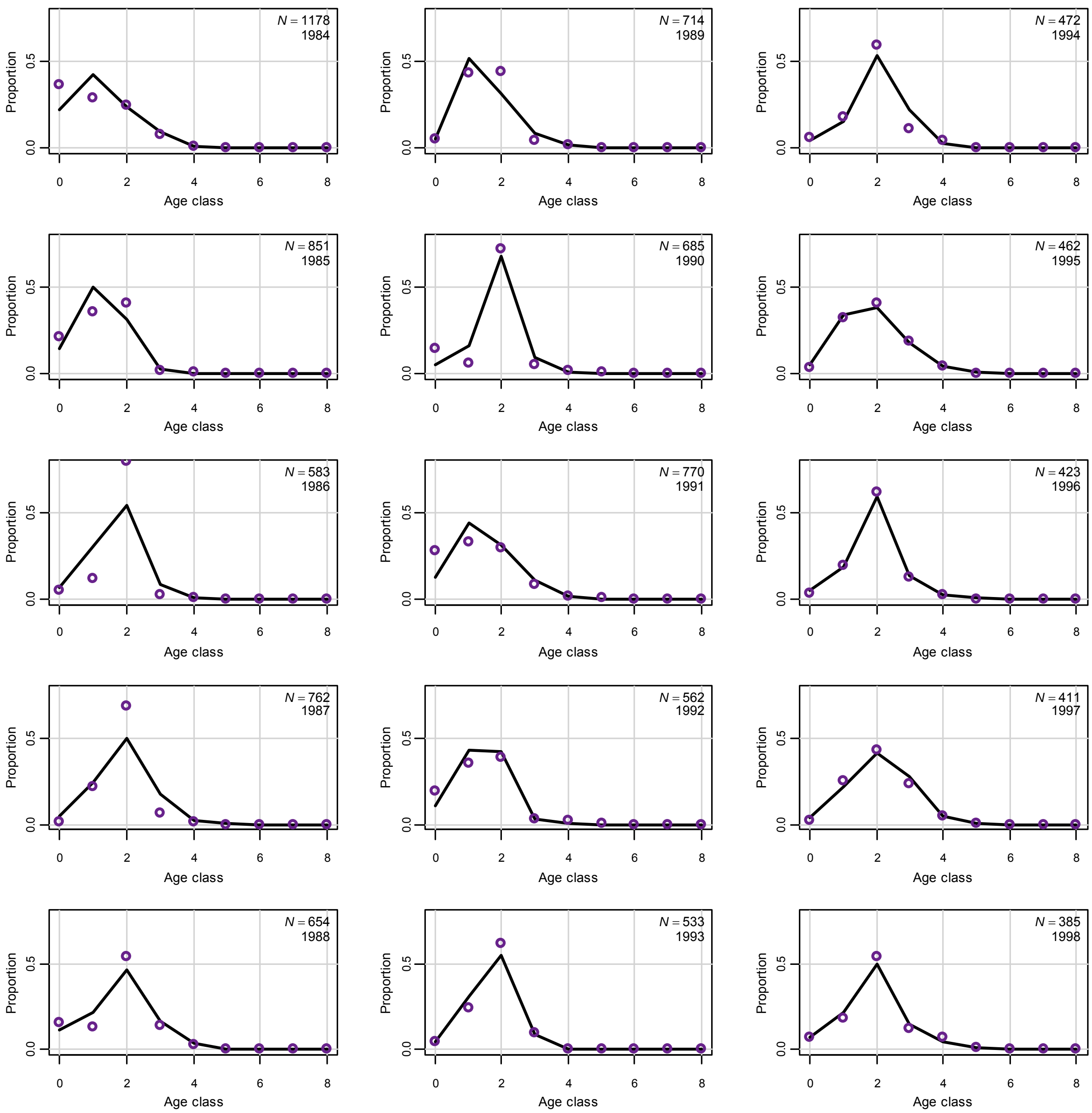


Figure 7.3 (*continued*)

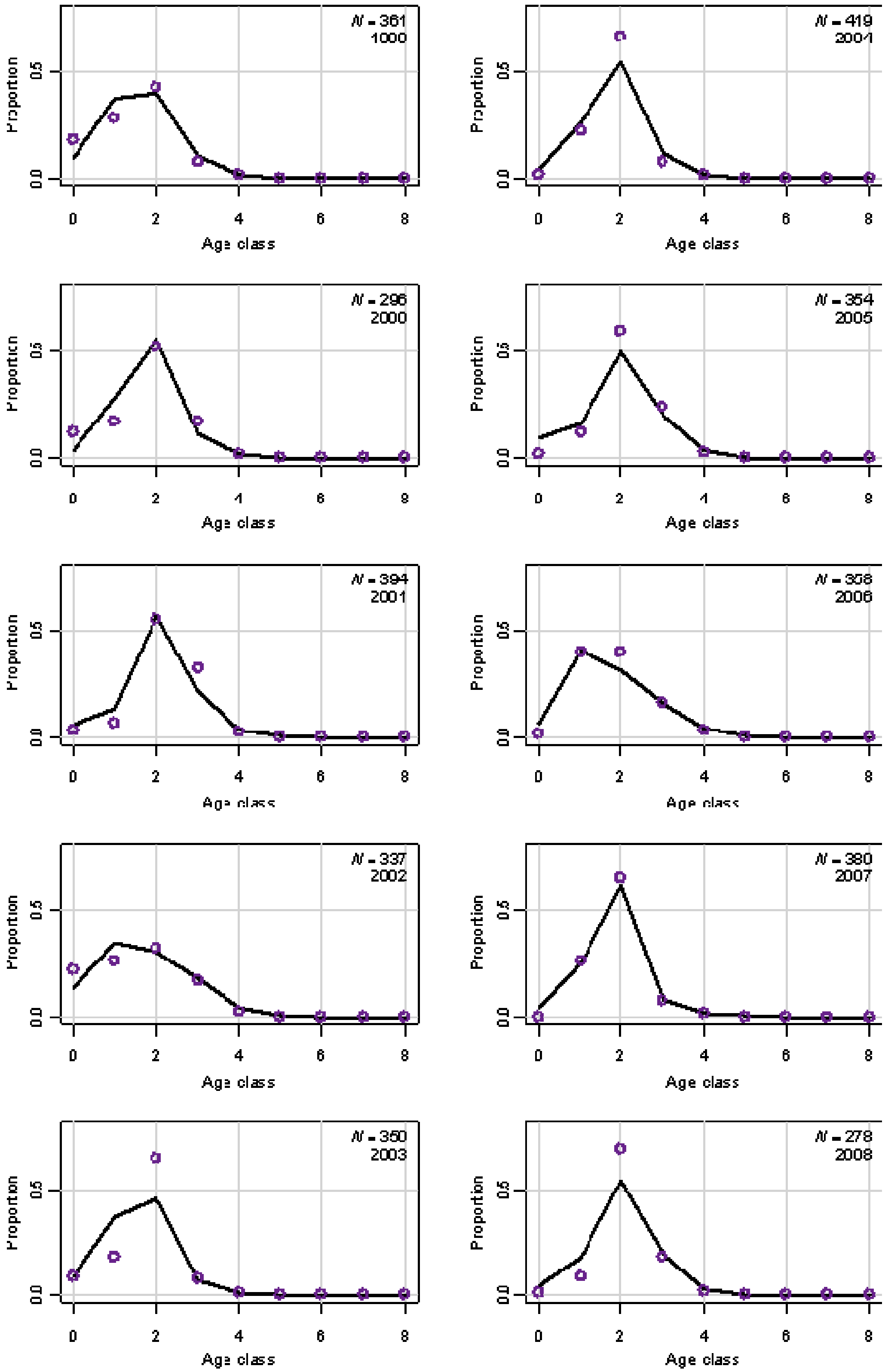


Figure 7.4 Bubble plot of Atlantic menhaden commercial reduction fishery catch-at-age residuals from the base BAM model.

[Area of circles is relative to the size of the residual and blue (dark) circles indicate an overestimate by the BAM model.]

Figure 7.5 Annual observed (open circles) and predicted (connected points) proportions at age for Atlantic menhaden from the bait fishery from the base BAM model.
[The number of trips sampled (*N*) is indicated for each year.]

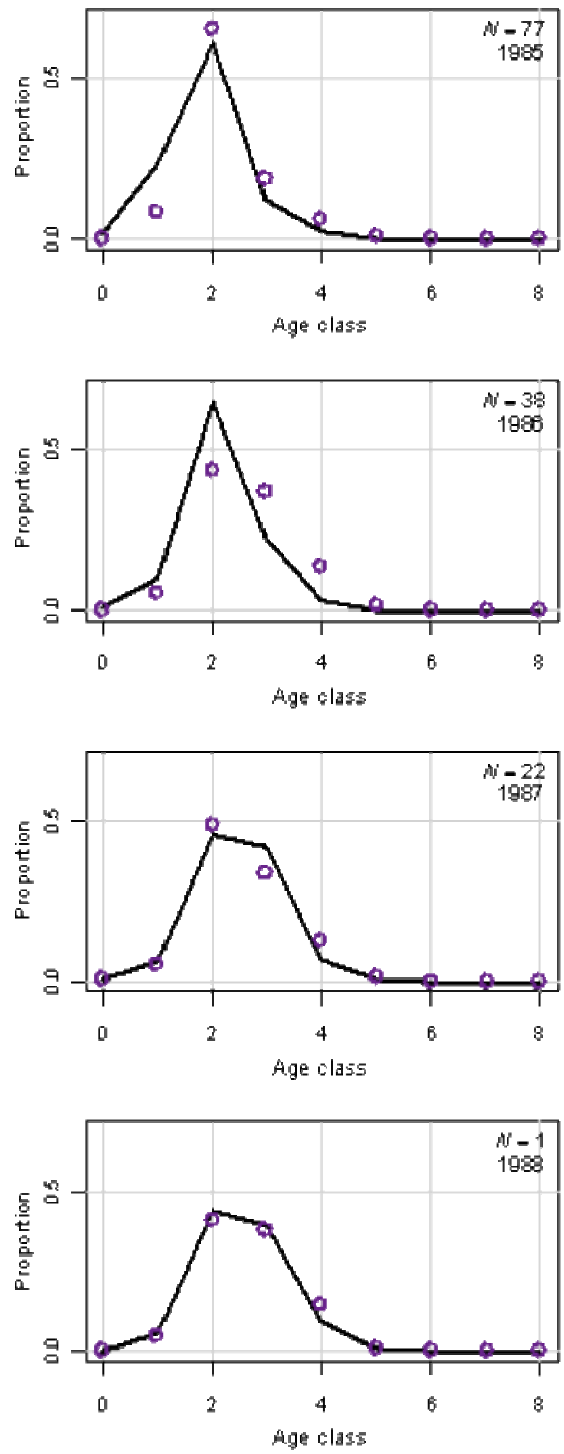


Figure 7.5 (*continued*)

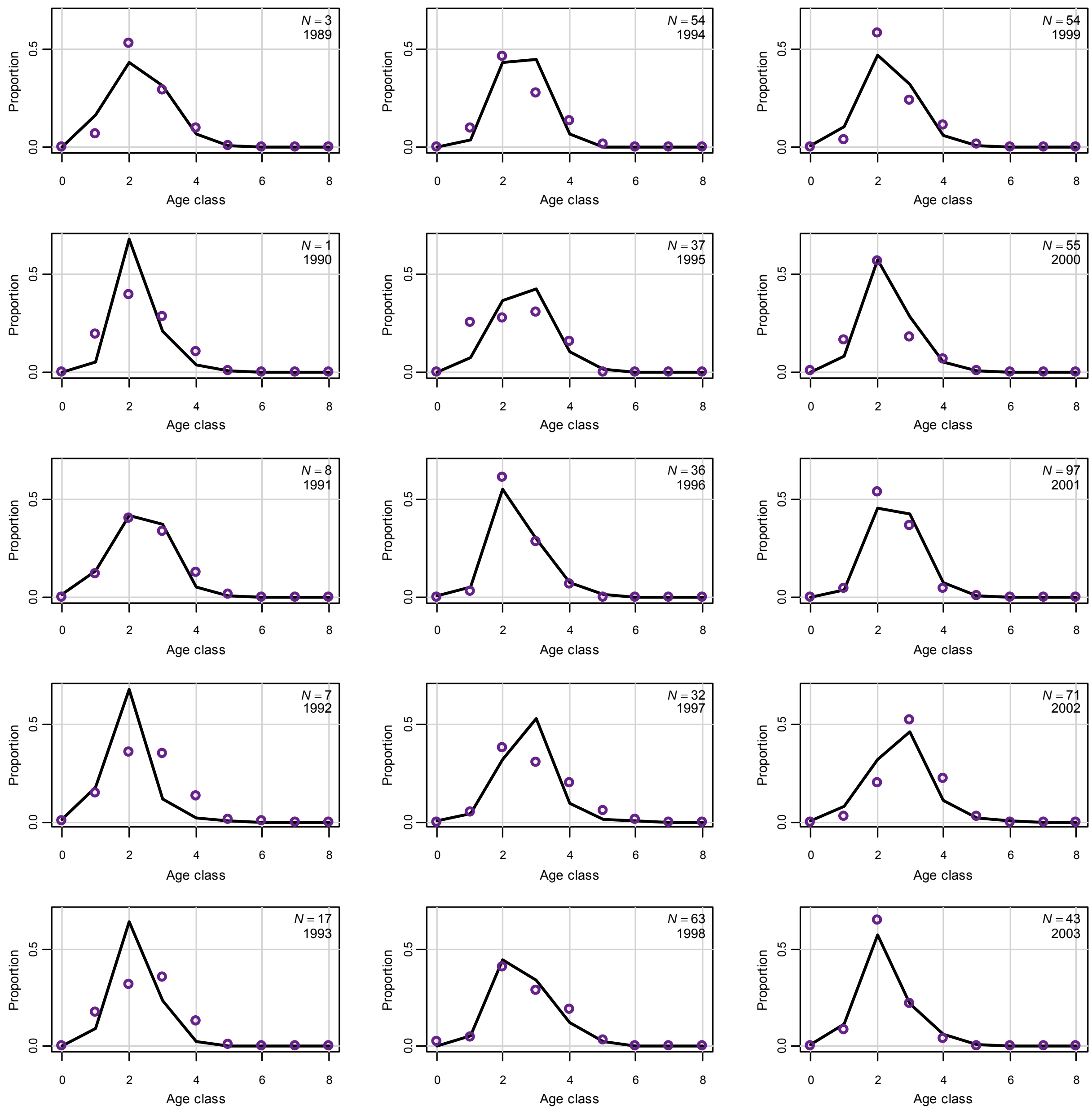


Figure 7.5 (*continued*)

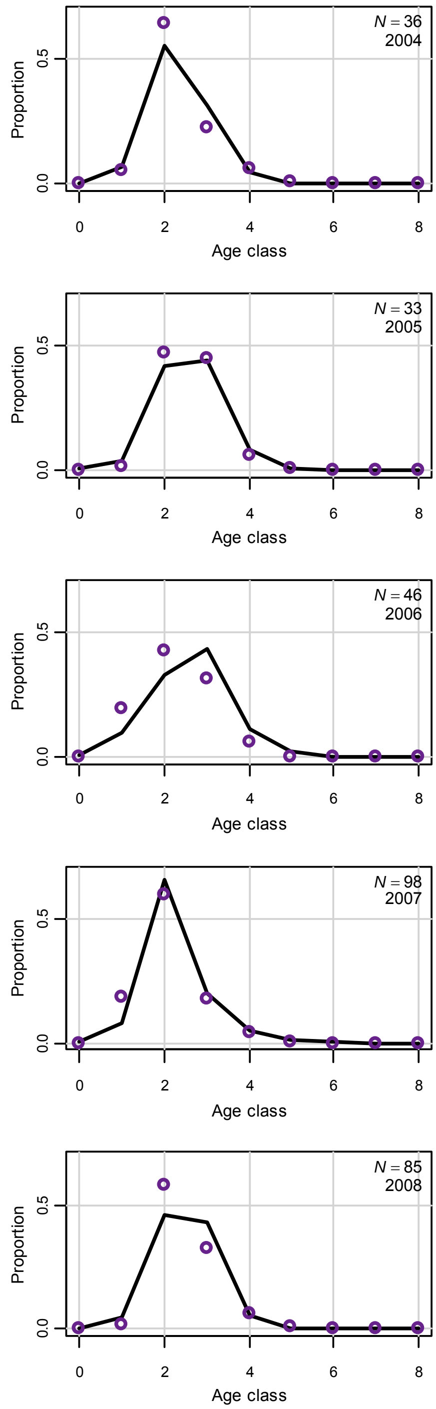


Figure 7.6 Bubble plot of Atlantic menhaden bait fishery catch-at-age residuals from the base BAM model.

[Area of circles is relative to the size of the residual and blue (dark) circles indicate an overestimate by the BAM model.]

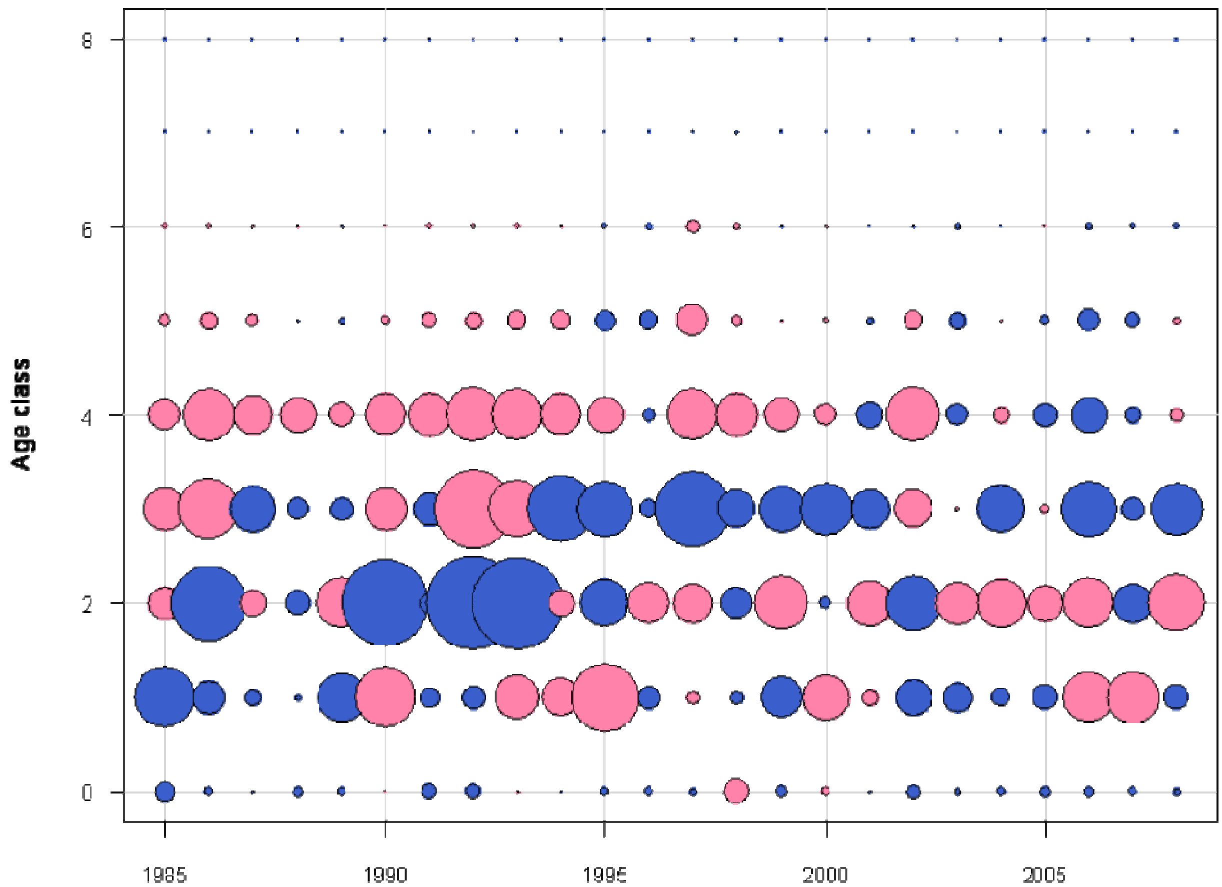


Figure 7.7 Observed (open circles) and predicted (connected points) juvenile abundance index values for Atlantic menhaden from the base BAM model.

[Bottom panel indicates pattern and magnitude of log-transformed residuals of model fit.]

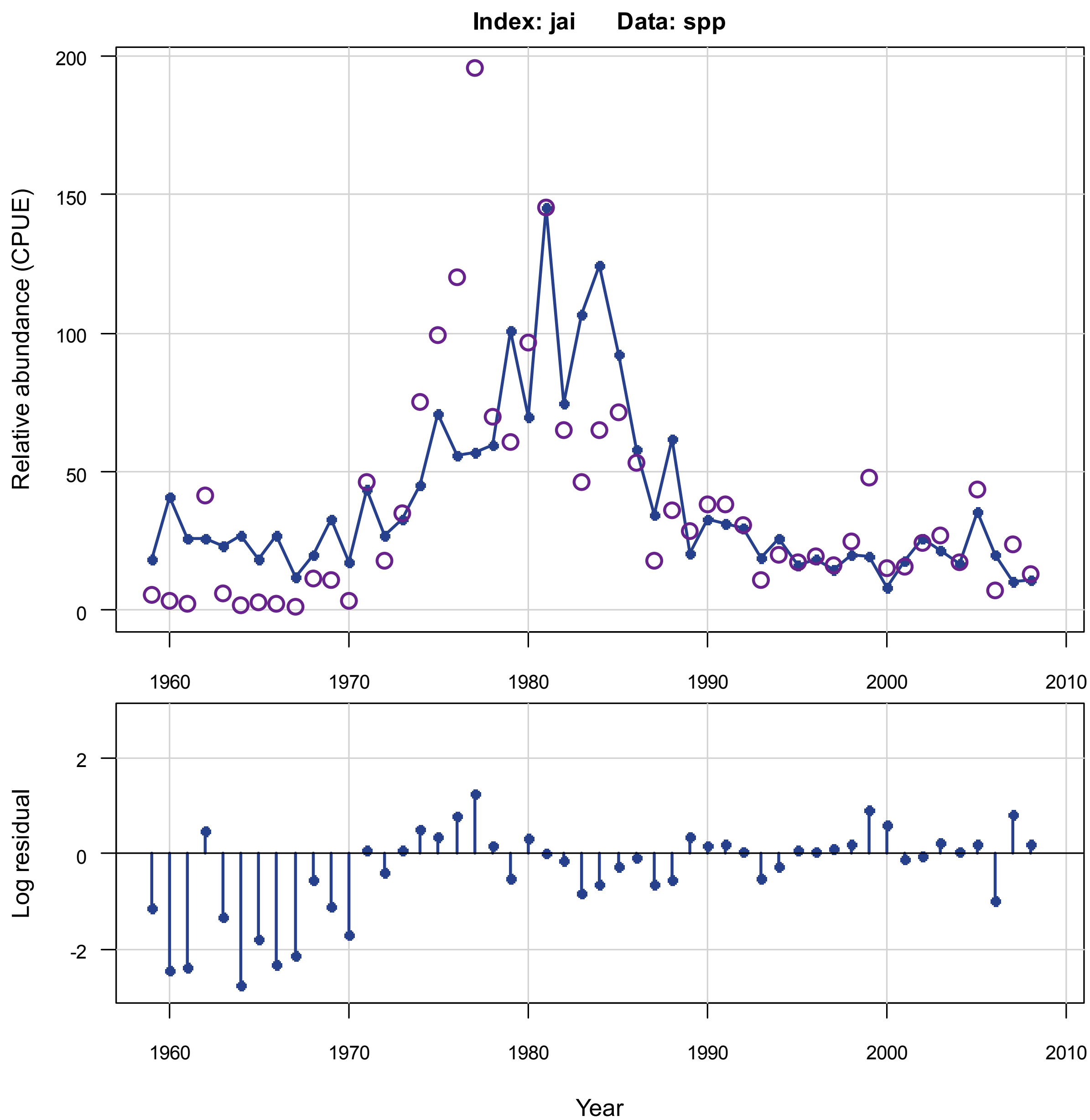


Figure 7.8 Observed (open circles) and predicted (connected points) PRFC pound net CPUE index values for Atlantic menhaden from the base BAM model.

[Bottom panel indicates pattern and magnitude of log-transformed residuals of model fit.]

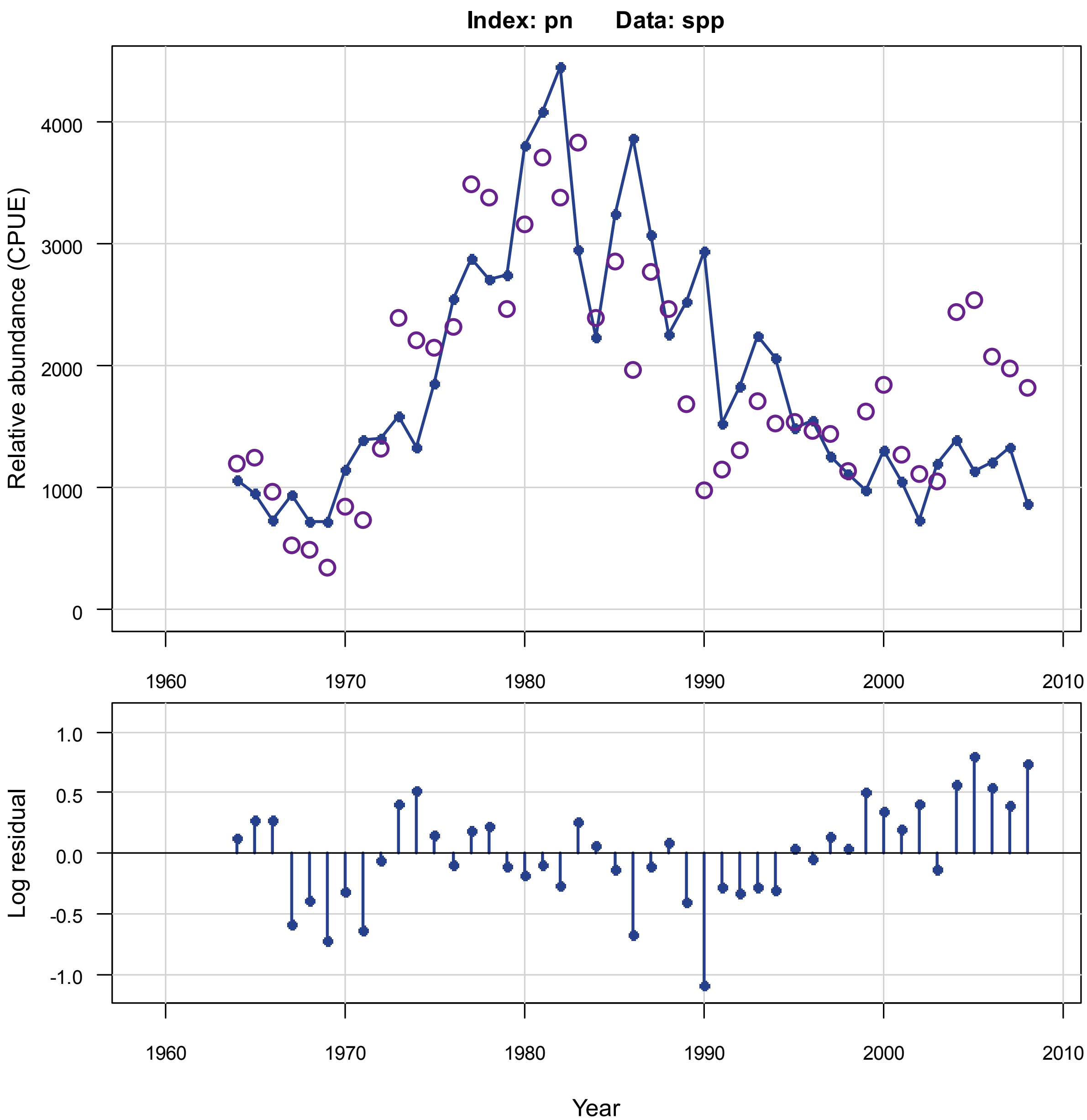


Figure 7.9 Estimated age-specific selectivity pattern for the Atlantic menhaden commercial reduction fishery from the base BAM model.

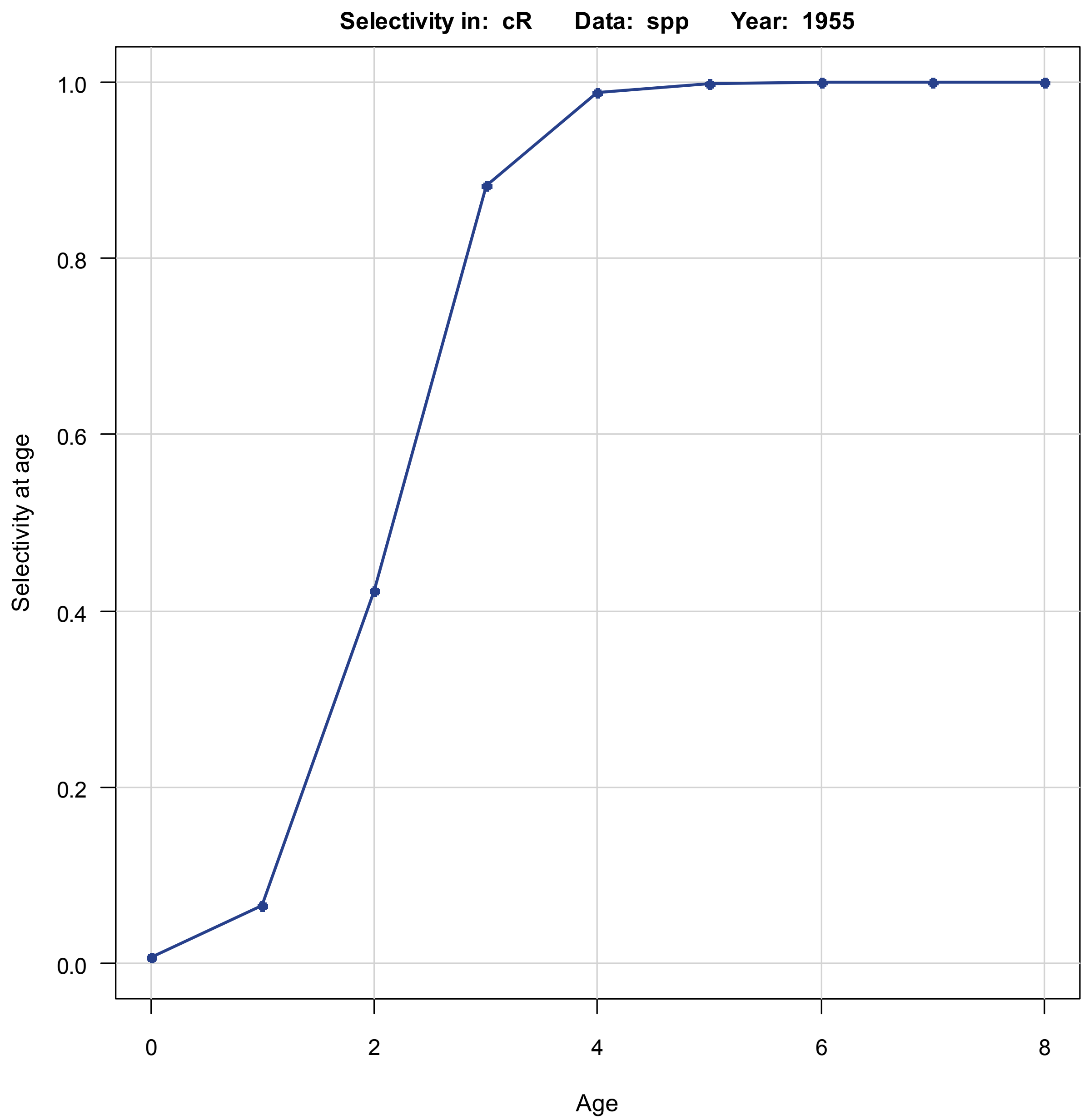


Figure 7.10 Estimated age-specific selectivity pattern for the Atlantic menhaden bait fishery from the base BAM model.

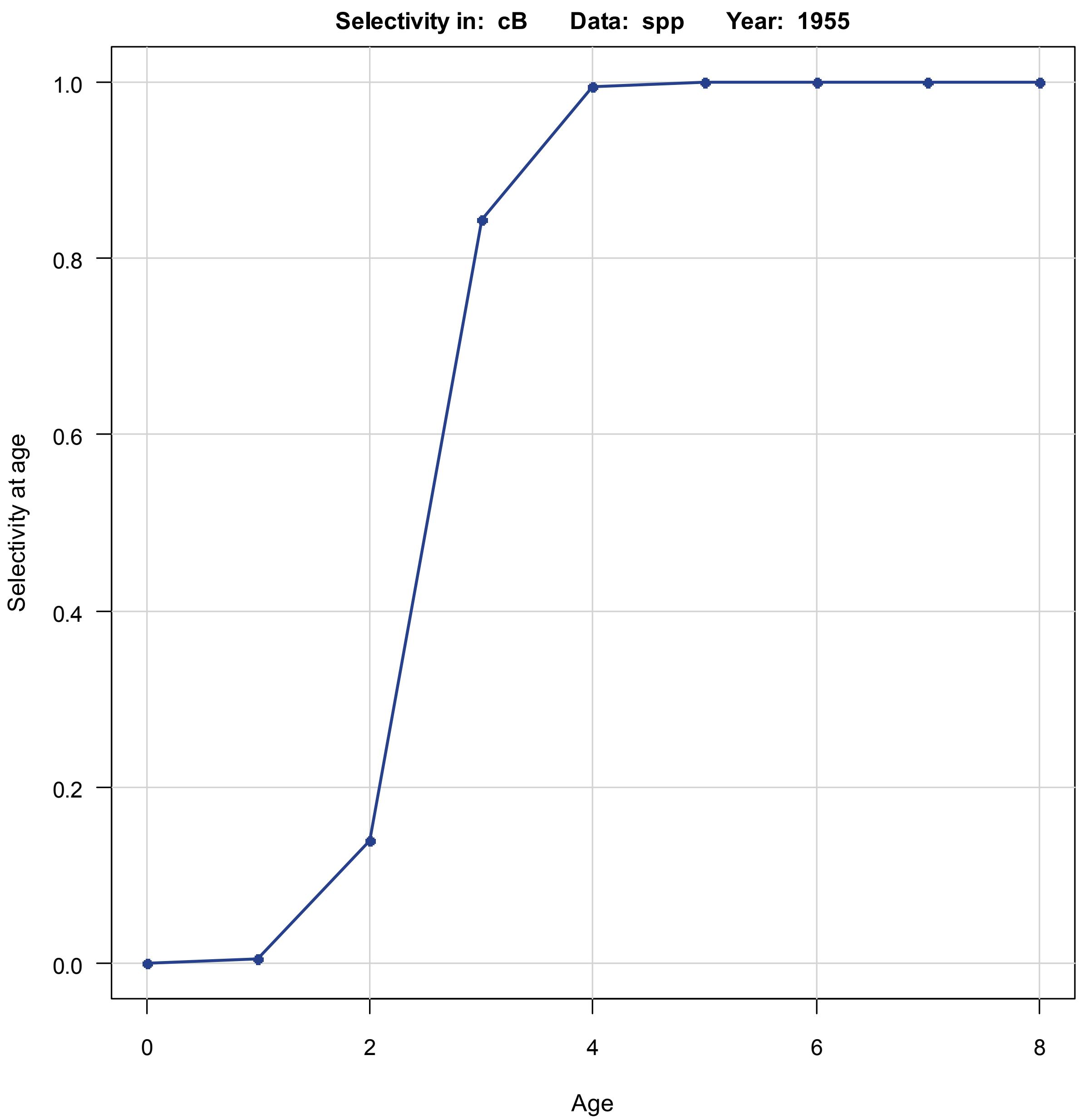


Figure 7.11 Estimated annual total N-weighted fishing mortality rates, *F* (ages 2+) from the base BAM model (connected points).

[Shaded area represents the 90% confidence interval of the bootstrap runs.]

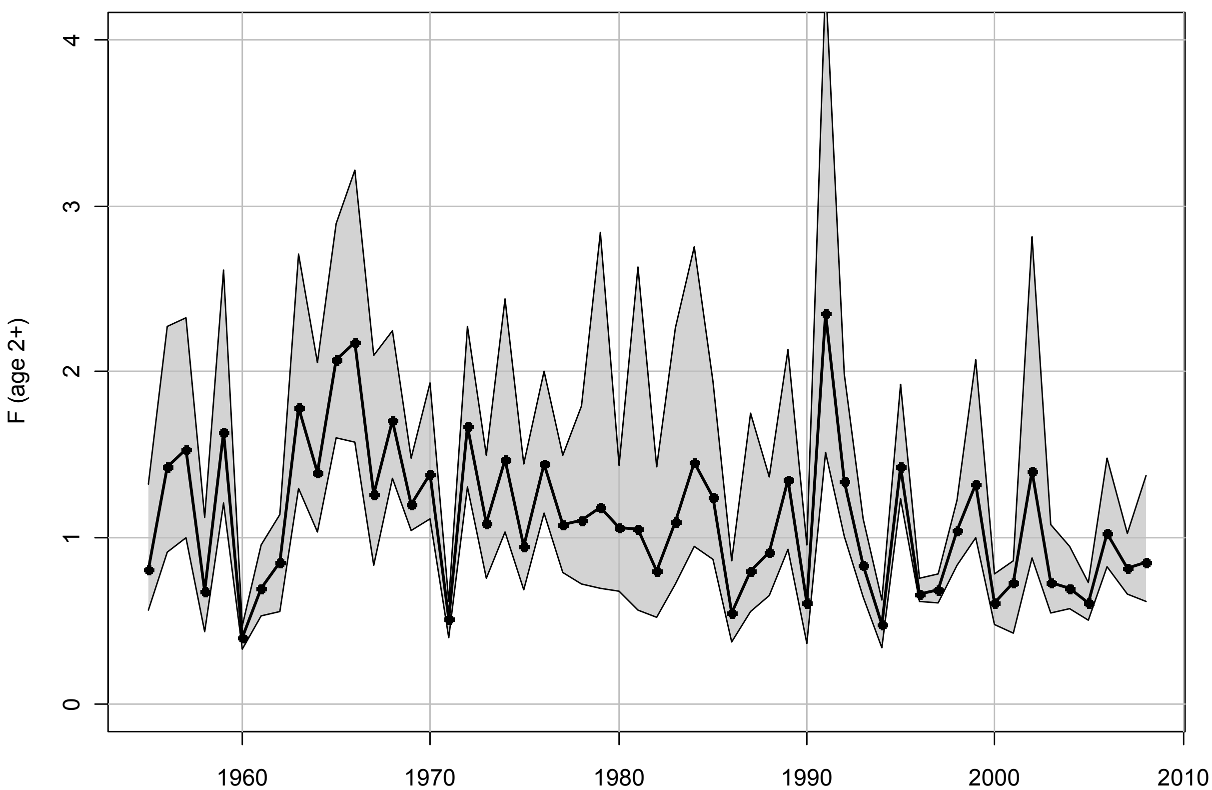


Figure 7.12 Estimated annual fishing N-weighted mortality rates, *F* (ages 2+) for the commercial reduction fishery from the base BAM model.

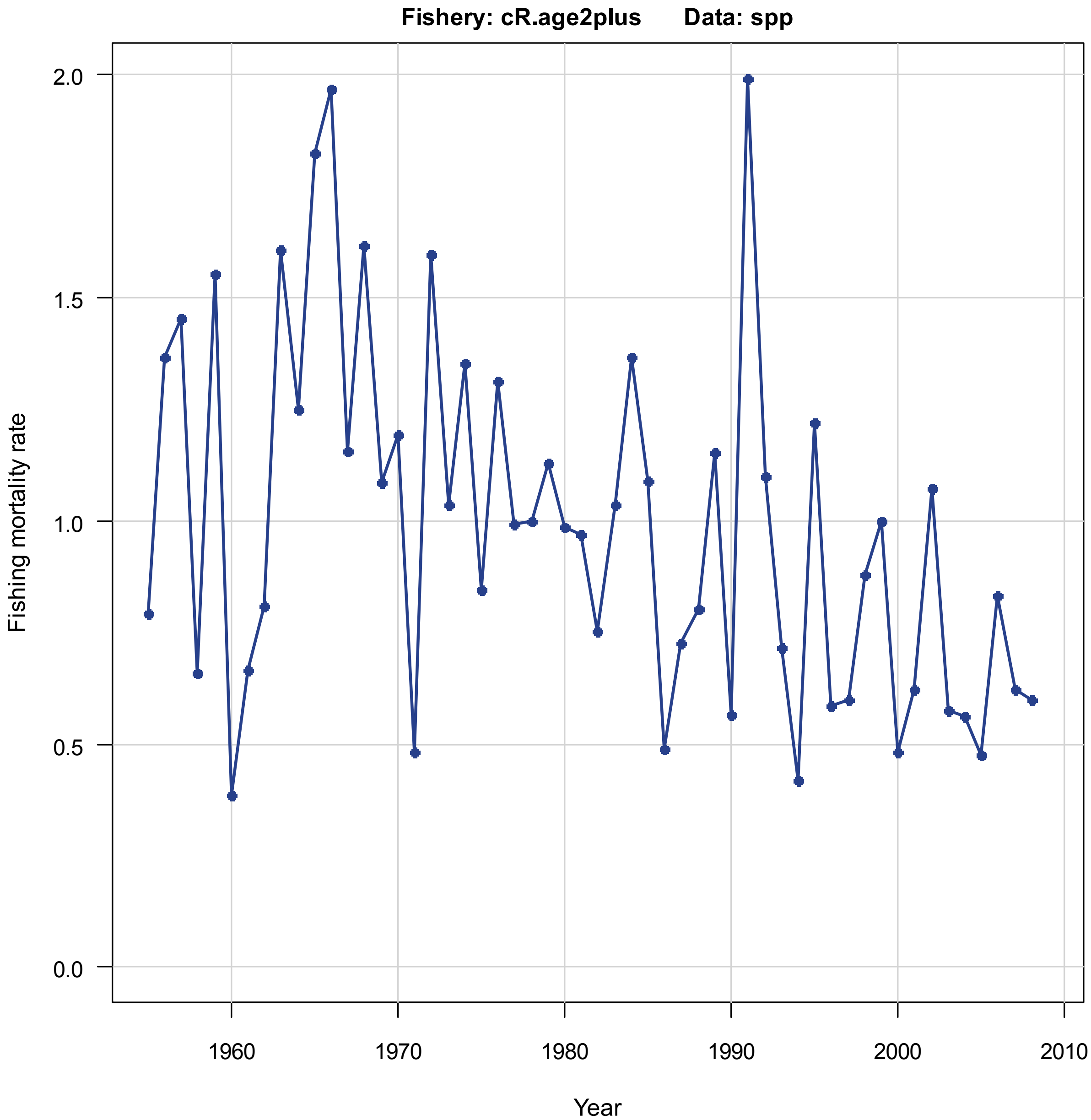


Figure 7.13 Estimated annual N-weighted fishing mortality rates, *F* (ages 2+) for the bait fishery from the base BAM model.

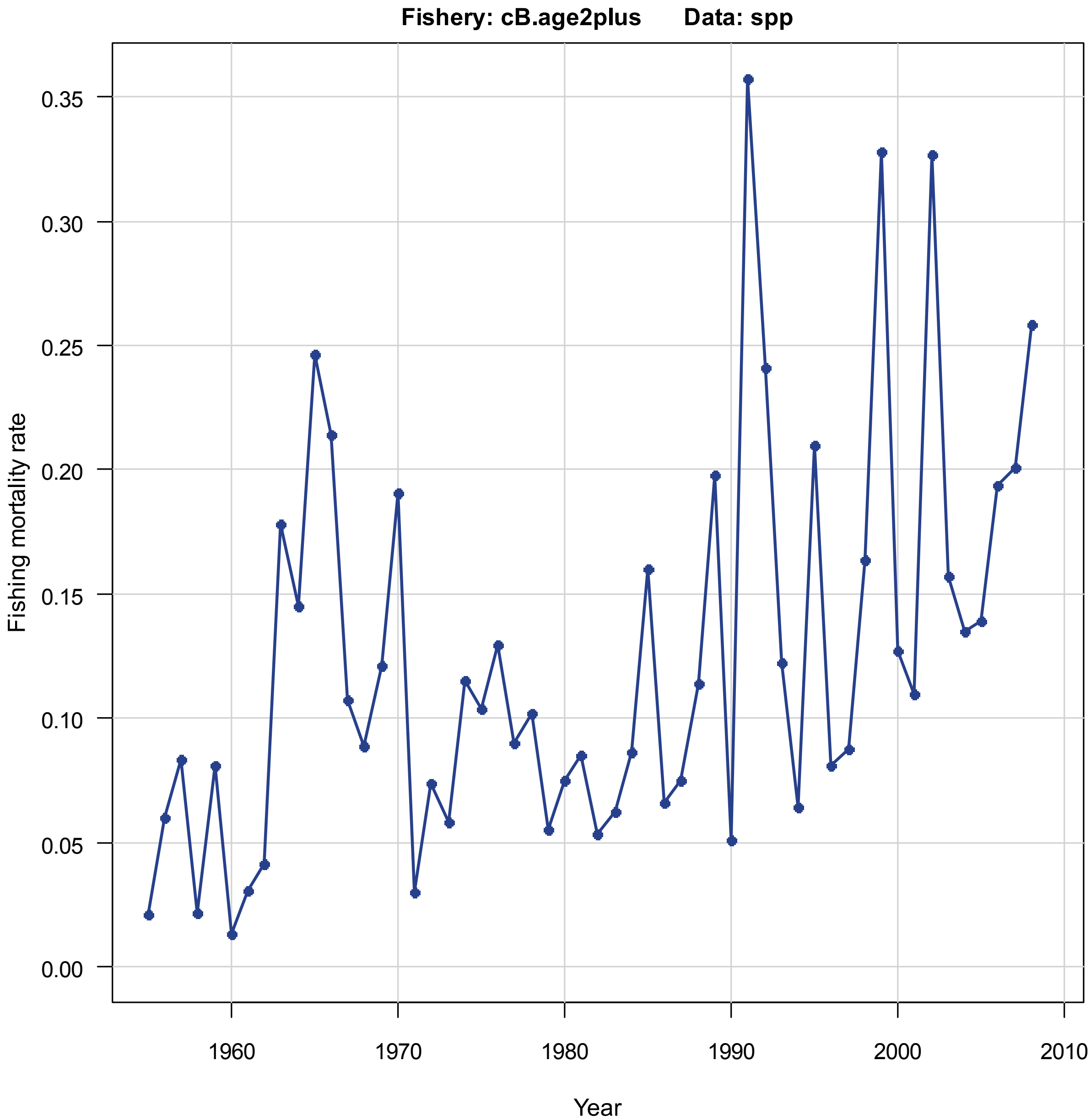


Figure 7.14 Estimated annual full fishing mortality rates, full *F,* for combined reduction and bait fisheries from the base BAM model.

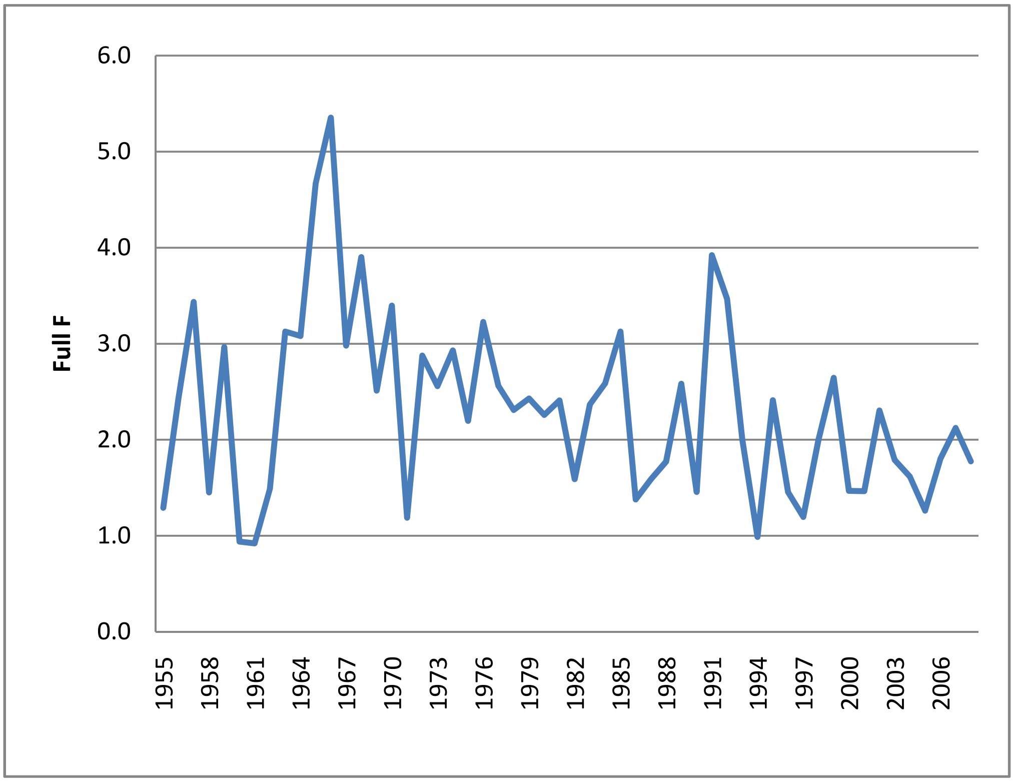


Figure 7. 15 Estimated numbers at age of Atlantic menhaden (billions) at the start of the fishing year from the base BAM model.

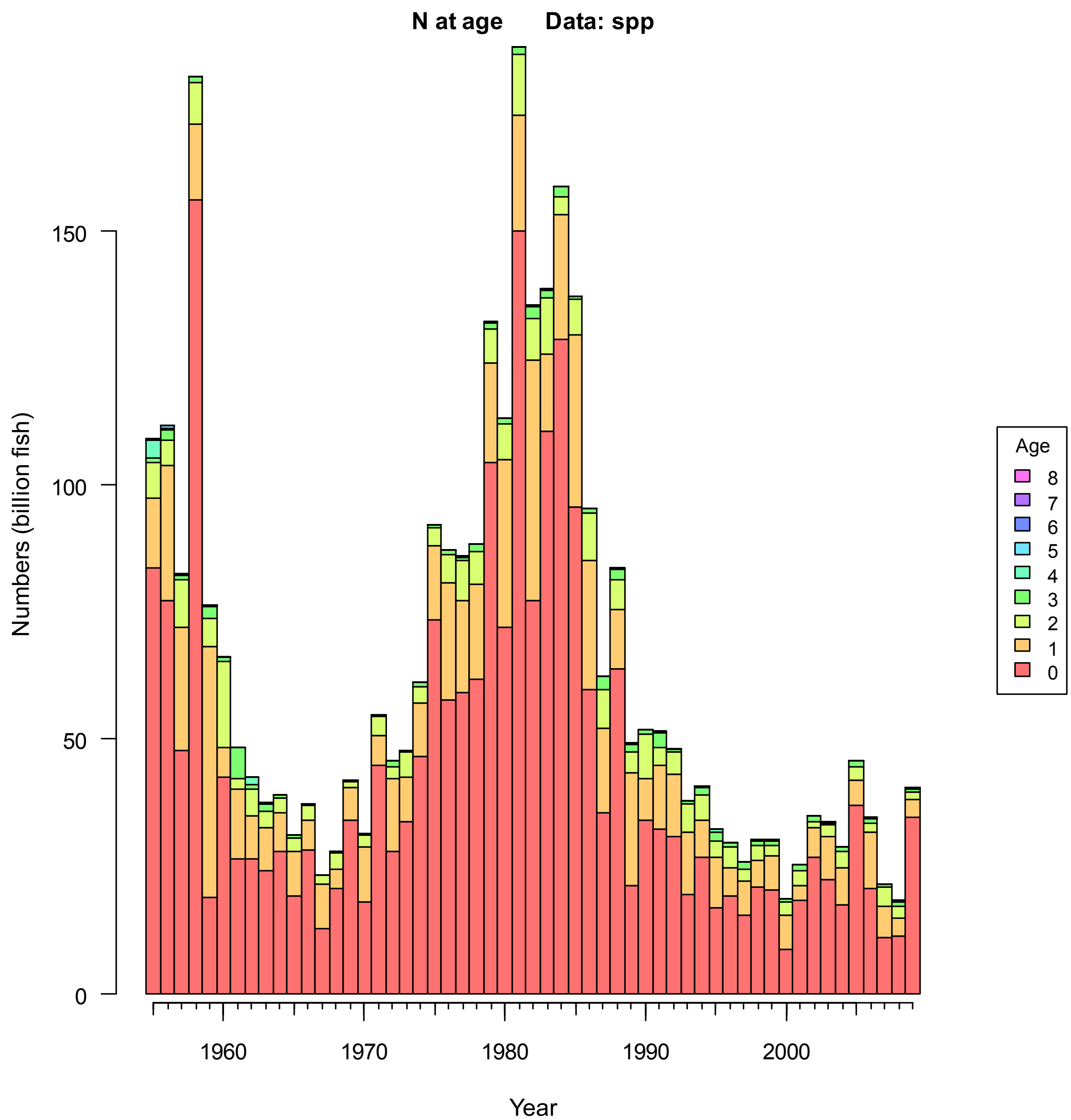


Figure 7.16 Estimated annual fecundity (billions of eggs) from the base BAM model (connected points). Shaded area represents the 90% confidence interval of the bootstrap runs.

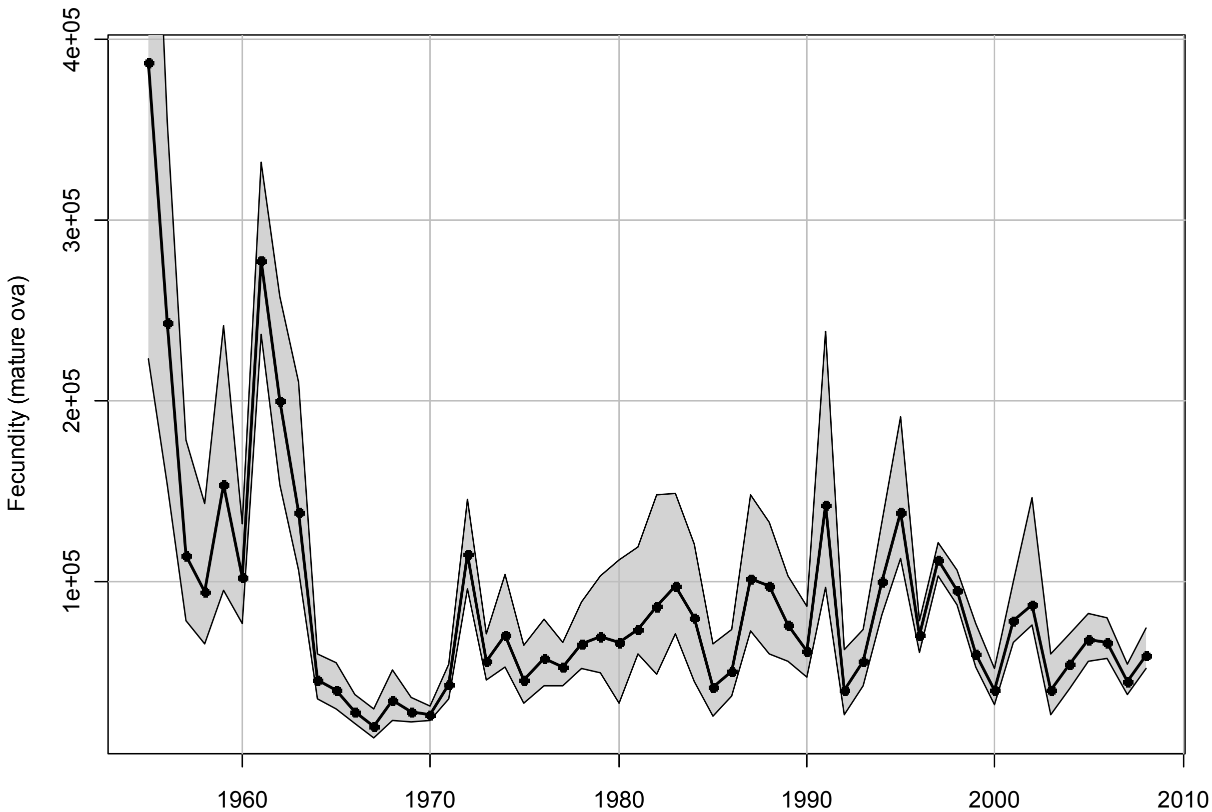


Figure 7. 17 Estimated total fecundity (billions of mature ova) at age of Atlantic menhaden at the start of the fishing year from the base BAM model.

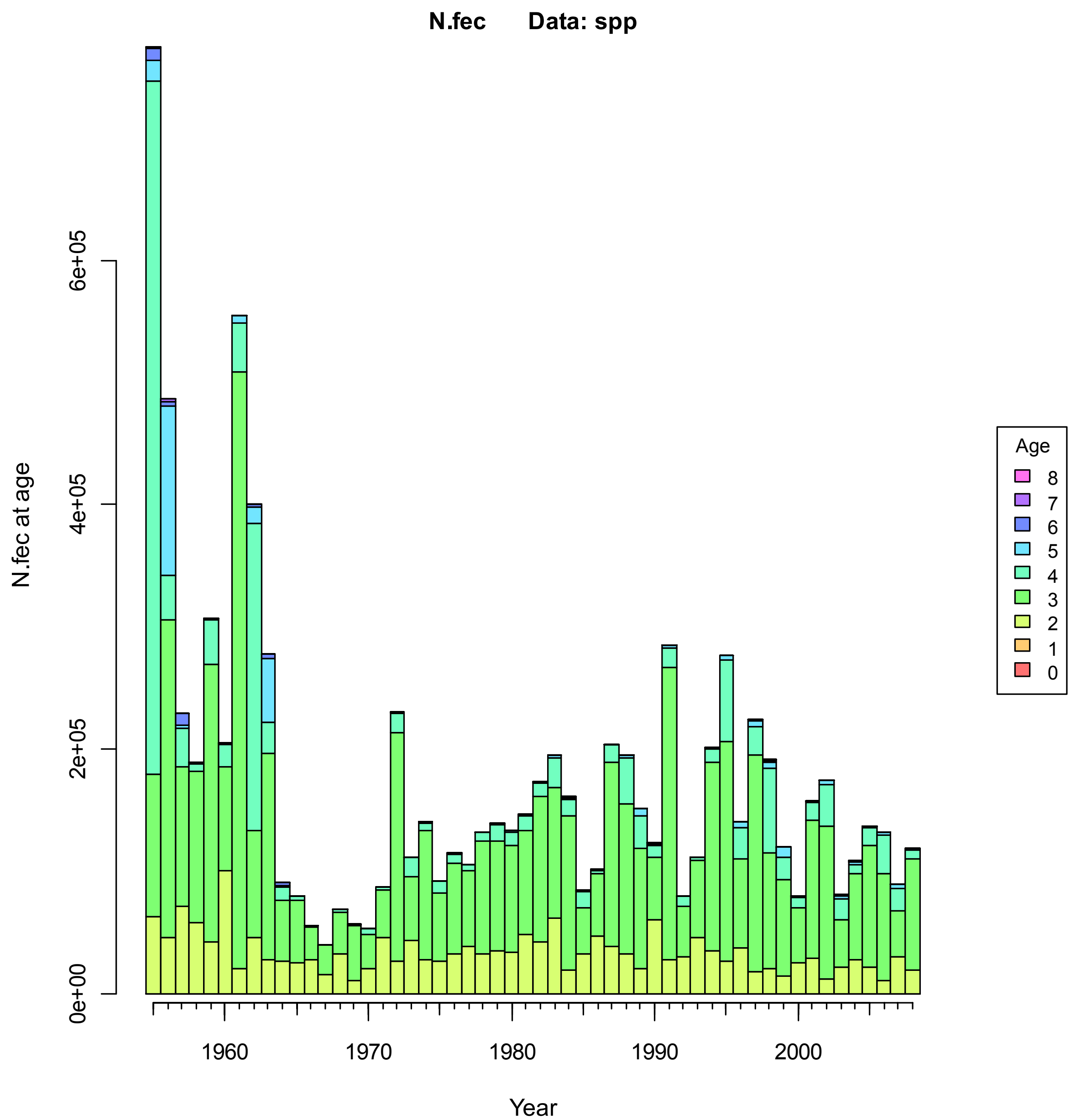


Figure 7.18 Estimated annual recruitment to age-0 (billions) from the base BAM model (connected points). Shaded area represents the 90% confidence interval of the bootstrap runs.

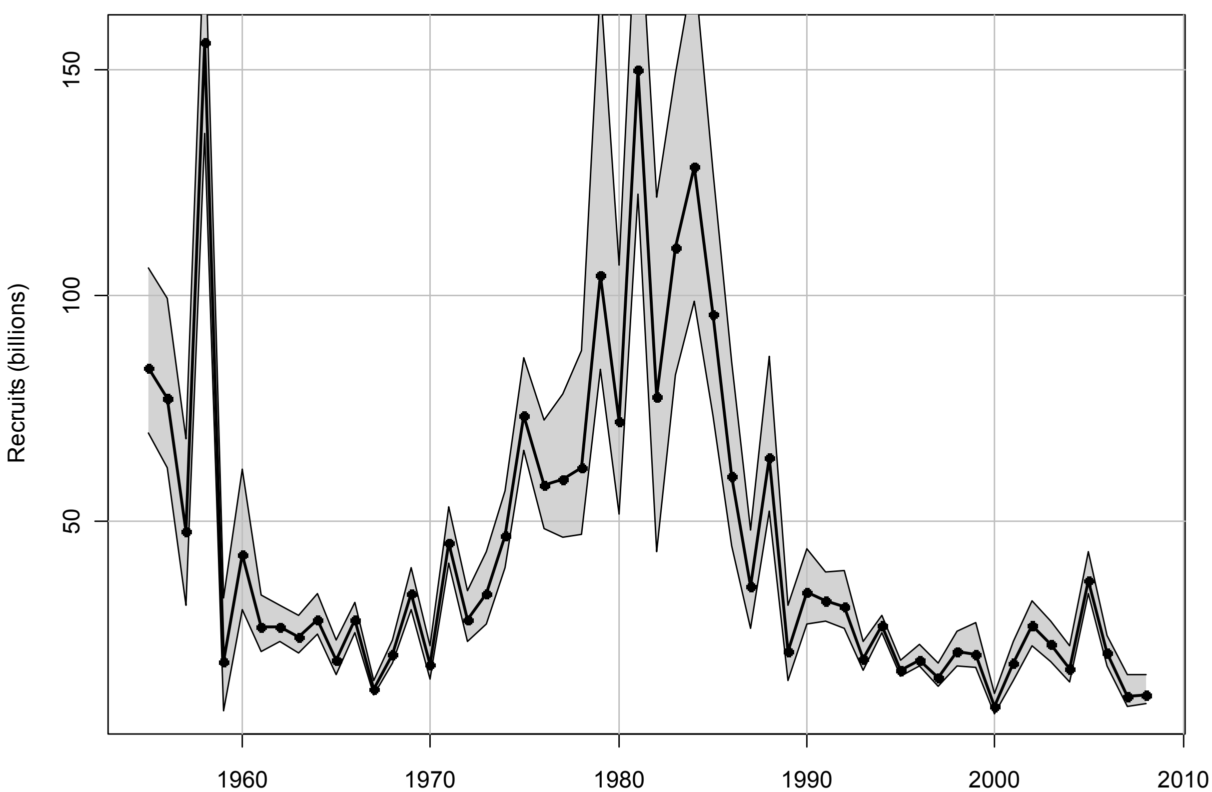


Figure 7.19 Estimated annual recruitment to age-0 (billions) from the base BAM model (connected points).

[Dashed line represents the median recruitment from the entire time series. The recruitment estimate for 2009 shown in this figure is a projection based on the long term geometric mean.]

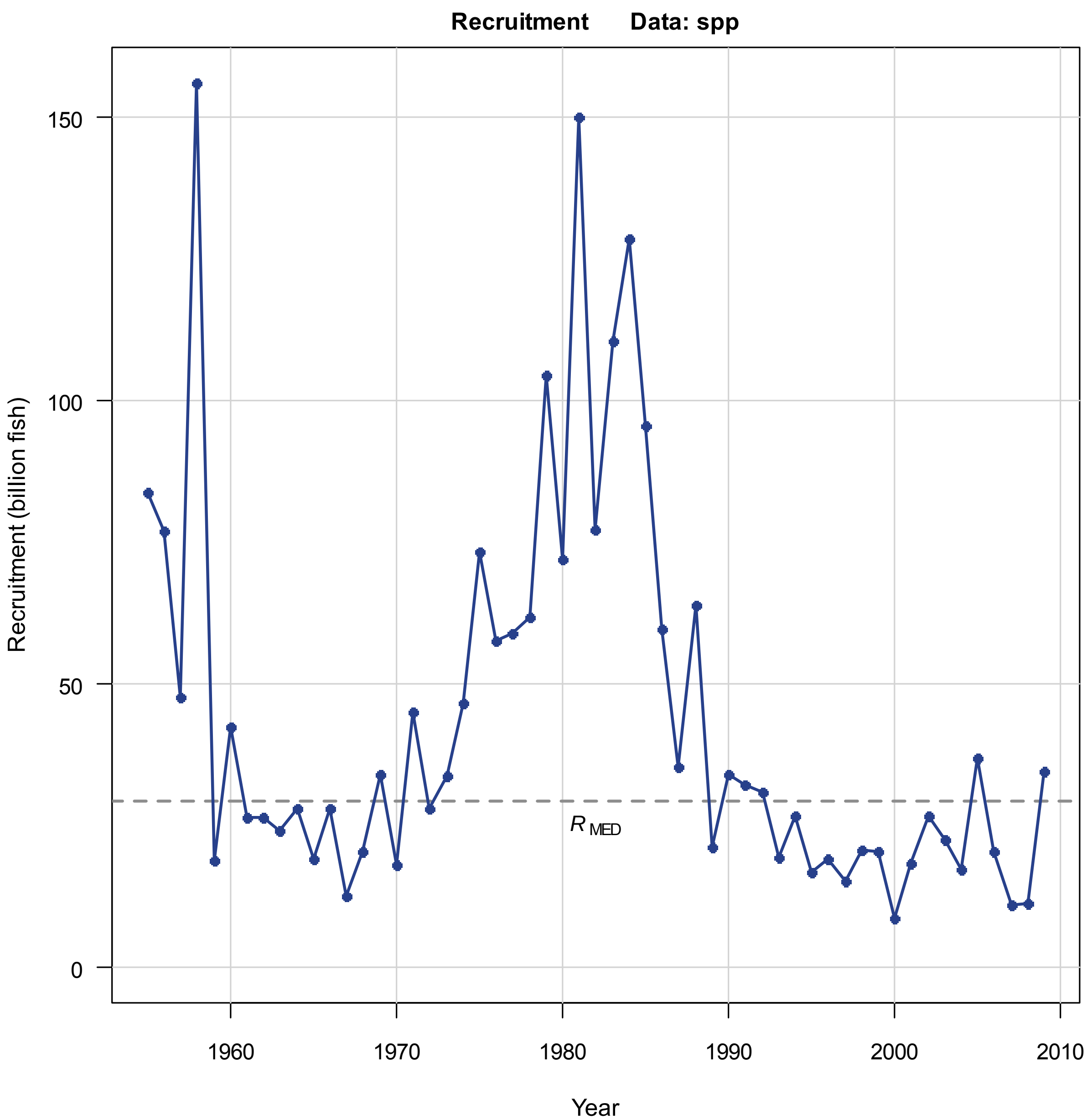


Figure 7.20 Estimated spawning stock (billions of mature ova) and recruitment (billions of age-0 fish) from the base BAM model (points).

[Lines indicate the median recruitment (horizontal) and the 50th and 75th percentile of spawners-per-recruit.]

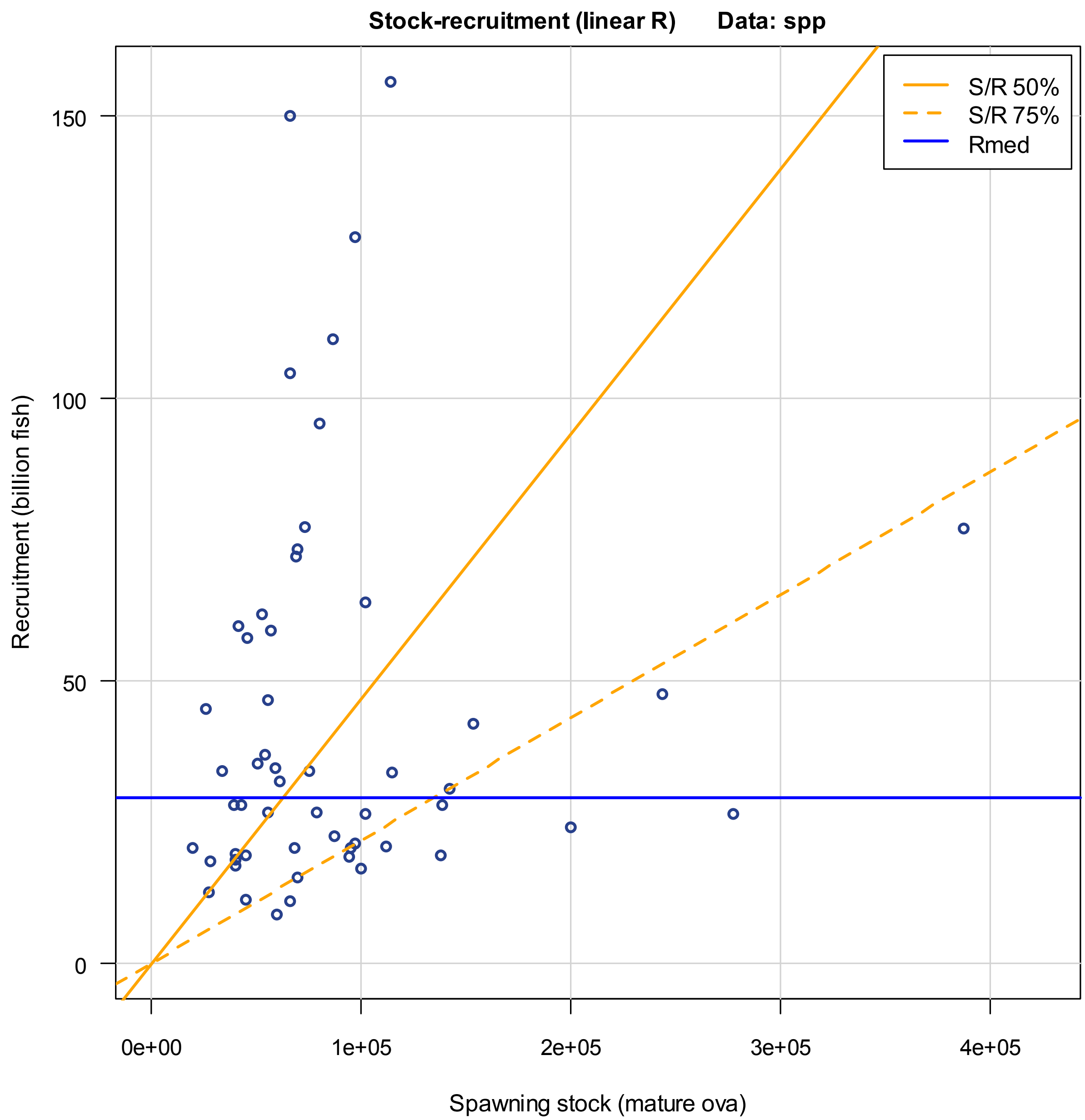


Figure 7.21 Estimated annual total N-weighted fishing mortality rates, *F* (ages 2+) from the base BAM model (connected open circles) and various sensitivity runs (see section 6.2.1.6 for details).

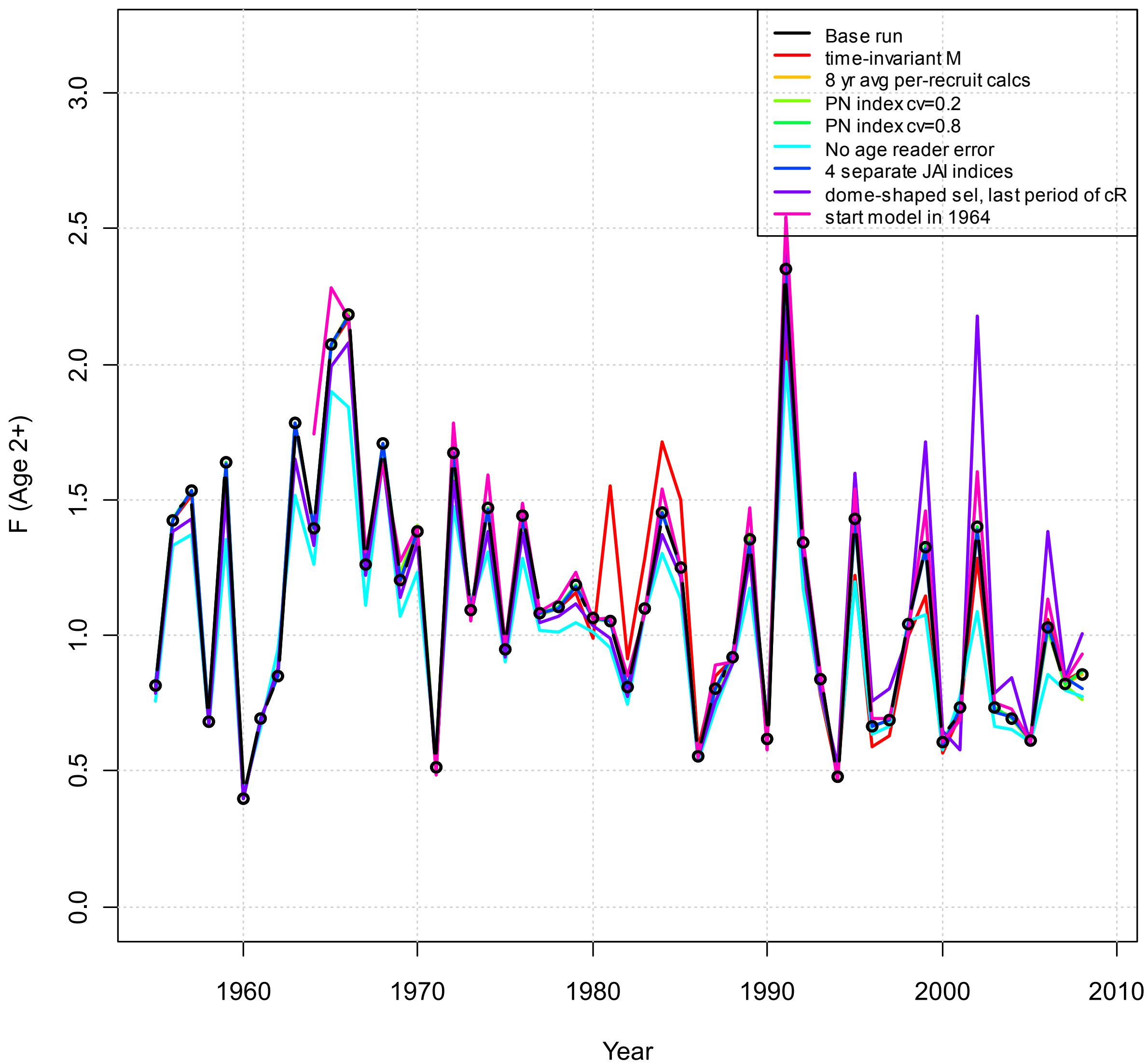


Figure 7.21 (*continued*)

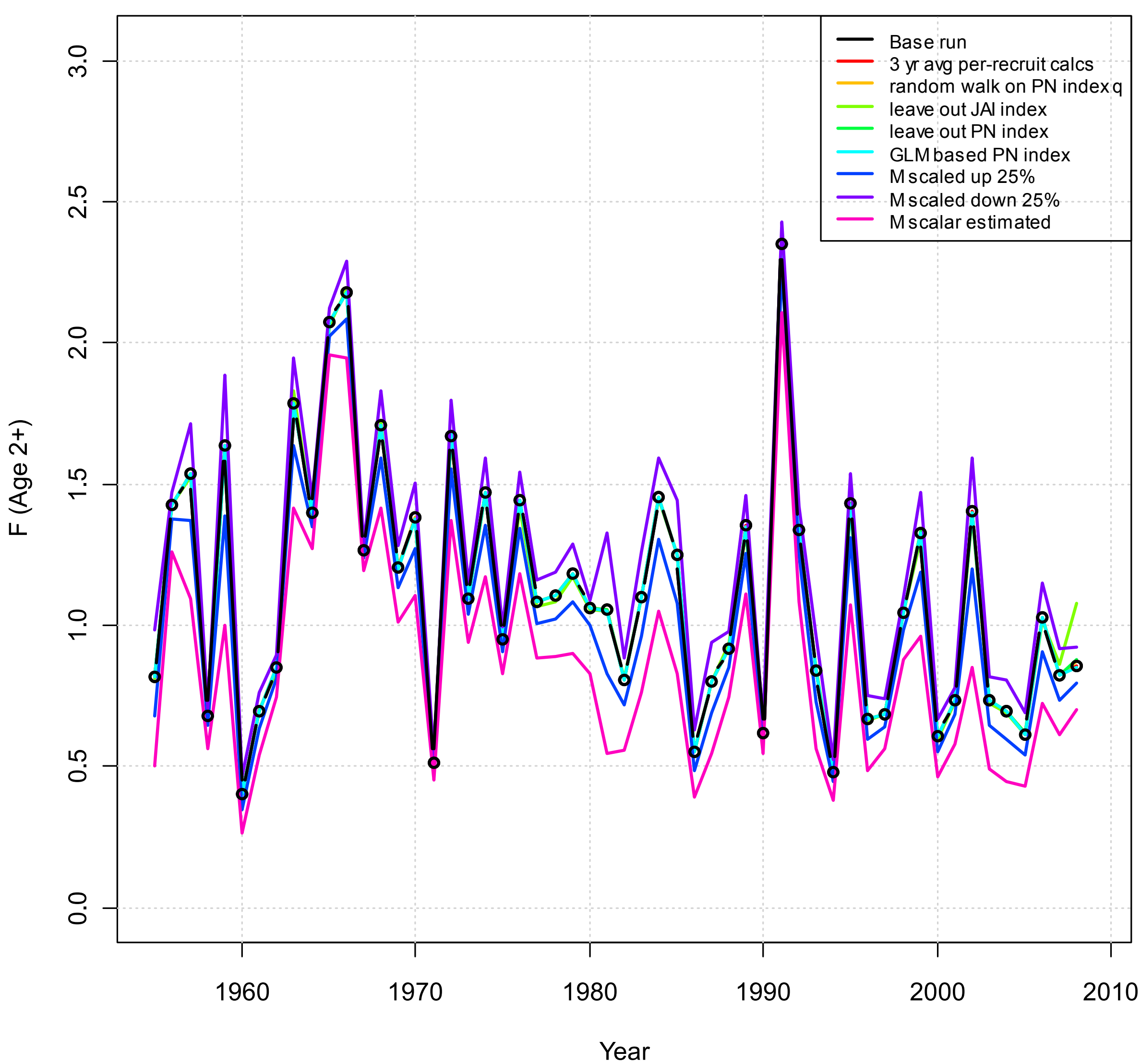


Figure 7.22 Estimated annual recruitment of age-0 fish (billions) from the base BAM model (connected open circles) and various sensitivity runs (see section 6.2.1.6 for details).

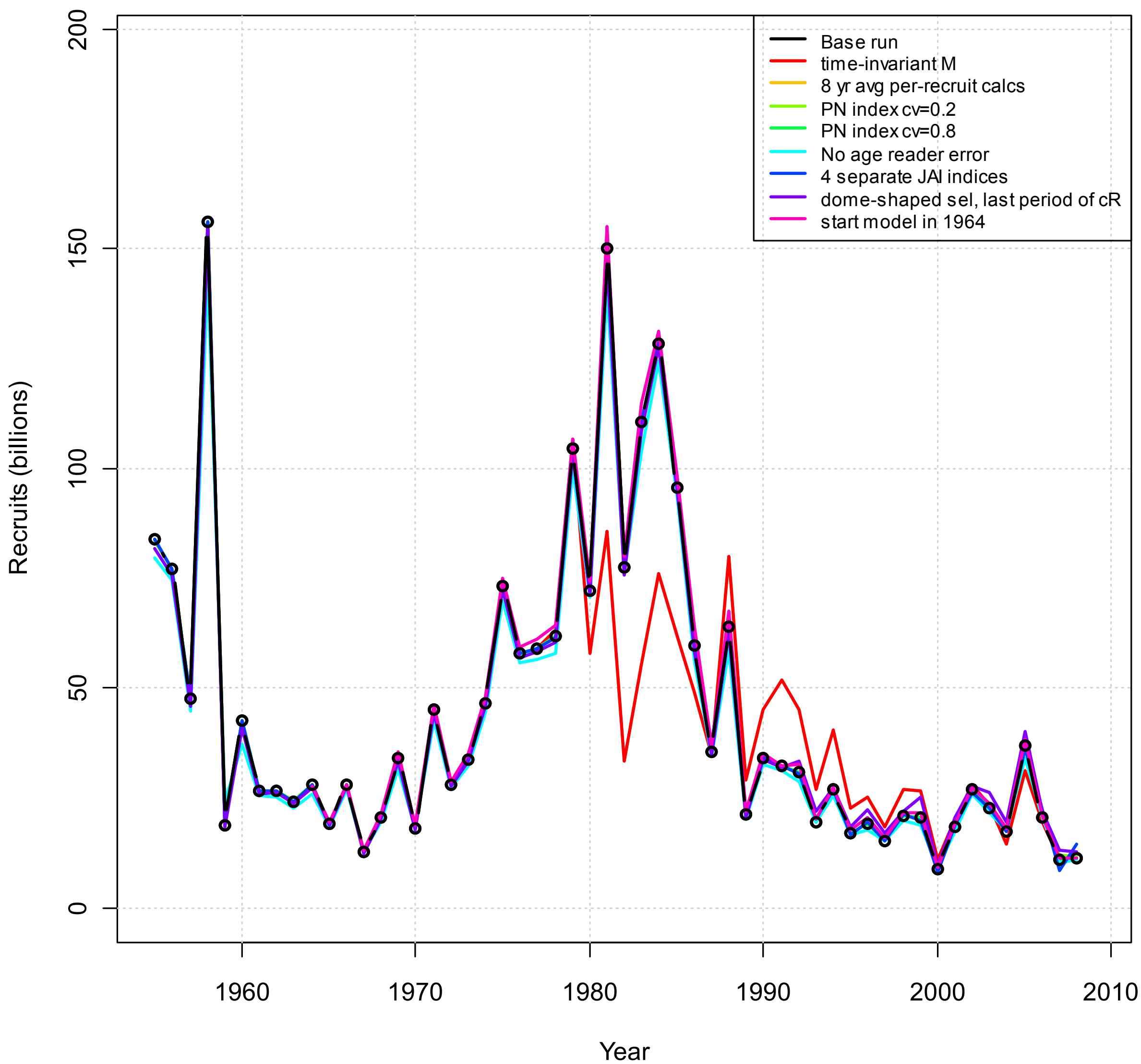


Figure 7.22 (*continued*)

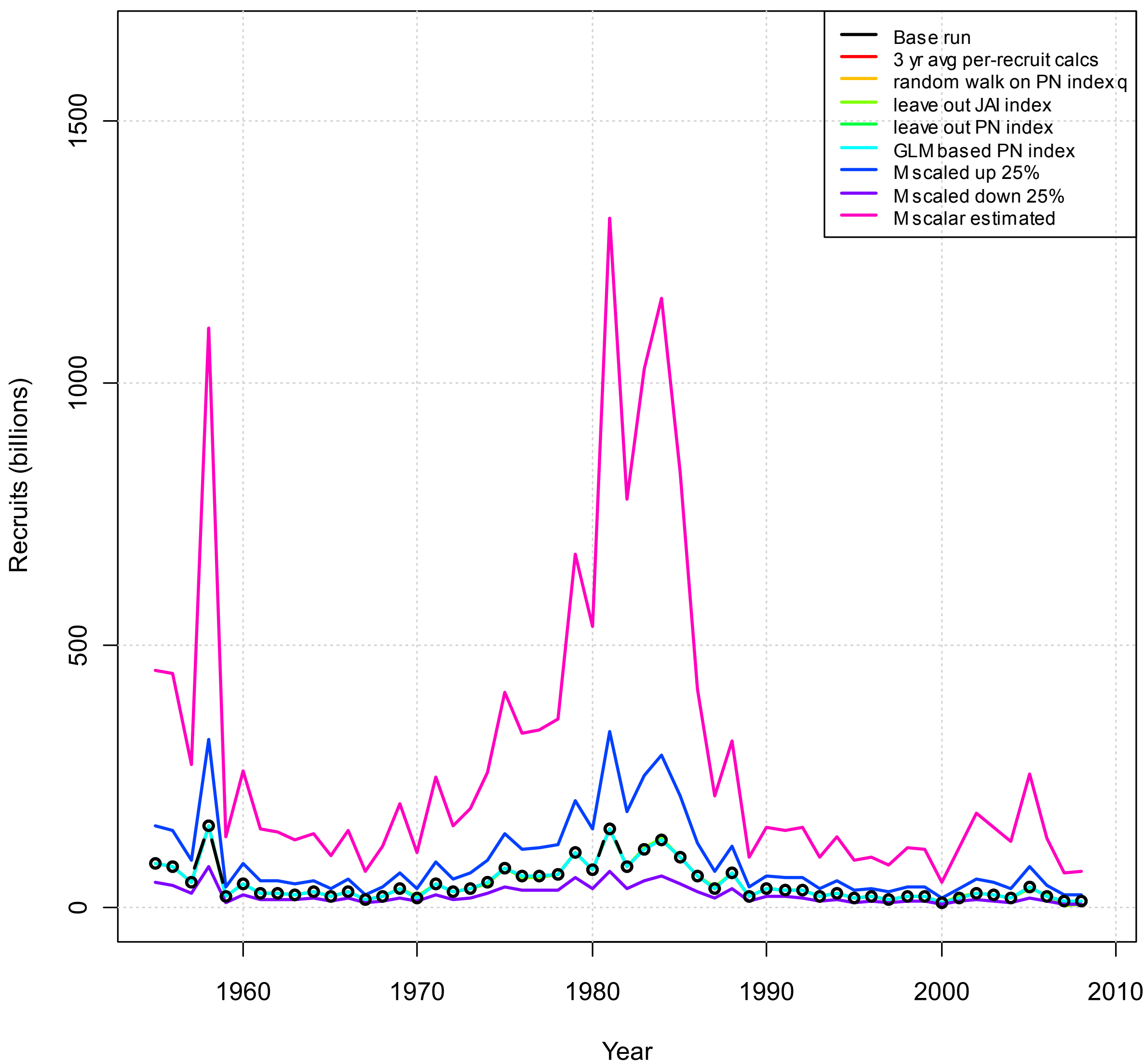


Figure 7.23 Estimated annual fecundity (billions of mature eggs) from the base BAM model (connected open circles) and various sensitivity runs (see section 6.2.1.6 for details).

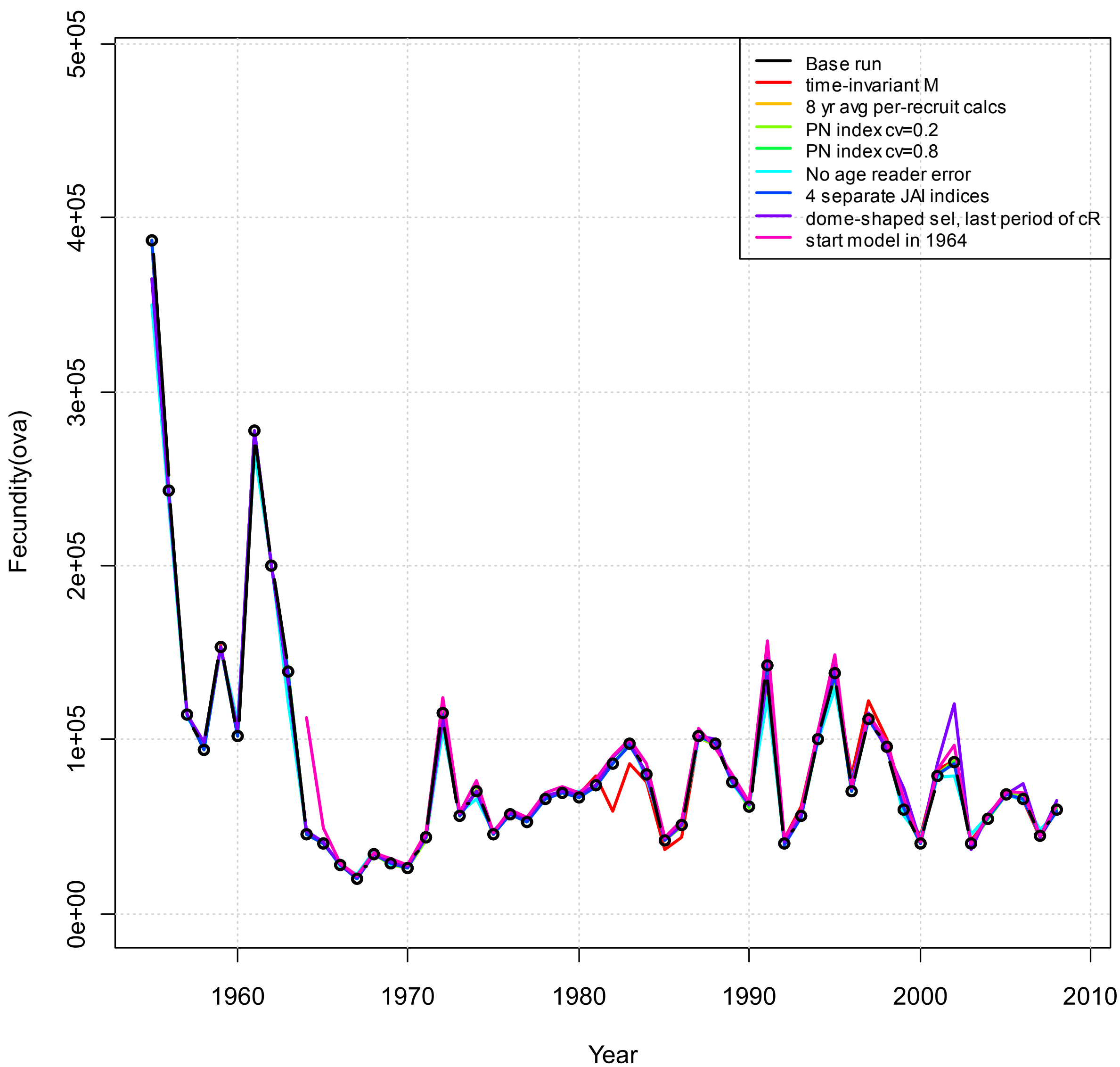


Figure 7.23 (*continued*)

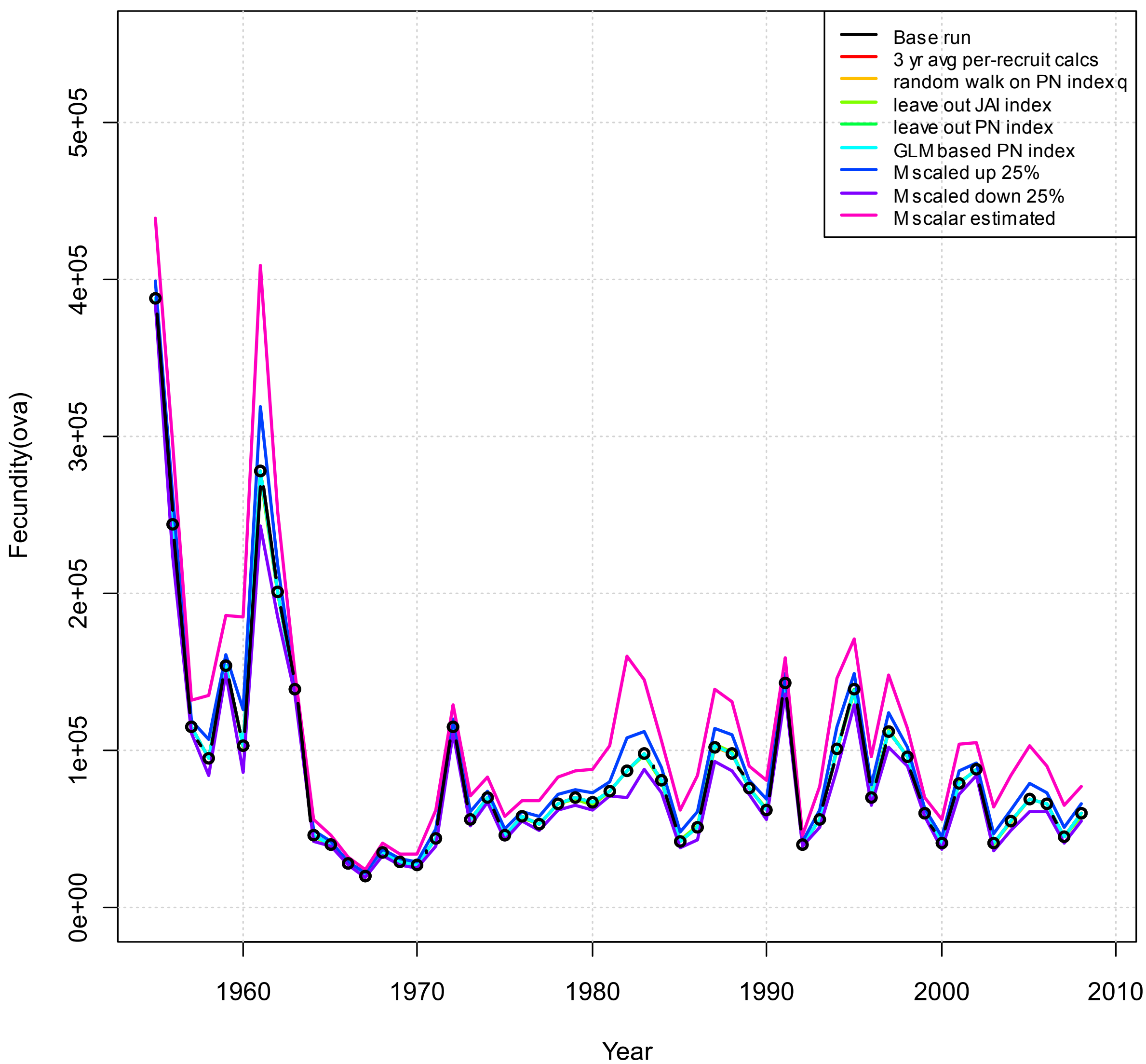


Figure 7.24 Estimated annual total N-weighted fishing mortality rates, *F* (ages 2+) from the base BAM model (connected open circles) and retrospective analysis runs.

[The last year of data used in the model run is indicated in the legend (see section 6.2.1.7 for details).]

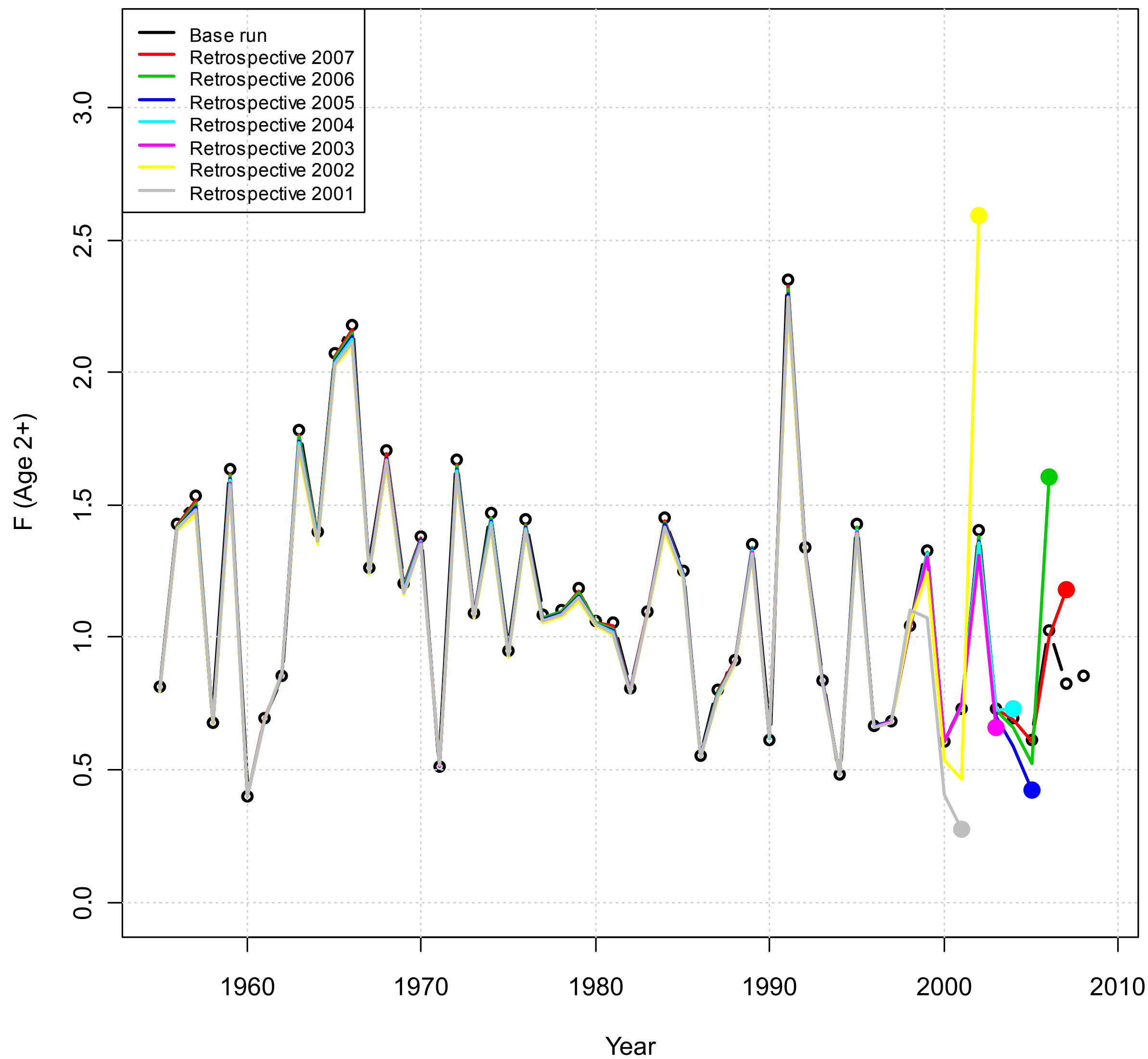


Figure 7.25 Estimated annual recruitment of age-0 fish (billions) from the base BAM model (connected open circles) and retrospective analysis runs.

[The last year of data used in the model run is indicated in the legend (see section 6.2.1.7 for details).]

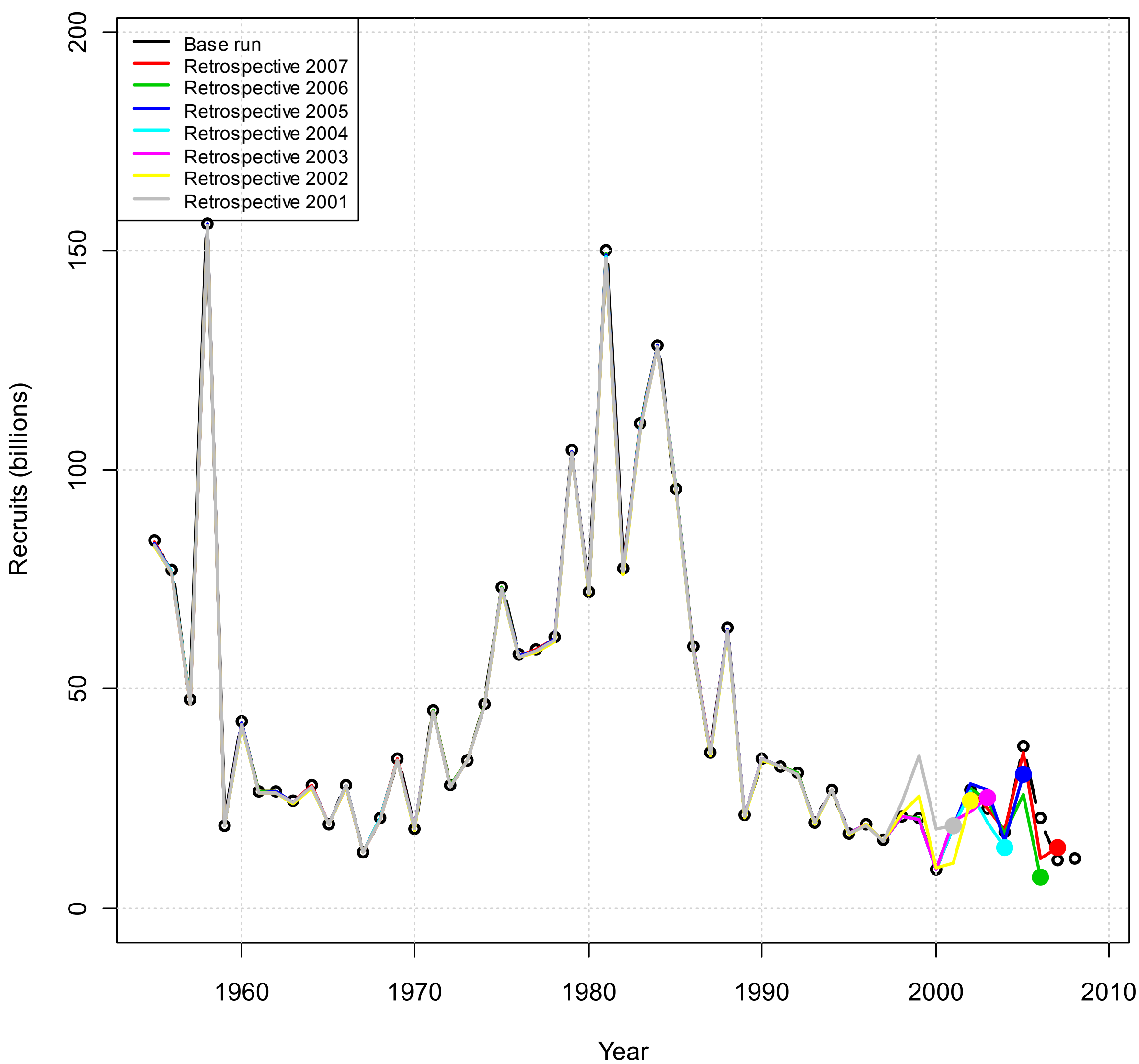


Figure 7.26 Estimated annual population fecundity (billions of mature ova) from the base BAM model (connected open circles) and retrospective analysis runs.

[The last year of data used in the model run is indicated in the legend (see section 6.2.1.7 for details).]

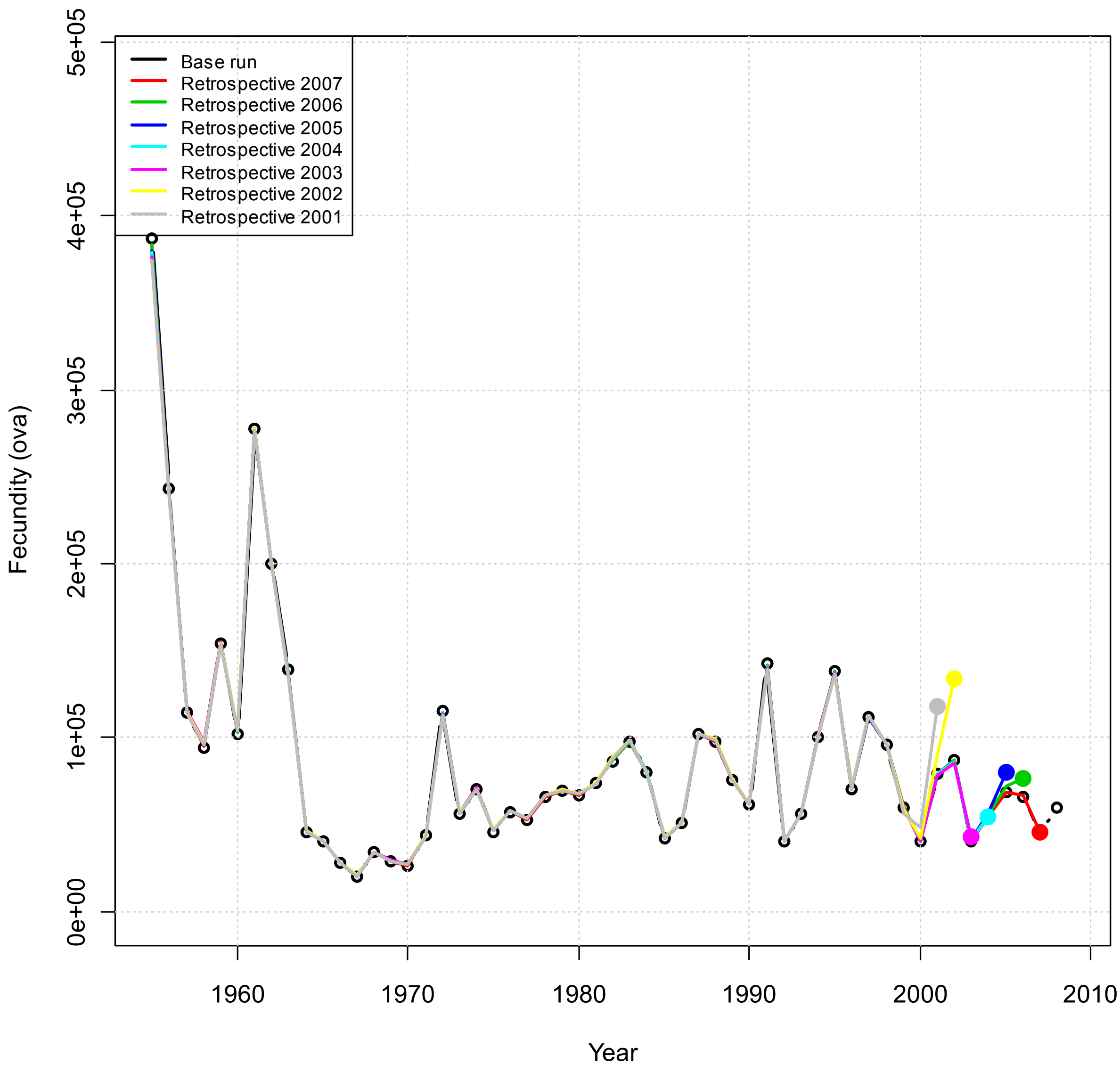


Figure 7.27 Estimates of the proportional (re-scaled to max of 1.0) fecundity-per-recruit as a function of the total N-weighted fishing mortality rate (age 2+) from the base BAM model.

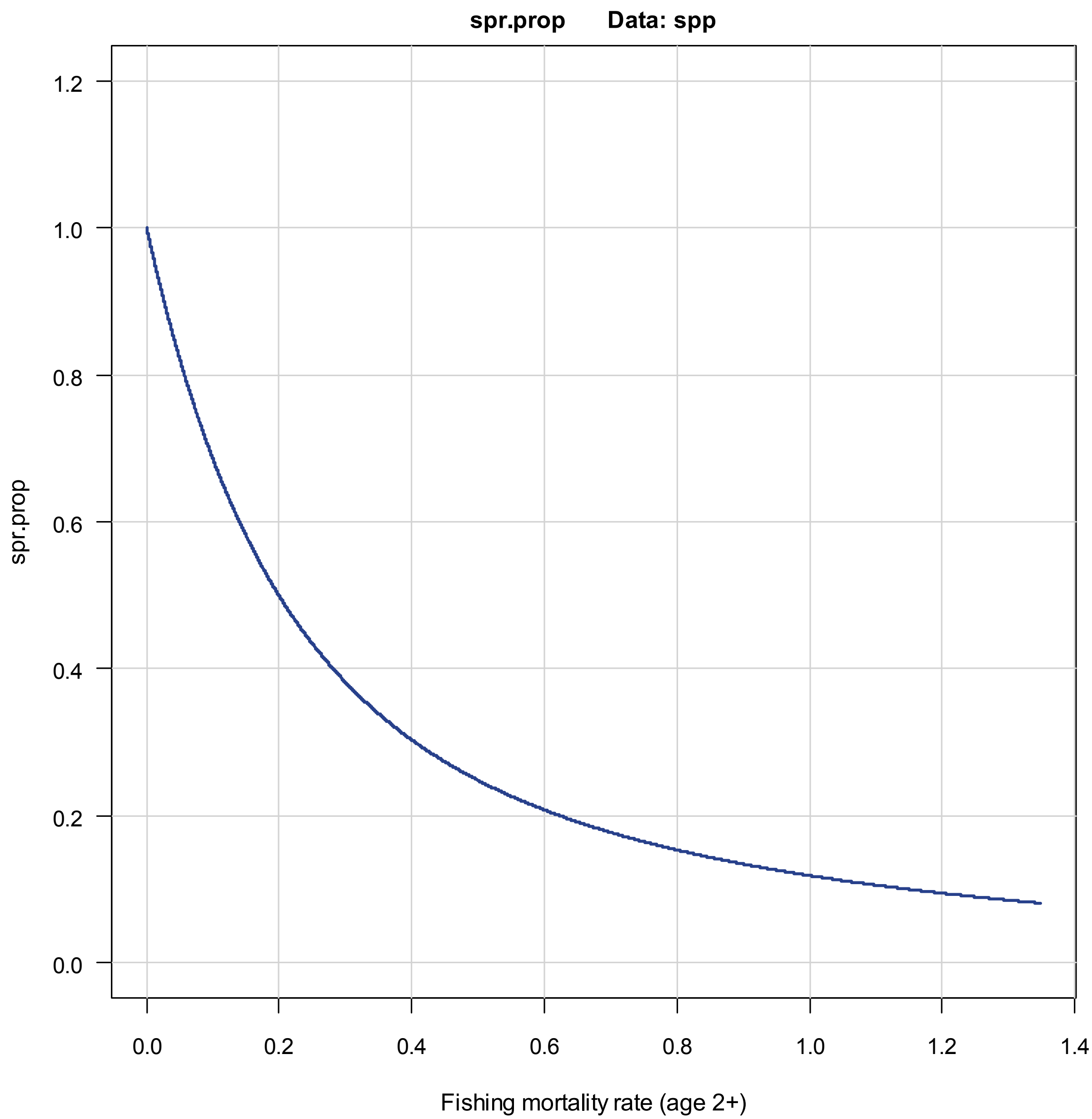


Figure 7.28 Estimates of the yield-per-recruit (mt/million) as a function of the total fishing mortality rate (age 2+) from the base BAM model.

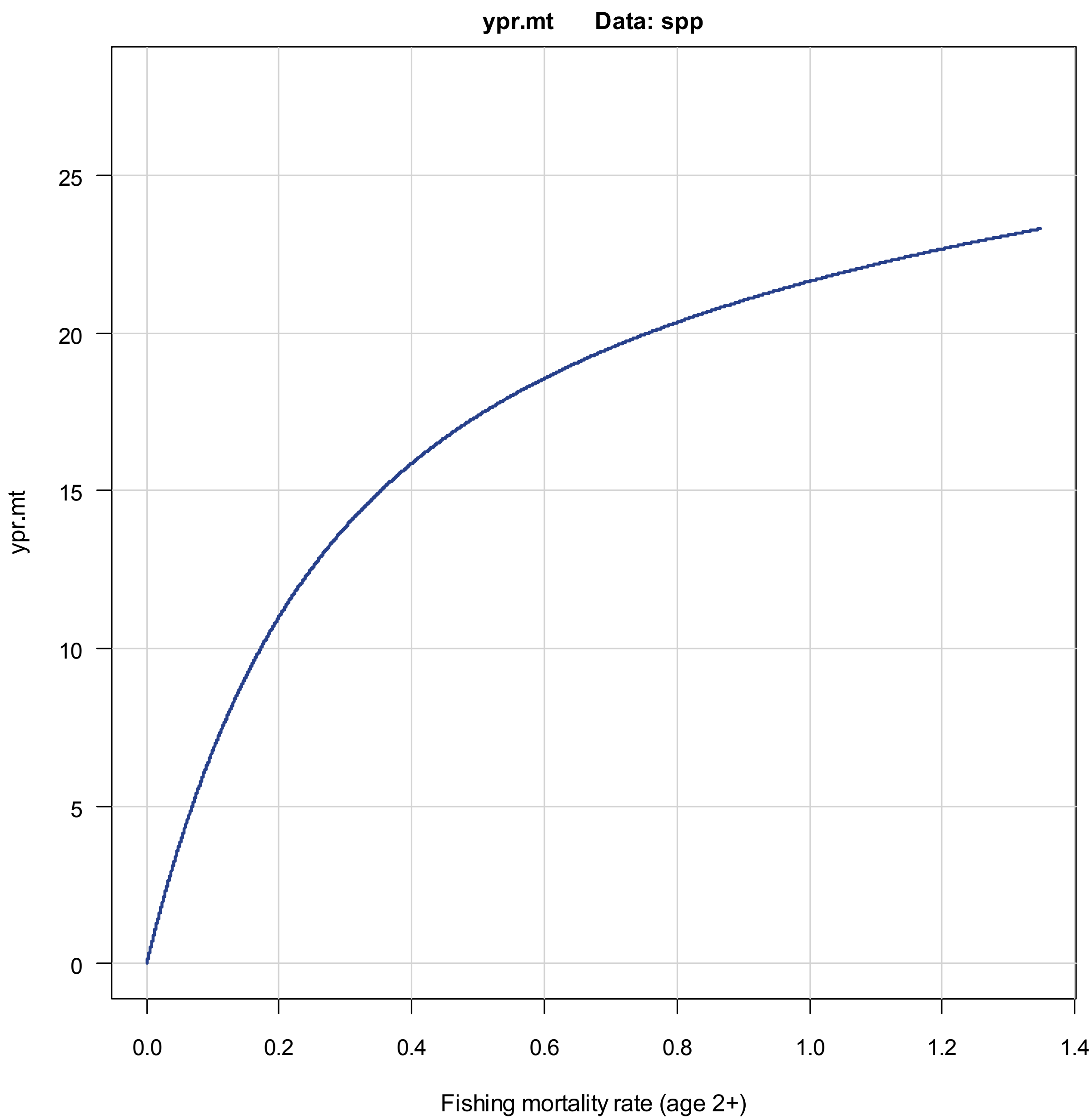


Figure 7.29 Estimates of the total N-weighted fishing mortality rate (age 2+) relative to the F_{MED} benchmark (fishing limit value) from the base BAM model (connected points).

[Shaded area represents the 90% confidence interval of the bootstrap runs.]

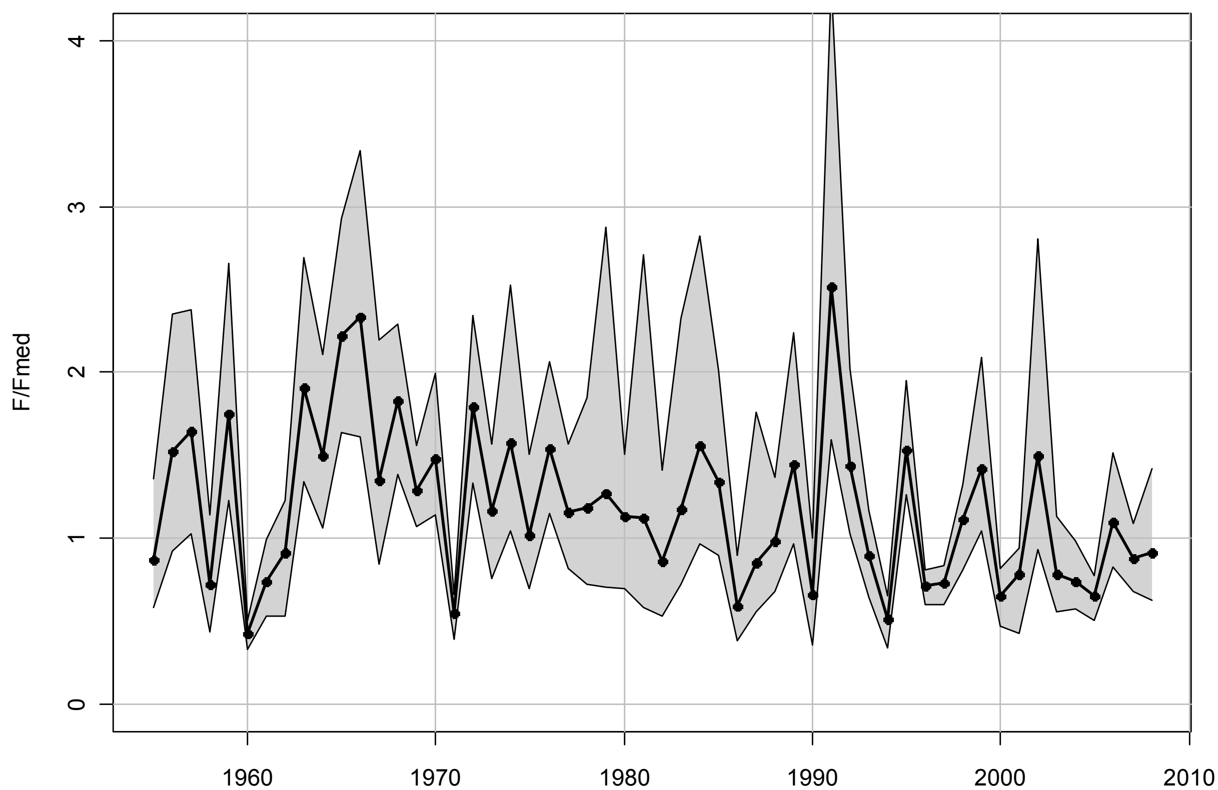


Figure 7.30 Estimates of the population fecundity (SSB) relative to the target benchmark (SSB_{MED}) from the base BAM model (connected points).

[Shaded area represents the 90% confidence interval of the bootstrap runs.]

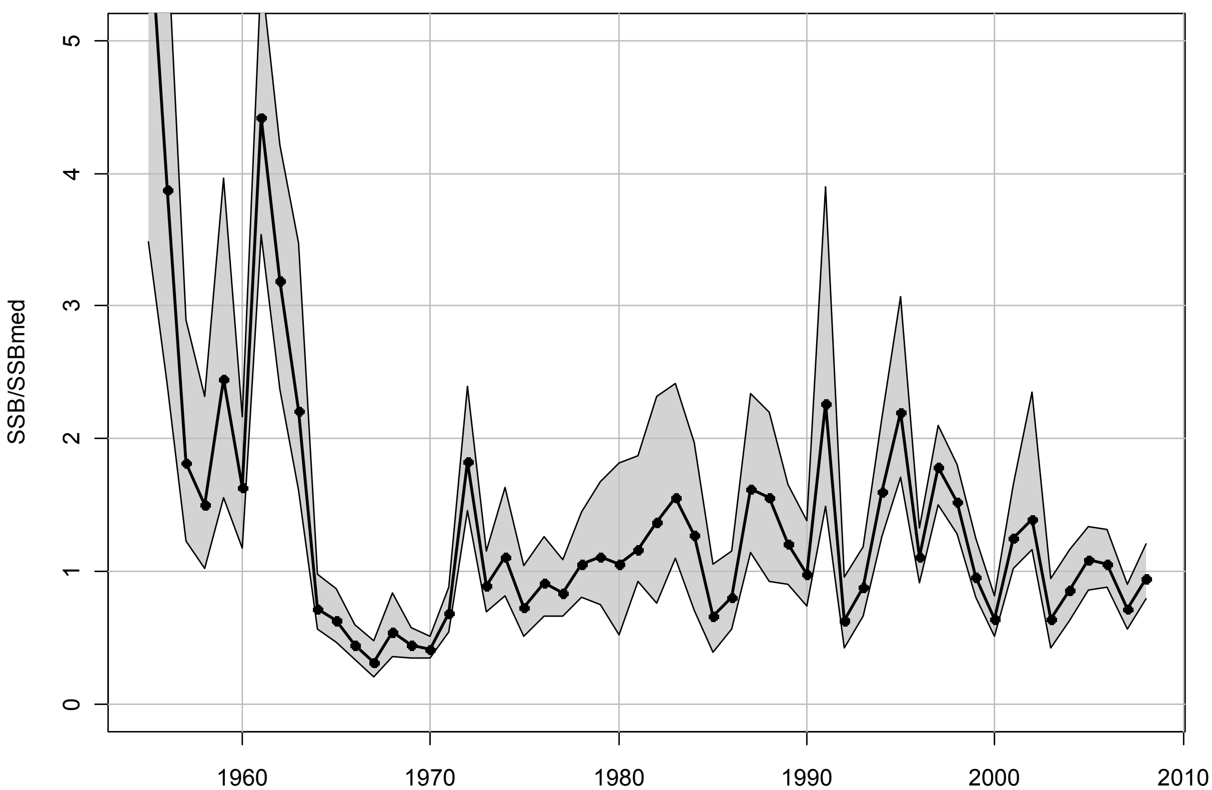


Figure 7.31 Phase plot of recent estimates of the population fecundity (mature ova in billions) and total N-weighted fishing mortality rate (age 2+) from the base BAM model.

[Solid vertical and horizontal lines indicate the targets and limits for each respective axis. Double digit number in circles indicates the year of the point estimate (e.g. 08 = 2008).]

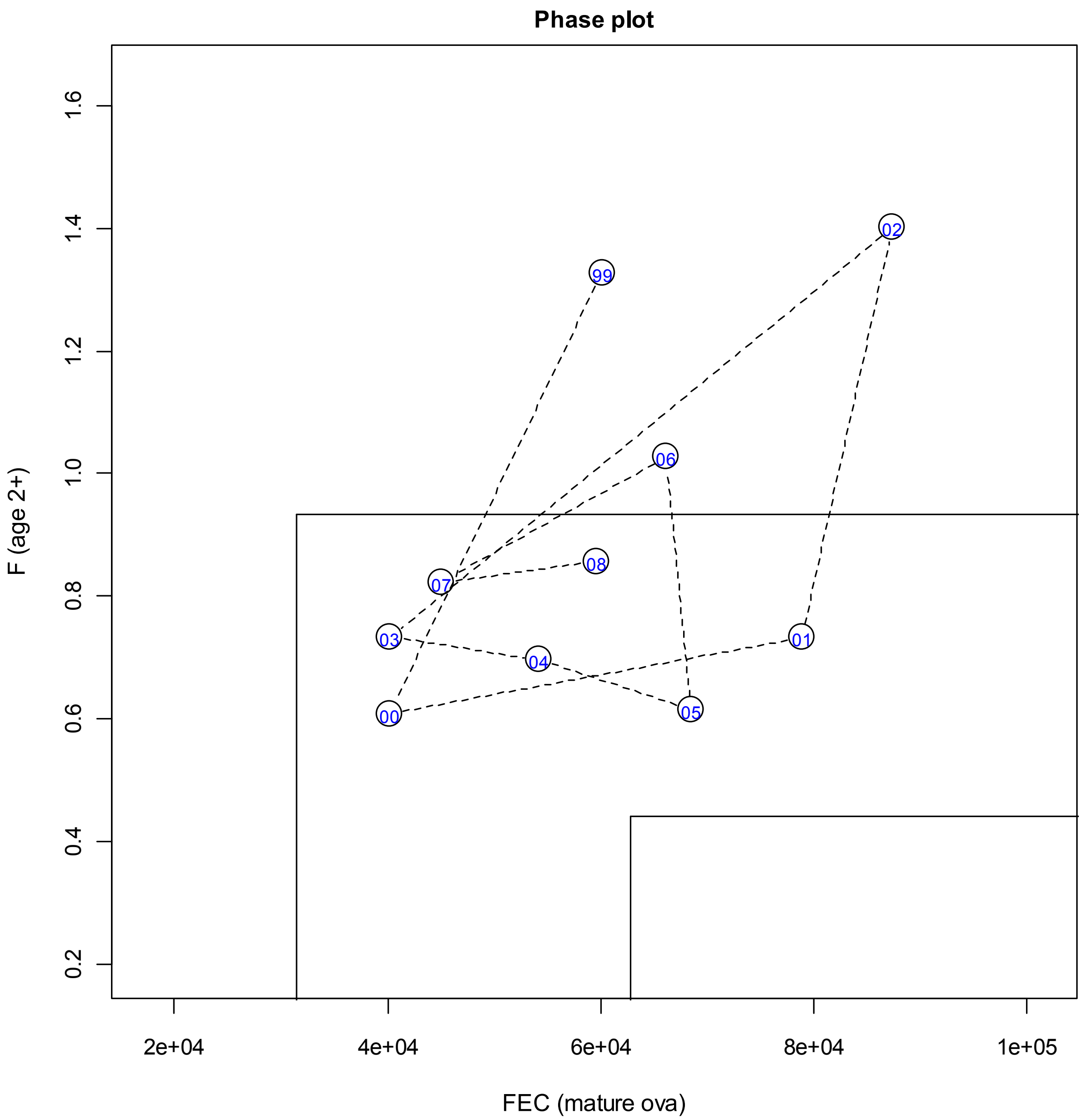


Figure 7.32 Cumulative probability density distribution of total N-weighted fishing mortality rate (age 2+) in 2008 relative to the fishing limit value (F_{MED}) from the bootstrap estimates from the base BAM model.

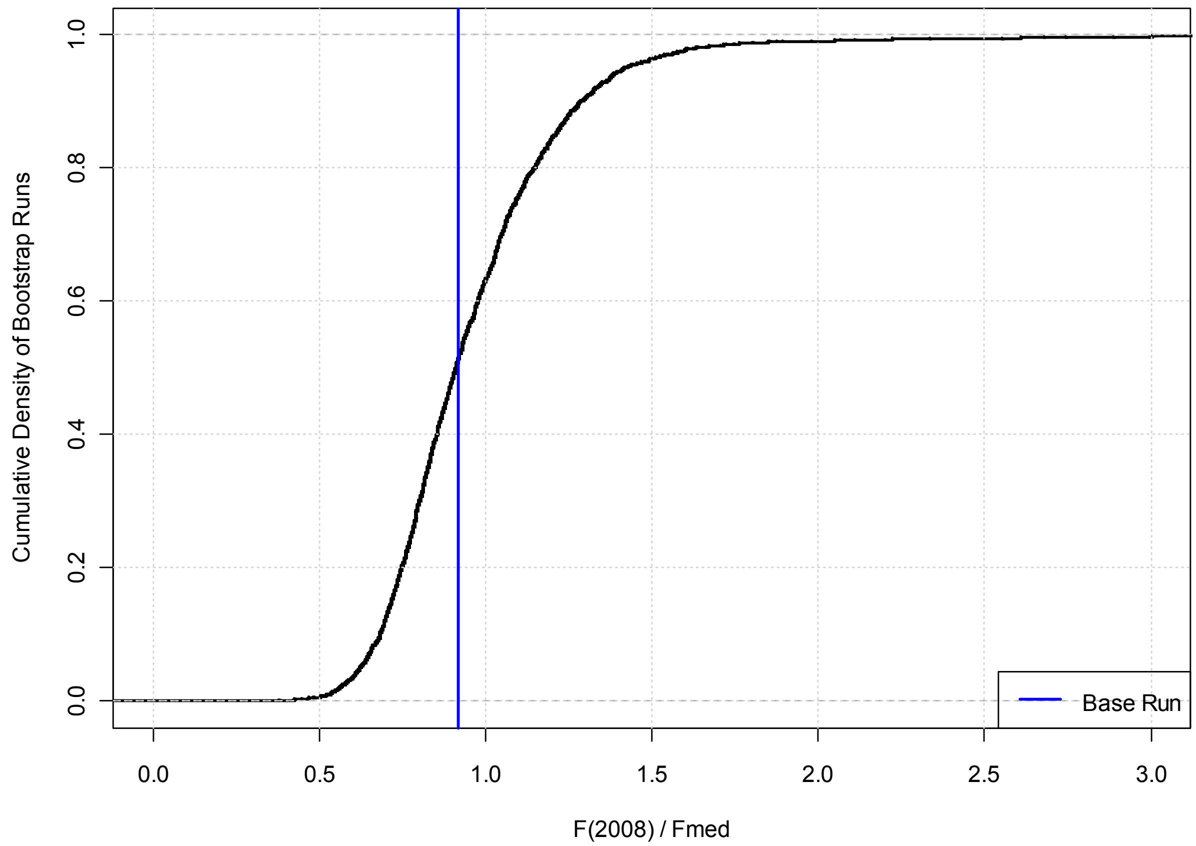


Figure 7.33 Cumulative probability density distribution of the population fecundity in 2008 relative to the limit value from the bootstrap estimates from the base BAM model.

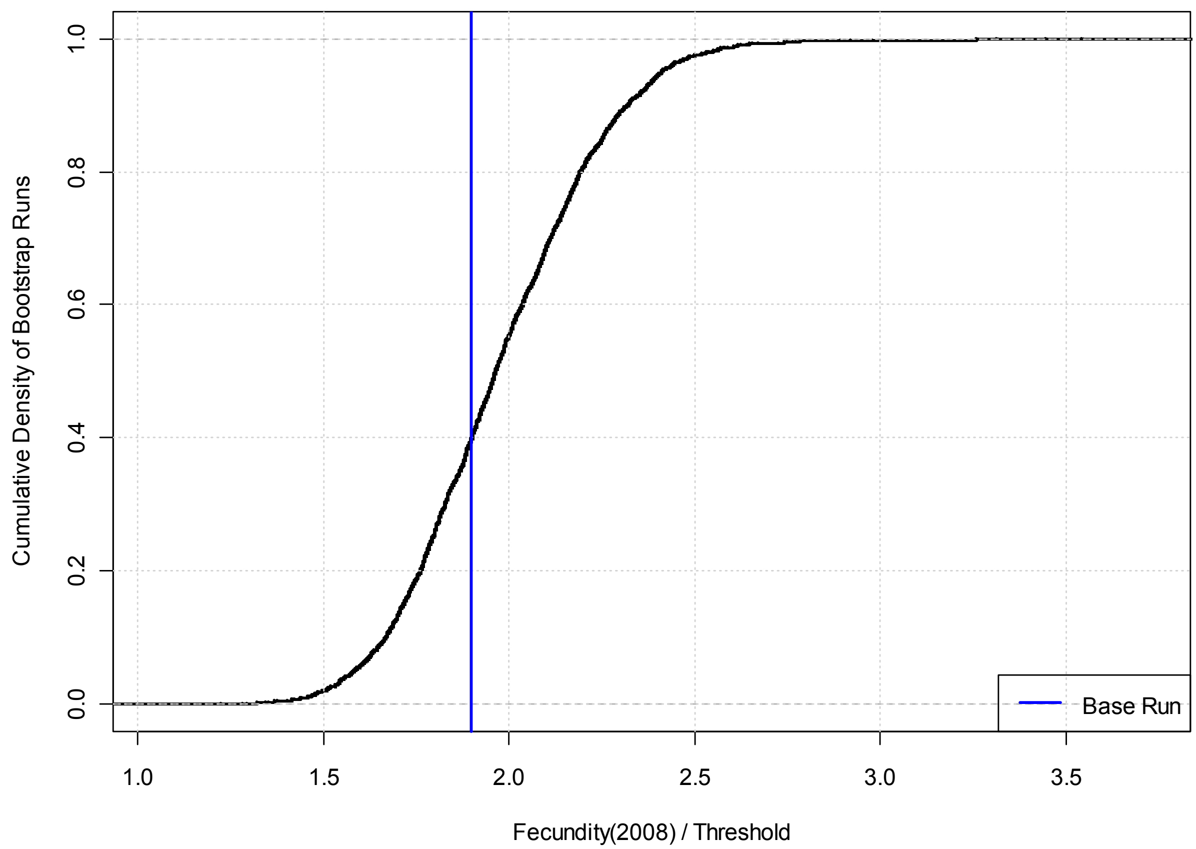


Figure 7.34 Scatter plot of the 2008 estimates relative to the benchmarks (limits) from the 2,000 bootstrap estimates from the base BAM model.

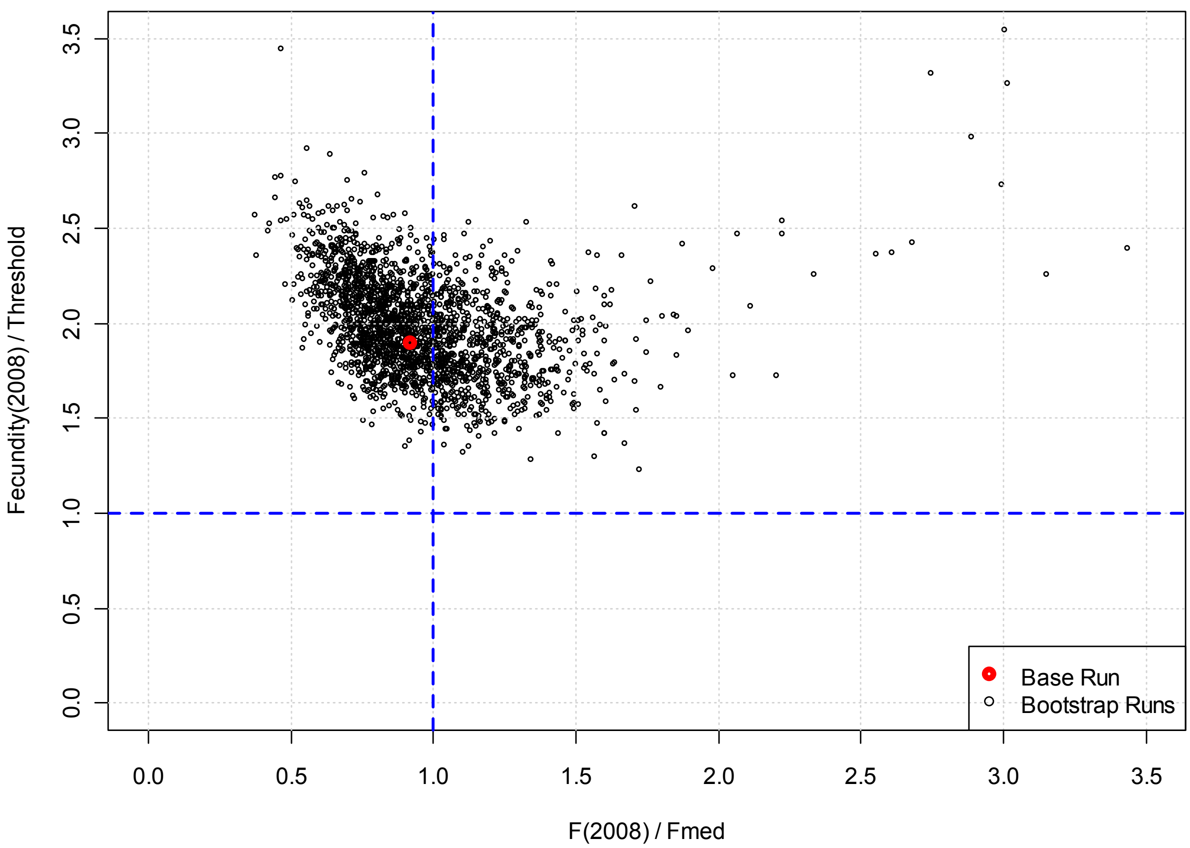


Figure 8.1. R/SSB plot for 1959 -2008. Horizontal lines represent average survival R/eggs for the 1970 - 1988 and 1989 – 2008 periods.

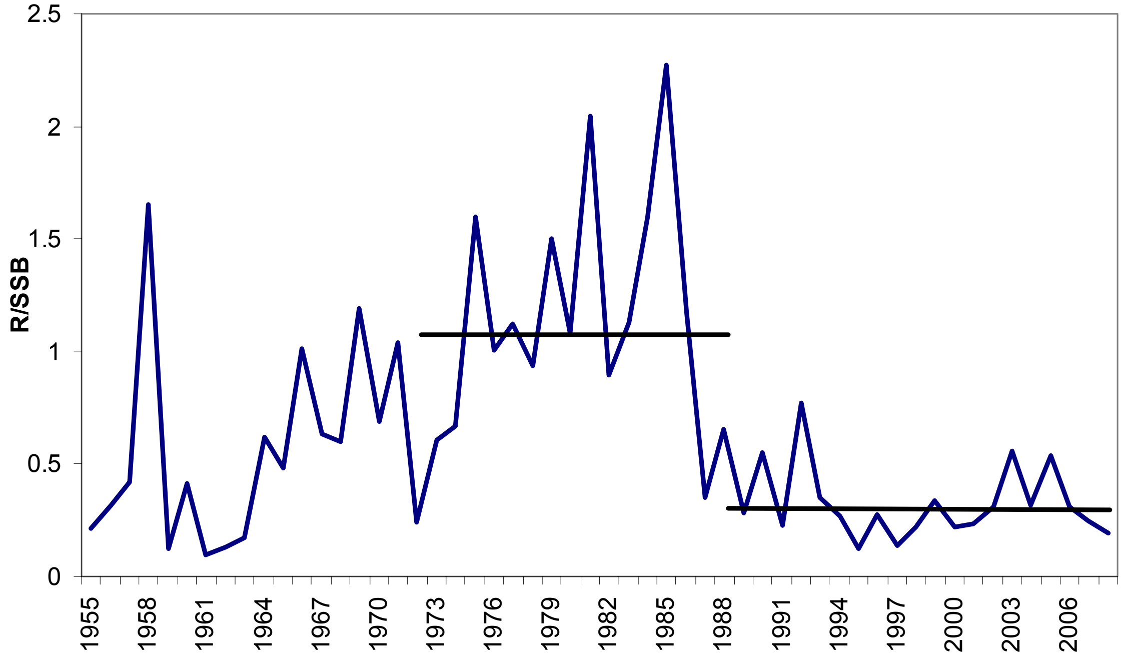


Figure 8.2. Recruitment (age 0) versus spawning stock total fecundity for 1959 - 2008.

[Blue points represent 1959 - 1988. Pink points represent 1989 - 2008. Dotted lines are medians for R/SSB for 1959-2008 and 1989-2008.]

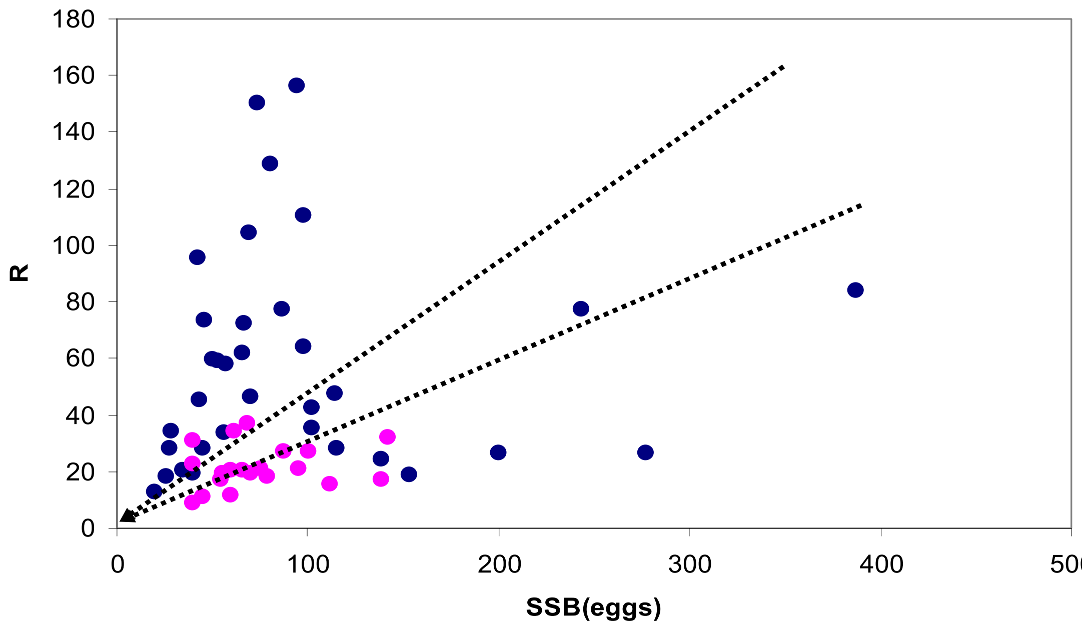


Figure 8.3 Plot of Atlantic menhaden fecundity (billions of mature ova) and age-0 recruitment (billions) estimates lagged by one year from the base BAM model.

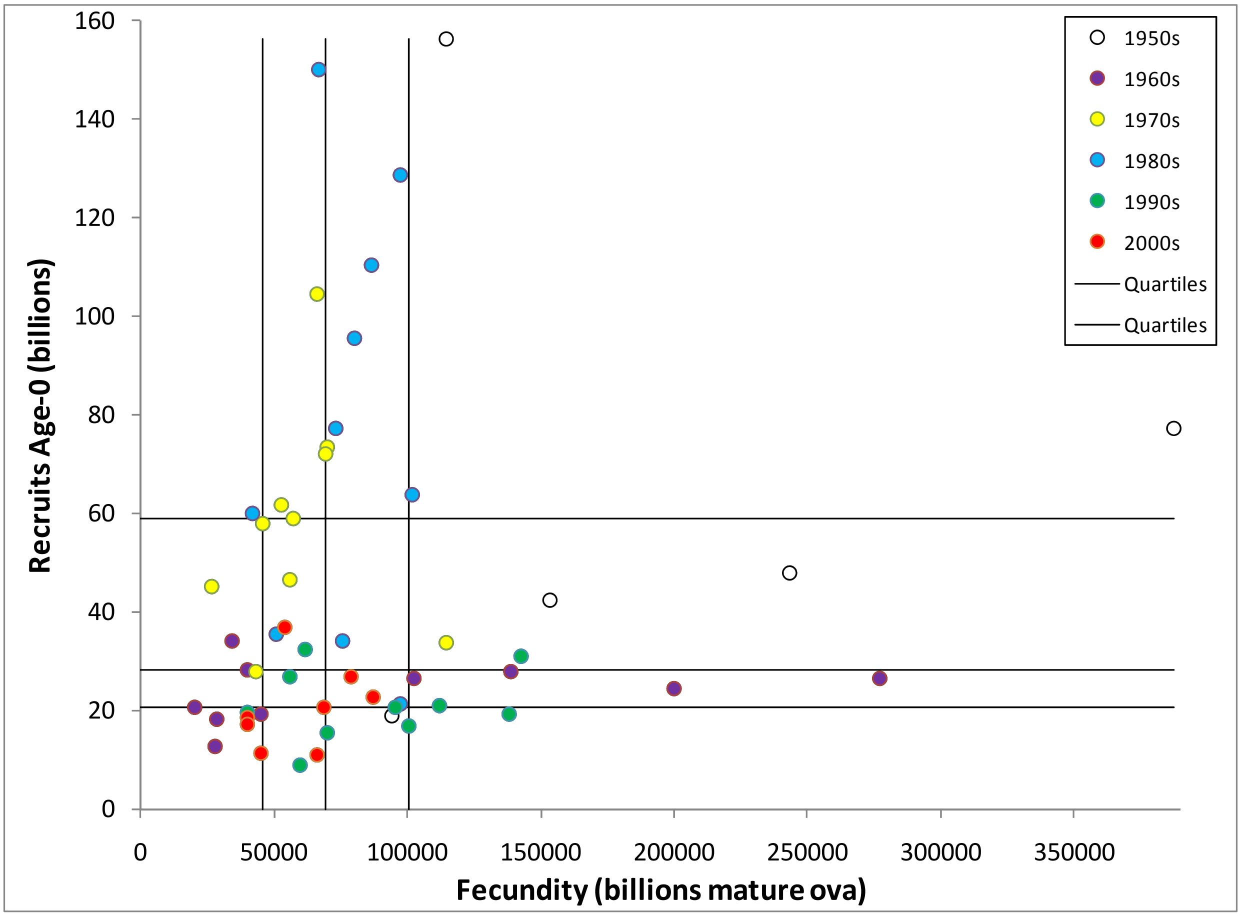


Figure 8.4. Annual fishing mortality rate (full F) relative to F_{MED} = 1.91 for base run (for comparison: F_{target} = 0.79).

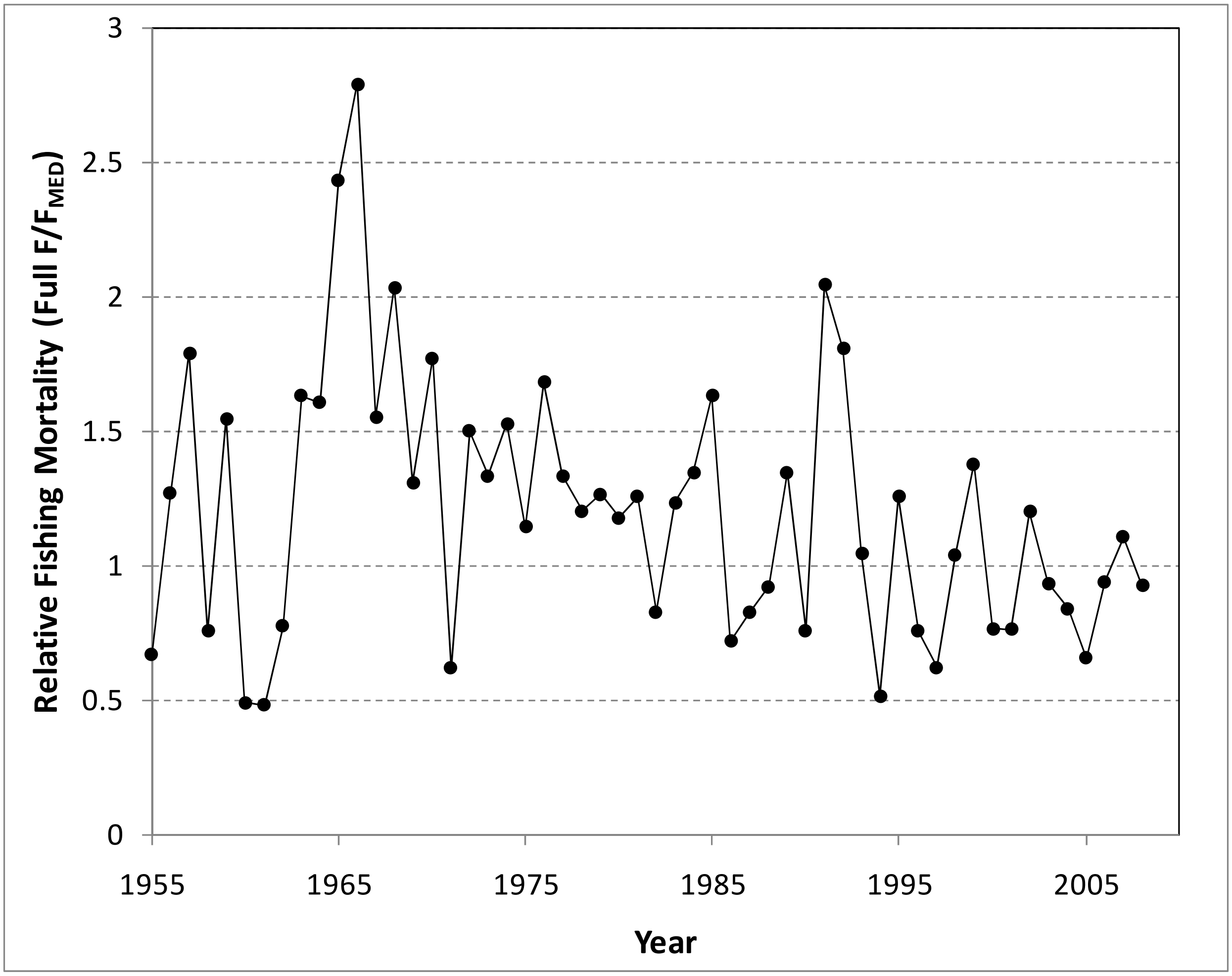
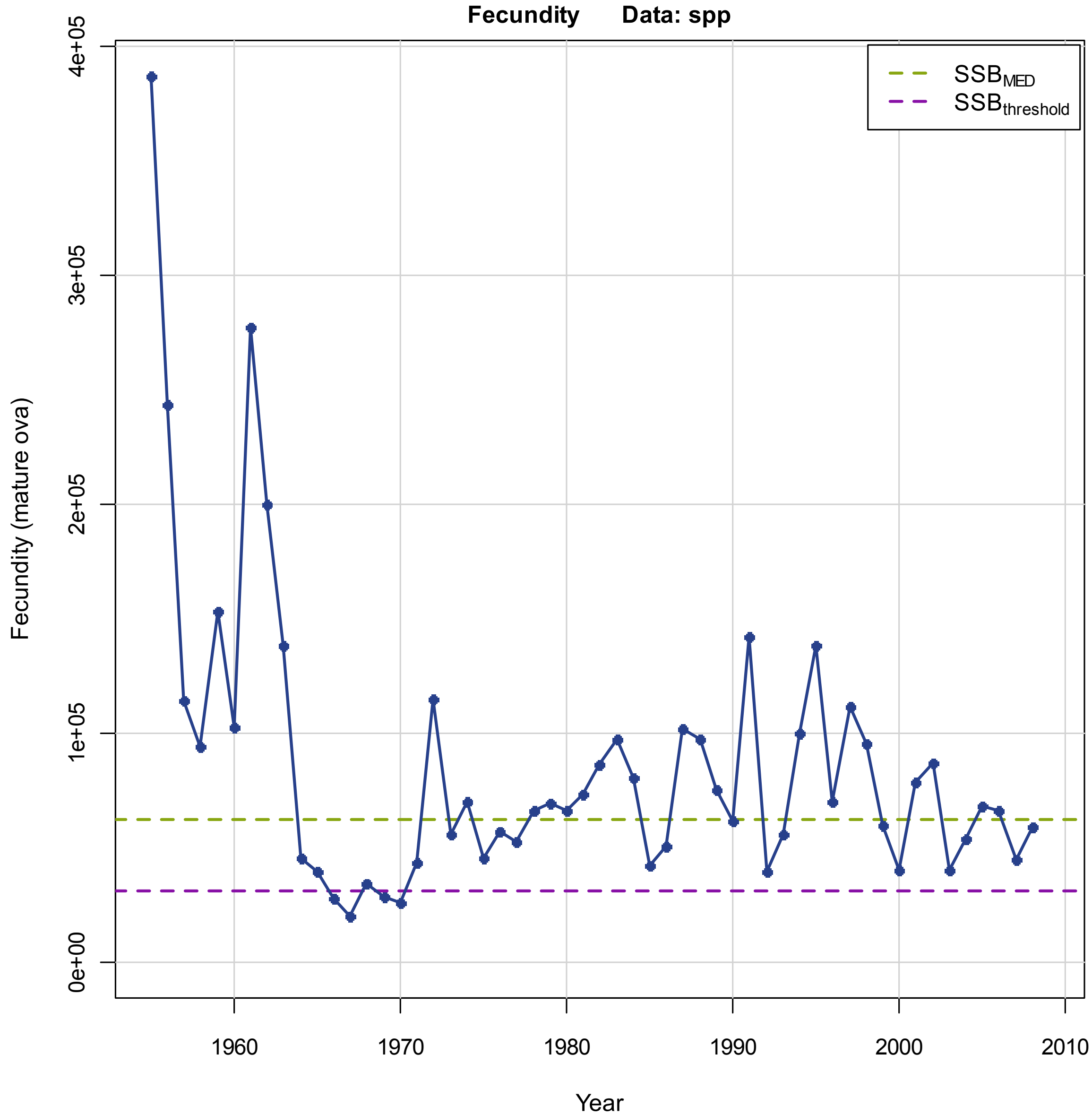


Figure 8.5. Annual fecundity compared to target and limit.



Appendices

A.1. Participants in Data and Assessment Workshops

A.2. MSVPA-X comparison for striped bass and weakfish.

A.3. BAM input file for base run

A.4. BAM program file

Appendix A.1. Listing of Participants in Data and Assessment Workshops

Data Workshop (May 12–13, 2009; Richmond, Virginia)

Subcommittee members and participants in attendance:

Douglas Vaughan, Chair, NOAA Fisheries Beaufort NC
Matt Cieri, ME DMR
Jason McNamee, RI DEM
Jeff Brust, NJ DEP
Alexei Sharov, MD DNR
Rob Latour, VIMS
Behzad Mahmoudi, FL DEP
Joseph Smith, NOAA Fisheries Beaufort NC
Erik Williams, NOAA Fisheries Beaufort NC
Julie Defilippi, ACCSP
Brad Spear, ASMFC
Genny Nesslage, ASMFC
Jerry Benson, CCA-VA
Ron Lukens, Omega Protein
Patrick Lynch, VIMS grad student
Bradley O'Bier, NOAA Fisheries Reedville VA
Bill Windley, ASMFC Menhaden Advisory Panel Chair

Assessment Workshop (October 19-22, 2009; Beaufort, North Carolina)

Stock Assessment Subcommittee Members:

Doug Vaughan (NOAA), Chair
Joe Smith (NOAA)
Erik Williams (NOAA)
Alexei Sharov (MD)
Matt Cieri (ME)
Genny Nesslage (ASMFC)
Jeff Brust (NJ)
Jason McNamee (RI)
Behzad Mahmoudi (FL)
Rob Latour (VIMS)
Brad Spear (ASMFC), Staff

Other Attendees:

Amy Schueller (NOAA)
Kyle Shertzer (NOAA)
Paul Conn (NOAA)
Rob Cheshire (NOAA)
Ron Lukens (Omega Protein)
Jeff Kaelin (Lunds Seafood)
Patrick Lynch (VIMS)

Appendix A.2. Comparison of abundance and fishing mortality estimates between single species assessments and MSVPA-X for striped bass and menhaden.

Figure A.1. Comparison of annual single species assessment and MSVPA-X abundance and fishing mortality estimates for striped bass.

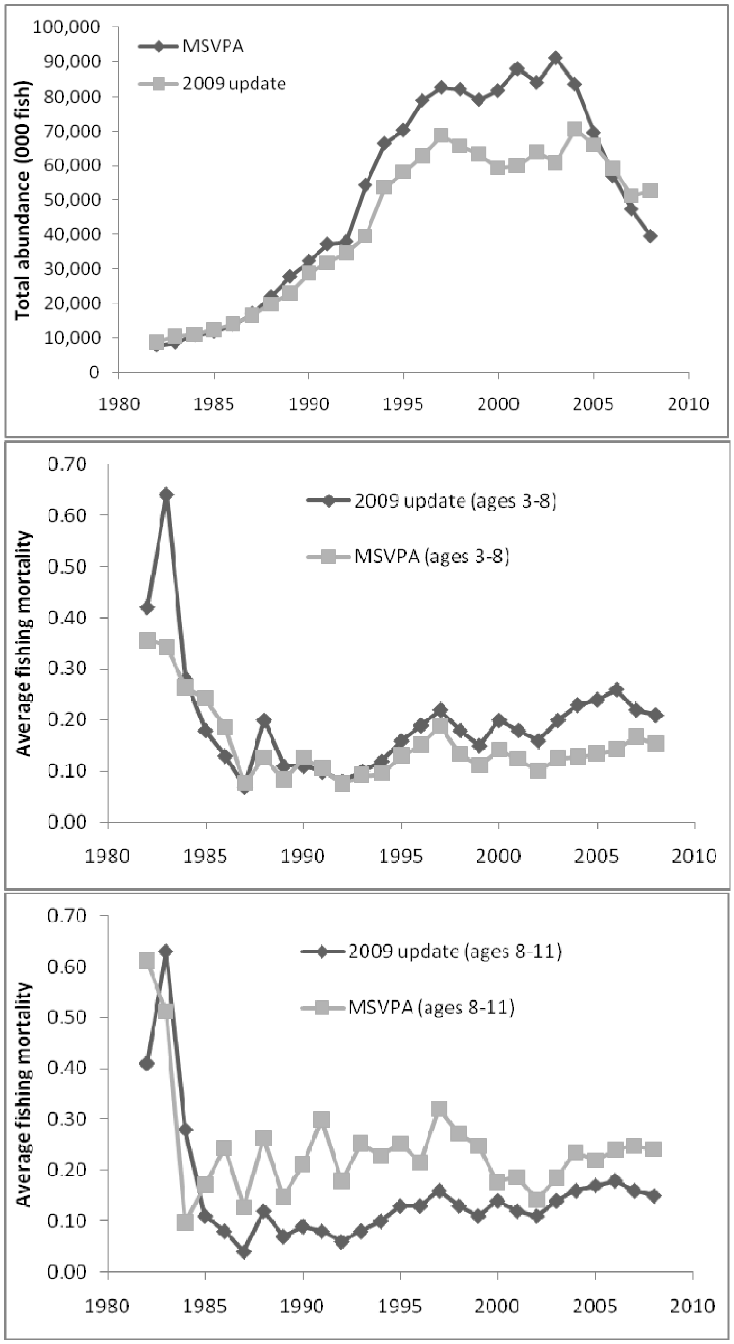
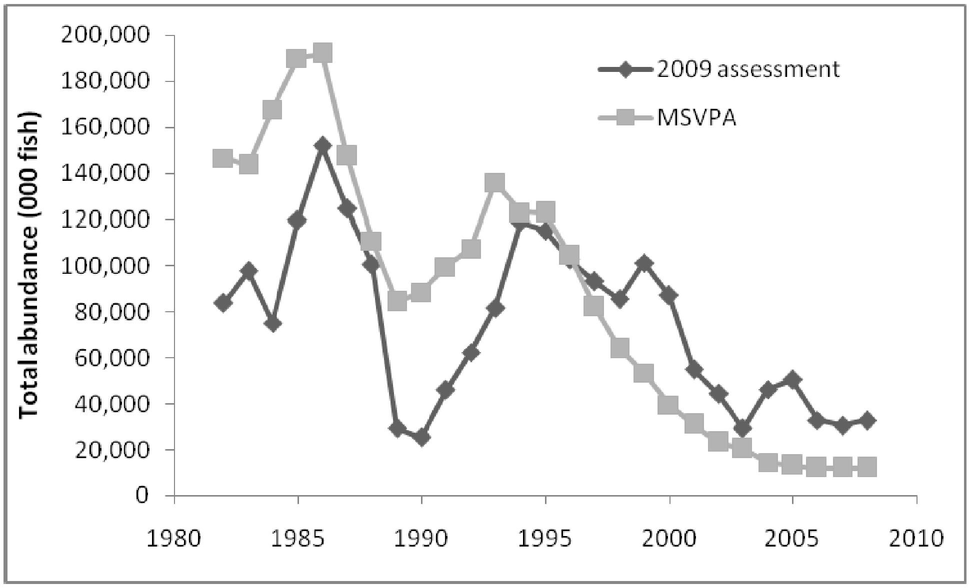
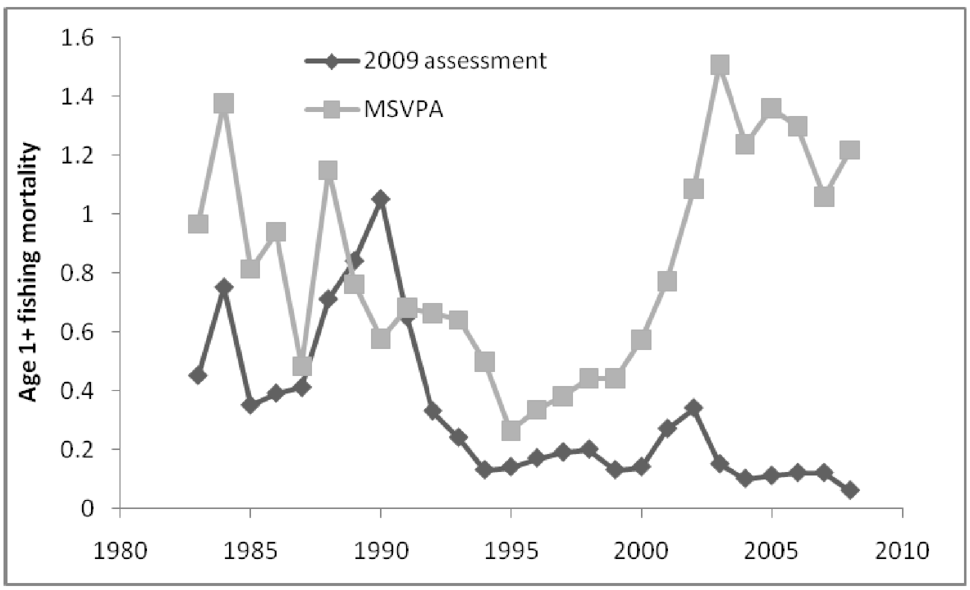


Figure A.2. Comparison of annual single species assessment and MSVPA-X abundance and fishing mortality estimates for weakfish.





Appendix A.3. AD Model Builder data file from the base BAM model.

```
##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
## Data Input File
## ASMFC Assessment: Atlantic Menhaden
##
##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>

#starting and ending year of model
1955
2008
#Starting year to estimate recruitment deviation from S-R curve
1955
#3 phases of constraints on recruitment deviations: allows possible heavier constraint in early and late period, with lighter
constraint in the middle
#ending years of recruitment constraint phases
1956
2007
#4 periods of changing selectivity for reduction fishery: yr1-1963, 1964-1975, 1976-1993, 1994-2008
#ending years of regulation period
1963
1975
1993

#starting and ending years to use for benchmark calculations
1955
2008

#Number of ages (last age is plus group)
9
##vector of agebins, last is a plus group
0 1 2 3 4 5 6 7 8

#max value of F used in spr and msy calculations
3.0
#number of iterations in spr calculations
30001
#number of iterations in msy calculations
30001
#Number years at end of time series over which to average sector Fs, for weighted selectivities
54
#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

##time-invariant vector of % maturity-at-age for females (ages 0-8+)
0       0       0.125   0.851   1       1       1       1       1
##time-invariant vector of % maturity-at-age for males (ages 0-8+)
1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0     1.0
#time-variant vector of proportion female (ages 0-8+)
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
#time of year (as fraction) for spawning: mid-April=115d/365d
0.0
#age-dependent natural mortality at age
1.140   0.897   0.673   0.559   0.508   0.483   0.468   0.468   0.468
#1.066  0.806   0.614   0.521   0.476   0.446   0.425   0.425   0.425
#age-independent natural mortality (used only to compute MSST=(1-M)SSBmsy)
0.45
#age and year specific natural mortality
```

1.140	**0.897**	**0.673**	**0.559**	**0.508**	**0.483**	**0.468**	**0.468**	**0.468**
1.140	**0.897**	**0.673**	**0.559**	**0.508**	**0.483**	**0.468**	**0.468**	**0.468**
1.140	**0.897**	**0.673**	**0.559**	**0.508**	**0.483**	**0.468**	**0.468**	**0.468**
1.140	**0.897**	**0.673**	**0.559**	**0.508**	**0.483**	**0.468**	**0.468**	**0.468**
1.140	**0.897**	**0.673**	**0.559**	**0.508**	**0.483**	**0.468**	**0.468**	**0.468**
1.140	**0.897**	**0.673**	**0.559**	**0.508**	**0.483**	**0.468**	**0.468**	**0.468**
1.140	**0.897**	**0.673**	**0.559**	**0.508**	**0.483**	**0.468**	**0.468**	**0.468**
1.140	**0.897**	**0.673**	**0.559**	**0.508**	**0.483**	**0.468**	**0.468**	**0.468**
1.140	**0.897**	**0.673**	**0.559**	**0.508**	**0.483**	**0.468**	**0.468**	**0.468**
1.140	**0.897**	**0.673**	**0.559**	**0.508**	**0.483**	**0.468**	**0.468**	**0.468**
1.140	**0.897**	**0.673**	**0.559**	**0.508**	**0.483**	**0.468**	**0.468**	**0.468**
1.140	**0.897**	**0.673**	**0.559**	**0.508**	**0.483**	**0.468**	**0.468**	**0.468**
1.140	**0.897**	**0.673**	**0.559**	**0.508**	**0.483**	**0.468**	**0.468**	**0.468**
1.140	**0.897**	**0.673**	**0.559**	**0.508**	**0.483**	**0.468**	**0.468**	**0.468**
1.140	**0.897**	**0.673**	**0.559**	**0.508**	**0.483**	**0.468**	**0.468**	**0.468**
1.140	**0.897**	**0.673**	**0.559**	**0.508**	**0.483**	**0.468**	**0.468**	**0.468**
1.140	**0.897**	**0.673**	**0.559**	**0.508**	**0.483**	**0.468**	**0.468**	**0.468**
1.140	**0.897**	**0.673**	**0.559**	**0.508**	**0.483**	**0.468**	**0.468**	**0.468**
1.140	**0.897**	**0.673**	**0.559**	**0.508**	**0.483**	**0.468**	**0.468**	**0.468**
1.140	**0.897**	**0.673**	**0.559**	**0.508**	**0.483**	**0.468**	**0.468**	**0.468**
1.140	**0.897**	**0.673**	**0.559**	**0.508**	**0.483**	**0.468**	**0.468**	**0.468**
1.140	**0.897**	**0.673**	**0.559**	**0.508**	**0.483**	**0.468**	**0.468**	**0.468**
1.140	**0.897**	**0.673**	**0.559**	**0.508**	**0.483**	**0.468**	**0.468**	**0.468**
1.140	**0.897**	**0.673**	**0.559**	**0.508**	**0.483**	**0.468**	**0.468**	**0.468**
1.140	**0.897**	**0.673**	**0.559**	**0.508**	**0.483**	**0.468**	**0.468**	**0.468**
1.140	**0.897**	**0.673**	**0.559**	**0.508**	**0.483**	**0.468**	**0.468**	**0.468**
1.140	**0.897**	**0.673**	**0.559**	**0.508**	**0.483**	**0.468**	**0.468**	**0.468**
1.624	**1.350**	**0.993**	**0.826**	**0.597**	**0.527**	**0.506**	**0.506**	**0.506**
1.487	**1.272**	**0.917**	**0.662**	**0.586**	**0.516**	**0.495**	**0.495**	**0.495**
1.313	**1.123**	**0.845**	**0.595**	**0.524**	**0.506**	**0.468**	**0.468**	**0.468**
1.314	**1.128**	**0.930**	**0.610**	**0.521**	**0.516**	**0.499**	**0.499**	**0.499**
1.279	**1.106**	**0.863**	**0.675**	**0.525**	**0.516**	**0.532**	**0.532**	**0.532**
1.117	**0.936**	**0.757**	**0.602**	**0.511**	**0.495**	**0.499**	**0.499**	**0.499**
1.044	**0.940**	**0.711**	**0.581**	**0.516**	**0.493**	**0.489**	**0.489**	**0.489**
0.950	**0.789**	**0.678**	**0.565**	**0.510**	**0.490**	**0.482**	**0.482**	**0.482**
0.981	**0.736**	**0.603**	**0.537**	**0.500**	**0.486**	**0.476**	**0.476**	**0.476**
0.948	**0.814**	**0.609**	**0.526**	**0.501**	**0.491**	**0.481**	**0.481**	**0.481**
0.900	**0.670**	**0.588**	**0.503**	**0.481**	**0.451**	**0.452**	**0.452**	**0.452**
0.986	**0.802**	**0.562**	**0.519**	**0.485**	**0.458**	**0.429**	**0.429**	**0.429**
0.993	**0.783**	**0.596**	**0.504**	**0.483**	**0.460**	**0.432**	**0.432**	**0.432**
1.089	**0.764**	**0.584**	**0.514**	**0.497**	**0.473**	**0.448**	**0.448**	**0.448**
1.038	**0.778**	**0.540**	**0.482**	**0.467**	**0.459**	**0.442**	**0.442**	**0.442**
1.062	**0.793**	**0.541**	**0.470**	**0.453**	**0.450**	**0.443**	**0.443**	**0.443**
1.118	**0.853**	**0.564**	**0.478**	**0.445**	**0.448**	**0.450**	**0.450**	**0.450**
1.124	**0.763**	**0.588**	**0.496**	**0.466**	**0.448**	**0.464**	**0.464**	**0.464**
1.096	**0.732**	**0.548**	**0.495**	**0.475**	**0.461**	**0.454**	**0.454**	**0.454**
1.137	**0.785**	**0.570**	**0.510**	**0.483**	**0.474**	**0.465**	**0.465**	**0.465**
1.143	**0.842**	**0.591**	**0.516**	**0.504**	**0.479**	**0.471**	**0.471**	**0.471**
1.114	**0.841**	**0.618**	**0.533**	**0.492**	**0.479**	**0.458**	**0.458**	**0.458**
1.241	**0.895**	**0.673**	**0.557**	**0.535**	**0.487**	**0.465**	**0.465**	**0.465**
1.199	**0.997**	**0.653**	**0.565**	**0.526**	**0.496**	**0.458**	**0.458**	**0.458**
1.212	**0.962**	**0.696**	**0.572**	**0.538**	**0.500**	**0.463**	**0.463**	**0.463**
1.149	**0.895**	**0.723**	**0.585**	**0.536**	**0.497**	**0.464**	**0.464**	**0.464**
1.130	**0.863**	**0.639**	**0.605**	**0.550**	**0.498**	**0.463**	**0.463**	**0.463**

##Spawner-recruit parameters
#switch for S-R function to use Ricker (1) or Beverton-Holt (2)
2
#steepness (fixed or initial guess)
0.99
#standard error of steepness (from meta-analysis)

0.2
#log_R0 - log virgin recruitment
2.7
R autocorrelation
0.0

##--><>--><>--><>-- Weight-at-age in the fishery (g) --><>--><>--><>--><>--><>--><>--><>--><>--><>

36.2	124.3	274.3	390.3	451.5	523.3	610.8	681.9	674.8
25.2	105.1	267.1	428.1	498.1	558.8	601.7	633.0	710.4
41.2	91.3	230.8	413.4	553.1	595.6	645.8	668.9	649.8
22.8	109.9	231.7	382.2	555.5	655.8	686.9	719.8	728.9
60.5	75.2	231.4	373.5	507.5	643.9	697.1	726.6	739.2
32.2	129.6	189.6	375.4	513.3	636.2	738.3	752.7	789.3
48.3	116.0	258.4	336.7	512.9	618.3	727.6	789.9	771.3
60.1	131.0	267.1	394.1	466.5	591.0	644.3	731.1	754.8
63.5	145.6	257.7	424.9	567.3	635.0	727.1	742.6	835.6
67.1	150.4	281.1	380.3	550.2	721.1	767.2	811.7	786.5
53.0	145.8	275.5	386.3	462.2	621.2	835.8	853.3	852.3
66.8	121.9	278.1	387.7	455.6	509.7	648.2	899.7	887.3
62.1	157.6	252.4	434.2	507.2	535.7	581.5	722.8	1063.5
74.7	128.1	316.8	424.3	583.3	596.3	583.3	620.6	751.8
83.3	152.8	268.9	500.0	649.2	759.4	705.9	655.1	689.9
58.7	185.4	269.3	419.1	595.1	790.4	814.4	705.8	631.7
50.6	169.4	341.9	406.3	589.4	654.5	905.8	844.3	695.9
24.7	122.7	328.9	493.1	566.4	800.0	713.2	1048.6	897.8
43.1	121.1	263.3	475.2	636.9	752.9	1039.3	764.4	1175.1
28.7	103.4	263.0	408.7	582.0	764.0	968.3	1344.6	817.8
27.1	84.5	214.8	379.8	560.5	666.2	877.0	1204.4	1682.8
17.3	67.4	192.4	345.3	474.1	732.6	761.3	1023.0	1543.4
20.2	64.4	151.3	317.3	471.6	533.0	878.5	821.9	1126.2
28.4	68.7	163.2	252.6	420.4	556.1	543.8	944.0	817.6
24.8	68.7	168.8	279.1	366.8	516.4	638.4	562.1	1028.2
21.7	56.6	148.1	288.8	391.6	482.0	593.8	702.3	573.1
19.5	68.2	118.8	239.7	396.9	475.8	575.8	637.1	732.7
26.7	76.2	167.7	212.4	341.0	486.7	533.9	643.0	650.7
31.4	70.8	171.6	258.4	303.4	414.5	534.0	553.5	675.8
25.6	71.9	165.8	291.7	368.6	440.4	525.8	623.9	621.0
22.6	68.4	139.3	260.6	374.2	430.8	546.0	579.3	641.6
24.3	64.4	149.8	230.7	375.2	470.7	516.2	715.8	683.0
26.6	75.5	153.6	249.4	338.2	476.8	533.3	566.0	847.6
27.8	69.4	159.9	241.3	329.2	429.6	541.5	556.9	580.4
39.1	91.1	150.3	256.1	341.1	427.5	567.7	657.1	632.2
35.8	113.1	208.5	248.2	340.4	419.4	494.0	670.6	713.7
52.0	92.8	224.1	309.7	334.8	393.4	461.9	521.5	723.5
28.3	123.1	186.4	318.7	392.3	420.5	445.0	512.0	565.8
49.8	93.4	243.6	294.7	396.0	457.6	501.1	488.5	553.9
23.5	118.8	214.3	355.7	395.0	450.3	504.8	572.6	523.3
22.6	112.6	229.7	331.8	423.1	453.4	456.3	501.1	586.3
17.0	96.5	288.8	371.6	483.5	529.8	564.3	517.7	564.7
28.8	87.6	246.6	447.0	491.0	594.2	585.9	625.8	536.0
60.3	93.9	227.2	390.9	547.0	574.4	662.1	608.2	654.1
39.1	131.1	214.0	354.9	496.6	597.8	627.1	699.9	612.1
27.1	131.5	252.7	345.5	456.5	577.9	633.4	674.5	736.3
55.0	125.1	280.6	382.9	462.1	522.0	624.5	643.7	697.6
40.4	149.4	290.1	422.1	526.3	581.0	588.9	683.6	677.6
49.5	121.7	277.0	440.1	557.5	701.6	725.3	678.0	779.9
27.0	113.9	238.6	339.2	482.6	572.9	738.6	722.8	638.4
37.3	81.3	214.5	328.6	369.5	495.8	572.7	760.5	714.6
45.3	111.1	185.4	321.5	411.2	407.1	537.6	619.3	862.4
50.2	119.8	219.0	297.3	390.9	434.4	399.2	514.3	588.0
52.4	123.8	247.9	313.7	424.9	473.5	479.2	419.4	539.6

##--><>--><>--><>-- Weight-at-age for the spawning population - start of year (g) --><>--><>--><>--><>

21.2	66.1	191.5	332.3	387.5	476.8	474.8	618.8	442.8
12.0	55.8	194.2	356.7	448.7	511.9	568.6	631.7	706.1
25.9	41.6	163.5	342.6	499.2	554.5	612.4	645.4	649.8
12.4	61.2	158.6	310.0	494.6	618.3	654.1	697.0	712.8
43.1	36.4	166.3	301.5	443.6	598.2	673.6	702.6	724.9
15.7	79.6	126.2	303.5	449.5	580.6	703.2	737.4	770.8
29.7	55.1	190.0	260.8	445.3	568.6	683.7	765.1	762.0
38.3	77.2	193.1	324.1	397.6	539.8	612.8	702.6	740.3
42.1	85.0	194.3	353.4	490.5	565.4	680.6	717.7	811.8
45.9	90.8	215.1	323.4	494.2	648.1	706.2	774.5	769.1
36.5	88.2	209.0	332.1	418.4	581.6	770.7	802.7	823.6
43.5	73.5	208.7	329.8	417.4	479.5	622.8	847.0	849.1
47.0	91.6	180.8	358.2	455.9	506.7	558.3	704.2	1013.1
57.4	83.5	238.3	338.3	513.2	557.0	563.9	604.7	739.7
55.0	101.8	197.4	422.2	550.8	694.6	674.7	641.4	678.3
31.6	111.0	202.5	331.2	535.5	699.4	764.7	684.9	623.4
32.2	90.9	259.0	329.3	490.3	611.9	826.2	807.4	682.1
8.4	69.4	247.0	414.9	479.4	686.5	681.7	974.8	868.6
27.5	52.9	193.1	410.7	571.3	661.0	917.6	742.2	1110.9
16.5	58.7	192.3	334.8	535.4	709.2	868.1	1206.4	801.3
17.8	44.3	157.5	329.6	490.8	634.8	833.5	1099.7	1532.6
8.5	37.8	135.8	284.2	441.7	667.1	739.5	986.9	1427.3
10.8	29.4	106.1	256.9	415.2	514.2	822.2	807.9	1098.2
19.1	33.5	110.4	199.7	368.2	511.4	534.1	901.3	809.4
17.5	39.8	115.1	221.4	310.3	473.0	602.7	556.9	994.5
11.8	33.9	105.6	228.7	338.0	426.4	559.6	675.0	570.4
9.7	33.6	83.4	190.1	340.4	431.6	524.9	611.6	712.6
16.2	36.9	117.7	165.5	291.2	440.7	501.4	601.3	633.4
22.3	38.3	119.6	208.9	250.4	369.0	498.6	530.2	642.0
15.4	44.1	116.9	236.4	321.4	377.9	481.5	594.3	602.8
13.0	36.8	101.2	208.4	328.1	393.0	482.0	541.5	619.8
13.9	32.7	105.2	182.3	320.4	430.7	483.5	643.0	646.8
16.6	40.1	108.1	201.4	285.3	427.8	503.5	541.5	776.6
13.9	38.5	115.2	195.3	286.2	377.6	501.3	535.9	562.8
21.9	43.5	105.5	208.6	295.3	386.6	510.6	619.2	615.0
22.6	60.9	148.3	198.1	299.2	380.7	460.5	616.7	683.1
33.2	53.4	168.9	259.2	288.7	362.5	433.0	497.0	677.9
15.3	71.5	135.9	272.7	353.0	378.0	420.6	488.9	546.2
32.5	47.0	184.2	242.5	362.5	429.8	464.4	470.3	536.3
8.3	69.0	149.5	301.5	346.5	427.0	485.4	541.1	509.6
9.6	47.5	171.4	269.7	383.3	415.7	442.4	489.4	562.9
6.0	41.5	201.3	308.5	422.2	496.7	530.1	507.8	556.1
15.5	35.1	168.8	374.3	435.2	543.7	562.1	599.0	529.7
41.8	46.8	154.5	319.4	498.0	530.2	624.2	592.1	634.2
19.1	80.5	149.5	290.7	441.9	567.7	593.9	672.4	601.5
9.6	65.1	188.6	279.0	407.9	538.4	615.2	649.6	716.2
31.8	54.9	207.1	317.3	404.3	489.2	598.2	633.3	679.8
21.8	87.0	213.1	361.6	463.1	532.3	566.7	665.6	671.3
32.3	62.6	218.1	379.1	509.8	637.8	681.5	661.5	766.2
15.6	67.9	177.8	303.4	449.1	545.2	690.7	693.3	629.1
19.8	43.1	162.9	283.0	349.9	478.4	557.0	725.2	694.9
28.0	58.0	129.0	270.4	377.3	395.4	527.5	609.0	831.7
21.1	68.6	166.6	238.9	351.3	414.2	393.3	509.4	582.5
23.0	56.5	181.8	271.8	365.5	440.3	465.7	416.0	536.9

##--><>--><>--><>-- Fecundity-at-age - not adjusted for maturity (g) --><>--><>--><>--><>

13463	27660	71747	135469	165103	219032	217740	321215	197636
10233	24296	72102	146296	198365	238715	278272	326059	387985
15428	20472	60931	137238	224019	259559	299712	323917	327225

10666	26237	57710	117364	211476	289036	313736	344903	356689
20917	18821	61418	116011	187290	282759	336617	358600	376132
12263	32755	47772	115336	185702	261358	343690	368737	394034
17011	25036	70012	97435	183960	254960	331452	391833	389392
18151	29948	70150	128512	168105	259983	315659	392635	427908
19711	32553	68999	135948	208853	255173	335926	364507	443039
20457	33674	75370	119892	207922	307939	351183	406166	401612
18237	34048	75932	128808	172836	273148	420039	448402	467517
20068	29310	77431	132904	181346	220185	325457	538380	540608
21964	35909	66557	143144	195394	225602	258464	364216	656569
24285	32187	86618	130604	226649	254766	259346	287397	391507
22385	35628	65678	158388	227292	319609	305825	283479	308310
16182	40033	71523	125826	239545	358396	413289	346808	300046
16345	34342	98269	132074	227586	318080	521103	500891	378173
8763	28730	96288	185087	226597	390623	386319	708822	578342
14754	22426	70424	178248	289225	364405	639178	441371	912764
11782	25141	71533	135920	257501	396200	553580	1001315	483573
12253	20637	57577	130162	220146	320777	494628	799846	1507572
9077	18868	49093	103812	177278	313545	365766	578387	1105788
10058	16325	39217	90510	157887	207920	406384	395594	645832
12879	17450	40638	70425	139391	212757	225751	491521	414559
12366	19345	41904	77701	112508	189067	263044	235543	565097
10294	17459	38722	79681	123164	163676	234456	305897	240762
9663	17774	32855	67809	127673	170870	220932	272912	340566
11321	17653	41867	57673	106595	180427	215633	280868	303798
13532	18542	44385	77593	95158	153582	232534	254408	340344
10981	19719	41641	84316	121001	148589	206248	280104	286135
10385	18098	38260	77328	131778	166631	220916	261679	321083
11194	17507	40211	66869	124164	179809	209812	314420	317127
11694	19044	39900	72507	107028	178377	223223	247684	430450
10781	18729	43140	72525	112059	159064	235350	259482	279125
14167	21067	40486	76556	111879	154549	222090	290944	288137
14328	26370	54852	72906	114475	153221	195960	294199	342191
17301	23607	63019	100508	114209	151802	192481	233508	372828
11794	30181	52052	107864	147453	160861	185035	227120	265781
17271	21825	68848	92673	150265	187929	208910	212599	256089
9100	29252	56433	119239	141157	184363	219109	255020	234350
9443	22337	66500	110187	171898	191874	209152	241463	296939
8052	20339	74449	119511	176526	219312	240032	226078	256774
11702	18123	61582	149569	181602	246020	257940	282628	237196
20099	21649	56881	125462	224089	244805	310820	287369	318397
12914	32600	56379	115806	198170	283248	302967	366460	308808
9448	27803	71927	111449	180157	265805	324435	352755	411527
16749	24031	79355	131544	181048	237106	320982	350990	393221
12987	32813	77921	148231	208483	255753	281249	362328	367363
16723	25692	76840	145560	215084	296236	327068	312738	391655
11381	27874	65996	121075	202863	268489	387280	389664	334063
12405	19744	61521	116790	154373	241983	306415	475127	441406
15423	24841	48597	107766	164962	175774	265745	331510	555314
2563	27610	63581	96542	160275	203292	188400	279302	347428
2563	2563	68958	110408	162892	212289	230685	195515	286783

##--><>--><>--><>-- Juvenile Abundance Index from seine surveys --><>--><>--><>--><>--><>
##Switch to use single index (=1) or let model combine indices (not equal to 1)
1
##Starting and ending years of time series, respectively
1959
2008
##Observed CPUE (numbers) and CV vectors, respectively
5.750801 3.603601 2.349221 41.41866 6.247221 1.71665 3.1228 2.644466 1.430185 11.390287 10.877719 3.25509 46.439433 18.004169 34.811355 75.246895 99.399895

```
        119.951046      195.337198      69.817846       60.591416       96.428657       145.325256
        65.270146       46.196682       65.19235 71.233884      53.46075 17.926022      35.898472
        28.725499       38.383986       38.008169       30.785115       11.215752       19.848584
        17.514069       19.271607       16.332323       24.695283       47.967632       15.518712
        15.747987       24.225217       26.762735       17.203377       43.507604       7.403461
        24.021313       13.199752
0.6149945       0.412245 0.6160166      0.5175259       0.6059944       0.6200932       0.4278114
        0.4703037       0.7686192       0.4633106       0.3882979       0.4985982       0.3803475
        0.2439761       0.2031494       0.1462078       0.1691979       0.1807786       0.1408642
        0.1947331       0.2519605       0.1905337       0.1827339       0.1738832       0.1962348
        0.1773661       0.1731615       0.168699 0.1597693      0.166871 0.1596836      0.1524848
        0.1479088       0.1606522       0.1832679       0.1860425       0.1733196       0.1620341
        0.1871491       0.1951792       0.1807595       0.1645394       0.1669403       0.1965344
        0.1854634       0.1703203       0.1428576       0.1330186       0.1542845       0.1482553

##--><>--><>--><>-- Juvenile Abundance Indices (4 groups) from seine surveys --><>--><>--><>--><>--><>
##Series 1 Observed CPUE (numbers) and CV vectors, respectively
##must have zeros in place of missing values and all series must be the same length as single index above
3.2151464       2.0907619       1.296065 24.0666941     3.4964167       0.962149 1.7673552
        1.4678251       0.8035215       6.4005171       6.2359334       1.8481459       26.5419328
        10.423499       17.788682       39.1936394      50.5308363      73.2540075      112.3537838
        37.3330648      36.1268775      49.2822717      73.5580815      30.3372085      24.0607934
        40.1662515      47.8323004      45.4911007      23.9066903      42.5253985      23.1469572
        33.018126       34.2912605      14.6780396      11.4196804      11.3316663      9.4401652
        13.8334461      7.2871333       6.8303088       9.1563389       3.1189741       9.8610045
        2.9694595       9.1957716       7.3823787       29.5901617      4.3980814       8.6606127
        12.1693148
0.6196695       0.4182117       0.6146519       0.5190947       0.605684 0.6198442      0.4307864
        0.4746417       0.772157 0.4622209      0.38851  0.5008351      0.3791538       0.2446993
        0.2030896       0.1456319       0.1697192       0.1814878       0.1396919       0.1921808
        0.2525552       0.2037137       0.1844774       0.1880418       0.2126051       0.200659
        0.2053178       0.1788212       0.1780087       0.2075233       0.2065729       0.2109375
        0.1895979       0.2071288       0.209001 0.2367578      0.2560394       0.2218841
        0.2726946       0.3319883       0.2167609       0.2125969       0.2640029       0.2549398
        0.2489007       0.1951689       0.1817646       0.1939705       0.1995067       0.1703956
##Series 2 Observed CPUE (numbers) and CV vectors, respectively
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       21.3418573      0.5390835       19.4082953      2.8614657       15.6901809
        11.0745694      65.3924476      0.4455194       12.1423391      3.9588828       20.0226198
        0.4131422       25.6203651      252.5772802     49.2616698      48.2596546      210.6206898
        71.7733531      76.1008091      42.2135115      9.9147803       161.7790276     3.3456304
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       0.9170423       0.6665231       0.8077591       0.657774 0.6303226      0.595977
        0.6454505       0.7063529       0.6372563       0.4940303       0.5191645       0.6372243
        0.7399235       0.6030919       0.5332693       0.5192834       0.5548404       0.5625752
        0.5751671       0.5455987       0.4713823       0.521328 0.7065397
##Series 3 Observed CPUE (numbers) and CV vectors, respectively
0       0       0       0       0       0       0       0       0       0       0       0       0
        0       0       0       0       0       0       0       0       62.6893134      259.2783574
        51.8810532      12.2443508      30.9959456      14.1435884      2.3832303       1.5905358
        5.8567029       8.145969 13.1786803     7.4515134       6.3196687       1.2897558
        10.3979867      13.436357       3.5883454       8.64925  3.8668316       26.4074946
        2.6622985       1.089944 2.0327237      1.9672035       0.3815253       12.2755695
        1.6988698       1.4698375       1.1856853
0       0       0       0       0       0       0       0       0       0       0       0       0
        0       0       0       0       0       0       0       0       0.6100114       0.7673876
        0.4563601       0.5643986       0.3666978       0.3004134       0.5151165       0.3213347
        0.3180115       0.2841494       0.2579026       0.2837902       0.2688518       0.4544062
        0.3454617       0.2981172       0.3135442       0.321363 0.2960134      0.3096394
```

```
	0.2708529	0.3130682	0.3179908	0.3103309	0.3233245	0.258085
	0.2679273	0.2771044	0.2998046
##Series 4 Observed CPUE (numbers) and CV vectors, respectively
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	5.798786 36.682552	114.432077	88.413428	457.305185
	720.60668	125.110058	76.98277 31.049442	270.940064	252.012355
	1990.351097	180.398169	586.980987	234.406695	881.609674	1533.95439
	557.335098	27.657342	7.583182 452.320643	23.885976
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	0.484021 0.4013174	0.4930011	0.5355576	0.5371519
	0.5340335	0.4895519	0.575322 0.5688208	0.5077108	0.5219801
	0.4456174	0.5576982	0.6027831	0.4460296	0.6735579	0.578154 0.56118
	0.5660324	0.5055432	0.5770563	0.747471

##--><>--><>--><>-- PRFC pound net index --><>--><>--><>--><>--><>--><>--><>--><>--><>
##Starting and ending years of time series, respectively
1964
2008
##Observed CPUE (numbers) and CV vectors, respectively
1200.034827	1253.47176	968.6025307	526.5643746	491.3551115	350.0381583
	844.3270832	738.4494723	1318.00342	2388.332307	2213.956559	2156.071384
	2320.080977	3493.875143	3384.639318	2470.892705	3164.342746	3703.970913
	3379.37838	3837.60589	2392.945932	2854.073898	1967.828042	2765.947626
	2465.256195	1692.525183	986.646892	1148.029682	1315.305353	1710.162139
	1524.597216	1538.066769	1467.940839	1448.316981	1144.909144	1626.076021
	1845.551788	1277.655637	1120.800936	1055.591783	2448	2538	2075	1985
	1819
0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
#0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2

##--><>--><>--><>-- Commercial Reduction fishery --><>--><>--><>--><>--><>--><>--><>
#Starting and ending years of landings time series, respectively
1955
2008
##Observed landings (1000 mt) and assumed CVs
641.4	712.1	602.8	510	659.1	529.8	575.9	537.7	346.9	269.2	273.4	219.6	193.5
	234.8	161.6	259.4	250.3	365.9	346.9	292.2	250.2	340.5	341.1	344.1	375.7
	401.5	381.3	382.4	418.6	326.3	306.7	238	327	309.3	322	401.2	381.4
	297.6	320.6	260	339.9	292.9	259.1	245.9	171.2	167.2	233.7	174	166.1
	183.4	146.9	157.4	174.5	141.1
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	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 hook and line fishery
54
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
##sample sizes of age comps by year  (first row observed N, second row effective N: effective may be set to observed)
```

15009 17963 18389 14303 17938 12783 12898 15458 12716 10286 18955 15486 14653
25888 14858 8239 8118 6198 6348 5361 7262 6401 7266 7025 6231
7046 8870 8552 11279 11594 8507 5826 7548 7349 6374 6790 7614
5440 5348 4862 4504 4275 3982 3688 3468 3068 4102 3654 3108
3759 3102 3300 3759 3204
305 497 502 434 508 465 425 513 531 513 907 776 754
1340 902 425 417 656 638 561 740 676 728 712 637
731 922 908 540 1178 851 583 762 654 714 685 770
562 533 472 462 423 411 385 361 296 394 337 350
419 354 358 380 278
#age composition samples (year,age)
0.244021051 0.216174805 0.339151289 0.085737126 0.098527746 0.01219106
0.003397508 0.00059956 0.000199853
0.010187608 0.581584368 0.253242777 0.089628681 0.012581417 0.042253521
0.008072148 0.00189278 0.0005567
0.085322747 0.455598456 0.387786177 0.02757083 0.020175105 0.011528631
0.010495405 0.001196367 0.000326282
0.039012795 0.315598126 0.601412291 0.026497937 0.006362302 0.005872894
0.003355939 0.0018178 0.000139831
0.002118526 0.754418242 0.159000948 0.072531639 0.006244076 0.002230027
0.002285778 0.00083626 0.000334504
0.025971994 0.101228194 0.795900806 0.027536572 0.036845811 0.00852695
0.002894469 0.000860518 0.000234687
7.75374E-05 0.320384586 0.19384353 0.46553462 0.007366054 0.011320462
0.001085524 0.00031015 7.75374E-05
0.02458274 0.244857032 0.397399405 0.103441584 0.201643162 0.014620261
0.011709147 0.001423211 0.000323457
0.054895792 0.410460087 0.401966182 0.069445537 0.025481715 0.02965002
0.005898545 0.001887534 0.000314589
0.174995139 0.407155357 0.349893059 0.048318102 0.010402489 0.004569318
0.003791561 0.000777756 0.000194439
0.170509101 0.49042469 0.277341071 0.051173833 0.008018992 0.0012134
0.000791348 0.000474809 5.27565E-05
0.260687072 0.410887253 0.301433553 0.02363425 0.00290585 0.000258298
6.45745E-05 6.45745E-05 0
0.007029757 0.643393393 0.26992902 0.073983074 0.005187005 0.00047775 0
0 0
0.134386588 0.328723733 0.469483931 0.057207973 0.009309333 0.000849815
3.86279E-05 0 0
0.182124108 0.428859873 0.327500337 0.055054516 0.006259254 0.000201911 0
0 0
0.015293118 0.620706396 0.337783712 0.023303799 0.002912975 0.000121374 0
0 0
0.075141661 0.271741808 0.541019956 0.091155457 0.018354274 0.002586844 0
0 0
0.029202969 0.572442723 0.284930623 0.101000323 0.011132623 0.001129397 0
0 0
0.030403277 0.31931317 0.625393825 0.020951481 0.003780718 0.00015753 0
0 0
0.158552509 0.319903003 0.495243425 0.02443574 0.001305727 0.000746129 0
0 0
0.138116221 0.332966125 0.502478656 0.023271826 0.003029468 0.000137703 0
0 0
0.083580691 0.490860803 0.408373692 0.014685205 0.002343384 0.000156226 0
0 0
0.131865107 0.273503097 0.566689608 0.022711631 0.004817619 0.000412939 0
0 0
0.148327402 0.215231317 0.541637011 0.083701068 0.010106762 0.00113879 0
0 0
0.385714286 0.160995185 0.414285714 0.033065811 0.005617978 0.000321027 0
0 0

0.026539881 0.443514051 0.437553222 0.066846438 0.020720976 0.004257735
0.000425773 0 0
0.298049825 0.175402999 0.454627438 0.055799797 0.011949047 0.003832713
0.000338181 0 0
0.035898036 0.289522919 0.547708138 0.11950421 0.005144995 0.001870907
0.000116932 0.000116932 0
0.244613884 0.131217306 0.581700505 0.028991932 0.012057807 0.001241245
8.86603E-05 0 8.86603E-05
0.364757633 0.288683802 0.25142315 0.076505089 0.014145248 0.004312575
0.000172503 0 0
0.210625294 0.35554772 0.404795487 0.014574518 0.011753644 0.002115656
0.000587682 0 0
0.051493306 0.117233093 0.796429797 0.025575009 0.005492619 0.003261243
0.000514933 0 0
0.018550417 0.217967404 0.685835431 0.065588976 0.010865244 0.000927521
0.000265006 0 0
0.157028167 0.131038236 0.53639951 0.139610831 0.032385359 0.00326575
0.000136073 0.000136073 0
0.056941176 0.438901961 0.440313725 0.041254902 0.018039216 0.004392157
0.000156863 0 0
0.142709867 0.061561119 0.719734904 0.050515464 0.019587629 0.005743741
0.000147275 0 0
0.278434463 0.326503809 0.2987917 0.080246914 0.011951668 0.003414762
0.000656685 0 0
0.194669118 0.354227941 0.3875 0.032169118 0.025 0.005330882 0.000735294
0.000183824 0
0.04262479 0.237801458 0.616563844 0.093475416 0.006917181 0.002430361
0.000186951 0 0
0.059440559 0.184080625 0.595639654 0.110654052 0.045043192 0.005141917
0.000205677 0 0
0.034635879 0.32482238 0.40874778 0.188055062 0.0410746 0.002664298 0
0 0
0.030877193 0.191578947 0.621988304 0.127251462 0.026432749 0.001871345 0
0 0
0.025364139 0.247865394 0.426418885 0.238322451 0.051732798 0.009040683
0.00125565 0 0
0.072396963 0.18356833 0.536605206 0.12527115 0.072396963 0.008947939
0.000813449 0 0
0.183626405 0.28509657 0.426635918 0.077543961 0.023637936 0.003170943
0.000288268 0 0
0.118318123 0.173728814 0.518252934 0.170143416 0.016949153 0.002933507 0
0 0
0.034365099 0.065074336 0.552035096 0.325127955 0.022422618 0.000974896 0
0 0
0.22194855 0.263546798 0.323481117 0.169129721 0.02134647 0.000547345 0
0 0
0.086872587 0.182754183 0.640604891 0.076898327 0.011261261 0.001287001
0.00032175 0 0
0.018355946 0.21867518 0.666666667 0.077414206 0.017823889 0.000798085 0
0 0
0.018703644 0.121573686 0.590454692 0.237665269 0.028700419 0.00290229 0
0 0
0.012121212 0.396363636 0.398181818 0.161212121 0.031212121 0.000606061 0
0 0
0.001330141 0.256451184 0.653099229 0.074487896 0.013833466 0.000798085 0
0 0
0.013732834 0.09082397 0.683832709 0.184769039 0.025280899 0.001872659 0
0 0

##--><>--><>--><>-- Commercial Bait fishery --><>--><>--><>--><>--><>--><>--><>
#Starting and ending years of landings time series, respectively

```
1955
2008
##Observed landings (1000 mt) and assumed CVs (includes MRFSS landings)
14.63884933	23.2524426	24.70652539	14.68842703	20.58422767	19.44384973
	25.06794822	26.57963731	24.39023505	20.23364571	23.6195807	13.72241021
	11.61043627	9.46008836	10.60745162	21.64214241	13.47143725	10.34826864
	14.76866762	14.53933104	21.69122116	19.62859813	23.0913264	25.86574285
	13.01907585	26.11487286	22.55375629	19.98822101	19.18707964	14.48075815
	26.81988828	28.32722974	30.87501664	36.5594712	31.16703051	30.96914625
	36.61063487	39.56650702	42.98974317	39.25288199	42.62665817	35.402871
	36.62586427	39.4442713	36.4241429	35.37175383	36.43607921	37.24231295
	34.05667597	35.83327691	38.96713326	26.85606595	43.13648682	47.73852678
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
#0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
	0.20	0.20	0.20	0.20	0.20	0.10	0.10	0.10	0.10	0.10	0.10	0.10
	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
	0.10	0.10	0.10	0.10	0.10
##Number and vector of years of age compositions for bait fishery
24
1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
##sample sizes of age comps by year  (first row observed N, second row effective N: effective may be set to observed)
770	380	220	10	30	10	78	70	169	539	362	357	313
	626	538	543	962	702	427	354	322	454	973	842
77	38	22	1	3	1	8	7	17	54	37	36	32
	63	54	55	97	71	43	36	33	46	98	85
#age composition samples (year,age)
0.003	0.085	0.651	0.187	0.062	0.010	0.002	0.0000	0.0000
0.002	0.054	0.430	0.365	0.135	0.013	0.002	0.0000	0.0000
0.002	0.048	0.481	0.332	0.124	0.012	0.001	0.0000	0.0000
0.002	0.051	0.411	0.377	0.144	0.014	0.002	0.0000	0.0000
0.002	0.069	0.531	0.291	0.096	0.010	0.001	0.0000	0.0000
0.004	0.198	0.396	0.286	0.104	0.010	0.001	0.0000	0.0000
0.001	0.121	0.405	0.333	0.125	0.013	0.002	0.0000	0.0000
0.003	0.151	0.356	0.346	0.129	0.014	0.002	0.0000	0.0000
0.005	0.173	0.317	0.359	0.129	0.014	0.002	0.0000	0.0000
0.002	0.096	0.463	0.282	0.136	0.019	0.001	0.0000	0.0000
0.000	0.255	0.275	0.310	0.160	0.000	0.000	0.0000	0.0000
0.000	0.029	0.615	0.285	0.068	0.002	0.000	0.0000	0.0000
0.000	0.049	0.380	0.308	0.198	0.054	0.011	0.0000	0.0000
0.029	0.046	0.408	0.286	0.193	0.031	0.006	0.0000	0.0000
0.001	0.041	0.589	0.242	0.111	0.014	0.002	0.0000	0.0000
0.006	0.163	0.570	0.179	0.071	0.009	0.002	0.0000	0.0000
0.002	0.046	0.538	0.363	0.044	0.006	0.001	0.0000	0.0000
0.000	0.029	0.197	0.522	0.220	0.031	0.001	0.0000	0.0000
0.005	0.084	0.645	0.221	0.044	0.002	0.000	0.0000	0.0000
0.000	0.057	0.649	0.228	0.059	0.007	0.001	0.0000	0.0000
0.000	0.013	0.471	0.449	0.059	0.007	0.001	0.0000	0.0000
0.000	0.196	0.424	0.317	0.061	0.002	0.000	0.0000	0.0000
0.000	0.187	0.594	0.175	0.041	0.002	0.001	0.0000	0.0000
0.000	0.021	0.582	0.322	0.067	0.008	0.000	0.0000	0.0000


#################Parameter values and initial
guesses#########################################################################
###Selectivity parameters.
```

###Initial guess must be within boundaries.
Initial guesses initialized near solutions from preliminary model runs
age at size limits (12, 20 inches)= 1.42, 3.62
zero in slope2 provides logistic selectivity

1.4 #selpar_L50_cR
3.3 #selpar_slope_cR
6.0 #selpar_L502_cR
0.0 #selpar_slope2_cR

2.2 #selpar_L50_cB
3.9 #selpar_slope_cB
6.5 #selpar_L502_cB
0.0 #selpar_slope2_cB

1.14 #selpar_L50_cPN
7.62 #selpar_slope_cPN
1.72 #selpar_L502_cPN
7.77 #selpar_slope2_cPN

#################Likelihood Component
Weighting##
##Weights in objective fcn
1.0 #landings
1.0 #age comps
1.0 #JAI index
1.0 #PN index
1.0 #S-R residuals
0.0 #constraint on early recruitment deviations
1.0 #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)
0.0 #weight on tuning F (penalty not applied in final phase of optimization)
1.0 #weight for penalty to keep JAI combination weights summing to 1.0

##
#########
##log catchabilities (initial guesses)
-1.8 #JAI survey
6.4 #PN survey

#exponent for JAI cpue index
1.0

#JAI combination weights
0.25
0.25
0.25
0.25

#rate increase switch: Integer value (choose estimation phase, negative value turns it off)
-1
##annual positive rate of increase on all fishery dependent q 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

##log mean F (initial guesses)
0.2                 #commercial reduction
-1.2                #commercial bait
#Initialization F as a proportion of  first few assessment years (set to 1.0 without evidence otherwise)
1.0

#Tuning F (not applied in last phase of optimization)
1.5
#Year for tuning F
2008

#threshold sample sizes (greater than or equal to) for age comps
1.0 #cR
1.0 #cB

#switch to turn priors on off (-1 = off, 1 = on)
-1

###########################################################################################################
########
#Ageing error matrix (columns are true age 1-20, rows are ages as read for age comps)
#1      0       0       0       0       0       0       0       0
#0      1       0       0       0       0       0       0       0
#0      0       1       0       0       0       0       0       0
#0      0       0       1       0       0       0       0       0
#0      0       0       0       1       0       0       0       0
#0      0       0       0       0       1       0       0       0
#0      0       0       0       0       0       1       0       0
#0      0       0       0       0       0       0       1       0
#0      0       0       0       0       0       0       0       1

0.989574885     0.010425115     3.41132E-08     8.71309E-12     4.9779E-12      3.69962E-10
        1.06845E-07     1.57149E-05     0.000623385
0.010425115     0.979149769     0.036041469     2.7224E-05      5.8031E-07      8.37634E-07
        1.08755E-05     0.000198104     0.001951093
2.07379E-12     0.010425115     0.927916994     0.089249633     0.001764541     0.000311433
        0.000471017     0.001762145     0.006387882
0       2.07379E-12     0.036041469     0.821446286     0.163648594     0.019751402     0.008711424
        0.010519756     0.017424063
0       0       3.41132E-08     0.089249633     0.669172569     0.226878066     0.069393527
        0.042182061     0.039598326
0       0       0       2.7224E-05      0.163648594     0.506116523     0.24003818      0.113684332
        0.074981978
0       0       0       8.71314E-12     0.001764541     0.226878066     0.362749737     0.206038939
        0.118305185
0       0       0       0       5.8031E-07      0.019751402     0.24003818      0.251197896
        0.155534864
0       0       0       0       4.97791E-12     0.000312271     0.078586951     0.374401052
        0.585193224

###########################################################################################################
#########
999 #end of data file flag
```

Appendix A.4. AD Model Builder model code for the base BAM model.

```
//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//##
//##  ASMFC Assessment: Atlantic Menhaden, October 2009
//##
//##  Erik Williams, NMFS, Beaufort Lab
//##  Erik.Williams@noaa.gov
//##
//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>

DATA_SECTION
//Create ascii file for output
//!!CLASS ofstream report1("menhadresults.rep",ios::out);  //create file for output

!!cout << "Starting Atlantic Menhaden Assessment Model" << endl;

// 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;
!!cout << styr_rec_dev <<endl;
//possible 3 phases of constraints on recruitment deviations
init_int endyr_rec_phase1;
init_int endyr_rec_phase2;

//3 periods of size regs: styr-83 no restrictions, 1984-91 12-inch TL, 1992-08 20-in TL
init_int endyr_period1;
init_int endyr_period2;
init_int endyr_period3;

//starting and ending years to use for benchmark calculations
init_int styr_bench;
init_int endyr_bench;

//Total number of ages
init_int nages;

// Vector of ages for age bins
init_ivector 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-styr_rec_dev+1.;
 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;

//Female maturity and proportion female at age
init_vector maturity_f_obs(1,nages);          //proportion females mature at age
init_vector maturity_m_obs(1,nages);          //proportion males mature at age
init_vector prop_f_obs(1,nages);              //proportion female at age

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 set_M_constant; //age-independent: used only for MSST
init_matrix set_M_mat(styr,endyr,1,nages); //age and year specific M
//Spawner-recruit parameters (Initial guesses or fixed values)
init_number set_SR_switch;
init_number set_steep;
init_number set_steep_se;
init_number set_log_R0;
init_number set_R_autocorr;

//-->&lt;>--&gt;<>--><>-- Weight-at-age in the fishery (g) --><>--><>--><>--><>--><>--><>--><>--><>
init_matrix wgt_fish_g(styr,endyr,1,nages);

//--><>--><>--><>-- Weight-at-age for the spawning population - start of year (g) --><>--><>--><>--><>
init_matrix wgt_spawn_g(styr,endyr,1,nages);

//--><>--><>--><>-- Fecundity-at-age - not adjusted for maturity (g) --><>--><>--><>--><>
init_matrix fec_eggs(styr,endyr,1,nages);

//--><>--><>--><>-- Juvenile Abundance Index from seine surveys --><>--><>--><>--><>--><>
init_int JAI_cpue_switch;
//CPUE
init_int styr_JAI_cpue;
init_int endyr_JAI_cpue;
init_vector obs_JAI_cpue(styr_JAI_cpue,endyr_JAI_cpue);   //Observed CPUE
init_vector JAI_cpue_cv(styr_JAI_cpue,endyr_JAI_cpue);    //CV of cpue

//--><>--><>--><>-- Juvenile Abundance Indices from seine surveys --><>--><>--><>--><>--><>
//CPUE, must have zeros in place of missing values
init_vector obs_JAI1_cpue(styr_JAI_cpue,endyr_JAI_cpue);   //Observed CPUE 1
init_vector JAI1_cpue_cv(styr_JAI_cpue,endyr_JAI_cpue);    //CV of cpue 1
init_vector obs_JAI2_cpue(styr_JAI_cpue,endyr_JAI_cpue);   //Observed CPUE 2
init_vector JAI2_cpue_cv(styr_JAI_cpue,endyr_JAI_cpue);    //CV of cpue 2
init_vector obs_JAI3_cpue(styr_JAI_cpue,endyr_JAI_cpue);   //Observed CPUE 3
init_vector JAI3_cpue_cv(styr_JAI_cpue,endyr_JAI_cpue);    //CV of cpue 3
init_vector obs_JAI4_cpue(styr_JAI_cpue,endyr_JAI_cpue);   //Observed CPUE 4
init_vector JAI4_cpue_cv(styr_JAI_cpue,endyr_JAI_cpue);    //CV of cpue 4

//--><>--><>--><>-- PRFC pound net index --><>--><>--><>--><>--><>--><>--><>--><>--><>
//CPUE
init_int styr_PN_cpue;
init_int endyr_PN_cpue;
init_vector obs_PN_cpue(styr_PN_cpue,endyr_PN_cpue);   //Observed CPUE
init_vector PN_cpue_cv(styr_PN_cpue,endyr_PN_cpue);    //cv of cpue

//--><>--><>--><>-- Commercial Reduction fishery --><>--><>--><>--><>--><>--><>--><>
// Landings  (1000 mt)
init_int styr_cR_L;
init_int endyr_cR_L;
```

```
init_vector obs_cR_L(styr_cR_L,endyr_cR_L); //vector of observed landings by year
init_vector cR_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_cR_agec(1,nyr_cR_agec);
init_vector neff_cR_agec(1,nyr_cR_agec);
init_matrix obs_cR_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_cB_L(styr_cB_L,endyr_cB_L);
init_vector cB_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_cB_agec(1,nyr_cB_agec);
init_vector neff_cB_agec(1,nyr_cB_agec);
init_matrix obs_cB_agec(1,nyr_cB_agec,1,nages);

//##################################################################################
//#################Parameter values and initial guesses ################################
//Initial guesses of estimated selectivity parameters
init_number set_selpar_L50_cR;
init_number set_selpar_slope_cR;
init_number set_selpar_L502_cR;
init_number set_selpar_slope2_cR;

init_number set_selpar_L50_cB;
init_number set_selpar_slope_cB;
init_number set_selpar_L502_cB;
init_number set_selpar_slope2_cB;

init_number set_selpar_L50_PN;
init_number set_selpar_slope_PN;
init_number set_selpar_L502_PN;
init_number set_selpar_slope2_PN;

//--weights for likelihood components-----------------------------------------------------------------------------
init_number set_w_L;
init_number set_w_ac;
init_number set_w_I_JAI;
init_number set_w_I_PN;
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_JAI_wgts;      //weight for penalty to keep JAI combination weights summing to 1.0

////--index catchability-------------------------------------------------------------------------------------------------------
init_number set_logq_JAI;    //catchability coefficient (log) for MARMAP RVC
init_number set_logq_PN;    //catchability coefficient (log) for MARMAP CVT

init_number set_JAI_exp;    //exponent for cpue index

//--JAI index combination weights----------------------------------------------------
```

```
init_number set_wgt_JAI1;
init_number set_wgt_JAI2;
init_number set_wgt_JAI3;
init_number set_wgt_JAI4;

//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_PN_var;     //assumed variance of RW q

////--F's--------------------------------
init_number set_log_avg_F_cR;
init_number set_log_avg_F_cB;
init_number set_F_init_ratio;  //defines initialization F as a ratio of that from first several yrs of assessment

//Tune Fapex (tuning removed in final year of optimization)
init_number set_Ftune;
init_int set_Ftune_yr;

//threshold sample sizes for age comps
init_number minSS_cR_agec;
init_number minSS_cB_agec;

//switch to turn priors on off (-1 = off, 1 = on)
init_number switch_prior;

//ageing error matrix (columns are true ages, rows are ages as read for age comps)
init_matrix age_error(1,nages,1,nages);

// #######Indexing integers for year(iyear), age(iage) ###############
int iyear;
int iage;
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

init_number end_of_data_file;
//this section MUST BE INDENTED!!!
 LOCAL_CALCS
   if(end_of_data_file!=999)
   {
    for(iyear=1; iyear<=1000; iyear++)
    {
      cout << "*** WARNING: Data File NOT READ CORRECTLY ****" << endl;
      cout << "" <<endl;
    }
   }
```

```
  else
  {
   cout << "Data File read correctly" << endl;
  }
 END_CALCS

//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>

PARAMETER_SECTION
//////---------------------------------------------------------------------------------------

  matrix wgt_fish_kg(styr,endyr,1,nages);
  matrix wgt_fish_mt(styr,endyr,1,nages);
  matrix wgt_spawn_kg(styr,endyr,1,nages);
  matrix wgt_spawn_mt(styr,endyr,1,nages);

  matrix wgt_cR_mt(styr,endyr,1,nages);      //wgt of cR landings in 1000 mt
  matrix wgt_cB_mt(styr,endyr,1,nages);      //wgt of cB landings in 1000 mt

  matrix pred_cR_agec(1,nyr_cR_agec,1,nages);
  matrix ErrorFree_cR_agec(1,nyr_cR_agec,1,nages); //age comps prior to applying ageing error matrix
  matrix pred_cB_agec(1,nyr_cB_agec,1,nages);
  matrix ErrorFree_cB_agec(1,nyr_cB_agec,1,nages);

  //nsamp_X_allyr vectors used only for R output of comps with nonconsecutive yrs, given sample size cutoffs
  vector nsamp_cR_agec_allyr(styr,endyr);
  vector nsamp_cB_agec_allyr(styr,endyr);

//effective sample size applied in multinomial distributions
  vector neff_cR_agec_allyr(styr,endyr);
  vector neff_cB_agec_allyr(styr,endyr);

//Computed effective sample size for output (not used in fitting)
  vector neff_cR_agec_allyr_out(styr,endyr);
  vector neff_cB_agec_allyr_out(styr,endyr);

//-----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
  init_bounded_vector log_Nage_dev(2,nages,-5,5,1); //log deviations on initial abundance at age
  //vector log_Nage_dev(2,nages);
  vector log_Nage_dev_output(1,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);                  ///Total spawning biomass by year
  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 female mature at age
  vector maturity_m(1,nages);              //Proportion of female mature at age
  matrix reprod(styr,endyr,1,nages);
  vector wgted_reprod(1,nages);            //average reprod in last few years
//
////---Stock-Recruit Function (Beverton-Holt, steepness parameterization)----------
  init_bounded_number log_R0(1,10,1);      //log(virgin Recruitment)
  //number log_R0;
  number R0;                               //virgin recruitment
  init_bounded_number steep(0.21,0.99,-3);   //steepness
//  number steep;  //uncomment to fix steepness, comment line directly above
```

```
  init_bounded_dev_vector log_rec_dev(styr_rec_dev,endyr,-5,5,1); //log recruitment deviations
  //vector log_rec_dev(styr_rec_dev,endyr);
  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
                                //Estimate from yrs with unconstrainted S-R(XXXX-XXXX)
  number BiasCor;                        //Bias correction in equilibrium recruits
  init_bounded_number R_autocorr(-1.0,1.0,2);  //autocorrelation in SR
  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);               //SSB / virgin SSB

////---Selectivity-------------------------------------------------------------------

//Commercial reduction-----------------------------------------------
  matrix sel_cR(styr,endyr,1,nages);
  init_bounded_number selpar_slope_cR1(0.5,10.0,1); //period 1
  init_bounded_number selpar_L50_cR1(0.5,4.0,1);
  init_bounded_number selpar_slope2_cR1(0.0,10.0,-1); //period 1
  init_bounded_number selpar_L502_cR1(0.0,6.0,-1);
  vector sel_cR1_vec(1,nages);

  init_bounded_number selpar_slope_cR2(0.5,10.0,-2); //period 2
  init_bounded_number selpar_L50_cR2(0.5,4.0,-2);
  init_bounded_number selpar_slope2_cR2(0.0,10.0,-3); //period 2
  init_bounded_number selpar_L502_cR2(0.0,6.0,-3);
  vector sel_cR2_vec(1,nages);

  init_bounded_number selpar_slope_cR3(0.5,10.0,-2); //period 3
  init_bounded_number selpar_L50_cR3(0.5,4.0,-2);
  init_bounded_number selpar_slope2_cR3(0.0,10.0,-3); //period 3
  init_bounded_number selpar_L502_cR3(0.0,6.0,-3);
  vector sel_cR3_vec(1,nages);

  init_bounded_number selpar_slope_cR4(0.5,10.0,-2); //period 4
  init_bounded_number selpar_L50_cR4(0.5,4.0,-2);
  init_bounded_number selpar_slope2_cR4(0.0,10.0,-3); //period 4
  init_bounded_number selpar_L502_cR4(0.0,6.0,-3);
  vector sel_cR4_vec(1,nages);

//Commercial bait-----------------------------------------------
  matrix sel_cB(styr,endyr,1,nages);
  init_bounded_number selpar_slope_cB(0.5,10.0,1);
  init_bounded_number selpar_L50_cB(0.5,4.0,1);
  init_bounded_number selpar_slope2_cB(0.5,10.0,-1);
  init_bounded_number selpar_L502_cB(0.0,6.0,-1);
  vector sel_cB_vec(1,nages);

//Commercial bait-----------------------------------------------
  matrix sel_PN(styr,endyr,1,nages);
  number selpar_slope_PN; //period 1
  number selpar_L50_PN;
  number selpar_slope2_PN; //period 1
  number selpar_L502_PN;
  vector sel_PN_vec(1,nages);

  //effort-weighted, recent selectivities
  vector sel_wgted_L(1,nages);  //toward landings
  vector sel_wgted_tot(1,nages);//toward Z
```

```
//-------CPUE Predictions-------------------------------
  vector obs_JAI_cpue_final(styr_JAI_cpue,endyr_JAI_cpue);     //used to store cpue used in likelihood fit
  vector JAI_cpue_cv_final(styr_JAI_cpue,endyr_JAI_cpue);
  vector pred_JAI_cpue(styr_JAI_cpue,endyr_JAI_cpue);         //predicted JAI U
  vector N_JAI(styr_JAI_cpue,endyr_JAI_cpue);         //used to compute JAI index
  vector pred_PN_cpue(styr_PN_cpue,endyr_PN_cpue);         //predicted PN U
  matrix N_PN(styr_PN_cpue,endyr_PN_cpue,1,nages);         //used to compute PN index

//------Index exponent--------------------------------
  init_bounded_number JAI_exp(0.01,1.0,-3);

//------Index combination weights--------------------------------
  init_bounded_number wgt_JAI1(0.001,1.0,-3);
  init_bounded_number wgt_JAI2(0.001,1.0,-3);
  init_bounded_number wgt_JAI3(0.001,1.0,-3);
  init_bounded_number wgt_JAI4(0.001,1.0,-3);
  number JAI_wgt_sum_constraint;

////---Catchability (CPUE q's)----------------------------------------------------------
  init_bounded_number log_q_JAI(-10,10,1);
  init_bounded_number log_q_PN(-10,10,1);
  init_bounded_number q_rate(0.001,0.1,set_q_rate_phase);
  //number q_rate;
  vector q_rate_fcn_PN(styr_PN_cpue,endyr_PN_cpue);        //increase due to technology creep (saturates in 2003)

  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

  init_bounded_vector q_RW_log_dev_PN(styr_PN_cpue,endyr_PN_cpue-1,-3.0,3.0,set_q_RW_phase);
  vector q_PN(styr_PN_cpue,endyr_PN_cpue);

//---Landings in numbers (total or 1000 fish) and in wgt (klb)-------------------------------------------------
  matrix L_cR_num(styr,endyr,1,nages);            //landings (numbers) at age
  matrix L_cR_mt(styr,endyr,1,nages);            //landings (1000 mt) at age
  vector pred_cR_L_knum(styr,endyr); //yearly landings in 1000 fish summed over ages
  vector pred_cR_L_mt(styr,endyr);  //yearly landings in 1000 mt summed over ages

  matrix L_cB_num(styr,endyr,1,nages);             //landings (numbers) at age
  matrix L_cB_mt(styr,endyr,1,nages);            //landings (1000 mt) at age
  vector pred_cB_L_knum(styr,endyr);     //yearly landings in 1000 fish summed over ages
  vector pred_cB_L_mt(styr,endyr);      //yearly landings in 1000 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 1000 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 (1000 mt) by yr summed over ages

////---Fmed calcs---------------------------------------------------------------------------
  number quant_decimal;
  number quant_diff;
  number quant_result;

  number R_med;                           //median recruitment for chosen benchmark years
  vector R_temp(styr_bench,endyr_bench);
  vector R_sort(styr_bench,endyr_bench);
  number SPR_med;                           //median SSB/R (R = SSB year+1) for chosen SSB years
  number SPR_75th;
  vector SPR_temp(styr_bench,endyr_bench);
```

```
  vector SPR_sort(styr_bench,endyr_bench);
  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;

////---MSY calcs---------------------------------------------------------------------------
  number F_cR_prop;      //proportion of F_sum attributable to reduction, last X=selpar_n_yrs_wgted yrs, used for avg body
weights
  number F_cB_prop;      //proportion of F_sum attributable to bait, last X yrs
  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 mature biomass) at msy
  number F_msy_out;           //F at msy
  number msy_mt_out;          //max sustainable yield (1000 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(1000 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 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);
  number SdSSB_msy_end;
  number FdF_msy_end;

  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)

////--------Mortality------------------------------------------------------------------
  vector M(1,nages);                       //age-dependent natural mortality
  number M_constant;                       //age-indpendent: used only for MSST
  matrix M_mat(styr,endyr,1,nages);
  vector wgted_M(1,nages);                 //weighted M vector for last few years
  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
```

```
  matrix Z(styr,endyr,1,nages);

  vector E(styr,endyr);                    //Exploitation rate
  vector F_age2plus(styr,endyr);           //population weighted age 2+ F
  vector F_cR_age2plus(styr,endyr);           //population weighted age 2+ F
  vector F_cB_age2plus(styr,endyr);           //population weighted age 2+ F

  init_bounded_number log_avg_F_cR(-5,2.0,1);
  init_bounded_dev_vector log_F_dev_cR(styr_cR_L,endyr_cR_L,-10.0,5.0,2);
  matrix F_cR(styr,endyr,1,nages);
  vector F_cR_out(styr,endyr); //used for intermediate calculations in fcn get_mortality
  number log_F_dev_init_cR;
  number log_F_dev_end_cR;

  init_bounded_number log_avg_F_cB(-10,0.0,1);
  init_bounded_dev_vector log_F_dev_cB(styr_cB_L,endyr_cB_L,-10.0,5.0,2);
  matrix F_cB(styr,endyr,1,nages);
  vector F_cB_out(styr,endyr); //used for intermediate calculations in fcn get_mortality
  number log_F_dev_init_cB;
  number log_F_dev_end_cB;

  init_bounded_number F_init_ratio(0.05,2.0,-1);

//---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 F_spr_age2plus(1,n_iter_spr);  //values of F age2+ 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
  vector spr_F0(styr,endyr);        //Spawning biomass per recruit at F=0
  vector bpr_F0(styr,endyr);        //Biomass per recruit at F=0
  number wgted_spr_F0;

  number iter_inc_spr;             //increments used to compute msy, equals max_F_spr_msy/(n_iter_spr-1)


////-------Objective function components-----------------------------------------------------------------------------
  number w_L;
  number w_ac;
  number w_I_JAI;
  number w_I_PN;
  number w_rec;
  number w_rec_early;
  number w_rec_end;
  number w_fullF;
  number w_Ftune;
  number w_JAI_wgts;
```

```
  number f_JAI_cpue;
  number f_PN_cpue;

  number f_cR_L;
  number f_cB_L;

  number f_cR_agec;
  number f_cB_agec;

  number f_PN_RW_cpue; //random walk component of indices

  //Penalties and constraints. Not all are used.
  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_Ftune;                //penalty for tuning F in Ftune yr.  Not applied in final optimization phase.
  number f_fullF_constraint;     //penalty for Fapex>X
  number f_JAI_wgts;

  number f_priors;               //prior information on parameters

  objective_function_value fval;
  number fval_unwgt;

//--Dummy variables ----
  number denom;                  //denominator used in some calculations
  number numer;                  //numerator used in some calculations
  vector temp_agevec(1,nages);
  number dum1;

//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
INITIALIZATION_SECTION


//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
GLOBALS_SECTION
  #include "admodel.h"          // Include AD class definitions
  #include "admb2r.cpp"    // Include S-compatible output functions (needs preceding)

//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
RUNTIME_SECTION
 maximum_function_evaluations 1000, 4000,8000, 10000;
 convergence_criteria 1e-2, 1e-5,1e-6, 1e-7;

//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
PRELIMINARY_CALCS_SECTION

// Set values of fixed parameters or set initial guess of estimated parameters
  M=set_M;
  M_constant=set_M_constant;
  M_mat=set_M_mat;
  steep=set_steep;
  R_autocorr=set_R_autocorr;

  log_q_JAI=set_logq_JAI;
  log_q_PN=set_logq_PN;

  JAI_exp=set_JAI_exp;
```

```
wgt_JAI1=set_wgt_JAI1;
wgt_JAI2=set_wgt_JAI2;
wgt_JAI3=set_wgt_JAI3;
wgt_JAI4=set_wgt_JAI4;

q_rate=set_q_rate;
q_rate_fcn_PN=1.0;
q_DD_beta=set_q_DD_beta;
q_DD_fcn=1.0;
q_RW_log_dev_PN.initialize();

if (set_q_rate_phase<0 & q_rate!=0.0)
{
   for (iyear=styr_PN_cpue; iyear<=endyr_PN_cpue; iyear++)
   {   if (iyear>styr_PN_cpue & iyear <=2003)
      {//q_rate_fcn_cL(iyear)=(1.0+q_rate)*q_rate_fcn_cL(iyear-1); //compound
         q_rate_fcn_PN(iyear)=(1.0+(iyear-styr_PN_cpue)*q_rate)*q_rate_fcn_PN(styr_PN_cpue);  //linear
      }
      if (iyear>2003) {q_rate_fcn_PN(iyear)=q_rate_fcn_PN(iyear-1);}
   }
} //end q_rate conditional

w_L=set_w_L;
w_ac=set_w_ac;
w_I_JAI=set_w_I_JAI;
w_I_PN=set_w_I_PN;
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_JAI_wgts=set_w_JAI_wgts;

log_avg_F_cR=set_log_avg_F_cR;
log_avg_F_cB=set_log_avg_F_cB;
F_init_ratio=set_F_init_ratio;

log_R0=set_log_R0;

selpar_L50_cR1=set_selpar_L50_cR;
selpar_slope_cR1=set_selpar_slope_cR;
selpar_L502_cR1=set_selpar_L502_cR;
selpar_slope2_cR1=set_selpar_slope2_cR;

selpar_L50_cR2=set_selpar_L50_cR;
selpar_slope_cR2=set_selpar_slope_cR;
selpar_L502_cR2=set_selpar_L502_cR;
selpar_slope2_cR2=set_selpar_slope2_cR;

selpar_L50_cR3=set_selpar_L50_cR;
selpar_slope_cR3=set_selpar_slope_cR;
selpar_L502_cR3=set_selpar_L502_cR;
selpar_slope2_cR3=set_selpar_slope2_cR;

selpar_L50_cR4=set_selpar_L50_cR;
selpar_slope_cR4=set_selpar_slope_cR;
selpar_L502_cR4=set_selpar_L502_cR;
selpar_slope2_cR4=set_selpar_slope2_cR;

selpar_L50_cB=set_selpar_L50_cB;
```

```
 selpar_slope_cB=set_selpar_slope_cB;
 selpar_L502_cB=set_selpar_L502_cB;
 selpar_slope2_cB=set_selpar_slope2_cB;

 selpar_L50_PN=set_selpar_L50_PN;
 selpar_slope_PN=set_selpar_slope_PN;
 selpar_L502_PN=set_selpar_L502_PN;
 selpar_slope2_PN=set_selpar_slope2_PN;

 sqrt2pi=sqrt(2.*3.14159265);
 //g2mt=0.000001;        //conversion of grams to metric tons
 g2mt=1.0;
 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;        //additive constant to prevent division by zero

 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;
 maturity_m=maturity_m_obs;
 prop_f=prop_f_obs;

//Fill in sample sizes of comps sampled in nonconsec yrs.
//Used primarily for output in R object

      nsamp_cR_agec_allyr=missing;
      nsamp_cB_agec_allyr=missing;

      neff_cR_agec_allyr=missing;
      neff_cB_agec_allyr=missing;

      for (iyear=1; iyear<=nyr_cR_agec; iyear++)
        {
         if (nsamp_cR_agec(iyear)>=minSS_cR_agec)
         {
           nsamp_cR_agec_allyr(yrs_cR_agec(iyear))=nsamp_cR_agec(iyear);
           neff_cR_agec_allyr(yrs_cR_agec(iyear))=neff_cR_agec(iyear);
         }
        }
      for (iyear=1; iyear<=nyr_cB_agec; iyear++)
        {
         if (nsamp_cB_agec(iyear)>=minSS_cB_agec)
         {
            nsamp_cB_agec_allyr(yrs_cB_agec(iyear))=nsamp_cB_agec(iyear);
            neff_cB_agec_allyr(yrs_cB_agec(iyear))=neff_cB_agec(iyear);
         }
        }

//fill in Fs for msy and per-recruit analyses
  F_msy(1)=0.0;
  for (int 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_cR.initialize();
  L_cR_num.initialize();
  F_cB.initialize();
  L_cB_num.initialize();

  F_cR_out.initialize();
  F_cB_out.initialize();

  L_total_knum_yr.initialize();
  L_total_mt_yr.initialize();

  log_rec_dev_output.initialize();
  log_Nage_dev_output.initialize();
  log_rec_dev.initialize();
  log_Nage_dev.initialize();


//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
TOP_OF_MAIN_SECTION
  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(500);


//>--><>--><>--><>--><>
//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
PROCEDURE_SECTION

 R0=mfexp(log_R0);

 //cout<<"start"<<endl;
 get_weight_at_age();
 get_reprod();
 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;
 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_age_comps();
 //cout<< "got age comps"<< endl;
 evaluate_objective_function();
 //cout << "objective function calculations complete" << endl;

FUNCTION get_weight_at_age
  //compute mean length (mm) and weight (whole) at age
    wgt_fish_kg=g2kg*wgt_fish_g;                    //wgt in kilograms
    wgt_fish_mt=g2mt*wgt_fish_g;                    //mt of whole wgt: g2mt converts g to mt
    wgt_spawn_kg=g2kg*wgt_spawn_g;                  //wgt in kilograms
    wgt_spawn_mt=g2mt*wgt_spawn_g;                  //mt of whole wgt: g2mt converts g to mt

FUNCTION get_reprod

  //product of stuff going into reproductive capacity calcs
  for (iyear=styr; iyear<=endyr; iyear++)
  {
    //reprod(iyear)=elem_prod((elem_prod(prop_f,maturity_f)+elem_prod((1.0-prop_f),maturity_m)),wgt_spawn_mt(iyear));
    //reprod(iyear)=elem_prod((elem_prod(prop_f,maturity_f)+elem_prod((1.0-prop_f),maturity_m)),fec_eggs(iyear));
    reprod(iyear)=elem_prod(elem_prod(prop_f,maturity_f),fec_eggs(iyear));
  }

  //compute average natural mortality
  wgted_M=M_mat(endyr)*0.0;
  for(iyear=(endyr-selpar_n_yrs_wgted+1); iyear<=endyr; iyear++)
  {
    wgted_M+=M_mat(iyear);
  }
  wgted_M=wgted_M/selpar_n_yrs_wgted;

  //average reprod for last few years for eq calculations
  wgted_reprod=reprod(endyr)*0.0;
  for(iyear=(endyr-selpar_n_yrs_wgted+1); iyear<=endyr; iyear++)
  {
    wgted_reprod+=reprod(iyear);
  }
  wgted_reprod=wgted_reprod/selpar_n_yrs_wgted;

FUNCTION get_weight_at_age_landings

  wgt_cR_mt=wgt_fish_mt;
  wgt_cB_mt=wgt_fish_mt;

FUNCTION get_spr_F0

  for (iyear=styr; iyear<=endyr; iyear++)
  {
    //at mdyr, apply half this yr's mortality, half next yr's
    N_spr_F0(1)=1.0*mfexp(-1.0*M_mat(iyear,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)));
      dum1=M_mat(iyear,iage-1)*(1.0-spawn_time_frac) + M_mat(iyear,iage)*spawn_time_frac;
      N_spr_F0(iage)=N_spr_F0(iage-1)*mfexp(-1.0*(dum1));
      N_bpr_F0(iage)=N_bpr_F0(iage-1)*mfexp(-1.0*(M_mat(iyear,iage-1)));
    }
    N_spr_F0(nages)=N_spr_F0(nages)/(1.0-mfexp(-1.0*M_mat(iyear,nages))); //plus group (sum of geometric series)
    N_bpr_F0(nages)=N_bpr_F0(nages)/(1.0-mfexp(-1.0*M_mat(iyear,nages)));

    spr_F0(iyear)=sum(elem_prod(N_spr_F0,reprod(iyear)));
```

```
   bpr_F0(iyear)=sum(elem_prod(N_bpr_F0,wgt_spawn_mt(iyear)));
  }

  N_spr_F0(1)=1.0*mfexp(-1.0*wgted_M(1)*spawn_time_frac); //at peak spawning time
  for (iage=2; iage<=nages; iage++)
  {
   dum1=wgted_M(iage-1)*(1.0-spawn_time_frac) + wgted_M(iage)*spawn_time_frac;
   N_spr_F0(iage)=N_spr_F0(iage-1)*mfexp(-1.0*(dum1));
  }
  N_spr_F0(nages)=N_spr_F0(nages)/(1.0-mfexp(-1.0*wgted_M(nages))); //plus group (sum of geometric series
  wgted_spr_F0=sum(elem_prod(N_spr_F0,wgted_reprod));

FUNCTION get_selectivity

//// ------- compute landings selectivities by period

  for (iage=1; iage<=nages; iage++)
  {
    sel_cR1_vec(iage)=(1./(1.+mfexp(-1.*selpar_slope_cR1*(double(agebins(iage))-
                selpar_L50_cR1))))*(1.-(1./(1.+mfexp(-1.*selpar_slope2_cR1*
                (double(agebins(iage))-(selpar_L50_cR1+selpar_L502_cR1)))))); //double logistic

    sel_cR2_vec(iage)=(1./(1.+mfexp(-1.*selpar_slope_cR2*(double(agebins(iage))-
                selpar_L50_cR2))))*(1.-(1./(1.+mfexp(-1.*selpar_slope2_cR2*
                (double(agebins(iage))-(selpar_L50_cR2+selpar_L502_cR2)))))); //double logistic

    sel_cR3_vec(iage)=(1./(1.+mfexp(-1.*selpar_slope_cR3*(double(agebins(iage))-
                selpar_L50_cR3))))*(1.-(1./(1.+mfexp(-1.*selpar_slope2_cR3*
                (double(agebins(iage))-(selpar_L50_cR3+selpar_L502_cR3)))))); //double logistic

    sel_cR4_vec(iage)=(1./(1.+mfexp(-1.*selpar_slope_cR4*(double(agebins(iage))-
                selpar_L50_cR4))))*(1.-(1./(1.+mfexp(-1.*selpar_slope2_cR4*
                (double(agebins(iage))-(selpar_L50_cR4+selpar_L502_cR4)))))); //double logistic

    sel_cB_vec(iage)=(1./(1.+mfexp(-1.*selpar_slope_cB*(double(agebins(iage))-
                selpar_L50_cB))))*(1.-(1./(1.+mfexp(-1.*selpar_slope2_cB*
                (double(agebins(iage))-(selpar_L50_cB+selpar_L502_cB)))))); //double logistic

    sel_PN_vec(iage)=(1./(1.+mfexp(-1.*selpar_slope_PN*(double(agebins(iage))-
                selpar_L50_PN))))*(1.-(1./(1.+mfexp(-1.*selpar_slope2_PN*
                (double(agebins(iage))-(selpar_L50_PN+selpar_L502_PN)))))); //double logistic
  }
  sel_cR1_vec=sel_cR1_vec/max(sel_cR1_vec); //re-normalize double logistic
  sel_cR2_vec=sel_cR2_vec/max(sel_cR2_vec); //re-normalize double logistic
  sel_cR3_vec=sel_cR3_vec/max(sel_cR3_vec); //re-normalize double logistic
  sel_cR4_vec=sel_cR4_vec/max(sel_cR4_vec); //re-normalize double logistic
  sel_cB_vec=sel_cB_vec/max(sel_cB_vec); //re-normalize double logistic
  sel_PN_vec=sel_PN_vec/max(sel_PN_vec); //re-normalize double logistic

//-----------fill in years--------------------------------------------

  for (iyear=styr; iyear<=endyr; iyear++)
  {  //time-invariant selectivities
    sel_cB(iyear)=sel_cB_vec;
    sel_PN(iyear)=sel_PN_vec;
  }
  //Period 1:
  for (iyear=styr; iyear<=endyr_period1; iyear++)
  {
    sel_cR(iyear)=sel_cR1_vec;
  }
```

```
//Period 2:
for (iyear=endyr_period1+1; iyear<=endyr_period2; iyear++)
{
  //sel_cR(iyear)=sel_cR2_vec;
  sel_cR(iyear)=sel_cR1_vec;
}

//Period 3
for (iyear=endyr_period2+1; iyear<=endyr_period3; iyear++)
{
  //sel_cR(iyear)=sel_cR3_vec;
  sel_cR(iyear)=sel_cR1_vec;
}

//Period 4
for (iyear=endyr_period3+1; iyear<=endyr; iyear++)
{
  //sel_cR(iyear)=sel_cR4_vec;
  sel_cR(iyear)=sel_cR1_vec;
}

FUNCTION get_mortality
 Fsum.initialize();
 Fapex.initialize();
 F.initialize();
 ////initialization F is avg of first 3 yrs of observed landings
 log_F_dev_init_cR=sum(log_F_dev_cR(styr_cR_L,(styr_cR_L+2)))/3.0;
 log_F_dev_init_cB=sum(log_F_dev_cB(styr_cB_L,(styr_cB_L+2)))/3.0;

 for (iyear=styr; iyear<=endyr; iyear++)
 {
  //-------------
  if(iyear>=styr_cR_L & iyear<=endyr_cR_L)
   {F_cR_out(iyear)=mfexp(log_avg_F_cR+log_F_dev_cR(iyear));}
  if (iyear<styr_cR_L)
   {F_cR_out(iyear)=mfexp(log_avg_F_cR+log_F_dev_init_cR);}
  F_cR(iyear)=sel_cR(iyear)*F_cR_out(iyear);
  Fsum(iyear)+=F_cR_out(iyear);

  //-------------
  if(iyear>=styr_cB_L & iyear<=endyr_cB_L)
     {F_cB_out(iyear)=mfexp(log_avg_F_cB+log_F_dev_cB(iyear));}
  if (iyear<styr_cB_L)
   {F_cB_out(iyear)=mfexp(log_avg_F_cB+log_F_dev_init_cB);}
  F_cB(iyear)=sel_cB(iyear)*F_cB_out(iyear);
  Fsum(iyear)+=F_cB_out(iyear);

  //Total F at age
  F(iyear)=F_cR(iyear); //first in additive series (NO +=)
  F(iyear)+=F_cB(iyear);

  Fapex(iyear)=max(F(iyear));
  Z(iyear)=M_mat(iyear)+F(iyear);
 }  //end iyear

FUNCTION get_bias_corr
 //may exclude last BiasCor_exclude_yrs yrs bc constrained or lack info to estimate
 var_rec_dev=norm2(log_rec_dev(styr_rec_dev,(endyr-BiasCor_exclude_yrs))-
            sum(log_rec_dev(styr_rec_dev,(endyr-BiasCor_exclude_yrs)))
            /(nyrs_rec-BiasCor_exclude_yrs))/(nyrs_rec-BiasCor_exclude_yrs-1.0);
```

```
  if (set_BiasCor <= 0.0) {BiasCor=mfexp(var_rec_dev/2.0);}   //bias correction
  else {BiasCor=set_BiasCor;}


FUNCTION get_numbers_at_age
//Initialization
  S0=spr_F0(styr)*R0;
  if(set_SR_switch>1) //Beverton-Holt
  {
    R_virgin=(R0/((5.0*steep-1.0)*spr_F0(styr)))*
             (BiasCor*4.0*steep*spr_F0(styr)-spr_F0(styr)*(1.0-steep));
  }
  if(set_SR_switch<2) //Ricker
  {
    R_virgin=R0/spr_F0(styr)*(1+log(BiasCor*spr_F0(styr))/steep);
  }
  B0=bpr_F0(styr)*R_virgin;

  temp_agevec=wgt_fish_mt(styr);
  B0_q_DD=R_virgin*sum(elem_prod(N_bpr_F0(set_q_DD_stage,nages),temp_agevec(set_q_DD_stage,nages)));

  F_initial=sel_cR(styr)*mfexp(log_avg_F_cR+log_F_dev_init_cR)+
          sel_cB(styr)*mfexp(log_avg_F_cB+log_F_dev_init_cB);
  Z_initial=M+F_init_ratio*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
//    N_spr_F_init_mdyr(1,(nages-1))=elem_prod(N_spr_initial(1,(nages-1)),
//                              mfexp((-1.*(M(nages-1)+ F_initial))/2.0));

  spr_initial=sum(elem_prod(N_spr_initial,reprod(styr)));

  if(set_SR_switch>1) //Beverton-Holt
  {
    if (styr=styr_rec_dev) {R1=(R0/((5.0*steep-1.0)*spr_initial))*
             (4.0*steep*spr_initial-spr_F0(styr)*(1.0-steep));} //without bias correction (deviation added later)
    else {R1=(R0/((5.0*steep-1.0)*spr_initial))*
             (BiasCor*4.0*steep*spr_initial-spr_F0(styr)*(1.0-steep));} //with bias correction
  }
  if(set_SR_switch<2) //Ricker
  {
    if (styr=styr_rec_dev) {R1=R0/spr_initial*(1+log(BiasCor*spr_initial)/steep);} //without bias correction (deviation added
later)
    else {R1=R0/spr_initial*(1+log(BiasCor*spr_initial)/steep);} //with bias correction
  }

  if(R1<0.0) {R1=1.0;} //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)*(1.0-spawn_time_frac) + Z_initial(iage)*spawn_time_frac));
```

```
 }
 //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_mdyr(styr)(1,nages)=elem_prod(N(styr)(1,nages),(mfexp(-1.*(Z_initial(1,nages))*0.5))); //mid year
 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(styr)));

 temp_agevec=wgt_fish_mt(styr);
 B_q_DD(styr)=sum(elem_prod(N(styr)(set_q_DD_stage,nages),temp_agevec(set_q_DD_stage,nages)));

//Rest of years
 for (iyear=styr; iyear<endyr; iyear++)
 {
  if(iyear<(styr_rec_dev-1)) //recruitment follows S-R curve exactly
  {
     //add dzero to avoid log(zero)
     if(set_SR_switch>1) //Beverton-Holt
     {
       N(iyear+1,1)=BiasCor*mfexp(log(((0.8*R0*steep*SSB(iyear))/(0.2*R0*spr_F0(iyear)*
         (1.0-steep)+(steep-0.2)*SSB(iyear)))+dzero));
     }
     if(set_SR_switch<2) //Ricker
     {
       N(iyear+1,1)=mfexp(log(BiasCor*SSB(iyear)/spr_F0(iyear)*mfexp(steep*(1-SSB(iyear)/(R0*spr_F0(iyear))))+dzero));
     }
     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))); //mid year
     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(iyear+1)));
     temp_agevec=wgt_fish_mt(iyear+1);
     B_q_DD(iyear+1)=sum(elem_prod(N(iyear+1)(set_q_DD_stage,nages),temp_agevec(set_q_DD_stage,nages)));

  }
  else   //recruitment follows S-R curve with lognormal deviation
  {
     //add dzero to avoid log(zero)
     if(set_SR_switch>1) //Beverton-Holt
     {
       N(iyear+1,1)=mfexp(log(((0.8*R0*steep*SSB(iyear))/(0.2*R0*spr_F0(iyear)*
         (1.0-steep)+(steep-0.2)*SSB(iyear)))+dzero)+log_rec_dev(iyear+1));
     }
     if(set_SR_switch<2) //Ricker
     {
       N(iyear+1,1)=mfexp(log(SSB(iyear)/spr_F0(iyear)*mfexp(steep*(1-
SSB(iyear)/(R0*spr_F0(iyear))))+dzero)+log_rec_dev(iyear+1));
     }
     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))); //mid year
```

```
      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(iyear+1)));
      temp_agevec=wgt_fish_mt(iyear+1);
      B_q_DD(iyear+1)=sum(elem_prod(N(iyear+1)(set_q_DD_stage,nages),temp_agevec(set_q_DD_stage,nages)));
   }
 }


   //last year (projection) has no recruitment variability
   if(set_SR_switch>1) //Beverton-Holt
   {
    N(endyr+1,1)=mfexp(log(((0.8*R0*steep*SSB(endyr))/(0.2*R0*spr_F0(endyr)*
          (1.0-steep)+(steep-0.2)*SSB(endyr)))+dzero));
   }
   if(set_SR_switch<2) //Ricker
   {
    N(endyr+1,1)=mfexp(log(SSB(iyear)/spr_F0(iyear)*mfexp(steep*(1-SSB(iyear)/(R0*spr_F0(iyear))))+dzero));
   }
   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));


//Time series of interest
 rec=column(N,1);
 SdS0=SSB/S0;
 for (iyear=styr; iyear<=endyr; iyear++)
 {
   pred_SPR(iyear)=SSB(iyear)/rec(iyear+1);
 }

FUNCTION get_landings_numbers //Baranov catch eqn
 for (iyear=styr; iyear<=endyr; iyear++)
 {
   for (iage=1; iage<=nages; iage++)
   {
    L_cR_num(iyear,iage)=N_mdyr(iyear,iage)*F_cR(iyear,iage)*
      (1.-mfexp(-1.*Z(iyear,iage)))/Z(iyear,iage);
    L_cB_num(iyear,iage)=N_mdyr(iyear,iage)*F_cB(iyear,iage)*
      (1.-mfexp(-1.*Z(iyear,iage)))/Z(iyear,iage);
   }

   pred_cR_L_knum(iyear)=sum(L_cR_num(iyear));
   pred_cB_L_knum(iyear)=sum(L_cB_num(iyear));
 }

FUNCTION get_landings_wgt

////---Predicted landings------------------------
 for (iyear=styr; iyear<=endyr; iyear++)
 {
   L_cR_mt(iyear)=elem_prod(L_cR_num(iyear),wgt_cR_mt(iyear));     //in 1000 mt
   L_cB_mt(iyear)=elem_prod(L_cB_num(iyear),wgt_cB_mt(iyear));     //in 1000 mt

   pred_cR_L_mt(iyear)=sum(L_cR_mt(iyear));
   pred_cB_L_mt(iyear)=sum(L_cB_mt(iyear));
 }

FUNCTION get_catchability_fcns
 //Get rate increase if estimated, otherwise fixed above
```

```
 if (set_q_rate_phase>0.0)
 {
    for (iyear=styr_PN_cpue; iyear<=endyr_PN_cpue; iyear++)
    {   if (iyear>styr_PN_cpue & iyear <=2003)
        {//q_rate_fcn_cL(iyear)=(1.0+q_rate)*q_rate_fcn_cL(iyear-1); //compound
           q_rate_fcn_PN(iyear)=(1.0+(iyear-styr_PN_cpue)*q_rate)*q_rate_fcn_PN(styr_PN_cpue);  //linear
        }
        if (iyear>2003) {q_rate_fcn_PN(iyear)=q_rate_fcn_PN(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-----------------------
 //combined JAI index
 if(JAI_cpue_switch==1)
 {
   obs_JAI_cpue_final=pow(obs_JAI_cpue,JAI_exp);
   JAI_cpue_cv_final=JAI_cpue_cv;
 }
 else
 {

obs_JAI_cpue_final=(obs_JAI1_cpue*wgt_JAI1+obs_JAI2_cpue*wgt_JAI2+obs_JAI3_cpue*wgt_JAI3+obs_JAI4_cpue*wgt_
JAI4)
                  /(wgt_JAI1+wgt_JAI2+wgt_JAI3+wgt_JAI4);
   obs_JAI_cpue_final=pow(obs_JAI_cpue_final,JAI_exp);

JAI_cpue_cv_final=(JAI1_cpue_cv*wgt_JAI1+JAI2_cpue_cv*wgt_JAI2+JAI3_cpue_cv*wgt_JAI3+JAI4_cpue_cv*wgt_JAI4)
                  /(wgt_JAI1+wgt_JAI2+wgt_JAI3+wgt_JAI4);
 }

 //JAI survey
 for (iyear=styr_JAI_cpue; iyear<=endyr_JAI_cpue; iyear++)
 {   //index in number units
     N_JAI(iyear)=N(iyear,1);
     pred_JAI_cpue(iyear)=mfexp(log_q_JAI)*N_JAI(iyear);
 }

 //PN index
 for (iyear=styr_PN_cpue; iyear<=endyr_PN_cpue; iyear++)
 {   //index in number units
     N_PN(iyear)=elem_prod(N_mdyr(iyear),sel_PN(iyear));
     pred_PN_cpue(iyear)=mfexp(log_q_PN)*sum(N_PN(iyear));
 }

FUNCTION get_age_comps

 //Commercial reduction
 for (iyear=1;iyear<=nyr_cR_agec;iyear++)
 {
   ErrorFree_cR_agec(iyear)=L_cR_num(yrs_cR_agec(iyear))/
                    sum(L_cR_num(yrs_cR_agec(iyear)));
```

```
   pred_cR_agec(iyear)=age_error*ErrorFree_cR_agec(iyear);
  }

 //Commercial bait
  for (iyear=1;iyear<=nyr_cB_agec;iyear++)
  {
   ErrorFree_cB_agec(iyear)=L_cB_num(yrs_cB_agec(iyear))/
                    sum(L_cB_num(yrs_cB_agec(iyear)));
   pred_cB_agec(iyear)=age_error*ErrorFree_cB_agec(iyear);
  }

////------------------------------------------------------------------------------------------------------------------------------------------------------------------------
----------------
FUNCTION get_weighted_current
  F_temp_sum=0.0;
  F_temp_sum+=mfexp((selpar_n_yrs_wgted*log_avg_F_cR+
       sum(log_F_dev_cR((endyr-selpar_n_yrs_wgted+1),endyr)))/selpar_n_yrs_wgted);
  F_temp_sum+=mfexp((selpar_n_yrs_wgted*log_avg_F_cB+
       sum(log_F_dev_cB((endyr-selpar_n_yrs_wgted+1),endyr)))/selpar_n_yrs_wgted);

  F_cR_prop=mfexp((selpar_n_yrs_wgted*log_avg_F_cR+
       sum(log_F_dev_cR((endyr-selpar_n_yrs_wgted+1),endyr)))/selpar_n_yrs_wgted)/F_temp_sum;
  F_cB_prop=mfexp((selpar_n_yrs_wgted*log_avg_F_cB+
       sum(log_F_dev_cB((endyr-selpar_n_yrs_wgted+1),endyr)))/selpar_n_yrs_wgted)/F_temp_sum;

  log_F_dev_end_cR=sum(log_F_dev_cR((endyr-selpar_n_yrs_wgted+1),endyr))/selpar_n_yrs_wgted;
  log_F_dev_end_cB=sum(log_F_dev_cB((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)+
        sel_cB(endyr)*mfexp(log_avg_F_cB+log_F_dev_end_cB);

  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+F_cB_prop;
  wgt_wgted_L_mt=F_cR_prop/wgt_wgted_L_denom*wgt_cR_mt(endyr)+
           F_cB_prop/wgt_wgted_L_denom*wgt_cB_mt(endyr);

FUNCTION get_msy

  //compute values as functions of F
  for(int 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=wgted_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,wgted_reprod));


  //Compute equilibrium values of R (including bias correction), SSB and Yield at each F
  if(set_SR_switch>1) //Beverton-Holt
  {
    R_eq(ff)=(R0/((5.0*steep-1.0)*spr_msy(ff)))*
           (BiasCor*4.0*steep*spr_msy(ff)-wgted_spr_F0*(1.0-steep));
  }
  if(set_SR_switch<2) //Ricker
  {
    R_eq(ff)=R0/spr_msy(ff)*(1+log(BiasCor*spr_msy(ff))/steep);
  }
  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,wgted_reprod));
  B_eq(ff)=sum(elem_prod(N_age_msy,wgt_fish_mt(endyr)));
  L_eq_mt(ff)=sum(elem_prod(L_age_msy,wgt_wgted_L_mt));
  L_eq_knum(ff)=sum(L_age_msy);
 }

 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

 //compute total landings- and discards-at-age in 1000 fish and klb
 L_total_num.initialize();
 L_total_mt.initialize();

 L_total_num=(L_cR_num+L_cB_num); //catch in number fish
 L_total_mt=L_cR_mt+L_cB_mt;   //landings in klb whole weight
```

```
 for(iyear=styr; iyear<=endyr; iyear++)
 {
      L_total_mt_yr(iyear)=sum(L_total_mt(iyear));
      L_total_knum_yr(iyear)=sum(L_total_num(iyear));

      B(iyear)=elem_prod(N(iyear),wgt_fish_mt(iyear));
      totN(iyear)=sum(N(iyear));
      totB(iyear)=sum(B(iyear));
 }
 B(endyr+1)=elem_prod(N(endyr+1),wgt_fish_mt(endyr));
 totN(endyr+1)=sum(N(endyr+1));
 totB(endyr+1)=sum(B(endyr+1));

//  steep_sd=steep;
//  fullF_sd=Fsum;

 if(F_msy_out>0)
   {
    FdF_msy=Fapex/F_msy_out;
    FdF_msy_end=FdF_msy(endyr);
   }
 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; 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);
  }

  //Compute the exploitation rate for ages 1+ and pop wgtd F for ages 2+
   for(iyear=styr; iyear<=endyr; iyear++)
   {
    E(iyear)=sum(L_cR_num(iyear)(2,nages)+L_cB_num(iyear)(2,nages))/sum(N(iyear)(2,nages));
    F_age2plus(iyear)=((F_cB(iyear)(3,nages)+F_cR(iyear)(3,nages))*N(iyear)(3,nages))/sum(N(iyear)(3,nages));
    F_cR_age2plus(iyear)=(F_cR(iyear)(3,nages)*N(iyear)(3,nages))/sum(N(iyear)(3,nages));
    F_cB_age2plus(iyear)=(F_cB(iyear)(3,nages)*N(iyear)(3,nages))/sum(N(iyear)(3,nages));
   }


//--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------
--------------
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(iyear)))/spr_F0(iyear);
 }


 //compute SSB/R and YPR as functions of F
 for(int 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=wgted_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)));
  F_spr_age2plus(ff)=F_L_age_spr(3,nages)*N_age_spr(3,nages)/sum(N_age_spr(3,nages));
  spr_spr(ff)=sum(elem_prod(N_age_spr,wgted_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); //in mt
  }
 }

FUNCTION get_effective_sample_sizes

   neff_cR_agec_allyr_out=missing;
   neff_cB_agec_allyr_out=missing;

   for (iyear=1; iyear<=nyr_cR_agec; iyear++)
     {if (nsamp_cR_agec(iyear)>=minSS_cR_agec)
       { numer=sum( elem_prod(pred_cR_agec(iyear),(1.0-pred_cR_agec(iyear))) );
         denom=sum( square(obs_cR_agec(iyear)-pred_cR_agec(iyear)) );
           if (denom>0.0) {neff_cR_agec_allyr_out(yrs_cR_agec(iyear))=numer/denom;}
           else {neff_cR_agec_allyr_out(yrs_cR_agec(iyear))=-missing;}
       } else {neff_cR_agec_allyr_out(yrs_cR_agec(iyear))=-99;}
     }

   for (iyear=1; iyear<=nyr_cB_agec; iyear++)
     {if (nsamp_cB_agec(iyear)>=minSS_cB_agec)
       { numer=sum( elem_prod(pred_cB_agec(iyear),(1.0-pred_cB_agec(iyear))) );
         denom=sum( square(obs_cB_agec(iyear)-pred_cB_agec(iyear)) );
```

```
            if (denom>0.0) {neff_cB_agec_allyr_out(yrs_cB_agec(iyear))=numer/denom;}
            else {neff_cB_agec_allyr_out(yrs_cB_agec(iyear))=-missing;}
        } else {neff_cB_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_bench,endyr_bench);
 SPR_temp=pred_SPR(styr_bench,endyr_bench);
 for(int jyear=endyr_bench; jyear>=styr_bench; jyear--)
 {
  R_sort(jyear)=max(R_temp);
  SPR_sort(jyear)=max(SPR_temp);
  for(iyear=styr_bench; iyear<=endyr_bench; 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_bench-styr_bench)*0.5;
 quant_whole=(endyr_bench-styr_bench)*0.5;
 quant_diff=quant_decimal-quant_whole;
 R_med=R_sort(styr_bench+quant_whole)*(1-quant_diff)+R_sort(styr_bench+quant_whole+1)*(quant_diff);
 SPR_med=SPR_sort(styr_bench+quant_whole)*(1-quant_diff)+SPR_sort(styr_bench+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_bench-styr_bench)*0.75;
 quant_whole=(endyr_bench-styr_bench)*0.75;
 quant_diff=quant_decimal-quant_whole;
 SPR_75th=SPR_sort(styr_bench+quant_whole)*(1-quant_diff)+SPR_sort(styr_bench+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(int 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);
   }
  }

FUNCTION evaluate_objective_function
  fval=0.0;
  fval_unwgt=0.0;

////---likelihoods--------------------------

////---Indices------------------------------
  f_JAI_cpue=0.0;
  for (iyear=styr_JAI_cpue; iyear<=endyr_JAI_cpue; iyear++)
  {
   f_JAI_cpue+=square(log((pred_JAI_cpue(iyear)+dzero)/
       (obs_JAI_cpue_final(iyear)+dzero)))/(2.0*log(1.0+square(JAI_cpue_cv_final(iyear))));
  }
  fval+=w_I_JAI*f_JAI_cpue;
  fval_unwgt+=f_JAI_cpue;

  f_PN_cpue=0.0;
  for (iyear=styr_PN_cpue; iyear<=endyr_PN_cpue; iyear++)
  {
   f_PN_cpue+=square(log((pred_PN_cpue(iyear)+dzero)/
       (obs_PN_cpue(iyear)+dzero)))/(2.0*log(1.0+square(PN_cpue_cv(iyear))));
  }
  fval+=w_I_PN*f_PN_cpue;
  fval_unwgt+=f_PN_cpue;

////---Landings------------------------------

  f_cR_L=0.0; //in 1000 mt
  for (iyear=styr_cR_L; iyear<=endyr_cR_L; iyear++)
  {
     f_cR_L+=square(log((pred_cR_L_mt(iyear)+dzero)/
       (obs_cR_L(iyear)+dzero)))/(2.0*log(1.0+square(cR_L_cv(iyear))));
  }
  fval+=w_L*f_cR_L;
  fval_unwgt+=f_cR_L;

  f_cB_L=0.0; //in 1000 mt
  for (iyear=styr_cB_L; iyear<=endyr_cB_L; iyear++)
  {
   f_cB_L+=square(log((pred_cB_L_mt(iyear)+dzero)/
```

```
      (obs_cB_L(iyear)+dzero)))/(2.0*log(1.0+square(cB_L_cv(iyear))));
 }
 fval+=w_L*f_cB_L;
 fval_unwgt+=f_cB_L;

//////---Age comps-------------------------------
 f_cR_agec=0.0;
 for (iyear=1; iyear<=nyr_cR_agec; iyear++)
 {
  if (nsamp_cR_agec(iyear)>=minSS_cR_agec)
  {
  f_cR_agec-=neff_cR_agec(iyear)*
        sum(elem_prod((obs_cR_agec(iyear)+dzero),
          log(elem_div((pred_cR_agec(iyear)+dzero),
            (obs_cR_agec(iyear)+dzero)))));
  }
 }
 fval+=w_ac*f_cR_agec;
 fval_unwgt+=f_cR_agec;


 f_cB_agec=0.0;
 for (iyear=1; iyear<=nyr_cB_agec; iyear++)
 {
  if (nsamp_cB_agec(iyear)>=minSS_cB_agec)
  {
  f_cB_agec-=neff_cB_agec(iyear)*
        sum(elem_prod((obs_cB_agec(iyear)+dzero),
          log(elem_div((pred_cB_agec(iyear)+dzero),
            (obs_cB_agec(iyear)+dzero)))));
  }
 }
 fval+=w_ac*f_cB_agec;
 fval_unwgt+=f_cB_agec;

////-----------Constraints and penalties--------------------------------
 f_rec_dev=0.0;
 f_rec_dev=norm2(log_rec_dev);
 f_rec_dev=pow(log_rec_dev(styr_rec_dev),2);
 for(iyear=(styr_rec_dev+1); iyear<=endyr; iyear++)
 {f_rec_dev+=pow(log_rec_dev(iyear)-R_autocorr*log_rec_dev(iyear-1),2);}
 fval+=w_rec*f_rec_dev;


 f_rec_dev_early=0.0; //possible extra constraint on early rec deviations
 if (styr_rec_dev<endyr_rec_phase1)
  {
   f_rec_dev_early=pow(log_rec_dev(styr_rec_dev),2);
   for(iyear=(styr_rec_dev+1); iyear<=endyr_rec_phase1; iyear++)
   {f_rec_dev_early+=pow(log_rec_dev(iyear)-R_autocorr*log_rec_dev(iyear-1),2);}
  }
 fval+=w_rec_early*f_rec_dev_early;

 f_rec_dev_end=0.0; //possible extra constraint on ending rec deviations
 if (endyr_rec_phase2<endyr)
  {
   for(iyear=(endyr_rec_phase2+1); iyear<=endyr; iyear++)
   {f_rec_dev_end+=pow(log_rec_dev(iyear)-R_autocorr*log_rec_dev(iyear-1),2);}
  }
 fval+=w_rec_end*f_rec_dev_end;
```

```
 f_Ftune=0.0;
 if (!last_phase()) {f_Ftune=square(Fapex(set_Ftune_yr)-set_Ftune);}
 fval+=w_Ftune*f_Ftune;

 //code below contingent on four phases
 f_fullF_constraint=0.0;
 if (!last_phase())
 {for (iyear=styr; iyear<=endyr; iyear++)
     {if (Fapex(iyear)>3.0){f_fullF_constraint+=mfexp(Fapex(iyear)-3.0);}}
  if (current_phase()==1) {w_fullF=set_w_fullF;}
  if (current_phase()==2) {w_fullF=set_w_fullF/10.0;}
  if (current_phase()==3) {w_fullF=set_w_fullF/100.0;}
 }

 fval+=w_fullF*f_fullF_constraint;

 //Random walk components of fishery dependent indices
 f_PN_RW_cpue=0.0;
 for (iyear=styr_PN_cpue; iyear<endyr_PN_cpue; iyear++)
    {f_PN_RW_cpue+=square(q_RW_log_dev_PN(iyear))/(2.0*set_q_RW_PN_var);}
 fval+=f_PN_RW_cpue;

 //JAI combination weights penalty to sum to 1.0
 f_JAI_wgts=0.0;
 f_JAI_wgts=square(1.0-(wgt_JAI1+wgt_JAI2+wgt_JAI3+wgt_JAI4));
 fval+=w_JAI_wgts*f_JAI_wgts;

 f_priors=0.0;
 f_priors=norm2(log_Nage_dev);
 f_priors+=square(steep-set_steep)/square(set_steep_se);
 f_priors+=square(R_autocorr-set_R_autocorr);
 f_priors+=square(q_DD_beta-set_q_DD_beta)/square(set_q_DD_beta_se);

 if(switch_prior==1)
 {
   fval+=f_priors;
 }
 //cout << "fval = " << fval << "  fval_unwgt = " << fval_unwgt << endl;


REPORT_SECTION

 //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();

 //><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
 report << "Likelihood " << "Value " << "Weight" << endl;
 report << "JAI_index " << f_JAI_cpue << " " << w_I_JAI << endl;
 report << "PN_index " << f_PN_cpue << " " << w_I_PN << endl;
 report << "reduction_agec " << f_cR_agec << " " << w_ac << endl;
 report << "L_reduction " << f_cR_L << " " << w_L << endl;
 report << "bait_agec " << f_cB_agec << " " << w_ac << endl;
```

```
  report << "L_bait " << f_cB_L << " " << w_L << endl;
  report << "R_dev " << f_rec_dev << " " << w_rec << endl;
  report << "R_dev_early " << f_rec_dev_early << " " << w_rec_early << endl;
  report << "R_dev_end " << f_rec_dev_end << " " << w_rec_end << endl;
  report << "F_tune " << f_Ftune << " " << w_Ftune << endl;
  report << "fullF_constraint " << f_fullF_constraint << " " << w_fullF << endl;
  report << "priors " << f_priors << " " << switch_prior << endl;

  report << "TotalLikelihood " << fval << endl;
  report << "UnwgtLikelihood " << fval_unwgt << endl;

  report << "Error levels in model" << endl;
  report << "JAI_cv " << JAI_cpue_cv << endl;
  report << "PN_cv " << PN_cpue_cv << endl;
  report << "L_reduction_cv " << cR_L_cv << endl;
  report << "L_bait_cv " << cB_L_cv << endl;

  report << "NaturalMortality Vector" << endl;
  report << "Age " << agebins << endl;
  report << "M_vector " << M << endl;
  report << "NaturalMortality Matrix " << endl;
  report << "Year " << agebins << endl;
  for(iyear=styr; iyear<=endyr; iyear++)
  {
    report << iyear << " " << M_mat(iyear) << endl;
  }

  report << "Steepness " << steep << endl;
  report << "R0 " << R0 << endl;

  report << "Recruits" << endl;
  report << "Year";
  for(iyear=styr; iyear<=endyr; iyear++)
  {
    report << " " << iyear;
  }
  report << endl;
  report << "Age-0_recruits " << column(N,1) << endl;
  report << "Age-1_recruits " << column(N,2) << endl;
  report << "SSB" << endl;
  report << "Year";
  for(iyear=styr; iyear<=endyr; iyear++)
  {
    report << " " << iyear;
  }
  report << endl;
  report << "FEC " << SSB << endl;
  //report << "SSB " << FEC << endl;
  report << "Lagged_R " << column(N,1)(styr+1,endyr) << endl;

//    cout<< mfexp(log_len_cv)<<endl;
//  report << "TotalLikelihood " << fval << endl;
 #include "menhad_make_Robject012.cxx"   // write the S-compatible report
```

Southeast Data, Assessment, and Review 20

Review Panel Consensus Report

Atlantic Menhaden

Members of the SEDAR 20 Review Panel
Kim McKown (Panel Chair), New York State Department of Environmental Conservation
Dr. Tim Miller, NMFS Northeast Fisheries Science Center
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Introduction

The Review Workshop of the 2010 Atlantic Menhaden Assessment Report was held March 8 – 12, 2010 in Charleston, South Carolina. The Review Workshop provided a comprehensive and in-depth evaluation of this assessment. This report contains the Panel's summary findings, detailed discussion of each TOR, and a summary of the results of analytical requests.

Summary of Findings

- The Panel is comfortable with the results from the menhaden base run. The model results and the status determination are robust.
- The 2008 point estimate of fishing mortality (F) was below the estimated F threshold, the status determination is that overfishing was not occurring and the 2008 point estimate of fecundity was above the fecundity threshold and target, the status determination is that the stock is not overfished.
- The Panel was concerned that the 2008 F estimate was very close to the threshold. If uncertainty in the estimate was considered there is a significant probability that overfishing occurred in 2008.
- The Panel was also concerned about the use of F_{med} and the fecundity associated with it as reference points. The concern is that there is no information on the relationship of the target and threshold fecundity in relation to virgin fecundity levels. Projections were run to examine this, and the estimated annual fecundity since 1998 was only 5 to 10% of the virgin fecundity.
- The Panel recommends that a model specification similar to the Panel's reference run be considered for future assessments. This includes capped effective sample size at 200, allow the gaps in the pound net index and bait fishery age composition where data are not available, modification of the reduction and bait fleets to northern and southern fleets, and time-varying domed selectivity for the southern region.

  This model specification combines information of the bait and reduction fisheries occurring together regionally because they are essentially using the same gear but fishing on different age components of the stock in the two areas. Removing the estimated age composition and indices for years where it is absent is desirable because the data from years where it is available is providing the correct amount of information, from a statistical perspective, to the assessment model. Allowing domed selectivity of the fisheries in the southern region allows for the lack of availability of older fish in that region when the fishery is occurring. The reduction of effective sample sizes is intended to better reflect the actual information content of the age composition data (the residuals in the base model were inconsistent with the large assumed effective sample sizes). Also, the time-varying selectivity in the southern region had the best AIC of comparable runs and reduced the undesirable pattern of residuals in the southern fishery.

2.1 Comments on specific Terms of Reference (TORs)

1. *Evaluate precision and accuracy of fishery-dependent and fishery-independent data used in the assessment:*
   The Atlantic menhaden fishery was modeled as one east coast stock. The Atlantic Menhaden Stock Assessment Subcommittee (Assessment Team) used commercial and recreational landings at age from Florida to Maine, a fishery dependent adult index developed from Potomac River Fisheries Commission (PRFC) pound net survey, and a juvenile index (JAI) developed from coastwide beach seine information. In addition, growth, weight, and maturity at age were developed using fishery dependent and independent information, while age and time variant natural mortality was estimated using a multi-species virtual population analysis (MSVPA-X, see TOR 2).

   The Assessment Team did a thorough and highly professional job of presenting and discussing the fishery-dependent and fishery-independent data used in the assessment. Landings and biological data from the commercial purse-seine reduction fishery have been well characterized. Reliable information from the commercial bait fishery has only been available since 1985. CVs were estimated for the reduction landings data whereas the bait landings were considered less reliable and given higher assumed values – especially in the early years. Commercial discard is not documented but is assumed trivial compared to total landings, so it was not included. Recreational harvest and discards were estimated through the Marine Recreational Fisheries Statistical Survey (MRFSS). Recreational harvest is minimal and is believed to be caught primarily with cast nets for use as bait. Biological data were not available for the recreational fishery, so the recreational landings were included with the bait fishery.

   Information from biological sampling for length and age for the reduction fishery was available from 1955 through 2008. Biological samples for the bait fishery are available since 1988, and sampling improved in 1994 when a pilot study was initiated to increase the sampling intensity comparable to the reduction fishery. Ages are determined using scales. Estimation of growth was complicated due to size dependent migration. This was accounted for by weighting mean fish weights by catch in numbers by year, season, and fishing area. The Panel agreed with the use of cohort specific weight and length at age to account for apparent density-dependent growth. Maturity was re-examined on the recommendation of the 2004 Peer Review Panel. New estimates were based on 2004 and 2008 collections. The results were similar to previous studies except for high percent mature of age 1's, which the Assessment Team assumed was due to low sample size (n-11). Some Panel members were concerned that maturity may be confounded by spatial and temporal movements of mature fish. The Assessment Team noted that samples for all the maturity work have been collected in the fall off North Carolina to account for spatial and temporal variability. Fecundity was estimated using length-specific fecundity data.

   Several fishery-dependent adult indices and fishery-independent juvenile indices (JAI) were developed. The 2004 Peer Review Panel recommended the evaluation of commercial purse seine fishery information for development of an adult index. Three effort based time series were developed, but were not used due to concerns that they may not measure population abundance and effort. The Panel concurs with the decision not to include these indices in the model. Two adult relative abundance indices were developed from pound-net bait fishery landings collected by the Potomac River Fisheries Commission (PRFC). One was a catch-per-unit-effort (CPUE) index and the other was developed using a generalized linear model (GLM). There were years where the data were not collected, producing data gaps. Values were estimated to fill the gaps in the CPUE index. CVs were assumed constant for the index and sensitivities were run to test the assumption. The PRFC adult CPUE index was used in the model, including the estimated values to fill in data gaps. Since the model can handle missing data, the Panel recommended leaving the gaps in the data. Filling the gaps underestimates the uncertainty. Juvenile indices (JAI) were produced using two methods. The first approach calculates a single coastwide juvenile index. The Assessment Team used this coastwide juvenile index in the model, assuming that each survey represents a component of the coastal juvenile relative abundance. The second approach combined relative abundance data from groups of states according to the similarity of trends in the state-specific time series (additive approach). The Panel recommends this latter approach since these regional indices may capture spatial patterns of juvenile abundance. (see short term research recommendation e). CVs were calculated from jackknife-derived standard errors for the JAI.

Specific questions specified in TOR 1. are addressed below.

a. *Discuss data strengths and weaknesses (e.g. temporal and spatial scale, gear selectivities, aging accuracy, sampling intensity).*

Strengths of the Fishery-dependent and fishery-independent data:

- The reduction fishery landings and biological sampling information have been collected since the 1950s in a consistent manner and represent one of the longest and most complete fisheries information series in the U.S.

- Daily logbooks (Captains Daily Fishing Reports) have been collected since 1985, and detail purse-seine set locations and estimated catch. Vessel compliance is 100%. This information is used to decrease "topping off" bias. Topping off is the practice of taking one more set to fill the hold at the end of a long trip. These added fish typically are smaller than fish in the rest of the hold.

- Scales have been used for ageing since the 1950s, and have been read by the same person since 1969. A re-aging program was conducted in 2009 to determine precision of aging. The standard deviations associated with age estimates were used to provide the error associated with the age composition data. The error was assumed constant over time

Data weaknesses:

- The Panel had some questions on the age structure and estimated selectivities of the commercial reduction and bait fisheries by area. After inspection, it was revealed that the age structure of the landings was a result of the area harvested rather than the type of fishery. The Panel recommend the commercial fishery be modeled by area (north vs south) rather than by fishery (reduction vs bait) (see short term research recommendation a)
- A re-aging study was conducted to estimate precision (see above), but little age validation work has been conducted. An ongoing validation study at Old Dominion University has had good agreement between scale and otolith ages, but few age 2 and 3 fish have been processed, and fish >3 are not included.
- The Potomac River Fisheries Commission (PRFC) pound-net index had a number of years with missing data, which the Assessment Team filled in with estimated values. The Panel recommended leaving the data gaps, because inclusion of the estimated values would lower uncertainty estimates. (see short term research recommendation a)

- The Panel had some concerns about the appropriateness of the length-based cut offs for age-0 juvenile menhaden for the state specific seine surveys which do not age menhaden. Raw data were not available at the Review to explore those concerns.

b. *Report metrics of precision for data inputs and use them to inform the model as appropriate.*

As mentioned above, a re-aging program was conducted in 2009 to determine precision of aging. The standard deviations associated with age estimates were used to provide the error associated with the age composition data. It was assumed constant over time.

Error levels for the fishery catch at age were based on the number of sampling trips (effective sample size). The Panel thought the effective sample size on the age composition data was too high, and recommended capping at 200 (see short term research recommendation a).

c. *Describe and justify index standardization methods.*

The Assessment Team developed several adult and juvenile (JAI) relative abundance indices for potential use in the model, including detailed methodology and justification. The Panel recommended using the alternative regional JAI (see discussion above). There was also discussion about developing an alternative coastwide adult index (see long term research recommendation a).

d. *Justify weighting or elimination of available data sources.*

As discussed above, the Assessment Team did several adjustments or weighting to account for size-variable migration (topping off adjustment, weighted mean weights and length at age). The Panel agreed with the Assessment Team's judgment not to include adult effort-based indices from the reduction fishery. For the PRFC adult index, the Panel recommended not to include estimated values, but to run the model with the data gaps (discussed in a).

2. *Evaluate models used to estimate population parameters (e.g., F, biomass, abundance) and biological reference points.*

The Beaufort Assessment Model (BAM) was the only model used to produce final assessment results. This is a statistical forward-projection model with separable selectivities using the Baranov catch equation. Catch histories, catch-at-age, juvenile and adult abundance indices were all fitted in the model assuming two fisheries (reduction and bait). Constant selectivities were estimated for the fisheries but fixed at assumed values for both the juvenile and adult indices. Catchability parameters were estimated for both indices. Lognormal likelihoods were assumed for the catch histories and indices, with multinomial likelihoods for the catch-at-age data.

The MSVPA-X model was used to estimate age and year specific natural mortality from 1982-2008. The estimates were then assumed known in the base BAM run in those years with the average at-age estimates applied to the years 1955-1981. The MSVPA-X model was peer reviewed in 2005 and recommended for use in estimating natural mortality but not as a full assessment model. The Panel did not revisit this recommendation. There were mixed views within the Panel on the appropriateness of using these estimates in the base model. All members agreed that, in reality, natural mortality was age and year specific. However, there was some concern that the natural mortality estimates were unreliable because of the difficulties of modeling the complexity of the Atlantic ecosystem as it relates to menhaden mortality. However, it was noted that the assessment results are not sensitive to the choice between age-specific natural mortality or age-and-year specific natural mortality.

The base model has a number of strengths:

- well tested software, population dynamics equations, and likelihoods
- based on a good understanding of stock structure and migration patterns
- reasonable certainty in the catch history over an extended period
- extensive catch-at-age data from the main fishery sampled in a consistent manner over many years
- defensible recruitment indices and an adult abundance time series (pound-net CPUE)
- defensible estimates of age and year specific natural mortality.

However, there are also some potential weaknesses in the base model:

- the definition of the fisheries in the model is based on the product produced rather than the fishing method or other attribute of the fishery or stock
- gaps in the catch-at-age data for the bait fishery and the pound-net CPUE indices were "filled in" with unobserved data
- the time series of juvenile and adult indices may not be representative of the whole population (the pound-net CPUE is spatially very limited)

- the input variance assumptions, especially with regard to effective sample sizes, are inconsistent with the model residuals (the effective sample sizes are too high, and therefore uncertainty in model outputs is underestimated)
- there are strong residual patterns for the reduction fishery catch-at-age.

Some of the problems with the base run were examined by the Panel in a number of sensitivity runs. A "reference run" was specified by the Panel:

- define two fisheries based on location (North – where the larger/older fish are typically caught; and South – where smaller/younger fish are typically caught; most catch in both areas is by purse-seine)
- reinstate the gaps in the data which were filled in with unobserved data
- use a maximum effective sample size of 200 for catch-at-age data
- allow the southern selectivity pattern to be domed

Sensitivities to this run included the use of time-blocked selectivities for the Southern fishery based on known changes in the fishery (three time blocks were used). This run had the lowest AIC amongst comparable runs, suggesting that the use of the additional parameters was justified by the improvement in fit. A visual examination of the catch-at-age residuals also showed some reduction in the extent of the residual patterns. The determination of stock status for the reference run and sensitivities was the same as in the base model.

The Panel also evaluated the status of the stock relative to unfished fecundity. Two alternative "productivity periods" were considered. A "recent" period (1992-present) and the "full" period (1955-present); productivity in each period was determined by the mean and variance of the recruits, and the average natural mortality and mean weight-at-age over the period. Unfished fecundity for each period was determined by running the model forward, with stochastic recruitment, without fishing until stochastic equilibrium was established (the mean fecundity is then, by definition, the unfished fecundity; representing the "carrying capacity" of the population under the assumed productivity regime).

For the base model, fecundity since 1998 was estimated at less than 10% of unfished fecundity for the full-regime and about 15% for the recent-regime. The results for the best-AIC model were similar, but higher (about 12% for the full-regime since 1998 and about 25% for the recent-regime), and also showed a slowly increasing trend since 1965 (the base model was fairly flat from 1965 to 2008).

Specific questions specified in TOR 2. are addressed below.

a. *Did the model have difficulty finding a stable solution?*

   The Panel requested that convergence be checked with some jittered starting values. Twenty five runs were performed and all runs converged to the same solution.

b. *Were sensitivity analyses for starting parameter values, priors, etc. and other model diagnostics performed?*

An extensive set of sensitivity runs were performed for the base model including higher and lower *M*, alternative weights on data sets, alternative selectivities, and an alternative start year. The only result of note was that leaving out the juvenile index (JAI) resulted in an over-fishing status in 2008. On investigation it was found that the JAI supported higher recruitment in the last three years than other data sets. Removal of the JAI was sufficient to move the point estimate of 2008 F just above the overfishing threshold.

c. *Have the model strengths and limitations been clearly and thoroughly explained?*

   These were discussed in the assessment document and were also considered by the Panel (see above).

d. *Have the models been used in other peer reviewed assessments? If not, has new model code been verified with simulated data?*

   BAM has been used in several other peer-reviewed assessments.

e. *Compare and discuss differences among alternative models.*

   The Panel formulated an alternative BAM run which addressed the main problems identified with the base run. Given the other uncertainties, the differences in the assessment results between the two models are relatively minor (see above).

3. *Evaluate the potential for conducting assessments at a sub-regional level (e.g. Chesapeake Bay).*

All of the recent research results are consistent with a single Atlantic coast-wide menhaden stock. Although data are available to enable assessments at a sub-regional level, the results would be meaningless from a biological point of view (and would be of no use in making sensible management decisions). The issue of potential sub-regional quotas or fishing limits is outside the TOR for this review. However, the Panel notes that the implementation of such an approach could not sensibly be done by sub-regional assessment (and setting sub-regional quotas on the basis of the assessments).

4. *State and evaluate assumptions made for all models and explain the likely effects of assumption violations on model outputs.*

These were discussed under TOR 2. However, each point in the checklist is addressed below.

a. *Calculation of M.*
   Discussed under *b.*

b. *Choice to incorporate constant or time-varying M and catchability.*

Year and age-specific M were estimated in the MSVPA-X model and assumed known in the base BAM run. Sensitivity runs with higher and lower M and age-specific but time-invariant M did not change the status determination.

c. *Choice of selectivity patterns.*
Fishery selectivities were estimated in the base run although domed-selectivities were not allowed. The potential impact of mis-specification was investigated by allowing domed-selectivities in some runs, but this did not change the status determination.

d. *Choice of time steps in models.*
The model had a simple annual cycle and assumed that all fisheries were operating year-round. This is a significant departure from reality but it is unlikely to have a major impact on assessment results. Nevertheless, it would be better to model the timing of the fisheries more accurately, particularly as the timing of some of them has changed in recent years.

e. *Error in the catch-at-age matrix.*
The catch at age data are assumed to follow a multinomial distribution in each year with effective sample sizes equal to the number of trips sampled. This is a mathematically convenient and commonly made assumption which is almost certainly violated. In this particular case, the effective sample sizes appear to be too high as the model residuals are much more variable than they should be given the assumed sample sizes. Also, there are obvious patterns in the residuals for the reduction fishery. Lower sample sizes and alternative splits of the fisheries, together with alternative selectivities alleviated these problems to some extent. Different point estimates were obtained but stock status determination was unaltered.

f. *Choice of a plus group for age-structured species.*
A plus group was used at an appropriate age.

g. *Constant ecosystem (abiotic and trophic) conditions.*
Ecosystem conditions are unlikely to have been constant over the period in which the stock was modeled. There are attempts in the model to deal with changing conditions in terms of year-specific natural mortality and cohort-specific growth. The reference points used assume that the time period modeled is representative of a single constant regime. This is a reasonable approach as without a full understanding of the processes involved it is not possible to know how long a "regime shift" might last (or even if it has occurred). There is some evidence of a "regime shift" in 1992 to lower productivity. This was considered by the Panel when calculating unfished fecundity (two alternatives: 1992-present or 1955-present).

h. *Choice of stock-recruitment function.*
   It is assumed that there is very little relationship between population fecundity and recruitment (i.e., steepness is close to 1). There is no evidence for a relationship in the model estimates of fecundity and recruitment. However, recruitment is quite variable and there could be a stock-recruit relationship which is not discernable for this reason. The current reference points are independent of steepness, so this assumption has no consequences for status determination.

i. *Choice of reference points (e.g. equilibrium assumptions).*
   The use of F_{MED} based reference points is of concern. It appears that the stock has been at low levels of population fecundity for many years and yet the current reference points (and the F_{MED} reference points of previous years) provide a determination of "not overfishing" and "not overfished". The Panel recommends that alternative reference points be considered and chosen on the basis of providing better protection for SSB or population fecundity relative to the unfished level.

5. *Evaluate uncertainty of model estimates and biological or empirical reference points.*

Sensitivity runs were discussed under TOR 2.b. Almost all sensitivity runs gave the same stock status determination as the base run. However, from the bootstrap analysis of the base run, it is clear that there is considerable uncertainty with regard to the overfishing status of the stock in 2008 (with 37% of the runs indicating that overfishing was occurring). The Panel notes that uncertainty is underestimated in the bootstrap analysis as the assumed effective sample sizes are too high (see discussion of potential base-model weaknesses under TOR 2.)

Specific questions specified in TOR 5. are addressed below.

a. *Choice of weighting likelihood components.*
   The likelihood components were each given equal weight which, along with incorporated estimates or assumed CVs for each component, attempts to provide relative influence on the objective function that reflects knowledge about the quality of the inputs. However, correct weighting procedures seems to be an open question.

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

A retrospective analysis was performed by the Assessment Team for the base model. There were no retrospective patterns of any consequence.

7. *Recommend stock status as related to reference points.*

The Panel supports the recommendation of the Assessment Team that the stock status determination is "not overfished" and there is "no overfishing", relative to the current reference points. Further, the Panel also agrees with the Assessment Team that the uncertainties in the assessment are such that there could have been overfishing in 2008 (removal of the JAI from the base model gave that determination and many bootstrap runs also fell in the overfishing zone).

The Panel also notes that a strictly valid determination of the overfishing status requires comparison of full Fs and not number-weighted Fs. This is not a well-known result, but it is obvious once the problem is identified.

Consider a population which is being fished at some reference level F_{REF} (e.g., F_{MSY}) with a constant selectivity pattern (e.g., domed or logistic). Suppose that recruitment is constant and that the population is at equilibrium. The number-weighted version of F_{REF}, say F^*_{REF}, can be calculated from the equilibrium distribution of numbers-at-age and F_{REF}. Now, consider what happens to the number-weighted version of F, say F^*, when a large recruitment pulse is introduced into the population. As the pulse enters the first vulnerable age class (which is included in the calculation of F^* and F^*_{REF}), there is a large increased weight on a partially selected age class, and hence F^* is not equal to F^*_{REF} (it will probably be less than F^*_{REF}, but this depends on the particular selectivity and population parameters). As the pulse travels through each age class, the value of F^* changes, but it is unlikely to achieve equality with F^*_{REF} at any age. When it reaches the first fully-recruited age class, it is likely that $F^* > F^*_{REF}$. In any case, in this example, F remains constant at F_{REF}, but the number-weighted version of F varies – if used in an overfishing determination, it will give an incorrect status in most if not all years. This is an extreme example but, mathematically, it is sufficient to prove that the use of number-weighted F is not appropriate for overfishing status determination. In general, full F should be used.

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

The Panel endorses the research recommendations in the menhaden assessment report and has additional short and long term research recommendations which are detailed below. The short and long term recommendations are in priority order.

Short term (improvements for the next benchmark review)

a. The Panel recommends that model specifications similar to the Panel's reference run be considered for future assessments. This includes capped effective sample size at 200, allow the gaps in the pound net index and bait fishery age composition where data are not available, modification of the reduction and bait fleets to northern and southern fleets, and time-varying domed selectivity for the southern region.

This model specification combines information of the bait and reduction fisheries occurring together regionally because they are essentially using the same gear. Removing the estimated age composition and indices for years where it is absent is desirable because the data from years where it is available is providing the correct amount of information, from a statistical perspective, to the assessment model. Allowing domed selectivity in the southern region fishery allows for the lack of availability of older fish in that region when the fishery is occurring. The reduction of effective sample sizes is intended to better reflect the actual information content of the age composition data (the residuals in the base model were inconsistent with the large assumed effective sample sizes). Also, the time-varying selectivity in the southern region had the best AIC of comparable runs and reduced the undesirable pattern of residuals in the southern fishery.

A reworking of the menhaden fishery into northern and southern fleets should be explored to support the assessment. This exploration should consider the spatial patterns of the stock and the fishery as the stock range and fishery have expanded and contracted over time, and may be expected to continue to do so in future and setting an appropriate fixed boundary (or fixed criteria to define a movable boundary) may be critical.

b. Fishing mortality should be calculated as full F. The N-weighted fishing mortalities relative to the N-weighted F-reference points do not provide correct interpretation with regard to overfishing.

c. The Panel has concerns about the use of F_{MED} and the fecundity associated with it as reference points. The concern is that there was no information on the relationship of the target and threshold fecundity in relation to virgin fecundity levels. Projections were run to examine this, and the estimated fecundity since 1998 was less than 10% of the virgin fecundity for the base model. We recommend examination of alternative reference points which provide more protection to SSB or fecundity than F_{MED}.

d. Examine weighting of datasets in the model. As a starting point, some experts assert that the input variance assumptions should be consistent with the estimated variance of residuals. Deviations from this weighting pattern may be desirable but the weightings ultimately used need to be justified. In the base model the effective sample sizes for catch-at-age data are far too high and consequently estimates of uncertainty are too low.

e. The Panel recommends the Assessment Team's alternative use of the juvenile indices: combining relative abundance data from groups of adjacent states according to the similarity of trends in the state-specific time series; and cumulatively-combining these indices within the model. This allows for different regional patterns of recruitment to provide a stock-wide recruitment pattern.

f. Examine the timing of fisheries and indices in the model. Many of the fisheries are seasonal and need to be timed appropriately with the abundance indices. Incorrect timing may affect model fits.

Long Term

a. Develop a coast-wide adult menhaden survey. Possible methodologies include an air-spotter survey, a hydro-acoustic survey, or an industry-based survey with scientific observers on board collecting the data. In all cases, a sound statistical design is essential (involve statisticians in the development and review of the design; some pilot surveys may be necessary).

2.2 Summary results of analytical requests

1) *Supply a time series of fully recruited Fs along with the traditional N-weighted Fs and comparable F-reference points.*

   Rationale: The N-weighted fishing mortalities relative to the N-weighted F-reference points will not provide correct interpretation with regard to overfishing.

   Outcome: It was observed that the relationship of fully recruited Fs to the F-reference points was different than that of the N-weighted Fs and F-reference points.

2) *Present a map showing the age composition of the bait fishery catches in 2008 similar to the plot for the reduction fishery.*

   Rationale: Understanding of the location and time of the fishery and index information will be facilitated for reviewers not familiar with the locale.

   Outcome: Presentation of these maps helped the reviewers understand the location and timing of the fisheries and indices.

3) *Reverse prediction of recruits from adults.*

   Rationale: A reviewer was interested in whether the same predictability of recruits from adults is obtained as the reverse relationship.

   Outcome: It was shown that the predictability was also quite good in the reverse relationship.

4) *Do base run with gaps in the adult fishery dependent index and with gaps in bait catch at age.*

   Rationale: Removing the estimated age composition and indices for years where it is absent is desirable because the data from years where it is available is providing the correct amount of information, from a statistical perspective, to the assessment model.

   Outcome: These results were not noticeably different from the base run without gaps in the index and catch at age.

5) *Calculate standardized residuals for indices and catch-at-age and present standard deviation of standardized residuals with Q-Q plots.*

Rationale: These are diagnostics with regard to whether the statistical assumptions of the model are satisfied or not.

Outcome: The results showed that the juvenile abundance index was being fitted better (standard deviation around 0.7) than other data components which had standard deviations substantially greater than 1. In particular, the results showed that the sample sizes of the catch-at-age data were too high. The Q-Q plots also showed that residuals departed from normality.

6) *Run allowing dome-shaped selectivity in reduction and bait fishery.*

Rationale: The reviewers were concerned about the availability of larger fish to these fisheries and whether there was information in these age composition data to determine this.

Outcome: The assessment team presented these results which showed that there were substantial drops in selectivity of older fish for both fisheries.

7) *If time permits, do a run with fishery split between two regional "fleets" based on latitude.*

Rationale: This run combines information of the bait and reduction fisheries occurring together regionally because they are essentially using the same gear while accounting for the availability of fish of different ages in the two regions.

Outcome: The Assessment Team were able to put this run together in time. It altered the determination of over-fishing, compared to the base model, with current F estimated to be greater than F_{MED}.

8) *Likelihood profile across R_0 and components for each data component and any penalties.*

Rationale: The reviewers were interested in how the maximized likelihood components change across R_0, which provides information on the relative influence of the components on estimation of R_0.

Outcome: Plots of scaled log-likelihood components were presented, but the Panel made a follow-up request below (11).

9) *The following reference run with specified data and sensitivities is requested.*
a) northern and southern regional fisheries
b) gaps in age composition and indices
c) effective sample sizes truncated at 200
d) selectivity in the southern region allowed to be dome-shaped

Sensitivities:
a) original effective sample sizes
b) time-block-specific selectivities in the southern region
c) logistic selectivity in the southern region
d) age-specific and time-invariant natural mortality

Provide total and component likelihood profiles for the run (not the sensitivities).
Provide AIC values and standard deviations for standardized residuals for all runs and sensitivities.

Rationale: The reference run combines information of the bait and reduction fisheries occurring together regionally because they are essentially using the same gear. Removing the estimated age composition and indices for years where it is absent is desirable because the data from years where it is available is providing the correct amount of information, from a statistical perspective, to the assessment model. Allowing domed-selectivity in the southern region allows for the lack of availability of older fish in that region when the fishery is occurring. Sensitivities (a-d) allow some idea of the influence of the respective model attributes on the results to be understood.

Outcome: For most runs and selectivities, the overfishing and overfished status were the same as the base model. However, the sensitivity run of the reference model where logistic selectivity is assumed in the southern region estimated current fishing mortality to be greater than F_{MED}.

10) *Plots comparing output of the base run and the reference run and sensitivities.*

Rationale: These plots will help the Panel understand the differences in results for the various runs.

Outcome: Comparison plots were presented by the Assessment Team for the base model, and a number of the original sensitivities, the reference run and its sensitivities.

11) *Provide profile log-likelihood components (across R_0) for different data sources and penalties with minima subtracted.*

Rationale for Request: The change in the maximized log-likelihood values for each of the data components and penalties across fixed values of R_0 is representative of the effect each has on the total log-likelihood.

Outcome: The figure showed the trade-offs between the various components in the maximized log-likelihood components with respect to R_0.

12) *For the base model, stochastic projections of population without fishing to obtain mean unfished fecundity. Future recruitments should be drawn from a log-normal distribution with mean and variance being empirical values from past recruitments.*
a) Use entire recruitment time series for projections

b) Use recruitments from low-productivity period (1992-2006).
c) Provide standard deviation of the log-recruitment used for projections.
d) Present estimated historical fecundity trajectories as a percentage of unfished fecundity.

Rationale: The Menhaden Technical Committee requested the Panel's thoughts on reference points for Menhaden. Some members of the Panel thought that it would be important to ensure that fecundity does not get lower than some critical value relative to the unfished fecundity. These projections allow the stochastic equilibrium unfished fecundity to be determined which can then be compared to estimates from the current assessment. The shorter time series of recruits were of interest because Wood and Austin (2009) found a change in productivity in the Chesapeake in 1992. Furthermore, a trend in higher natural mortality for menhaden occurred during this period also from the MSVPA-X model.

Outcome: Results were presented by the assessment team. Estimated fecundity since 1998 was between 5 and 10% of the unfished mean fecundity when the entire time series of historic recruitments were used and between 10 and 15% of the unfished mean fecundity when the shorter time series of recruitments were used.

13) As for (R12), but use the reference run with time-varying selectivity blocks in the south.

Rationale: These plots will help the Panel understand the differences in results for the two runs.

Outcome: Results were presented by the Assessment Team. Estimated current fecundity was about 15% of unfished mean fecundity when the entire time series of historical recruitments were used and between 25 and 30% of the unfished mean fecundity when the shorter time series of recruitments were used.

14) Vary the starting values of parameters for the base model to check for convergence issues.

Rational: There is the possibility that the value of the maximized log-likelihood and resulting parameter estimates is sensitive to the starting values.

Outcome: Random restart analysis included catchability coefficients, selectivity parameters, average fishing mortality, and R_0. Results showed that virtually the same likelihood was achieved in all runs.

15) Determine reasons that the juvenile abundance index affects the overfishing status.

Rational: This index may be a poor measure of juvenile abundance and its impact on the overfishing status is of concern to the Panel.

Outcome: Estimated recruitments strengths are different between the runs in last three years (2006-2008). The catch-at-age data and the juvenile index must be giving different signals on the strength of these year classes.

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