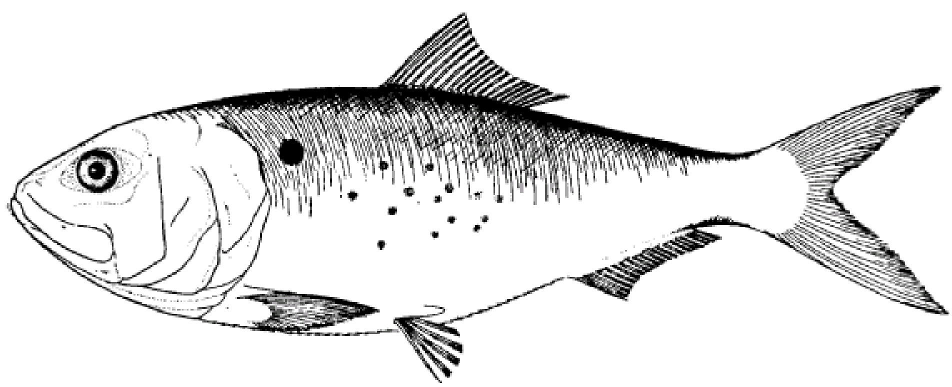
Stock Assessment Report No. 04-01 (Supplement)
of the

Atlantic States Marine Fisheries Commission

Atlantic Menhaden Stock Assessment Report for Peer Review



February 2004

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

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Conducted on
October 6 & 7, 2003
Raleigh, North Carolina

A publication of the Atlantic States Marine Fisheries Commission pursuant to National Oceanic and Atmospheric Administration Award No. NA03NMF4740078.

Preface

Summary of the Commission Peer Review Process

The Stock Assessment Peer Review Process, adopted in October 1998 by the Atlantic States Marine Fisheries Commission, was developed to standardize the process of stock assessment reviews and validate the Commission's stock assessments. The purpose of the peer review process is to: (1) ensure that stock assessments for all species managed by the Commission periodically undergo a formal peer review; (2) improve the quality of Commission stock assessments; (3) improve the credibility of the scientific basis for management; and (4) improve public understanding of fisheries stock assessments. The Commission stock assessment review process includes evaluation of input data, model development, model assumptions, scientific advice, and review of broad scientific issues, where appropriate.

The Stock Assessment Peer Review Process report outlines four options for conducting a peer review of Commission managed species. These options are, in order of priority:

1. The Stock Assessment Workshop/Stock Assessment Review Committee (SAW/SARC) conducted by the National Marine Fisheries Service (NMFS), Northeast Fisheries Science Center (NEFSC) or the Southeast Data and Assessment Review (SEDAR) conducted by the National Marine Fisheries Service (NMFS), Southeast Fisheries Science Center (SEFSC).
2. A Commission stock assessment review panel composed of 3-4 stock assessment biologists (state, federal, university) will be formed for each review. The Commission review panel will include scientists from outside the range of the species to improve objectivity.
3. A formal review using the structure of existing organizations (i.e. American Fisheries Society, International Council for Exploration of the Sea, or the National Academy of Sciences).
4. An internal review of the stock assessment conducted through the Commission's existing structure (i.e. Technical Committee, Stock Assessment Committee).

Twice annually, the Commission's Interstate Fisheries Management Program (ISFMP) Policy Board prioritizes all Commission managed species based on species Management Board advice and other prioritization criteria. The species with highest priority are assigned to a review process to be conducted in a timely manner.

In November 2002, the Atlantic menhaden stock assessment was prioritized for a SEDAR peer review. A review panel was convened of stock assessment biologists and representatives from the fishing community and non-government organizations. Panel members had expertise in Atlantic menhaden life history and stock assessment methods. The SEDAR review for the Atlantic menhaden stock assessment was conducted October 6-7, 2003 in Raleigh, North Carolina.

Acknowledgments

Thanks are due to the many individuals who contributed to the Commission's Atlantic menhaden Stock Assessment Peer Review. Special thanks are extended to the Atlantic Menhaden Peer Review Panel (Dr. Steve Bobko, Old Dominion University, William Goldsborough, Chesapeake Bay Foundation, Najih Lazar, Rhode Island Division of Environmental Management Marine Fisheries Section, Dr. Tom Miller, Chesapeake Biological Laboratory, Dr. Jim Nance, NOAA Fisheries NMFS SEFSC, Dr. Paul Nitschke, NOAA Fisheries, NMFS NEFSC, Lee Paramore, North Carolina Division of Marine Fisheries, Dr. Stephen Smith, Bedford Institute of Oceanography, Dr. Elizabeth Wenner, South Carolina Department of Natural Resources, Geoffrey White, Atlantic States Marine Fisheries Commission, William T. Windley, Jr., Maryland Saltwater Sportfish Association) for their hard work in reviewing the meeting materials and providing advice on improvements to the Commission's Atlantic menhaden stock assessment. The Commission would like to extend its appreciation to the members of the Atlantic Menhaden Technical Committee and Stock Assessment Subcommittee for development of the Atlantic Menhaden Stock Assessment Report for Peer Review (Stock Assessment Peer Review Report 04-01 Supplement) and specifically to the following members for presenting this report at the Peer Review meeting: Dr. Doug Vaughan (National Marine Fisheries Service, Beaufort Laboratory), and Dr. Eric Williams (National Marine Fisheries Service, Beaufort Laboratory).

Special appreciation is given to the staff dedicated to the performance of the Peer Review and finalization of peer review reports, specifically – Dr. Lisa Kline, Dr. John Merriner, and Nancy Wallace.

Executive Summary

Amendment 1 to the Interstate Fishery Management Plan for Atlantic Menhaden was approved in July 2001. This Amendment replaced the Atlantic Menhaden Fishery Management Plan, 1992 Revision.

Since the 1992 revision, concerns have been expressed over declines in the Atlantic menhaden population. A benchmark stock assessment and external peer review were conducted in 1998 to address these concerns. The November 1998 external peer review provided some major recommendations for improving the stock assessment and management of Atlantic menhaden (ASMFC 1999b). Upon receiving the report of the Peer Review Panel in January 1999, the Atlantic Menhaden Management Board recommended that the Peer Review Panel report be addressed through the development of a full amendment to the 1992 FMP. Amendment 1 to the Interstate Fishery Management Plan for Atlantic Menhaden adopted a new overfishing definition in order to better measure the status of the menhaden resource. In addition, Amendment 1 requires mandatory reporting from all menhaden purse seine fisheries (ASMFC 2001). In 2003, a new benchmark assessment for Atlantic menhaden was completed and peer reviewed through the Southeast Data and Assessment Review (SEDAR) process. This document served as the primary source document for the SEDAR Panel.

Atlantic menhaden are found in the continental waters of North America from Nova Scotia to central Florida. Spawning occurs in the ocean, while larvae and juveniles utilize coastal estuarine nursery areas. Atlantic menhaden undergo extensive seasonal migrations north and south along the United States East Coast. Based on tagging studies, the Atlantic menhaden fishery is believed to exploit a single stock or population of fish. The management unit for Atlantic menhaden is the Atlantic coastal and estuarine waters from Maine through Florida.

Atlantic menhaden have supported one of the United States' largest fisheries since colonial times. Native Americans were the first to harvest menhaden, primarily as fertilizer. During the 1940s, the primary use changed to high protein animal feeds and oil production. Following World War II, the industry grew rapidly, reaching peak production during 1953-62. Sharp declines in landings thereafter resulted in factory closings and fleet reductions through the 1960s and into the early 1970s. In 1955, 24 reduction plants operated on the Atlantic coast, with a decline to only two plants in 1998. Since the 1970s, the menhaden industry has experienced major changes in fishery efficiency, processing capacity, resource accessibility, and development of new product markets.

The Atlantic menhaden fishery consists of two components, the reduction fishery and the bait fishery. The reduction fishery uses steam to cook the raw fish, presses to remove liquid from the cooked fish, and centrifuges to separate oil from water in the liquid fraction. The pressed fish is dried, milled and sold as fishmeal. Fish oil is a significant ingredient in high quality aquaculture feeds and pet foods, as well as being used in the production of paints and cosmetics. Fish soluables, the water-fraction of the processing, are often recombined with the fishmeal to form an 'enriched' meal. Menhaden are taken as bait in almost all Atlantic coast states and are used for bait in crab pots, lobster pots, and hook-and-line fisheries (both recreational and commercial).

Landings and nominal effort (vessel-weeks, measured as number of weeks a vessel unloaded during the fishing year) are available since 1940. Landings rose during the 1940s, peaked during the 1950s (high of 712,000 t in 1956), and then declined to low levels during the 1960s (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. Landings during the 1990s declined from 401,200 t in 1990 to 171,200 t in 1999. Reduction landings in recent years declined further to174,000 t in 2002.

In recent years, menhaden purse seine fisheries for bait have operated primarily in North Carolina, Virginia, and New Jersey. Purse seine landings in these three states account for about 90% (1998-2002) of the coast wide menhaden bait landings. Small scale directed gill net fisheries for menhaden as bait exist in many states. Additionally, menhaden for bait are taken as an aggregate bycatch in other coastal states by a variety of gears such as gill nets, pound nets and trawls.

Previous stock assessment analyses of Atlantic menhaden have used untuned virtual population analysis (VPA) methods. In the current stock assessment, a forward-projecting model was preferred over the VPA method primarily because of the increased flexibility in formulation and statistical treatment of the data sources. The forward-projecting statistical age-structured model estimates population numbers at age (0-8) for 1955-2002. From these estimates and growth data, different estimates of population biomass and reproductive capacity can be developed (e.g., population fecundity).

Spawning stock biomass (SSB, weight of mature female biomass at start of fishing year) was high in the late 1950s and early 1960s, low in the late 1960s, and generally increasing since then. The largest values of SSB were present in 1955 and 1961, resulting from two very strong recruitment events in 1951 and 1958 as noted in earlier stock assessments. The historical time period 1955-2002 produced a median SSB of 76,800 t. Estimates of SSB from 1964 until 1971 were relatively low (below the 25th percentile). Historically high levels of spawning stock biomass (greater than the 75th percentile) occurred during 1955-1956, 1958-1962, 1987-1988, 1994-1995 and 1997. The estimate for spawning stock biomass in 2002 was 91,900 t, or between the median and 75th percentile.

Similarly, population fecundity (number of maturing or ripe ova) followed a similar pattern to spawning stock biomass. The historical time period 1955-2002 produced a median population fecundity of 30.1 x 10^{12} ova. Estimates of fecundity from 1964 through 1971 and 1975 to 1976 were relatively low (below the 25th percentile). Historically high levels of population fecundity (greater than the 75th percentile) occurred during 1955-1956, 1958-1962, 1988, and 1994-1997. The estimate for population fecundity in 2002 was 40.6 x 10^{12}, again between the median and the 75th percentile.

Recruits of Atlantic menhaden to age-0 and age-1 were high during the late 1950s, especially the 1958 year class. Recruitment was generally poor during the 1960s, with values below the 25th percentile for the recruitment time series. High recruitment occurred during the 1970s. Moderate to high recruitment occurred during the 1980s, with generally low recruitment since the mid-1990s. The most recent estimate of recruitment has the greatest uncertainty and the estimate for 2002 is likely to be modified as more data from the cohort (age-1 in 2003, age-2 in 2004, etc.) are added to the analysis. The current estimate of recruits to age-0 in 2002 is between the median and 75th percentiles, while the current estimate of recruits to age-1 in 2002 falls below the 25th percentile.

The Atlantic Menhaden Technical Committee is recommending changing from an SSB based target and threshold to a fecundity based target and threshold. They are also recommending that the fishing mortality target and threshold be modified. Based on an overall examination of stock and fishery information, the Technical Committee has concluded that on a coastwide basis, Atlantic menhaden are not overfished and overfishing is not occurring.

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Terms of Reference for the Atlantic Menhaden Peer Review

1. Evaluate adequacy and appropriateness of fishery-dependent and fishery- independent data used in the assessment (i.e. was the best available data used in the assessment).

2. Evaluate adequacy, appropriateness, and application of models used to assess the species and to estimate population benchmarks.

3. Evaluate adequacy and appropriateness of the Technical Committee's recommendations of current stock status based on biological-reference points.

4. Develop recommendations for future research for improving data collection and the assessment.

5. Prepare a report summarizing the peer review panel's evaluation of the stock assessment. (Drafted during the Review Workshop; Final report due two weeks after the workshop.)

6. Prepare a summary stock status report including research recommendations. (Drafted during the Review Workshop, Final report due two weeks later.)

1.0 Introduction

Amendment 1 to the Interstate Fishery Management Plan (ISFMP) for Atlantic Menhaden was approved in July 2001. This Amendment replaced the "Atlantic Menhaden Fishery Management Plan, 1992 Revision"

The original Atlantic menhaden fishery management plan (FMP) was prepared during the years 1976 through 1981 and approved by the Atlantic States Marine Fisheries Commission (ASMFC *or* Commission) in October 1981 (ASMFC 1981). This plan did not recommend any specific management measures, but provided a discussion of options, for future consideration. In 1982, the Atlantic Menhaden Management Board (AMMB) recommended seasonal limits as a means to provide long-term benefits to the fishery. The recommendation was approved by the Commission and referred to the states for implementation, however full implementation was not achieved. Changes in operation of the ISFMP, of which the menhaden program is a component, resulted in disbanding the AMMB during the mid-1980s. Oversight for the menhaden program passed to the ISFMP Policy Board, which was concerned with numerous FMPs in addition to menhaden.

A number of developments in the late 1980s greatly affected the Atlantic menhaden fishery, resulting in the need to amend the 1981 FMP. The most important of these developments included the following:

1. The Atlantic menhaden stock progressed toward recovery from a severely depressed condition during the mid 1960s-mid 1970s to the point where it was considered healthy in

the early 1990s. There was improved spawning stock biomass, good recruitment, and improved age structure. Heavy fishing continued throughout this period of recovery, although at a less intensive level.

2. Most Atlantic menhaden processing plants operating in 1981 were closed by 1988. Of 11 plants that processed menhaden along the United States Atlantic coast in 1981, only two are still in business. Closures were related to international market conditions, which affect the prices of menhaden products, as well as to localized social problems involving menhaden processing plants and neighboring residential areas.

3. In 1987, a Canadian plant began processing menhaden caught by United States vessels in the Gulf of Maine - the first direct foreign use of menhaden as a raw product.

4. In 1988, a Maine company contracted with the Soviet Union to conduct an Internal Waters Processing (IWP) venture in the Gulf of Maine under Section 306 of the Magnuson Fishery Conservation and Management Act of 1976. About 7-10 small purse-seine vessels supplied raw product to the Russian factory processing ship anchored within the internal territorial waters of the State of Maine. The IWP provisions of the Magnuson Act opened new harvesting and processing opportunities that were not considered in the original FMP.

5. Research on specialty meals for aquaculture, the use of menhaden oil for human food and medicinal products in the United States, and potential production of surimi from menhaden gave promise for development of diversified products and markets for the menhaden industry.

In light of these and other social and economic developments, the Commission determined in 1988 that the 1981 menhaden FMP was no longer sufficient to guide management of the fishery and authorized preparation of a revision to the plan.

The 1992 plan revision objectives included public education; continuation of the existing fishery monitoring program; improvement in collection of data on menhaden taken in directed bait fisheries and as bycatch in other fisheries; improvement of the Captains Daily Fishing Report (CDFR) program; promotion of needed research on biological, economic, sociological, and habitat issues; encouragement of product research; maintenance of an adequate stock; optimal utilization of the available resource, habitat maintenance, and enhancement; and utilization of the best available scientific data as the basis for coordinated management actions (ASMFC 1999a).

Since the 1992 revision there have been concerns over declines in the Atlantic menhaden population. This decline led the Menhaden Management Board to recommend that the Commission conduct an external peer review of the menhaden stock assessment, which was conducted annually through the Atlantic Menhaden Advisory Committee, or AMAC (ASMFC 1999a). This peer review was completed in November 1998 and provided some major recommendations for improving the assessment and management of menhaden (ASMFC 1999b). Upon receiving the report of the Peer Review Panel in January 1999, the Board recommended that a full amendment to the current FMP be developed and that the recommendations of the Peer Review Panel be addressed through the development of this amendment. Amendment 1 addressed a number of management measures and set up a process for the future management of Atlantic menhaden pursuant to the requirements of the Atlantic Coastal Fisheries Cooperative Management Act, which was enacted in 1993 (ACFCMA). This amendment also adopted a new overfishing definition by which the Management Board can measure the status of the resource. In addition, Amendment 1 requires mandatory reporting from all menhaden purse seine fisheries. (ASMFC 2001)

Amendment 1 is designed to minimize the chance of a population collapse due to overfishing, reduce the risk of recruitment failure, reduce impacts on species that are ecologically dependent on Atlantic menhaden, promote improved water quality through the maintenance of a healthy menhaden population, and minimize adverse effects on participants in the fishery (ASMFC 2001).

Atlantic menhaden are distributed along the Atlantic coast from Florida to Nova Scotia. Spawning occurs over much of the species' range, with a peak off North Carolina during late fall and winter. Menhaden are estuarine-dependent, utilizing coastal estuaries from Florida through southern New England as nursery areas. Young fish join the coastal migration late in their first year of life. After their first year, menhaden migrate along the Atlantic coast, with older, larger fish moving farthest north each spring and summer. Most fish migrate to the North Carolina area each fall and early winter (ASMFC 1999a).

Menhaden are primary consumers as adults, transforming phytoplankton into animal protein. They, in turn, serve as prey for many fish-eating fish, sea birds, and marine mammals, as do many other species of fish, including anchovies, herring, sardines, sand lance, and the young of most other fishes.

Atlantic menhaden have been harvested since colonial times, when they were used for fertilizer. Oil recovery began in the early 1800s. With the introduction of purse seine fishing gear in the 1850s, large-scale fisheries were established. Oil was used for industrial purposes and "scrap" (dried fish) was used for fertilizer. By World War II, the primary product of the industry had changed from scrap to production of high protein fishmeal for poultry and swine feeds, the major contemporary uses (ASMFC 1999a). Since the 1990s, greater proportions of menhaden fishmeal have gone into formulations of aquaculture feeds.

Bycatch (or incidental catch) of other fishes in menhaden purse seines has been examined since the late 1800s. Taking of non-target species is a relatively rare event, and the overall bycatch is insignificant.

The number of reduction plants along the U.S. Atlantic coast has declined from more than 20 during the late 1950s to 2 plants (North Carolina and Virginia) in 2003. Similarly, the number of purse seine vessels in the reduction fishery has declined from more than 130 vessels during the late 1950s to 12 vessels during 2003.

A major change in the industry took place following the 1997 fishing season, when the two reduction plants operating in Reedville, VA consolidated, which 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. Two large vessels continued to be active at the plant located in North Carolina (Vaughan et al. 2002b). With the decline in effort and landings by the reduction fishery in recent years, the relative importance of the bait fishery has increased, averaging about 16% for the years 1998-2002.

2.0 Life History

General Information

Atlantic menhaden are members of the worldwide family Clupeidae, one of the most important families of fishes both economically and ecologically (Ahrenholz 1991). Clupeids are characteristically very numerous and form large, dense schools. Many of the species are filter feeders, being either primary consumers - feeding on phytoplankton - or secondary consumers - feeding on zooplankton - or both. Many clupeids are, in turn, prey for various piscivorous predators through virtually their entire life (ASMFC 2001).

Atlantic menhaden are euryhaline species that inhabit nearshore and inland tidal waters from Florida to Nova Scotia, Canada (Ahrenholz 1991). Spawning occurs principally at sea with some activity in bays and sounds in the northern portion of its range. Eggs hatch at sea and the larvae are transported to estuaries by ocean currents where they undergo metamorphosis and develop into juveniles. Adults stratify by size during summer, with older, larger individuals found farther north. During fall, Atlantic menhaden migrate south and disperse from near shore surface waters off North Carolina by late January or early February. Schools of adult menhaden reassemble in late March or early April and migrate northward. By June the population is redistributed from Florida to Maine (Ahrenholz 1991).

2.1 Age

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 primarily in late fall and winter. Thus, most Atlantic menhaden spawn for the first time at age-2 or -3 - just before or after their third birthday (by convention, on March 1) and continue spawning every year until death. First-spawning age-3 fish have accounted for most of the stock’s egg production since 1965 (Vaughan and Smith 1988). 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 230mm 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 father north than smaller fish of the same cohort (Lewis et al. 1987).

2.2 Growth

The growing season begins in spring and ends in fall as water temperatures rise above and fall 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). Fish 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 rare since 1965 (Fig. 2.1). The oldest fish 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 454,000 Atlantic menhaden aged between 1955 and 2002. 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.

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 correct for this problem, catch in numbers by season and fishing (1955-2002) are developed for weighting corresponding lengths used in the von Bertalanffy length-age regressions.

Annual regressions of fork length (mm) on age (yr) are based on the von Bertalanffy growth curve [$FL = L_\infty(1-\exp(-K(age-t_0)))$] and use the Marquardt algorithm for the nonlinear minimization (PROC NLIN in SAS). Annual regressions of weight (g) on fork length (mm) are conducted based on the natural logarithm transformation ($ln\ W = a+b\ ln\ FL$) and corrected for transformation bias (root MSE) when retransformed back to $W = a(FL)^b$. Parameters from these regressions were averaged for the most recent five years (1998-2002) and used to calculate lengths and weight at age at the middle of the fishing year (age+0.5; Table 2.1). 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. Annual parameters for these regressions are summarized with sample sizes in Table 2.2. Matrices of weight at ages-0 to -8 for 1955-2002 were developed from these equations to represent the average weight of menhaden at the start of the fishing year (i.e. spawning biomass for appropriate ages) and middle of the fishing year (i.e. weight of fish landed) for use in population modeling (see data input to model in Appendix D).

2.3 Reproduction

Most Atlantic menhaden reach sexual maturity during their third year of life (late age-2) at lengths of 180-230 mm FL. Spawning occurs year-round throughout much of the species' range, with maximum spawning off the North Carolina coast during late fall and winter. 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.

2.3.1 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) (Fig. 2.2) according to an equation derived by Lewis et al. (1987):

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

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".

2.3.2 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.

The capture of a 138 mm juvenile Atlantic menhaden in an estuary on the Maine coast in October 1990 (T. Creaser, Maine DMR, pers. comm as cited in ASMFC 1992) suggests that a limited amount of spawning may occur as far north as the Gulf of Maine. Some ripening female menhaden were offloaded on to the Soviet processing ship near Portland, Maine in August and September 1991 (S. Young, Maine DMR observer on the M/V RIGA, pers. comm. as cited in ASMFC 1992). Egg and larval surveys have been restricted to waters south of Cape Cod (Judy and Lewis 1983) and, thus, would not have produced any evidence for spawning in the Gulf of Maine.

2.4 Early Life History Stages

2.4.1 Eggs

Atlantic menhaden produce pelagic eggs about 1.5 mm in diameter, which hatch within 2.5-2.9 days at an average temperature of 15.5^{o} C (Hettler 1981). Embryonic development is completed in <36 hr at 20-25^{o} C, but takes about 200 hr at 10^{o} C (Ferraro 1980). Egg mortalities observed in the laboratory were > 90% at 10^{o} C and 48-92% at 15, 20 and 25^{o} C (Ferraro 1980).

2.4.2 Larvae and Juveniles

Yolk-sac larvae hatched at 3-4 mm standard length (SL) and maintained at 16° and 24°C began to feed at 4.5-5 mm SL (Powell and Phonlor 1986). First feeding was a function of size, not age. Larvae raised at 16°C began feeding after 5 days, while larvae reared at 24°C began feeding after only 2 days. Larvae reached 10.7 mm SL after 21 days at 20°C. Caudal and dorsal fins developed at 9 mm and all fin rays were developed by 23 mm (Reintjes 1969). The swim bladder and acoustico-lateralis system become functional in larvae measuring approximately 20 mm (Hoss and Blaxter 1982).

Low temperatures (<3°C for >2 days) killed most larvae held in laboratory experiments (Lewis 1965, 1966), although mortality depended on acclimation temperature and the rate of thermal change. Best survival occurred at temperatures >4°C and salinities of 10-20‰.

Larvae, which hatch offshore, are transported shoreward and enter estuaries in the south Atlantic region after 1-3 months at sea (Reintjes 1961) at a size of 14-34 mm FL (Reintjes and Pacheco 1966). Larval migration into estuaries occurs during May-October in the north Atlantic region, October-June in the mid-Atlantic, and December-May in the south Atlantic (Reintjes and Pacheco 1966). Larval condition improved rapidly after fish entered two North Carolina inlets (Lewis and Mann 1971).

Metamorphosis to the juvenile stage occurs at about 38 mm TL during late April-May in North Carolina estuaries and later in the year farther north. Most larvae entered the White Oak estuary (North Carolina) in March and moved upstream to a fresh water/low salinity zone where they transformed into "pre-juveniles" in late March-April and then into juveniles in late April-May (Wilkens and Lewis 1971). Other studies (Weinstein 1979; Weinstein et al. 1980; Rogers et al. 1984) also show young menhaden are more abundant in shallow, low salinity (< 5‰) estuarine zones. Metamorphosis to the "pre-juvenile" stage occurs at lengths >30 mm TL and to the juvenile stage beyond 38 mm TL (Lewis et al. 1972). Metamorphosis is rarely successful outside of the low-salinity estuarine zone (Kroger et al. 1974), although Atlantic menhaden have been successfully reared from eggs to juveniles in high salinity water (Hettler 1981).

The morphological changes that occur at metamorphosis are associated with a change in feeding behavior. Larvae feed on individual zooplankton, whereas juveniles rely more heavily on filter feeding (June and Carlson 1971; Durbin and Durbin 1975). This shift in feeding behavior is associated with a loss of teeth and an increase in the number and complexity of the gill rakers through which seawater is filtered as it passes through the gills. Older larvae (25-32 mm) feed on large copepods, but only rarely on small zooplankton (Kjelson et al. 1975). Fish larger than 40 mm FL feed primarily on phytoplankton (June and Carlson 1971), but zooplankton have also been reported as an equally important food source in juvenile Atlantic menhaden (Richards 1963; Jeffries 1975). Juveniles are capable of filtering particles as small as 7-9 microns (Friedland et al. 1984) and, thus, directly utilize the abundant small photosynthetic organisms that are not consumed by most other species of fish. Detritus derived from saltmarsh cordgrass (*Spartina alterniflora*) has also been reported as a primary food source for juveniles in North Carolina saltmarshes (Lewis and Peters 1984). Based on calculations incorporating feeding rates and population estimates from eight East Coast estuaries, Peters and Schaaf (1981) concluded that juveniles must consume more food during estuarine residency than is available from a strictly phytoplankton-based food chain.

Young-of-the-year menhaden congregate in dense schools as they leave shallow, estuarine waters for the ocean, principally during August to November (earliest in the north Atlantic region) at lengths of 75-110 mm TL (Nicholson 1978). Many of these juveniles migrate south along the North Carolina coast as far as Florida in late fall and early winter and then redistribute northward by size as age-1 fish during the following spring and summer (Kroger and Guthrie 1973; Nicholson 1978). Larvae, which enter the estuaries late in the season, may remain there for an additional year and emigrate to the ocean at age-1. Age-1 menhaden migrate north and south along the coast over a greater distance than young-of-the-year juveniles (Nicholson 1978). Abundance and distribution of juvenile Atlantic menhaden is monitored by the marine resource agencies of most Atlantic coast states under a variety of estuarine surveys using trawls and seines.

Juveniles collected at 2-3 day intervals have shown growth rates of nearly 1 mm/day (Reintjes 1969). Water temperatures >33°C caused death in young-of-the-year and age-1 Atlantic menhaden (Lewis and Hettler 1968), although the time until death depended, in part, on acclimation factors. Sudden exposure to lethal temperatures, for example, caused greater mortality. Juvenile Atlantic menhaden can adjust rapidly to abrupt changes (increase or decrease) in salinity from 3.5 to 35‰ and vice-versa (Engel et al. 1987). Juveniles raised in low salinity water (5-10‰) were more active, ate more, had higher metabolic rates, and grew faster than juveniles raised in high salinity water (28-34‰) (Hettler 1976).

2.5 Adults

Adult Atlantic menhaden are strictly filter feeders, grazing on planktonic organisms. They can be observed swimming slowly in circles, in tightly packed schools, with their mouths wide open and their opercula (gill flaps) flaring. In laboratory experiments, they fed on small adult copepods as well as phytoplankton (Durbin and Durbin 1975). Organisms smaller than 13-16 microns (slightly larger than the minimum size reported by Friedland et al. (1984) for juveniles) were not retained in the gills. Menhaden did not feed on large zooplankton (10 mm brine shrimp) in these experiments. The filtering process is purely mechanical; particles are not selected by size (Durbin and Durbin 1975). These experiments showed that the filtering rate depended on mouth size, swimming speed, food particle concentration, and the mechanical efficiency of the gill rakers. The structure of the "branchial basket," the area underneath the opercula where the extremely fine and closely spaced gill filaments and gill rakers are located, was described in detail by Friedland (1985).

Growth occurs primarily during the warmer months. Older (age-6) fish reach an average length of 330 mm FL and a weight of 630 g, although growth varies from year to year and is inversely density-dependent (ASMFC 2001). Growth rates appear to be accelerated during the first year when juvenile population size is low and are reduced when juvenile population size is high. Adults migrate extensively along the entire United States East Coast. Following winter dispersal along the south Atlantic coast, adults begin migrating north in early spring, reaching as far north as the Gulf of Maine in June. Older and larger fish migrate farther than younger, smaller fish. The return southern migration occurs in late fall and early winter (ASMFC 2001).

2.6 Stock Structure

The Atlantic menhaden resource is believed to consist of a single unit stock or population, based on tagging studies (Dryfoos et al. 1973; Nicholson 1978). Adult Atlantic menhaden undergo extensive seasonal migrations north and south along the United States East Coast. 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) observed the disappearance of fish in October north of Chesapeake Bay and their appearance off the coast of North Carolina in November. Nicholson (1971) 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) have generally confirmed what was already concluded from earlier work and added some important details. Adults begin migrating inshore and north in early spring following the end of the major spawning season off the North Carolina coast during December-February. The oldest and largest fish migrate farthest, reaching the Gulf of Maine in May and June. Adults that remain in the south Atlantic region for spring and summer migrate south later in the year, reaching northern Florida by fall. Fish begin migrating south from northern areas to the Carolinas in late fall. During November, most of the adult population that summered north of Chesapeake Bay moves south around Cape Hatteras.

2.7 Mortality

Age-structured models try to reconstruct the fish population and fishing mortality rates by age and year, typically assuming a constant rate of natural mortality (M). In many stock assessments, constant values for M are obtained from life history analogies (e.g. maximum age, growth rates), with the methods of Pauly (1979) and Hoenig (1983) among the most widely used. Estimates of M in the early literature on Atlantic menhaden vary, although only moderately

(Ahrenholz et al. 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. Nearly 438,000 juvenile Atlantic menhaden were tagged coastwide during the years 1970–1986. Estimates were $M = 0.52\ yr^{-1}$ from a preliminary tag-recovery analysis (Dryfoos et al. 1973) and $M = 0.50\ yr^{-1}$ from a more extensive tag-recovery analysis (Reish et al. 1985). The mean of the range ($M = 0.45\ yr^{-1}$) has been used routinely in Atlantic menhaden assessments beginning with Ahrenholz et al. (1987b). This rate is equivalent to an annual reduction in population numbers of 36% in the absence of fishing and it is quite high compared to other pelagic marine species. Atlantic herring, for example, is characterized by an 18% annual natural mortality rate (Fogarty et al. 1989).

Coastal pollution and habitat degradation threaten marine fish species, such as Atlantic menhaden, which spend their first year of life in estuarine waters and the rest of their life in both ocean and estuarine waters. Other poorly understood sources of natural mortality for Atlantic menhaden are diseases and parasites. A partial list of parasites was given in Reintjes (1969), but there is no information available concerning the extent of parasitism or its possible effect on survival. Ahrenholz et al. (1987a) described the incidence of ulcerative mycosis (UM), a fungal infestation that was observed in menhaden over much of their range in 1984 and 1985 and in a more restricted area in 1986. A large fish kill in Pamlico Sound, North Carolina in November 1984 was associated with UM, but its primary effect may be to weaken fish, making them more susceptible to other causes of mortality, such as predation, parasites, other diseases, and low dissolved oxygen concentrations. The overall impact of UM on the 1984 and 1985 year classes could not be assessed, but it was not believed to be significant (Ahrenholz et al. 1987a). Vaughan et al. (1986b) believed that the mortality effects of a disease or other event must be "truly catastrophic" to be detectable.

Another source of natural mortality for Atlantic menhaden (and many other species) may be "red tide." The term refers to the color of water caused by the rapid multiplication, or "bloom", of single-celled planktonic organisms called dinoflagellates, which produce a toxic compound. The toxin accumulates in the tissues of filter-feeding animals, which ingest the dinoflagellate. An outbreak of red tide occurred along the coast of the Carolinas during November 1987 - April 1988 when Gulf Stream water containing the dinoflagellates was transported into coastal waters. Menhaden recruitment in Beaufort Inlet during this period was severely reduced (S. Warlen, NMFS, Beaufort N.C., pers. comm. as cited in ASMFC 1992). A new species of toxic dinoflagellate was identified as the causative agent in a major menhaden kill in the Pamlico River, North Carolina, in May 1991. Problems with toxic phytoplankton organisms may increase in the future since their appearance has been correlated with increasing nutrient enrichment in estuarine and coastal waters that are subject to increasing organic pollution (Smayda 1989).

An additional source of mortality are fish "kills", which occur when schools of menhaden enter enclosed inshore bodies of water in such large numbers that they consume all available oxygen and suffocate. The mean lethal dissolved oxygen concentration for menhaden has been reported to be 0.4 mg/l (Burton et al. 1980). Bluefish are known to follow (or even chase) schools of menhaden inshore, feeding on them, and may contribute to their mortality by preventing them from leaving an area before the oxygen supply is depleted. High water temperatures, which increase the metabolic rate of the fish, accelerate oxygen depletion. Concurrently, oxygen is less soluble in warm water. Menhaden that die from low oxygen stress can immediately be recognized by the red coloration on their heads caused by bursting blood capillaries. Just before death, the fish can be seen swimming very slowly in a disoriented manner just below the surface of the water. This is a common phenomenon that has been observed throughout the range of the species. Menhaden spotter pilots have reported menhaden "boiling up" from the middle of dense schools and washing up on the beach, apparently from oxygen depletion within the school. This phenomenon was observed during December 1979 in the ocean off Atlantic Beach, North Carolina (M. Street, NC DMF, pers. comm. as cited in ASMFC 1992). Smith (1999a) reported a similar event off Core Banks, North Carolina, in December 1997. Other species are not nearly as susceptible simply because they do not enter enclosed inshore waters in such large numbers.

Since menhaden are abundant in coastal waters during the warmer months of the year, predation mortality is probably the highest cause of natural mortality. This high rate of mortality is particularly acute among the youngest age classes, due to gap limitation of most piscivorous fishes. Menhaden are preyed upon by a variety of predators such as bluefish, striped bass, king mackerel, Spanish mackerel, pollock, cod, weakfish, silver hake, tunas, swordfish, bonito, tarpon, and a variety of sharks (ASMFC 2001). However, younger menhaden, due to their smaller size, tend to experience a high degree of natural mortality as a result of predation. Given the importance of menhaden as a forage species and the assumed high predation that presumably occurs on juvenile fish, age varied natural mortality rates maybe more appropriate for this species.

Natural mortality rates are generally treated as fixed and age-constant in single species age-structured or non-age structured models. However, using a Multi-Species Virtual Population Analysis model (MSVPA) allows further decomposition of natural mortality (M) into predation mortality, M_2, and other sources of mortality, M_1. M_2 is more appropriately described as natural mortality due to predators. Total mortality rate, Z, can then be formulated as:

$$Z = F + M_1 + M_2$$

Examinations of age variable predation mortality rates suggests greater mortality on the younger age classes and subsequently lower predation mortality on older age classes. The result is that overall natural mortality rates tend to be higher than assumed fixed rates for the youngest age classes. 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. 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 then empirically derived.

2.8 Ecology

Menhaden are ubiquitous in nearshore coastal waters because of their ability to directly utilize phytoplankton, which is the basic food resource in aquatic systems. Other species of marine fish are not equipped to filter such small organisms from the water. Consequently, such large populations of other species cannot be supported. Because menhaden are so abundant in nearshore coastal and estuarine waters, they are an important forage fish for a variety of larger piscivorous fishes, birds, and marine mammals. In ecological terms, menhaden occupy a very important link in the coastal marine food chain, transferring planktonic material into animal biomass. As a result of this, menhaden influence the conversion and exchange of energy and organic matter within the coastal ecosystem throughout their range (Peters and Schaaf 1981; Lewis and Peters 1984; Peters and Lewis 1984).

Because menhaden only remove planktonic organisms larger than 13-16 microns (7 microns for juveniles) from the water, the presence of large numbers of fish in a localized area could alter the composition of plankton assemblages (Durbin and Durbin 1975). Peters and Schaaf (1981) estimated that juvenile menhaden consumed 6-9% of the annual phytoplankton production in eight estuaries on the East Coast and up to 100% of the daily production in some instances.

A large school of menhaden can also deplete oxygen supplies and increase nutrient levels in the vicinity of the school. Enrichment of coastal waters by large numbers of menhaden can be expected to stimulate phytoplankton production. Oviatt et al. (1972) measured ammonia concentrations (from excretion) inside menhaden schools that were five times higher than ambient levels 4.5 km away. At the same time, chlorophyll values increased by a factor of five over the same distance, indicating the grazing effect of the fish on the phytoplankton standing crop. Oxygen values were not significantly reduced by the fish, but were much more variable inside the schools than outside them.

Also, in a study of energy and nitrogen budgets (Durbin and Durbin 1981), food consumption rates, energy expenditures, and growth efficiency were examined. Results indicated that swimming speed, the duration of the daily feeding period, and the concentration of plankton in the water controlled the energy and nitrogen budgets for this species.

3.0 Fishery Description

3.1 Brief Overview of Fisheries

Fishing fleets operating from Maine to Florida have caught over 18 million metric tons (mt) of Atlantic menhaden since 1940, as indicated by landings records. Native Americans were the first to use menhaden, primarily for fertilizer. During the 1940s, the primary use changed to high protein animal feeds and oil production. Menhaden meal was mixed into poultry, swine, and cattle feeds as the amount used for fertilizer was decreasing. The oil was used in the manufacturing of soap, linoleum, waterproof fabrics, and certain types of paint. Following World War II, the industry grew rapidly, reaching peak production during 1953-62. Sharp declines in landings thereafter resulted in factory closings and fleet reductions through the 1960s and into the early 1980s. Since that time, the menhaden industry has experienced major changes in processing capacity, resource accessibility, and development of new product markets (ASMFC 2001).

3.2 Internal Waters Processing

Section 306 of the Magnuson-Stevens Fishery Conservation and Management Act (PL 94-265) allows foreign fish processing vessels to operate within the internal waters of a state with the permission of the Governor of that state. Before granting such permission, the Governor must: 1) determine that the harvest of the target species of the proposed IWP operation exceeds the processing capacity for that species within the state, and 2) consult with the Governors of other states within which the fishery occurs, as well as with the appropriate regional fishery management council and interstate fisheries commission.

The commercial menhaden fleet operating in the North Atlantic region underwent considerable changes during the late 1980s and early 1990s, including the introduction of two conventional menhaden steamers, the addition of a number of small menhaden boats active in other fisheries during the off-season, and the development of a menhaden IWP venture with up to three Russian processing ships. In 1987, two New England-based menhaden vessels began to fish the Gulf of Maine area, landing the catch at a Canadian processing plant. Another Canadian factory in Nova Scotia processed menhaden in 1992 and 1993. No menhaden have been processed in the North Atlantic since the summer of 1993 (ASMFC 2001).

Within Maine's coastal waters, up to three IWP operations ran during 1988-1993. Under state jurisdiction, a foreign vessel was permitted to process menhaden caught by US vessels into fishmeal and oil during the 1988-1993 fishing seasons. The Gulf of Maine Atlantic menhaden fleet included about 20 small purse seine vessels and carriers serving the reduction and lobster bait markets. These vessels included some that were seasonal (boats active in other fisheries during the off-season), as well as vessels specifically built and rigged for purse seine fisheries (both menhaden and Atlantic herring). The majority of the vessels were based in Maine, but some operated out of the Boston area. Several of the catcher boats could hold their catch for direct transfer to the foreign processing vessel. Smaller catcher boats normally pumped the fish from the seine onto a carrier vessel for later transfer to the processing vessel. The small vessels used in the Gulf of Maine were not refrigerated and utilized a single purse boat (ASMFC 2001).

3.3 Fishing Gear

The early menhaden purse seine fishery utilized sailing vessels, while coal-fired steamers were introduced after the Civil War. In the 1930s, diesel-powered vessels began to replace the steamers, although a few sailing vessels were still in use. Reintjes (1969) described modern menhaden vessels and purse seines and summarized the significant technological advancements since World War II as follows:

1946 Use of spotter aircraft. The spotter pilot via radio communication with the purse boats now directs setting on a school.

1946 Use of pumps to transfer fish from the nets to the carrier vessel resulted in shorter transfer time and more fishing time.

1954 Use of synthetic net material rather than cotton twine resulted in increased net life.

1957 Use of hydraulic power blocks in the purse boats to haul in the net permitted a reduction in crew size and reduced net retrieval time. Strong synthetic net material was able to withstand the increased strain from the new haul technique.

1958 Introduction of lighter, stronger, and faster aluminum purse boats to replace wooden boats.

The refrigeration of vessel holds in the 1960s and 1970s was crucial for the industry to maintain its viability. Despite restricted access to a number of traditional grounds and a reduced fleet size, refrigerated holds enabled the fleet to maximize the harvest during peak resource availability. Refrigeration also allowed the fleet to range over a larger area and stay out longer, greatly improving the ability to catch fish when and where they are available (ASMFC 2001).

Currently, commercial menhaden purse seine fishing operations utilize spotter aircraft to locate schools of menhaden and direct vessels to the fish. When a school is located, two purse boats with a net stretched between them are deployed. The purse boats encircle the school and close the net to form a purse or bag. The net is then retrieved to concentrate the catch and the mother ship comes along side and pumps the catch into refrigerated holds. Individual sets can vary from 10 to more than 100 mt and large vessels can carry 400-600 mt of refrigerated fish.

Over the years, vessels participating in the Atlantic menhaden purse seine fishery have varied considerably in size, fishing methods, gear type, and intensity of effort. During the early 1960s, the commercial menhaden fleet experienced significant changes as larger, faster vessels replaced outdated models. Today, the 12 vessels operating in North Carolina and Virginia range from 166 ft (51 m) to 200 ft (61 m) in length. Typical menhaden vessels generally carry two purse boats approximately 39 ft (13 m) in length. A few small vessels have only one purse boat and are called "snapper rigs." These small boats have the ability to fish in shallow areas not available to the larger vessels. The catches of the snapper rigs (a small fraction of the total) are mostly sold for bait (e.g. sport fishery, crab pots, etc.) with minor quantities processed into meal, oil, and solubles (ASMFC 2001).

The typical purse seine net has a bar mesh of 3/4 in (1.9 cm) to 7/8 in (2.2 cm). The net length ranges from about 1,000 ft (305 m) to about 1,400 ft (427 m) and the depth from about 65 ft (20 m) to about 90 ft (27 m).

Historically, the total number of vessels fishing for menhaden was generally related to the availability of the resource. Greer (1915) reported 147 vessels in 1912. During 1955-1959, about 115-130 vessels fished during the summer season, while 30-60 participated in the North Carolina fall fishery. As the resource declined during the 1960s, fleet size decreased more than 50%. Through the 1970s, approximately 40 vessels fished during the summer season, while nearly 20 were active in the fall fishery. During 1980-1990, 16-33 vessels fished the summer season and the level of effort in the fall fishery ranged from a low of 3 vessels in 1986 to a maximum of 25.

During the 1990 season, the mid-Atlantic fleet, which was based in Virginia, was composed of 20 vessels and the south Atlantic fleet, based in North Carolina, consisted of one large vessel and two smaller vessels, each using two purse boats. One of the smaller vessels, however, fished exclusively for bait. An additional 3-4 large vessels from Virginia and/or the Gulf of Mexico fished in the south Atlantic during the fall fishery. Due to company consolidation in 1997, there are presently 10 vessels in the mid-Atlantic fleet (at Reedville, Virginia) and two vessels in the south Atlantic (at Beaufort, North Carolina).

Changes in fleet size since the 1980s are attributable to a number of factors. Reductions in effort during the mid-1980s were related largely to world commodity markets and economic considerations. The addition of vessels participating in the Gulf of Maine IWP ventures reflected resource availability in Maine. Reduction of the Chesapeake fleet by several vessels was accompanied by improved operating efficiency. Vessels from the Gulf of Mexico fishery were added to the Atlantic fleet for the fall fishery in order to maximize harvest when weather and fish migratory behavior provided opportunities for large catches. In November 1997, Omega Protein purchased its competitor in Reedville, AMPRO Fisheries. For the 1998 fishing season, Omega dismantled the AMPRO factory and reduced the Virginia reduction fleet from 20 to 13 vessels. In 2000, Omega further reduced their Virginia fleet to 10 vessels. Since 2000, only 12 reduction vessels have operated on the Atlantic Coast, 10 in Virginia and 2 in North Carolina.

All twelve vessels in the menhaden fleet currently utilize refrigerated fish holds, compared to only 60% of the fleet in 1980. Refrigeration enables vessels to deliver better quality raw material and serves to increase vessel range and extend time on the fishing grounds. This ability to maximize peak resource availability was critical in the 1970s and 1980s for the maintenance of the industry in the face of restricted access to traditional grounds and a reduced number of vessels landing at fewer plants.

Average hold capacity of menhaden vessels in the summer fishery declined from 1,101,000 standard fish (737,670 lbs or 334.6 mt) in 1980 to 997,000 standard fish (667,990 lbs or 303 mt) in 1990, a decrease of 9.4%. The total hold capacity of the current twelve-vessel menhaden fleet is well below that of the late 1950s (ASMFC 2001).

During peak landing years (1953-1962), an average of 112 vessels with a mean vessel capacity of about 678,000 standard fish (representing a total fleet capacity of approximately 76,000,000 standard fish) supplied the industry (Nicholson 1971). The fleet landed daily catches at 20 menhaden reduction plants from New York to Florida. In comparison, the 1990 fleet of 33 vessels, which operated within a more restrictive and regulated environment, landed their catch at five plants, including the foreign processing vessel. As previously noted, the current fleet of twelve vessels unloads menhaden at only two ports, Reedville, Virginia and Beaufort, North Carolina.

3.4 Fishing and Landings Area

The Chesapeake Bay area (including the mid-Atlantic area) accounted for about 77% of the Atlantic menhaden landings in 1990 and about 73% during 1980-1990. Plants in the north and south Atlantic areas, including one plant active during the fall fishery, processed about 27% of the annual landings. Three plants located in Virginia and North Carolina processed about 90% of the harvest.

In 1991, Chesapeake Bay, including the mid-Atlantic area, accounted for about 74% of the menhaden landings. The North Atlantic area contributed most of the balance of the landings, while the south Atlantic area contributed the remainder. The catch was landed at shoreside processing plants in Beaufort, North Carolina; Reedville, Virginia (2 plants); and Blacks Harbour, N.B., Canada. A Russian factory ship anchored at various locations within the territorial waters of southern Maine also processed menhaden under an IWP arrangement.

As no menhaden landings for reduction have occurred in New England since the summer of 1993, the Virginia and North Carolina vessels at Reedville, Virginia and Beaufort, North Carolina have exclusively landed Atlantic menhaden for reduction. Between 1994-1997, the factories at Reedville processed an average 89% of the Atlantic menhaden catch for reduction; the remainder was unloaded at Beaufort.

Recently, Smith (1999b) summarized catch estimates of menhaden vessel captains in the Virginia and North Carolina fleets (excluding New England vessels) from Captains Daily Fishing Reports (CDFRs) during 1985-1996. On average, over the twelve-year study period, 52% of the catch by the Virginia and North Carolina fleets came from the Virginia portion of Chesapeake Bay, 17% was caught in North Carolina coastal waters, 16% in Virginia ocean waters, and 15% in ocean waters of Rhode Island, New York, New Jersey, Delaware, and Maryland and Delaware Bay combined. However, the New Jersey portion of Delaware Bay has been closed to the reduction fishery since mid-1989, the Delaware portion since mid-1992, and most of Long Island Sound has now been closed to the reduction fishery (ASMFC 2001).

In recent summers (1999-2002), Virginia vessels, fishing 5-10 miles off the coast of New Jersey, have made significant catches of Atlantic menhaden. These catches with respect to distance from shore, appear noteworthy, considering a majority of catches off the New Jersey coast during the early 1990s came from within three miles from shore (Smith 1999b). Nevertheless, menhaden logbook data from the late 1950s (Roithmayr 1963) indicate that historical fishing patterns off New Jersey regularly included purse seine sets made up to 20-30 miles offshore.

3.5 Fishing Seasons

The directed menhaden purse seine fishery for reduction is seasonal. The presence of menhaden schools is dependent on the temperature of coastal waters. Two fairly distinct fishing seasons occur, the summer fishery and the fall fishery. The summer fishery begins in April with the appearance of schools of menhaden off the North Carolina coast. The fish migrate northward, appearing off southern New England in May-June. The fishery in the Gulf of Maine may extend into early October, although menhaden may not appear in the Gulf of Maine at all in some years. Menhaden stratify by age along their migration route with smaller, younger fish remaining in the southern area and larger, older fish traveling farther to the north. Peak landings occur during June-September.

The fall fishery begins about November as migratory fish appear off Virginia and North Carolina. In early fall, this southward migration is initiated by cooling ocean temperatures. By late November-early December, most of the fish are found between Cape Hatteras and Cape Fear, North Carolina. Menhaden vessels based in Beaufort, North Carolina and Reedville, Virginia harvest these fish during the fall fishery. Fishing may continue into January (and sometimes February), but is highly weather-dependent. Menhaden generally leave the nearshore coastal fishing grounds in January, dispersing in ocean waters off the south Atlantic states (ASMFC 2001).

3.6 Incidental catches

Incidental bycatch of other finfish species in menhaden purse seines has been a topic of interest and concern for many years in the commercial and recreational fishing industry, as well as the scientific community (Smith 1896; Christmas et al. 1960; Oviatt 1977). Numerous studies have shown that there is little or no bycatch in the menhaden purse seine fishery. Some states restrict bycatch on a vessel to 1% or less of the total catch by regulation.

The most recent study of bycatch of other species in the Atlantic menhaden fishery was completed through funding provided by the Federal Saltonstall-Kennedy grant program (Austin et al. 1994). The Virginia Institute of Marine Science studied levels of finfish bycatch in the Atlantic menhaden fishery. Results from that study indicated that bycatch in the 1992 Atlantic menhaden reduction fishery was minimal, comprising about 0.04% by number. The maximum percentage bycatch occurred in August (0.14%) and was lowest in September (0.002%). Among important recreational species, bluefish accounted for the largest bycatch, 1,206 fish (0.0075% of the total menhaden catch). No marine mammals, sea turtles, or other protected species were killed, captured, entangled or observed during sampling. A concurrent study was conducted by Louisiana State University for the Gulf of Mexico menhaden fishery (de Silva and Condrey 1997).

Additional data are available from the Gulf of Maine IWP fishery in 1991. A state observer inspected every catch unloaded onto the processing vessel. A total of 93 fish were taken as bycatch along with about 60,000,000 individual menhaden (D. Stevenson, Maine DMR, pers. comm. as cited in ASMFC 1992).

3.7 Commercial Reduction and Bait Fishing Activities

3.7.1 Reduction Fishery

Atlantic menhaden have supported one of the United State's largest fisheries since colonial times. Menhaden have repeatedly been listed as one the nation's most important commercial fisheries species in terms of quantity. Total menhaden landings (Gulf of Mexico and Atlantic) in 2001 were 1.7 billion lbs (816,467 mt) valued at $102.7 million (NMFS 2002). Atlantic menhaden landings for reduction in 2002 totaled 384 million lbs (174,068 mt).

Native Americans may have used menhaden for fertilizer before the European settlement of North America. Colonists soon recognized the value of whole menhaden for fertilizer and local seine fisheries gradually developed from New York to Maine. Farmers applied 6,000 to 8,000 fish per acre (Harrison 1931). The use of whole fish as fertilizer continued into the nineteenth century. Union soldiers returning home from North Carolina and Virginia after the Civil War provided anecdotal reports on the abundance of menhaden in Chesapeake Bay and coastal North Carolina, sparking interest in a southern fishery, which soon developed.

The menhaden oil industry began in Rhode Island in 1811 (Frye 1999). It has grown steadily, with significant mechanization, including boilers for rendering raw fish and presses for removing oil. Oil was initially used for fuel and industrial processes, while the remaining solids (scrap) were used for fertilizer. Numerous small factories were located along the coasts of the northeastern states. However, their supply was limited to fish that could be captured by the traditional shore-based seines. In 1845, the purse seine was introduced and an adequate supply of raw material was no longer a problem. By 1870, the industry had expanded southward, with several plants in the Chesapeake Bay and North Carolina areas (Whitehurst 1973).

The industry gradually developed during the late 1800s and early 1900s and was described in considerable detail prior to World War I by Greer (1915). During this period the number of factories and vessels varied with the supply of menhaden. The principal use for the scrap was fertilizer; with different companies each producing individual formulations. A small amount of scrap was used to feed cattle and chickens.

The primary use of menhaden changed from fertilizer to animal feed during the period following World War I. Harrison (1931) described the uses of menhaden during the late 1920s as follows: "... much is being used in mixed feeds for poultry, swine, and cattle and the amount going to fertilizer is steadily decreasing. Menhaden oil is used primarily in the manufacture of soap, linoleum, water proof fabrics, and certain types of paints."

Following World War II the industry grew rapidly, reaching peak production during 1953-1962. Sharp declines in landings thereafter resulted in factory closings and fleet reductions through the 1960s and into the early 1970s. Since that time, the menhaden industry has experienced major changes in processing capacity, resource accessibility, and access to new product markets.

Nine menhaden reduction plants on the Atlantic coast closed permanently during the 1980s while two new operations began. In 1990, five reduction plants with 37 vessels processed Atlantic menhaden for fishmeal and oil. In the United States, land-based plants are currently located at Beaufort, North Carolina and Reedville, Virginia. An IWP venture operated in Maine state waters during 1988-1993. Between 1987-1993 menhaden were also caught off the coast of southern Maine and transported to one of two reduction plants in Blacks Harbour, New Brunswick and Saulnierville, Nova Scotia in Canada.

Since preparation of the 1981 Atlantic Menhaden FMP (ASMFC 1981), there have been numerous regulatory changes affecting the menhaden fishery, such as season limits, area closures, and changes in license fees. In some state waters, a prohibition on commercial menhaden fishing operations using purse seines has been implemented.

3.7.2 Bait Fishery

Information on the harvest and use of menhaden for bait is difficult to obtain because of the nature of the bait fisheries and data collection systems. Harvest comes from directed fisheries, primarily small purse seines, pound nets, and gill nets, and bycatch in various food-fish fisheries, such as pound nets, haul seines, and trawls. Menhaden are taken 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). A specialized use involves live menhaden as bait for coastal pelagic species (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 for tournaments.

Reported annual landings of Atlantic menhaden for bait along the Atlantic coast averaged about 36,900 metric tons for the period 1985-2002. Reported bait landings averaged about 9% of the total Atlantic menhaden landings each year from 1985-1997. Since 1998, reported bait landings have averaged about 16% of the total Atlantic menhaden landings. The increase in percent of coastal landings is attributed to better data collection in the Virginia snapper rig bait seine fishery and a decline in coastal reduction landings due to reductions in processing plants and fleet size.

Closure of reduction plants in New England and the mid-Atlantic may have influenced growth in the bait fishery, making more product available for the lobster and crab pot fisheries, as well as bait and chum for sport fishermen. Additionally, the passage of a net ban in Florida in November 1994 reduced the availability of bait and chum in that state, which opened up new markets for menhaden bait caught in Virginia and the mid-Atlantic states. The appearance of growth in the Atlantic coast bait fishery must be tempered by the knowledge that systems reporting bait landings have historically been incomplete, particularly for Atlantic menhaden. In most cases, recent landings estimates are more accurate, but for some states, bait landings continue to 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 smaller-scale directed bait fisheries and bycatch fisheries supplying large quantities of bait with few, if any, reporting requirements. Menhaden taken as bycatch in other commercial fisheries is often reported as "bait" together with other fish species. The "over-the-side" sale of menhaden for bait among commercial fishermen is under-reported (and often unreported). Common practices such as utilizing menhaden for bait or chum in sportfishing 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.

3.7.2.1 New England

In the New England region, purse seine landings in Maine, Massachusetts and Rhode Island account for the majority of the recorded bait landings. In past years, an ocean trap net fishery operated in 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. Schools of large menhaden have been scarce in the New England region since the early 1990s (ASMFC 2001).

3.7.2.2 Mid-Atlantic

New Jersey dominates current mid-Atlantic reported bait landings. New Jersey requires reports of catch by fishing area under licensing of bait purse seine vessels. Pound nets and gill nets contribute significantly 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).

3.7.2.3 Chesapeake Bay

Virginia snapper rigs (small purse seines) dominate the reported menhaden bait landings in the Chesapeake Bay region, as documented in the Captain's Daily Fishing Reports beginning in 1998. Pound net landings also contribute significantly in Maryland, Virginia and the Potomac River. Most of the catch is used in the blue crab pot fishery (ASMFC 2001).

3.7.2.4 South Atlantic

Parts of North Carolina's landings 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 bycatch and cast netting 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 1994 (ASMFC 2001).

3.7.3 Domestic Processing Activities and Products

Menhaden reduction plants, through a process of heating, separating, and drying, produce fishmeal, fish oil, and fish solubles from fresh menhaden. Meal is a valuable ingredient in poultry and livestock feeds because of its high protein content (at least 60%). The broiler (chicken) industry is currently the largest user of menhaden meal, followed by the turkey, swine, pet food, and ruminant industries. The aquaculture industry has recently demonstrated an increased demand for fishmeal as well (ASMFC 2001).

Menhaden oil has been used for many years as edible oil in Europe. The oil is refined and used extensively in cooking oils and margarine. In 1989, the United States Food and Drug Administration (FDA) concluded that fully and partially hydrogenated menhaden oil is a safe ingredient for human consumption. In 1990, the FDA proposed an amendment, based on an industry petition, to the standard of identity for margarine to permit the use of marine oils. It was approved in 1997 and could provide a significant new market for omega-3 rich menhaden oil. In recent years a plethora of studies have reported on the nutritional and health benefits of omega-3 oils in the human diet.

Solubles are the aqueous liquid component remaining after oil removal. In general, most meal producers add the soluble component to the meal to create a product termed "full meal." The use of solubles as an export product is limited because most companies in the feed industry are not equipped with the necessary storage tanks, pumps, and meters to handle a liquid product.

The world fishmeal industry is in the process of adopting low temperature meal technology, a process that yields significantly higher protein content than previous technologies and produces feed components particularly valuable to aquaculturists. Investment in these new processes represents an opportunity for the U.S. industry to broaden its market base and add value to its products. Public sector support, in the form of research on markets, technology development, and new products, will be a key factor in maintaining the domestic menhaden industry's global competitive status (ASMFC 2001).

3.8 Management

3.8.1 Regulatory Measures

Major changes have occurred in the Atlantic menhaden industry since the completion of the 1981 menhaden FMP (ASMFC 1981). The Atlantic fishery became relatively more important, due in part to the continued improvement of the Atlantic menhaden population and the overall decrease in Gulf of Mexico landings. However, state government regulatory actions, local government land use rules, and changing economic conditions combined have resulted in plant closures. During the mid-1980s, historical low prices occurred for fishmeal, while oil prices fell to lows during 1987 and 1989-1990. Menhaden companies have either gone out of business or have adapted with internal restructuring, as well as adopting new organizational procedures and technology. An IWP fishery operated in Maine waters from 1988-1993, which maintained the menhaden fishing industry in that area. Controversy over operation of menhaden boats in coastal waters has caused the closure of some states' waters and restricted access in others. States that currently prohibit purse seining in their territorial waters (out to three miles) include Connecticut, Delaware, Maryland, and South Carolina. Other states have established seasons and/or restrictions for the use of purse seines (i.e. Maine, New Hampshire, Rhode Island – bait only, New York, New Jersey - bait only, Virginia, North Carolina and Florida). Massachusetts and Georgia require special permits. The taking of Atlantic menhaden by any means for fishmeal reduction is prohibited in New Jersey. New York has strict caveats on reduction purse seine fishing in Long Island Sound, which is nearly beyond the range of reduction vessels from Virginia. In Rhode Island, areas open to purse seines in Narragansett Bay continue to be restricted and the state continues to limit daily catches by purse seines. Fishing for reduction purposes is prohibited in Rhode Island's state waters. Likewise, Georgia has not prohibited purse seine fishing per se in its waters, but it is geographically outside the range of vessels from Beaufort. North Carolina has temporal distance-from-shore regulations along the Outer Banks.

3.8.2 Regulatory Trend

Since 1981, a number of areas along the Atlantic coast have closed to purse seine fishing. Combined with national and international economic factors, the closures have affected the viability of the Atlantic menhaden industry. Some states have closed specific riverine, estuarine, or near-shore ocean areas to menhaden purse seine fishing. Other states have more general area closures, such as Connecticut, Delaware, Maryland, and South Carolina where menhaden purse seine fishing for reduction is prohibited within 3.0 mi (4.8 km) of shore. In New Jersey and

Rhode Island state waters, the harvesting of menhaden for purposes of reduction is prohibited. There has been an increasing trend in expanding the areas where purse seining is prohibited in some states in response to spatial conflicts with other fishing activities and concerns over localized depletions of baitfish through purse seining operations. Since New Jersey closed its waters to menhaden reduction fishing in 2003, the reduction fishery has been essentially restricted to operating within two states, Virginia and North Carolina. The reduction fleets can technically still harvest menhaden outside of three miles off Maryland, Delaware, and New Jersey.

3.8.3 Conflict and Competition in the Menhaden Fishery

Management of coastal fisheries is inherently controversial because of the wide range of interests involved and the need to protect critical habitat. Competition takes place in fisheries when groups or individuals seek the same resource using different methods or try to utilize the same space for their activities, with neither party seeking dominance (Maiolo 1981). Both competition and conflict occur, depending on one's view, among the purse seine fishery, other fisheries, and other users of coastal resources.

As use of public waters, especially in the estuary and near-shore ocean areas, has grown, competition for space has increased, escalating spatial competition to conflict in some areas. In most states, various areas are closed to menhaden purse seining to separate purse seines from other commercial gears, such as crab and lobster pots or pound nets, to separate commercial from sport fishing activities, or to protect other uses of the coastal zone. Today's menhaden fleet is greatly reduced in number of vessels from that of the past, but most of the vessels are quite large and operate during the peak tourist and sport fishing seasons (summer-fall) in areas where marine sportfishing is concentrated (ASMFC 1999a).

Menhaden serve as a forage fish for sport fish, such as striped bass (ASMFC 1990; Hartman 1993; Hartman and Brandt 1995; Walter 1999), bluefish (Wilk 1977; Hartman and Brandt 1995), weakfish (Merriner 1975; Hartman and Brandt 1995), and king mackerel (Saloman and Naughton 1983). Because menhaden occupy this ecological role, some anglers insist that menhaden be abundantly available as prey for fishes higher in the food chain. The above studies all show that the noted game fish consume many other food items besides menhaden.

A past misconception frequently cited by anglers is that menhaden purse seines "entrap all fish within a large chunk of water. Anything bigger than a few inches is rounded up, and pulled alongside [the menhaden vessels]..." (Richard 1989). Studies on the menhaden bycatch issue have been conducted since the late 1800s to more recent times (Smith 1896; Knapp 1950; Baughman 1950; Christmas et al. 1960; Gunter 1964; White and Lane 1968; Ganz 1975; Oviatt 1977; Guillory and Hutton 1982; Austin et al. 1994). Bycatch has been extremely low, generally zero or much less than 1%, based on examination of thousands of sets over the years. Historically this has been an issue in the fishery, however today there is less conflict related to bycatch.

No studies have shown that the menhaden purse seine fishery has had any significant biological effect on any other species or fishery. Oviatt's (1977) classic study in Narragansett Bay demonstrated that even when menhaden vessels left the area because schools become diffuse and difficult to locate, there were still sufficient menhaden remaining to serve as forage for existing populations of bluefish and striped bass.

4.0 Habitat Description

4.1 Physical Description of Habitat

Atlantic menhaden occupy a wide variety of habitats during their life history. Adult Atlantic menhaden spawn primarily offshore in continental shelf waters. Larvae enter estuaries and transform into juveniles, utilizing coastal estuaries as nursery areas before migrating to ocean waters in the fall. They make extensive north-south migrations in the near-shore ocean.

4.1.2 Gulf of Maine

The Gulf of Maine is a semi-enclosed sea of 36,300 mi^2 (90,700 km^2) bordered on the east, north and west by the coasts of Nova Scotia, New Brunswick, and the New England states. To the south, the Gulf is open to the North Atlantic Ocean. Below about 165 ft (50 m) depth, however, Georges Bank forms a southern boundary for the Gulf. The interior of the Gulf of Maine is characterized by five major deep basins (>600 ft, 200 m), which are separated by irregular topography that includes shallow ridges, banks, and ledges. Water flows in and out of the Bay of Fundy around Grand Manan Island. Major tributary rivers are the St. John in New Brunswick; St. Croix, Penobscot, Kennebec, Androscoggin, and Saco in Maine; and Merrimack in Massachusetts.

The predominantly rocky coast north of Portland, Maine is characterized by steep terrain and bathymetry, with numerous islands, embayments, pocket beaches, and relatively small estuaries. Tidal marshes and mud flats occur along the margins of these estuaries. Farther south, the coastline is more uniform with few sizable bays, inlets, or islands, but with many small coves. Extensive tidal marshes, mud flats, and sandy beaches along this portion of the coast are gently sloped. Marshes exist along the open coast and within the coves and estuaries.

The surface circulation of the Gulf of Maine is generally counterclockwise, with an offshore flow at Cape Cod, which joins the clockwise gyre on the northern edge of Georges Bank. The counterclockwise gyre in the Gulf is more pronounced in the spring when river runoff adds to the southwesterly flowing coastal current. Surface currents reach velocities of 1.5 knots (80 cm/sec) in eastern Maine and the Bay of Fundy region under the influence of extreme tides, up to 30 ft (9 m) and gradually diminish to 0.2 knots (10-20 cm/sec) in Massachusetts Bay where tidal amplitude is about 10 ft (3 m).

There is great seasonal variation in sea surface temperature in the Gulf, ranging from 4°C in March throughout the Gulf to 18°C in the western Gulf and 14°C in the eastern Gulf in August. The salinity of the surface layer also varies seasonally, with minimum values in the west occurring during summer, from the accumulated spring river runoff, and during winter in the east under the influence of runoff from the St. Lawrence River (from the previous spring). With the seasonal temperature and salinity changes, the density stratification in the upper water column also exhibits a seasonal cycle. From well-mixed, vertically uniform conditions in winter, stratification develops through the spring and reaches a maximum in the summer. Stratification is more pronounced in the southwestern portion of the Gulf where tidal mixing is diminished (ASMFC 1999a).

4.1.3 Middle Atlantic Region (Cape Cod, MA to Cape Hatteras, NC)

The coastal zone of the mid-Atlantic states varies from a glaciated coastline in southern New England to the flat and swampy coastal plain of North Carolina. Along the coastal plain, the beaches of the barrier islands are wide, gently sloped, and sandy, with gradually deepening offshore waters. The area is characterized by a series of sounds, broad estuaries, large river basins (e.g. Connecticut, Hudson, Delaware, and Susquehanna) and barrier islands. Conspicuous estuarine features are Narragansett Bay (Rhode Island), Long Island Sound and Hudson River (New York), Delaware Bay (New Jersey and Delaware), Chesapeake Bay (Maryland and Virginia) and the nearly continuous band of estuaries behind barrier islands along southern Long Island, New Jersey, Delaware, Maryland, Virginia, and North Carolina. The complex estuary of Currituck, Albemarle, and Pamlico Sounds behind the Outer Banks of North Carolina (covering an area of 2,500 square miles) is an important feature of the region. Coastal marshes border small estuaries in Narragansett Bay and much of the glaciated coast from Cape Cod to Long Island Sound. Nearly continuous marshes occur along the shores of the estuaries behind the barrier islands and around Delaware Bay.

At Cape Hatteras, the Continental Shelf extends seaward approximately 20 mi (33 km) and widens gradually northward to about 68 mi (113 km) off New Jersey and Rhode Island where it is intersected by numerous underwater canyons. Surface circulation north of Cape Hatteras is generally southwesterly during all seasons, although coastal in-drafting and some reversal of flow at the northern and southern extremities of the area may interrupt this. Speeds of the drift north of Cape Hatteras are on the order of six miles (9.7 km) per day. There may be a shoreward component to this drift during the warm half of the year and an offshore component during the cold half. The western edge of the Gulf Stream meanders in and out off Cape Hatteras, sometimes coming within 12 mi (20 km) of the shore, but it becomes less discrete and veers to the northeast north of Cape Hatteras. Surface currents, as high as 4 knots (200 cm/sec), have been measured in the Gulf Stream off Cape Hatteras (ASMFC 1999a).

Hydrographic conditions in the mid-Atlantic region vary seasonally due to river runoff and warming in spring and cooling in winter. The water column becomes increasingly stratified in the summer and homogeneous in the winter due to fall-winter cooling of surface waters. In winter, the mean range of sea surface temperatures is 0-7°C off Cape Cod and 1-14°C off Cape Charles (at the southern end of the Delmarva Peninsula); in summer, the mean range is 15-21°C off Cape Cod and 20-27°C off Cape Charles. The tidal range averages slightly over 3 ft (1 m) on Cape Cod, decreasing to the west. Within Long Island Sound and along the south shore of Long Island, tide ranges gradually increase, reaching 6 ft (2 m) at the head of the Sound and in the New York Bight. South of the Bight, the tidal range decreases gradually to slightly over 3 ft (1 m) at Cape Hatteras. Prevailing southwest winds during the summer along the Outer Banks often

lead to nearshore upwelling of colder bottom water from offshore, so that surface water temperatures can vary widely during that period (15-27°C over a period of a few days).
The waters of the coastal middle Atlantic region have a complex and seasonally dependent circulation pattern. Seasonally varying winds and irregularities in the coastline result in the formation of a complex system of local eddies and gyres. Surface currents tend to be strongest during the peak river discharge period in late spring and during periods of highest winds in the winter. In late summer, when winds are light and estuarine discharge is minimal, currents tend to be sluggish and the water column is generally stratified (ASMFC 1999a).

4.1.4 South Atlantic Region

The south Atlantic coastal zone extends in a large oceanic bight from Cape Hatteras south to Biscayne Bay and the Florida Keys. North of Florida a coastal plain that stretches inland for a hundred miles and a broad continental shelf that reaches into the ocean for nearly an equal distance borders it. This broad shelf tapers down to a very narrow and precipitous shelf off the southeastern coast of Florida. The irregular coastline of North Carolina, South Carolina, Georgia, and eastern Florida is generally endowed with extensive bays and estuarine waters, bordered by nutrient-rich marshlands. Barrier beaches and dunes protect much of the shoreline. Along much of the southern coast from central South Carolina to northern Florida estuarine salt marsh is prominent. Most of the east coast of Florida varies little in general form. Mangrove swamps and low banks of earth and rock sporadically interrupt sand beaches with dunes.

The movements of oceanic waters along the South Atlantic coast have not been well defined. The surface currents, countercurrents, and eddies are all affected by environmental factors, particularly by winds. The Gulf Stream flows along the coast at 6-7 miles per hour (10-11 km/hr). It is nearest the coast off southern Florida and gradually moves away from the coast as it flows northward. A gyral current that flows southward inshore of the Gulf Stream exists for most of the year north of Cape Canaveral.

During the winter, sea surface temperatures increase southward from Cape Hatteras to Fort Lauderdale, Florida, with mean minimums ranging from 2-20°C and maximums ranging from 17-26°C. In the summer, the increases are more gradual, ranging north to south from minimums of 21-27°C to maximums of 28-30°C. Mean sea-surface salinity is generally in the range of 34 to 36 ppt year round. Mean tidal range is just over 3 ft (1 m) at Cape Hatteras and increases gradually to about 6-7 ft (2 m) along the Georgia coast. Tides decrease south of Cape Canaveral to 3 ft (1 m) at Fort Lauderdale (ASMFC 1999a).

4.2 Habitat Areas of Particular Concern

Almost all of the estuarine and nearshore waters along the Atlantic coast from Florida to Nova Scotia serve as important habitat for juvenile and/or adult Atlantic menhaden. 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). Larvae are carried by inshore currents into estuaries from May to October in the New England area, from October to June in the mid-Atlantic area, and from December to May in the south Atlantic area (Reintjes and Pacheco 1966). After entering the estuary, larvae congregate in large concentrations near the upstream limits of the tidal zone, where they 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.

Pollution and habitat degradation threaten the coastal menhaden population, particularly during the estuarine residency of larvae and juveniles. Concern has been expressed (Ahrenholz et al. 1987a) that the outbreaks of ulcerative mycosis in the 1980s may have been symptomatic of deteriorating water quality in estuarine waters along the east coast. The growth of the human population and increasing industrialization in the coastal zone are expected to further reduce water quality unless steps are taken to ameliorate their effect on the environment (Cross et al. 1985). 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.

Many factors in the estuarine environment affect the behavior and well being of 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 important factors affecting natural mortality in Atlantic menhaden are considered to be predators, parasites and fluctuating environmental conditions (Reish et al. 1985).

It is evident that estuarine and coastal areas along the Atlantic coast provide essential habitat for most life stages of Atlantic menhaden. However, an increasing number of people live near the coast, which precipitates associated industrial and municipal expansion, which accelerates competition for use of the same habitats. Consequently, 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).

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, even with existing habitat protection programs. Thus, the specific habitats of greatest long-term importance to the menhaden stock and fishery are increasingly at risk.

5.0 Data Sources

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. Landings for the menhaden reduction plants have been reported since 1940 and biostatistical samples of the catches have been continuously collected since 1955. As the directed bait fishery for menhaden has grown in importance 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. Deck logbooks (Captain's Daily Fishing Reports, or CDFRs) maintained by menhaden reduction vessels have helped reduce some sampling biases inherent in harvesting menhaden on distant fishing grounds. Recreational fishermen also catch Atlantic menhaden as bait for various game fish; however, the quantities removed are believed to be minimal and are currently not quantified. Fishery-independent data sources for Atlantic menhaden exist primarily as seine survey data collected by various states where menhaden are not the target species.

5.1 Commercial Data

The commercial fishery for menhaden consists of a reduction purse seine fishery, which currently accounts for about 84% of the landings, and a bait fishery, which exists as a directed purse seine fishery for menhaden and a mixed species aggregate-bycatch from pound nets, gill nets and trawls. Data used in this analysis are from the Atlantic menhaden reduction fishery from 1955 through 2002 and include landings and nominal fishing effort information (Fig. 5.1) and estimated landings in numbers by age (from NOAA Fisheries biostatistical port sampling; Table 5.1). Since the mid-1990s, data for the bait fishery have improved substantially because the ASMFC Menhaden Technical Committee (TC) and its predecessor AMAC, emphasized acquisition of additional biological samples from the bait fisheries and a better accounting of bait landings.

5.1.1 Data Collection Methods

Fishery-dependent data for the Atlantic menhaden reduction fishery are maintained by NOAA Fisheries at the Center for Coastal Fisheries and Habitat Research in Beaufort, NC (Beaufort Laboratory) in three large data sets. The biological sampling data, or port samples, for length and weight at age represent one of the longest and most complete time series of biostatistical fishery data in the nation (Table 5.2). Commercial catch and effort data (Fig. 5.1) for the reduction fishery are supplied to the Beaufort Laboratory by the menhaden industry on a monthly basis. Catches are enumerated in daily vessel unloads. The CDFRs (daily deck logbooks) itemize purse seine set location and estimated catch.

The Atlantic menhaden TC conducts an annual compilation of menhaden landings for bait by all gears along the U.S. East Coast. Amendment 1 allows states to use existing reporting forms for purse seining of menhaden instead of CDFRs. Fishery-dependent data for the bait fisheries consist of biological sampling of the purse seine landings for bait by federal and state port agents.

5.1.1.1 Survey Methods

Not applicable.

5.1.1.2 Sampling Intensity

See discussion of biological sampling in Section 5.1.1.4 below.

5.1.1.3 Biases

During the 1980s, the menhaden industry suggested that a "topping off" bias occurred in the NOAA Fishery's 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 1985-2002 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.

Prior to 1998, landings of menhaden for bait, especially for the Virginia snapper rigs (directed bait purse seine fishery), were probably underestimated.

5.1.1.4 Biological Sampling

Reduction Fishery - Biological sampling is based on a two-stage cluster design and it is conducted over the range of the fishery, both temporally and geographically (Chester 1984). The number of fish sampled in the first 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 have scales removed for ageing (June and Roithmayr 1960).

In recent years (2000-2002), about 3,400 Atlantic menhaden from the reduction fishery have been processed annually for size and age composition (Table 5.2). 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.

Bait Fishery - Biological sampling of bait landings has mostly been restricted to directed-bait, purse seine vessels in North Carolina, Virginia, and New Jersey, although during the early to mid-1990s additional port samples were acquired from the then extant bait purse seines in Narragansett Bay and southern Maine (Table 5.3). Protocols for acquiring size-at-age data from the bait fisheries are similar to sampling procedures for the reduction fishery. In North Carolina and Virginia, federal port agents meet bait vessels at dockside and then process samples for size and age composition. 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. Sampling for bait has been at a similar level to that of the reduction fleet for North Carolina, Virginia, and New Jersey, except during late 1980s. As described in Section 5.1.5, pooling samples across years within a geographic area was necessary for the bait catch-at-age matrix.

5.1.1.5 Ageing Methods

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.

5.1.1.6 Development of Estimates (e.g. Length/Catch at Age)

See Section 5.1.5 for development of catch-at-age matrices for the reduction and bait fisheries.

5.1.2 Commercial Landings

Reduction fishery - As noted in Ahrenholz et al. (1987b) some fishing for Atlantic menhaden has occurred since colonial times, but the purse seine fishery began in New England in about 1850. Landings and nominal effort (vessel-weeks, measured as number of weeks a vessel unloaded during the fishing year) are available since 1940 (Fig. 5.1). Landings rose during the 1940s (from 167,000 to 376,000 tons, t), peaked during the 1950s (high of 712,000 t in 1956), 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 t in 1983). Landings during the 1990s declined from 401,200 t in 1990 to 171,200 t in 1999. Reduction landings in recent years declined further to 167,200 t in 2000, rose to 233,700 t in 2001, and then declined again to 174,000 t in 2002.

For purse seine fisheries, it has been demonstrated, in general, that catch-per-unit-effort and nominal fishing effort are poor measures of population abundance and fishing mortality, respectively (Clark and Mangel 1979).

An approximate linear relationship was found between landings (L) and nominal fishing effort (E) for 1940-2002 (Fig. 5.2, $R^2 = 0.60$):

$$L = 0.148 \times E + 157.4 + \varepsilon$$

where ε is independent, identically distributed as $N(0,\sigma^2)$. Thus, at a rough level, declining nominal effort does equate approximately with declining landings.

The number of reduction plants along the U.S. Atlantic coast has declined from more than 20 during the late 1950s to 2 plants in 2002 (Table 5.4). Only 2 plants (North Carolina and Virginia) are operating during 2003. Similarly, the number of purse seine vessels in the reduction fishery has declined from more than 130 vessels during the late 1950s to 12 vessels during 2003.

A major change in the industry took place following the 1997 fishing season, when the two reduction plants operating in Reedville, VA, consolidated, which 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 its present number of 10 vessels. Two large vessels continued to be active at the plant in North Carolina.

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. Between 2000-2002 the entire reduction fleet (12 vessels) unloaded an average of 772 times during the fishing year; the average unload per vessel was 248 t.

Bait fishery - Throughout the development of the 1992 Atlantic Menhaden FMP, the AMAC compiled reported menhaden landings for bait along the US East Coast. The Atlantic menhaden TC continues to develop and update the reported annual coastal bait landings for all gear types. In recent years, menhaden purse seine fisheries for bait have operated primarily in North Carolina, Virginia, and New Jersey (Fig. 5.3). Purse seine landings in these three states account for about 90% (1998-2002) of the coastwide menhaden bait landings. Small scale directed gill net fisheries for menhaden as bait exist in many states. Additionally, menhaden for bait are taken as an aggregate bycatch in other coastal states by a variety of gears such as gill nets, pound nets and trawls.

In order to better document menhaden bait landings by purse seines in Virginia (snapper rigs), the AMAC requested that these vessels voluntarily complete CDFRs during 1998-2001. With the adoption of Amendment 1 to the FMP, Virginia snapper rigs, beginning in 2002, are 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 maintained by the NJ Division of Fish and Wildlife. Likewise, the bait purse seine fishery in North Carolina reports daily catch activity on a state trip ticket to the NC Division of Marine Fisheries.

5.1.3 Commercial Discards/Bycatch

Incidental bycatch of other finfish species in menhaden purse seines has been a topic of interest and concern for many years in the commercial and recreational fishing sectors, as well as the scientific community (Smith 1896; Christmas et al. 1960; Oviatt 1977). Numerous studies have shown that there is little or no bycatch in the menhaden purse seine fishery. Some states restrict bycatch to 1% or less of the total catch on a vessel by regulation.

The Virginia Institute of Marine Science completed the most recent study of bycatch of other species in the Atlantic menhaden fishery (Austin et al. 1994). Observations for bycatch were made at sea and at dockside. Results from that study indicate that bycatch in the 1992 Atlantic menhaden reduction fishery was minimal, comprising about 0.04% by number. The maximum percentage of bycatch occurred in August (0.14%) and the minimum occurred in September (0.002%). Among important recreational species, bluefish accounted for the largest bycatch, 1,206 fish or 0.0075% of the total menhaden catch. No marine mammals, sea turtles or other protected species were killed, captured entangled or observed during the sampling. A concurrent study was conducted by Louisiana State University for the Gulf of Mexico menhaden fishery (de Silva and Condrey 1997).

Additional bycatch data were recorded from the Gulf of Maine Internal Waters Processing venture for Atlantic menhaden in 1991. A state observer inspected every catch unloaded onto the Soviet factory ship. A total of 93 fish were taken as a bycatch along with about 60,000,000 individual menhaden (D. Stevenson, formerly of Maine DNR, pers. comm. as cited in ASMFC 1992).

5.1.4 Commercial Catch Rates

Catch-per-unit-effort was not analyzed because of the general problem of using effort data from a purse seine fishery (Clark and Mangel 1979); that is, effort is not a valid measure of fishing mortality, nor is catch-per-unit-effort a valid measure of stock abundance for pelagic schooling species such as menhaden.

Smith (1999b) summarized the distribution of Atlantic menhaden purse seine catches and sets between 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.

5.1.5 Commercial Catch-at-Age

Reduction Fishery - 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 provides an estimate of mean weight and the age distribution of fish caught. Hence, dividing landings for that port/week/area caught by the mean weight of fish allows the numbers of fish landed to be estimated. The age proportion then allows numbers at age to be estimated. Adjustments in these estimates (using CDFRs) are 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 1999b). Developing the catch matrix at the port/week/area caught level of stratification provides for considerably greater precision than is typical for most assessments (Table 5.1).

Bait Fishery - 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 5.3). 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 (New York and north); (2) Middle Atlantic (coastal Maryland, and Delaware through New Jersey); (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 (Fig. 5.4). When the number of samples for a given region and year was less than 50, data were pooled across the years available and substituted for that year (Table 5.5). For the New England region, data for 1986-1996 were pooled and used for individual years 1986-1993 and 1996-2002. Data for 1985 was kept separate because these were particularly small fish. For the middle Atlantic region, data for 1994-2002 were pooled and substituted for individual years 1985-1993. For the Chesapeake Bay region, data for 1992-2002 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) 1997-2002. Years within the respective temporal periods for which substitution was necessary were 1988-1990, 1996, and 1999-2001. The resultant catch-at-age matrix for the bait fishery is shown in Table 5.6.

The mean weight of menhaden landed can be estimated by dividing the catch in biomass by the catch in number. The mean weight of fish caught by the reduction fishery is typically less than that caught by the bait fishery (Fig. 5.5), with but one exception in 2001, when the mean weight in the two fisheries is almost the same. The total number of fish caught by the bait fishery represented 5-10% of the landings of menhaden during 1985-1997 (Fig. 5.6). Since 1998, bait landings have represent between 11-17% of the landings.

5.2 Recreational

Recreational fishermen catch menhaden primarily with cast nets for use as live or dead bait while angling for bluefish, striped bass, flounder, weakfish, mackerels, bluefin tuna and various other game fish. Menhaden frozen or processed by the bait purse seine fishery no doubt are utilized by anglers as bait or chum for various sport fishes. A market for menhaden as live bait for king mackerel exists in the Carolinas, Georgia and Florida; however, this enterprise is not quantified. Since no data are available to quantify the menhaden removed by the recreational fishery it is, therefore, not included in this report.

5.2.1 Data Collection Methods

Data not available

5.2.2 Recreational Landings

Data not available

5.2.3 Recreational Discards

Data not available

5.2.4 Recreational Catch Rate

Data not available

5.2.5 Recreational Catch at Age

Data not available

5.3 Fishery-Independent Survey Data

Sampling for juvenile Atlantic menhaden by NOAA Fisheries began in 1955 and in the 1970s sampling activities culminated in extensive coastwide trawl surveys conducted through 1978 (Ahrenholz et al. 1989). A four-stream survey (2 streams in North Carolina and 2 streams in Virginia) was continued through 1986. Ahrenholz et al. (1989) found no significant correlations between the relative juvenile abundance estimates and the fishery-dependent estimates of year-class strength.

With the new Atlantic menhaden stock assessment, calibration of the age-structured, forward projection model is based in part on a newly developed coastwide juvenile abundance index. The Assessment Workshop chose to restrict development of this coastwide juvenile abundance index to state seine indices and removed state trawl and gillnet surveys from consideration. These surveys include:

North Carolina Alosid seine survey (Program 100S; 1972-2002)
Virginia Striped Bass seine survey (1968-1973, 1980-2002)
Maryland Striped Bass seine survey (1959-2002)
Connecticut River seine survey (1987-2002)
Rhode Island Narragansett Bay seine survey (1988-2002)

5.3.1 Data Collection Methods

See Section 5.3.1.1

5.3.1.1 Survey Methods

North Carolina's Alosid seine survey (Program 100S) has been conducted continuously since 1972; the survey targets juvenile alosid fish and operates June through October.

Virginia's Striped Bass seine survey was conducted from 1968 to 1973, then from 1980 to the present; the survey targets juvenile striped bass with most sampling occurring July through September, and occasionally 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.

Maryland's Striped Bass seine survey has operated continuously since 1959 and targets juvenile striped bass; survey stations are sampled in June and September and the bagless beach seine's dimensions are 1.2 m x 30.5 m x 6.4 mm.

Connecticut River seine survey has been continuous since 1987 and targets juvenile alosids; the survey operates during July through October and the bag seine dimensions are 2.44 m x 15.2 m x 0.5 cm.

Rhode Island's Narragansett Bay seine survey has been continuous since 1988 and stations are sampled from June through October; the seine's dimensions are 3.05 m x 60 m.

5.3.1.2 Sampling Intensity

The numbers of hauls per year for each state seine survey are summarized in Table 5.7. From 1959-1967, only seine data from Maryland is available and from 1988-2002 seine data from all five states are available. Between 1968 and 1987, the South Atlantic and Chesapeake Bay regions are well represented.

5.3.1.3 Biases

Because of the schooling nature of Atlantic menhaden and the fact that state surveys were originally designed to measure the abundance of other species (such as striped bass), seine surveys may tend to overestimate juvenile menhaden abundance during years of good recruitment and underestimate juvenile menhaden abundance during years of poor recruitment.

5.3.1.4 Biological Sampling

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

5.3.1.5 Ageing Methods

For state seine surveys (North Carolina, Virginia, and Maryland) with length data, catch-per-tow were adjusted based on the convention cut-off sizes by month for age-0 Atlantic menhaden adopted by the Atlantic menhaden TC in March 2003. Age-0 cutoffs: June 1 - June 30 use 110 mm FL, July 1 - August 15 use 125 mm FL, August 16 - November 30 use 150 mm FL.

5.3.1.6 Development of Estimates

Catch-per-unit-effort (CPUE) indices were developed from the five seine surveys. The general approach taken to develop an index of menhaden abundance from each of these data sources was to use a general linear model (GLM). In some cases there were observations with zero CPUE values. Typically CPUE information is modeled as a lognormally distributed variable, which simply involves taking the natural logarithm of CPUE. However, the logarithm of zero cannot be computed. To get around this problem there have been several suggestions for added constants to CPUE ranging from 0.001 up to 10 times the maximum positive value (Porch and Scott 1994; Ortiz et al. 2000). An alternate suggestion to the additive constant has been to model the proportion positive as a binomial distributed process in a GLM. This can then be combined with a log(CPUE) GLM of the positive values into a delta-lognormal process, an approach that was adopted here (Lo et al. 1992; Stefansson 1996; Ortiz et al. 2000). Error estimates were obtained from a bootstrap procedure which re-samples residuals from the lognormal GLM model of the positive values and randomly draws values from a binomial distribution based on the observed and predicted proportion positive data from the GLM results (Efron and Tibshirani 1993). It should be noted that this bootstrap method for obtaining error estimates only accounts for modeling error and does not incorporate any sampling error from aggregated CPUE estimates. The bootstrapped mean and standard error of the delta-lognormal GLM are summarized for the five state seine surveys in a series of figures (Figs. 5.7 - 5.11).

Pair-wise correlations were estimated for each of the state seine indices that were developed using the delta-lognormal GLM (Table 5.8). The two seine indices from the Chesapeake Bay (Virginia and Maryland) were highly positively correlated with each other (r=0.455, $\propto$=0.013), while the two seine indices from New England (Connecticut and Rhode Island) were similarly positively correlated (r=0.455, $\propto$=0.096), but less significantly ($\propto \sim 0.1$). When comparing across regions, the North Carolina seine index was highly significantly correlated with the seine indices from the Chesapeake Bay (Virginia and Maryland seine indices: r = 0.773 and 0.735, respectively, $\propto$ = 0.0001). The New England indices, although not statistically significant, were negatively correlated with the seine indices to the south.

To develop a coastwide index, multiple indices within a region were first combined (e.g. Virginia and Maryland seine surveys in the Chesapeake Bay region, and the Connecticut and Rhode Island seine surveys in the New England region). The two indices from Chesapeake Bay were standardized and averaged; similarly the two indices from southern New England were also standardized and averaged. The North Carolina, Chesapeake Bay, and New England indices were then standardized. A weighted average of these standardized indices was then calculated based on the following weightings:

New England (CT-ME)	1.8%
Middle Atlantic (Coastal MD-NY)	12.5%
Chesapeake Bay (including coastal VA)	68.8%
South Atlantic (FL-NC)	16.9%

These weightings were derived from estuarine and fluvial drainage areas along the Atlantic coast (EDA; NOAA 1990), combined with menhaden productivity of streams along the Atlantic coast from data collected in the 1970s by the Beaufort Laboratory (Ahrenholz et al. 1989). The resultant percentages reflect the amount of estuarine area adjusted for relative menhaden production. Because no seine indices were available from the Middle Atlantic region, the weight of the other three regions were adjusted proportionately to sum to one. From 1959-1967, only the MD seine index was included into the coastwide index, and from 1988-2002 all five indices were included (Fig. 5.12). Varying state seine indices were represented in the coastwide index from 1968 to 1987.

Because of the schooling nature of Atlantic menhaden, the assessment workshop believed that these indices are biased high when abundance is high and biased low when abundance is low. Hence, the natural logarithm of the coastwide index was used for calibration in the assessment model. To avoid taking logarithm of negative or zero, the standardized coastwide index was re-standardized based on the weighted average of the individual means and variances from the original indices, and a small value added to all values.

5.3.2 Length/Weight/Catch-at-Age

See 5.3.1.4. Age-0s only used to calculate the indices of juvenile abundance.

5.3.3 Abundance Indices

Not available.

5.3.4 Biomass Indices

Potomac River Fisheries Commission Dependent CPUE index- Annual Potomac River pound net catches of menhaden and number of pound net licenses issued during 1964-2000 were available from the Potomac River Fisheries Commission (PRFC; A. C. Carpenter, PRFC, personal communication). Catch-per-unit-effort for each year was calculated as annual catch reported by all license holders divided by number of licenses. During 1964-1993, there were no restrictions on the number of licenses sold. After 1993, the number of licenses was capped at 100 (A. C. Carpenter, PRFC, personal communication). Pound net is a stationary nonselective fishing gear and it was believed to produce an index of relative abundance of menhaden (ages-0 through -5, primarily 1 through 3) in Potomac River and Chesapeake Bay (Fig. 5.13). The pound net CPUE, lagged 2-years, was highly positively correlated with the juvenile abundance seine indices from North Carolina, Virginia and Maryland, but negatively, although not significantly, with the seine indices from Connecticut and Rhode Island. This pattern is similar to the correlations among the seine indices between New England and the regions to the south.

5.3.5 Natural Mortality Estimates

See discussion of natural mortality in Section 2.7.

6.0 Methods

The Data Workshop recommended the use of a forward-projecting statistical catch-at-age model as the primary assessment tool for Atlantic menhaden in 2003. Previous stock assessment analyses of Atlantic menhaden have used untuned virtual population analysis (VPA) methods (Vaughan and Smith 1988; Vaughan 1993; Cadrin and Vaughan 1997; Vaughan et al. 2002a). A forward-projecting model was preferred over the VPA method primarily because of the increased flexibility in formulation and statistical treatment of the data sources.

6.1 Model(s)

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 and then used by Fournier and Archibald (1982), Deriso et al. (1985) in their CAGEAN model, and 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 (Anonymous 2002), and South Atlantic black sea bass (Anonymous 2003). Forward-projecting age-structured models share many attributes with ADAPT-style tuned and untuned VPAs.

6.2 Model Calibration

Properties of age-structured model
The forward-projecting statistical age-structured model for this assessment was implemented in the AD Model Builder (ADMB) software (Otter Research 2000) on a microcomputer. The ADMB model code and input data file are attached as Appendices C and D. A summary of the model equations may be found in Table 6.1. The formulation's major characteristics can be summarized as follows:

Natural morality rate- The natural mortality rate was assumed constant over time. A vector of age-specific *M* estimates obtained from an MSVPA analysis was used as a starting estimate (from multispecies VPA discussed in Section 2.7). The age-specific *M* vector was then multiplied by a model-estimated scaling parameter.

Stock dynamics- The standard Baranov catch equation was applied. This assumes exponential decay in population size due to fishing and natural mortality processes.

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

Recruitment- Both Ricker and Beverton–Holt recruitment models were estimated internally. Estimated recruitments were loosely conditioned on that model.

Biological benchmarks- Biological benchmarks were calculated based on per recruit analysis used in Amendment 1 (ASMFC 2001). Modifications and recalculations to benchmarks in Amendment 1 are described in detail in Section 8.

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 the reduction fishery and double–logistic model for the bait fishery, rather than estimating independent selectivity values for each age. That 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.

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

Abundance indices -The model used two separately modeled indices of abundance. They were a juvenile (age-0) index series (years 1959-2002) and a pound net CPUE index series (years 1964-2002).

Fitting criterion -The fitting criterion was a total likelihood approach in which total catch was fit almost exactly and the observed age compositions, as well as the abundance index patterns, were fit to the degree that they are compatible. Landings data and abundance index data were fit using a lognormal likelihood, the value of which is inversely related to the coefficient of variation (CV). CVs of abundance indices were assumed equal (CV=0.2); CVs of landings data were assumed for the reduction fishery (CV=0.01) and bait fishery (CV=0.3) landings. Composition data were fit using a multinomial likelihood. Due to the non-random distribution of fish, the multinomial likelihood sample sizes were down weighted by a factor of 0.1 for the reduction fishery samples and 0.5 for the bait fishery samples. In addition, penalties were added to the total likelihood for deviation from realistic biological or fishery characteristics (e.g. recruitments fluctuating greatly from year to year). Relative statistical weighting of each likelihood component for the central case was chosen at the assessment workshop after examining many candidate model runs. The criteria for choice were a balance of reasonable fit to all available data and a good degree of biological realism in estimated population trajectory.

7.0 Outputs/Results

This section describes the output and results of the forward-projecting statistical age-structured model described in Section 6 on Methods. Base runs were from underlying spawner-recruit relations for both the Ricker and Beverton-Holt models developed by the Assessment Workshop. Both base runs fit equally well to the data. Goodness-of-fit for the base Ricker model run is presented for the reduction and bait landings, catch-at-age for these landings, coastwide juvenile abundance index, and the pound net index (Section 7.1). Then parameter estimates for the two base runs are compared. These parameters include fishing mortality rate (F for ages 2+), exploitation rate (u for ages 1+), spawning stock biomass (SSB), population fecundity (number of maturing or ripe ova), and recruits to ages-0 and -1 (Section 7.2). No projections were necessary (Section 7.3). Sensitivity of the model was tested for model configuration (underlying spawner-recruit relation already described and varying fixed levels of steepness, h) and for data input (different fixed levels of M and knife-edged maturity; Section 7.4). Finally, results of a series of retrospective runs are presented for the base Ricker model by dropping 1 year of data at a time, back to 1997 (Section 7.5).

7.1 Goodness-of-Fit of Model Used

Goodness-of-fit is governed in the assessment model by the likelihood components in the objective function (Table 6.1). During the assessment workshop, goodness of fit was judged for each data source through examination of the model residuals. Observed and model predicted landings for the reduction fishery (1955-2002; Fig. 7.1) and the bait fishery (1985-2002; Fig. 7.2) are compared for the base Ricker run. The fit for the reduction fishery landings, which are known very precisely, fit almost perfectly. The more poorly estimated bait landings show some deviations, although the fit is quite close for these as well. Bubble plots of the catch-at-age are presented for the reduction fishery (Fig. 7.3) and bait fishery (Fig. 7.4). Observed and predicted coastwide juvenile abundance indices are compared for the base Ricker run (1959-2002; Fig. 7.5). The model suggests greater year-to-year variability in recruitment to age-0 than the index. Finally, the observed and predicted biomass pound net indices (pounds landed per license for 1964-2002; Fig. 7.6) fit poorly. However, the observed indices are based on commercial landings from the Potomac River and are divided by a fairly insensitive measure of effort (licenses).

7.2 Parameter Estimates

Results from both base (preferred) runs are described in this section. They are developed from both an underlying Ricker and Beverton-Holt spawner-recruit relation. These results include annual estimates of natural mortality rate at age, exploitation rates (e.g. fishing mortality rate and exploitation rate), abundance estimates (e.g. spawning stock biomass, population fecundity, and recruits to age-0 and age-1), and description of the precision of these estimates (specifically natural and fishing mortality rate, population fecundity, and recruits to age-0).

An important element of this model approach is that age-specific M is estimated in the base, sensitivity (except where fixed), and retrospective runs. These estimates are summarized in Table 7.1. Values of M for ages-3 and older from the base runs (0.55 for Ricker and Beverton-Holt) are similar to those obtained from historical tagging studies (0.52 from Dryfoos et al., 1973; 0.50 from Reish et al., 1985). These estimates are somewhat higher than the values of 0.45 used for ages-2 and older in prior stock assessments (Ahrenholz et al. 1987b; Vaughan and Smith 1988; Vaughan et al. 2002a; and annual assessments for ASMFC since 1994). Estimated M for age-1 (0.98 vs. 0.45) is more than double than previously used and M for age-0 (4.3 vs. 0.45) is almost an order of magnitude higher. Higher values of M (ages-2 and older) than those obtained in the Multispecies VPA suggest that the assumed value for M_1 used in that analysis was too small (0.3) and that a value more on the order of 0.5 would have been appropriate.

7.2.1 Exploitation Rates

Fishing mortality is 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 are compared graphically in Fig. 7.7. The reduction fishery was modeled by a single logistic equation (see Section 6), with age-3 and older found to be fully recruited and age-2 almost fully recruited (97%). The bait fishery was modeled with a dome-shaped double-logistic equation (see Section 6), with age-3 fully recruited and ages-2 and -4 almost fully recruited (98% and 93%, respectively). The catch-weighted selectivity for the final fishing year (2002) shows ages-3 to -5 as fully recruited (>99%), with age-2 (89%) and ages-6 to -8 (88-92%) almost fully recruited.

Fishing mortality rates on ages-2 to -8 (referred to as full F) were calculated as the weighted average of age-specific Fs for ages-2 to -8, weighted by population number at age (Fig. 7.8). Little difference is discernable between estimates of full F whether obtained from the model runs based on either the Ricker relation or the Beverton-Holt relation. Highest fishing mortality is noted in the mid-1960s during a period of poor recruitment, when the menhaden population declined dramatically and subsequently many reduction plants were shut down. Since the mid-1960s, fishing mortality has declined, such that it has generally been below 1.0 for the last 11 years. The historical time period 1955-2002 produced a median *F* of 1.04 with interquartile range between 0.83 and 1.27 (Table 7.2). The estimate of fishing mortality rate for 2002 of 0.79 is below the 25th percentile of the historical estimates.

Annual estimates of exploitation rate (*u*, ages-1 to -8), as should be expected, have shown a similar pattern of decline for the period 1965 through 2002 (Fig. 7.9). During much of the 1960s, *u* was about 35%, but has been mostly in the range of 15% - 20% over the last decade. The historical time period 1955-2002 produced a median *u* of 0.23 with interquartile range between 0.20 and 0.26 (Table 7.2). The estimate of exploitation rate for 2002 of 0.19 is below the 25th percentile of the historical estimates.

7.2.2 Abundance Estimates

The forward-projecting statistical age-structured model estimates population numbers at age (0-8) for 1955-2002 (Table 7.1 for base Ricker run). From these estimates and growth data, different estimates of population biomass and reproductive capacity can be developed.

Spawning stock biomass (SSB, weight of mature female biomass at start of fishing year) was high in the late 1950s and early 1960s, low in the late 1960s, and generally increasing since then (Fig. 7.10). The largest values of spawning stock biomass 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). The historical time period 1955-2002 produced a median SSB of 76,800 t with interquartile range between 56,600 t and 120,100 t (Table 7.2). Estimates of SSB from 1964 until 1971 were below the 25th percentile. Since 1972, an estimate of SSB below the 25th percentile occurred only in 1975, 1985, 1992, and 2000. Historically high levels of spawning stock biomass (greater than the 75th percentile) occurred during 1955-1956, 1958-1962, 1987-1988, 1994-1995 and 1997. The estimate for spawning stock biomass in 2002 was 91,900 t, or between the median and 75th percentile.

Similarly, population fecundity (number of maturing or ripe ova) followed a similar pattern to spawning stock biomass (Fig. 7.11). The historical time period 1955-2002 produced a median population fecundity of 30.1 x 10^{12} ova with interquartile range between 23.2 x 10^{12} and 48.6 x 10^{12} (Table 7.2). Estimates of fecundity from 1964 through 1971 and 1975 to 1976 were below the 25th percentile. Since 1978, an estimate of population fecundity below the 25th percentile occurred only in 1985 and 1992. Historically high levels of population fecundity (greater than the 75th percentile) occurred during 1955-1956, 1958-1962, 1988, and 1994-1997. The estimate for population fecundity in 2002 was 40.6 x 10^{12}, again between the median and the 75th percentile.

Recruits of Atlantic menhaden to age-0 (Fig. 7.12) and age-1 (Fig. 7.13) were high during the late 1950s, especially the 1958 year class. Median and interquartile values for recruits to age-0 and age-1 are summarized in Table 7.2. Recruitment was generally poor during the 1960s, with values below the 25th percentile for the recruitment time series. High recruitment occurred during the 1970s to levels above the 75th percentile. These values are comparable to the late 1950s (of course, with the exception of the 1958 year class). Moderate to high recruitment occurred during the 1980s, with generally low recruitment since the mid-1990s. The most recent estimate of recruitment has the greatest uncertainty and the estimate for 2002 is likely to be modified as more data from the cohort (age-1 in 2003, age-2 in 2004, etc.) are added to the analysis. The current estimate of recruits to age-0 in 2002 (406.8 billion for the Ricker model; 402.7 billion for the Beverton-Holt model) is between the median and 75th percentiles, while the current estimate of recruits to age-1 in 2002 (2.5 billion for both the Ricker and Beverton-Holt models) falls below the 25th percentile.

7.2.3 Precision of Parameter Estimates

Precision of model estimates are based on the use of the delta method that approximated variance estimates from each model run. It is important to note that the variance estimates obtained from the Delta-method reflect only model-fitting error and do not account for error in fixed values which are input into the model (see Section 7.4). For example, there is no attempt to model the error in the fixed input data, such as the size at age, fecundity at age, and natural mortality at age vectors (when fixed and not estimated). Furthermore, variance estimates derived from the delta method are biased low when additional constraints are added to the model. For these reasons, the estimated variance levels should be considered underestimates and their utility should be limited to judging relative variance among model output.

Based on the delta method, annual estimates of natural mortality rate, M (Fig. 7.14), full F (Fig. 7.15), population fecundity (Fig. 7.16), and recruits to age-0 (Fig. 7.17) are present for the base Ricker run, with dashed lines showing plus or minus twice the standard error. Estimates of M and population fecundity appear to be quite precise, with somewhat wider confidence interval for full F (especially in the most recent year, and wider confidence intervals associated with estimates of recruits to age-0).

7.3 Projection Estimates

The Sustainable Fisheries Act requires development and implementation of rebuilding schedules for those stocks that are overfished or approaching the overfished condition. Updates of assessments for stocks in a rebuilding phase requires calculation of stock projections to assess the status of the stock relative to the rebuilding target and to allow for consideration of management options for facilitating the rebuilding process. The menhaden stock is not overfished and overfishing is not occurring based on the results of this assessment. As such, projection estimates were not computed for the current assessment of the Atlantic menhaden population.

7.4 Sensitivity Analyses

Sensitivity of the forward-projecting statistical age-structured model was investigated in two fundamental ways. First, sensitivity to model configuration was investigated by considering two different spawner-recruit relations (Ricker and Beverton-Holt) that underlie the model fitting, and three additional sensitivity runs for each spawner-recruit relation in which steepness was fixed at different values ($h = 0.7, 0.8, 0.9$). Sensitivity to input data was investigated by fixing natural mortality (either $M = 0.45$ for all ages as used in previous assessments or age-specific values of M estimated in the Multispecies VPA described in Section 2.7). Earlier assessments had assumed knife-edge maturity between ages-2 and -3 (0% of age-2 mature and 100% of age-3). A separate run was made for this assumption of maturity. The comparison of runs with the two different spawner-recruit relations has been presented throughout Section 7.2. For the remaining comparison in this section, only those based on the Ricker model are shown.

7.4.1 Sensitivity to Model Configuration

A series of three runs were made with the variation from the base Ricker run by fixing the level of steepness (h) at 0.7, 0.8, and 0.9. The value of initial R_0 was fixed at the same value as that estimated in the base run. Lower values of age-specific M were estimated when fixing h, especially for $h = 0.9$ (Table 7.1). Annual estimates of full F (Fig. 7.18), population fecundity (Fig. 7.19), and recruits to age-0 (Fig. 7.20) were compared for the base run and three levels of fixed h.

7.4.2 Sensitivity to Input Data

A series of three runs were made with the variation from the base Ricker run fixing natural mortality rate at either the M vector from the Multispecies VPA or constant value of 0.45 used in prior assessments for Atlantic menhaden. In addition, another assumption investigated from past menhaden assessments was that of knife-edge maturity (0% age-2 and 100% age-3). Annual estimates of full F (Fig. 7.21), population fecundity (Fig. 7.22), and recruits to age-0 (Fig. 7.23) are compared for the base run and two variations on fixed M (vector and 0.45) and assumption of knife-edge maturity. Results from the assumption of knife-edge maturity were generally indistinguishable from the base run, including estimated M (Table 7.1). Small differences in full F and population fecundity are noted, with high full F from fixed (lower) M and lower population fecundity. For recruits to age-0, considerably lower values resulted from fixed (lower) M, especially fixed at 0.45.

7.5 Retrospective Analyses

A series of five runs were made with the variation from the base Ricker run dropped for the latest year of data. In the first run the last year of data was 2001, in the second run the last year of data was 2000, and so forth through 1997. Little, if any, retrospective bias was noted in estimates of M (Table 7.1). Annual estimates of full F (Fig. 7.24), population fecundity (Fig. 7.25), and recruits to age-0 (Fig. 7.26) were compared for the base run and the sequence of reduced data sets. There was some indication of retrospective bias arising from the constraint in the model runs that minimizes deviation of recruitment in the last three years near the predicted spawner-recruit value. This retrospective bias is relatively small for full F and population fecundity, but more significant for recruits to age-0.

8.0 Biological Reference Points

Under the re-authorization of the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA), biological reference points or benchmarks based on consideration of two population variables are described (Restrepo et al. 1998). The schematic (Fig. 8.1) summarizes this approach as modified from that in the Gulf of Mexico's SPR Management Strategy Committee report (1996). Fishing mortality rate (*F*, a measure of the rate of removal of the stock by the fishery) is on the vertical axis, and spawning stock biomass (*B*, a measure of the reproductive ability of the stock to replenish itself) on the horizontal axis. *F'* and *B'* represent targets, while *F"* and *B"* represent limits or thresholds.

Limits (or thresholds) are the basis for determining whether overfishing is occurring or a stock is overfished. When the fishing mortality rate (*F*) exceeds the *F*-limit or threshold, then overfishing is occurring such that 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 *B*-limit or threshold, then the stock is said to be overfished such that there is insufficient mature female biomass (SSB) or egg production (population fecundity) to replenish the stock. However, it should be noted that fishing is not the only cause of decline in spawning stock biomass (or population fecundity), because environmental conditions can also cause such declines.

Recruitment does not appear on this schematic, because it is not directly controllable by management actions. Maintenance of spawning stock or population fecundity at or above the target level is the primary management influence over recruitment. While targets represent desired long-term levels, limits or thresholds represent levels beyond which the long-term viability of the stock may be threatened.

8.1. Overfishing Definitions

With the approval of Amendment 1 to the Atlantic Menhaden Fishery Management Plan (ASMFC 2001), biological reference points based on the two population variables from the MSFCMA were adopted. Biological reference points for these population variables were as follows: *F* (target = 1.04 and threshold = 1.33) and SSB (target = 37,400 t, and threshold = 20,570 t). In this assessment, values of these and additional variables are estimated from the forward-projecting statistical age-structure model described in Section 6.

Fishing mortality rate, *F*, on the fully recruited ages was calculated from the weighted average of age-specific estimates of *F* for ages-2 and older (weighting based on population in numbers). Although estimates of *F* at age in the past were based on the untuned Murphy VPA (Vaughan and Smith 1988; Vaughan et al. 2002a, b), the weighted estimate of *F* for ages-2 and older to obtain full *F* is maintained.

The time series of data for Atlantic menhaden is one of the longest in the United States; hence consideration of historical performance is a reasonable approach to initially evaluate the ability of the stock to cope with various levels of fishing mortality. Levels of performance of *F* based on quartiles are summarized in Table 8.1 for the base Ricker model. A general decline has been noted in the fishing mortality rate since about 1965 (Fig. 7.8). The estimate of full *F* (0.79) in the terminal year (2002) is below the historical 25th percentile (0.83). This terminal value is well below the target in Amendment 1 (1.04).

In Amendment 1, the other variable specified was spawning stock biomass (SSB), which was calculated from the weight of mature females (one-half the weight of population ages-3 and older). The Assessment Workshop recommends using population fecundity (number of maturing or ripe ova; Lewis et al. 1997) as a better measure of reproductive output of the population compared to spawning stock biomass (SSB). For comparison purposes, the terminal estimate of spawning stock biomass (in 2002) is 91,900 t, which falls between the median (76,800 t) and 75th percentile (120,100 t; Table 7.2). This terminal value is also almost 2.5 times the target in Amendment 1.

Estimates of population fecundity are available for 1955 through 2002 (48 years), during which the population has undergone periods of high and low recruitment (Figs. 7.11-7.13). Following periods of low recruitment, population fecundity has declined, and following periods of high recruitment, population fecundity has increased. Levels of performance based on percentiles are summarized in Table 7.2 for the both base models. Population fecundity reached a recent high in 1997, decreased from that level, but increased significantly in 2002 (apparently resulting from moderate recruitment to age-0 in 1998 and 1999). The recent estimate of population fecundity (40.6 trillion maturing or ripe ova) is between the median (30.1 trillion maturing ova) and 75th percentile (48.6 trillion maturing ova).

8.2 Spawner Recruitment Analysis

As described in Section 6 on Methods, an underlying spawner-recruit relation was incorporated in the estimation of population characteristics. A plot of spawner versus recruitment demonstrates the uncertainty as to appropriateness of a particular codification of this relation, either Ricker or Beverton-Holt models (Figure 8.2). Hence, parallel base runs were made with both underlying relationships. The Assessment Workshop was uncomfortable with specifying a specific underlying spawner-recruit model, and, therefore, did not recommend the use of internal model estimates of MSY, F_{MSY} and $\mathrm{SSB}_{\mathrm{MSY}}$ (or $\mathrm{Fecundity}_{\mathrm{MSY}}$) as the basis for developing biological reference points.

8.3 Yield and SSB Per Recruit

Per recruit analyses include both yield per recruit and spawner-per-recruit. Yield-per-recruit maximizes yield to the fishery at an intermediate level of fishing mortality, which balances loss due to mortality with growth of individual fish. Spawner-per-recruits reflects decreased reproductive capacity with increasing mortality. The latter approach is often performed when the relationship between spawners and recruits cannot be explicitly quantified. The Assessment Workshop participants felt that fecundity was a better measure of reproductive capacity than spawning stock biomass.

8.3.1. *F*-based Benchmarks

Estimates of yield-per-recruit as a function of fishing mortality were calculated with the partial recruitment (selectivity) for 2002 in the forward-projecting statistical age-structured model (Figs. 8.3-8.4). F_{MAX}, which represents the level of fishing mortality that maximizes biomass-return to the fishery, occurs beyond the range of F over which yield was calculated (> 2.5). Although F_{MAX} was used as the F-target in Amendment 1, the conclusion of the Assessment Workshop was that F_{MAX} was no longer an appropriate target.

Annual estimates of equilibrium spawning potential ratio (static SPR; Fig. 8.5) and fecundity-per -recruit (FPR; Fig. 8.6) were estimated using the partial recruitment (selectivity) for 2002 (Prager et al. 1987; Gabriel et al. 1989). This analysis compares spawning stock biomass-per-recruit calculated for different levels of fishing mortality to spawning stock biomass-per-recruit calculated with F=0 under an equilibrium (static) assumption (or in terms of population fecundity). It is interesting to note that there were two periods when high values (>20%) of static-SPR and static-FPR, during the late 1950s and 1990s. Values of static-FPR above 20% occurred in 1960, 1986, 1993-1994, 1996, and 2000-2002.

Static-FPR is a decreasing function of F (Figs. 8.3-8.4), and is more properly related to fishing mortality than to spawning stock biomass or population fecundity. This approach does not calculate the virgin spawning stock biomass (or population fecundity), but rather a theoretical spawning stock biomass (or population fecundity) based on the assumption that the life history parameters are unaltered from this 'virgin' state.

Biological reference points based on static SPR (or static FPR) are given as F subscripted with the level desired for static SPR. Hence, F_{20} refers to the level of F that would produce a theoretical ratio of 20% SPR (or equivalently for 20% FPR). Definitions of overfishing (as opposed to overfished or depleted state of the stock) have typically ranged from 20% to 40%, with the higher values associated with long-lived, late-maturing species. For the static SPR approach, F_{10} occurs at a full F of about 1.4, and F_{20} at about 0.8, and for static FPR approach, F_{10} occurs at a full F of about 1.3, and F_{20} at about 0.8 (Table 8.1).

The limit reference point (threshold) adopted in Amendment 1 was based on spawning stock biomass-per-recruit, as described by Sissenwine and Shepherd (1987). For this limit (or threshold) reference point, F_{MED}, using the median of SSB/R to represent the replacement level of the stock, or F_{REP} (Figs. 8.7-8.8). The conclusion of the Assessment Workshop was to use fecundity/R_0 (1955-2002) to determine F_{MED}. This is accomplished by comparing this median value of fecundity/R_0 to the theoretical curve to obtain the corresponding value of F. The median of fecundity/R_0 for the historical Atlantic menhaden data was 73.8 expressed as thousands of maturing or ripe ova per age-0 recruit. The corresponding F (F-threshold) from the fecundity/R_0 curve generated for the partial recruitment (selectivity) during 2002 was estimated at about 1.2.

In Amendment 1, the F-target was based on F_{MAX}. The results of our analyses in this assessment suggest that F_{MAX} is extremely high and therefore unsuitable as a target since it exceeds the F-

threshold level. Therefore, we suggest an alternative *F*-target based on the same approach as that used to develop the *F*-threshold. Specifically, the *F*-target is calculated from the 75th percentile of fecundity/R_0, instead of the median used to determine F_{MED} (Figs. 8.7-8.8). The 75th percentile of fecundity/R_0 is 135.6, and corresponding *F* is 0.75, our recommended *F*-target (Table 8.1).

8.3.2. Fecundity (or SSB-based) Benchmarks

To obtain a population fecundity from the per recruit analyses that corresponds to F_{REP}, the fecundity/R_0 equivalent to the *F*-threshold is obtained first (Table 8.1). The median of fecundity/R_0 times the median recruits to age-0 gives an estimate of population fecundity that would become the *B*-threshold (the target B_{MSY} corresponds to the threshold F_{MSY}) (Restrepo et al. 1998). The median recruitment from the 48-year time series is 360.9 billion age-0 menhaden (base Ricker model). The estimate of population fecundity corresponding to F_{MED} is calculated from the product of 73,800 (median of fecundity/R_0 for 1955-2002) and 360.9 billion age-0 recruits, or 26.6 trillion maturing ova (Table 8.1). This estimate is analogous to the approach used in Amendment 1, but uses population fecundity rather than spawning stock biomass. For comparison with the SSB-based target in Amendment, the SSB corresponding to *F*-threshold is 68,600 t.

As in Amendment 1, we use the approach recommended by Restrepo et al. (1998) to obtain minimum spawning stock threshold (MSST). Using this approach, one simply multiplies the SSB-target by one minus the adult natural mortality [i.e. (1-*M*)**B*]. When *M* exceeds 0.5, then they recommend using simply 0.5**B* for MSST. Hence, the fecundity threshold is one-half the fecundity target (*M* > 0.5), or 13.3 trillion maturing or ripe eggs. The SSB threshold would be 34,300 t.

8.4 Stock Production Model.

None.

9.0 Recommendations and Findings

9.1 Evaluation of Current Status Based on Biological Reference Points (Fishery Control Rules)

Ideally, benchmarks for *F*-based and SSB-based reference variables would be based on an underlying population dynamics model (e.g. F_{MSY} and B_{MSY} from Ricker or Beverton-Holt spawner recruit models). However, these models perform poorly when applied to historical Atlantic menhaden data (Fig. 8.2). Hence, the benchmarks in Amendment 1 were developed from historical spawner and recruit data based primarily on F_{REP}, as estimated by F_{MED}. That is, F_{MED} became the threshold for *F* and its corresponding spawning stock biomass (SSB) became the target. The threshold for SSB was calculated as (1-*M*)*SSB-target, where *M* was 0.45. A different process was used to obtain the *F*-target. It was based on F_{MAX}. Values for these benchmarks were 1.04 and 1.33 for the F-target and F-threshold, respectively, while 37,400 t and 20,570 t were the SSB-target and SSB-threshold, respectively.

Because of concerns about the underlying spawner-recruit relationship, we have maintained the basic approach from Amendment 1, but with some modifications. We recommend that SSB be replaced with population fecundity (number of maturing or ripe ova) as an improved measure of reproductive capacity. We continue to use F_{MED} to represent F_{REP} as the F-threshold, but determined from the median of fecundity/R_0, rather than from the median of SSB/R_1 as in Amendment 1. Because F_{MAX} is greater than F_{MED} (and may be infinite), we recommend instead that F-target be based on the 75th percentile of fecundity/R_0. This approach would then be consistent with the approach used for the F-threshold. For biomass (or egg) benchmarks, we recommend following the approach of Amendment 1. The median of fecundity/R_0 is multiplied by the median R_0 to estimate the fecundity target. MSST (Minimum Spawning Stock Biomass), calculated by multiplying one-half times the fecundity-target (adult M is greater than 0.5), follows the approach used in Amendment 1 as recommended by Restrepo et al. (1998).

Confidence intervals, plus or minus twice the standard error from the delta method (Section 7.2.3), were calculated for annual estimates of F, SSB and fecundity (base Ricker and Beverton-Holt runs). Terminal year estimates, with associated confidence intervals in parentheses, are summarized along with benchmarks from Amendment 1 and from this assessment (Table 9.1). The confidence interval for the terminal value of full F includes the target, but not the threshold. The confidence intervals for the terminal value of both SSB and fecundity are above the target.

Annual estimates of full F (with plus/minus 2 standard errors as in Fig. 7.15) are compared with estimates of the target and threshold from this assessment (Fig. 9.1). Terminal value of F is near the F-target. Corresponding F-target and F-threshold from Amendment 1 are higher. Also, annual estimates of fecundity (from Fig. 7.16) are compared with estimates of the target and threshold from this assessment (Fig. 9.2). Since 1971, terminal values of population fecundity have been above the threshold and generally at or above the target. A similar comparison is shown for SSB with the target and threshold from Amendment 1 (Fig. 9.3).

Control plots corresponding to the schematic fishery control rule (Fig. 8.1) are shown summarizing estimates of F and population fecundity for 1985-2002 (Ricker: Fig. 9.4; and Beverton-Holt: Fig. 9.5). Values for the terminal year (2002) are shown as a solid square. Vertical and horizontal lines delineate the thresholds and targets from this assessment. As noted earlier, the terminal year estimate of F is near, but slightly above, the F-target, while the terminal year estimate of population fecundity is well above the fecundity target. Based on these benchmarks, the stock is neither overfished nor is overfishing occurring.

9.2 Research Recommendations

Research and Monitoring Recommendations (number reflects relative ranking with 1 being the highest priority)

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

   Develop coastwide tagging program to examine stock structure, spatial and temporal patterns in movement and migration, and to estimate exchange rate among geographic regions (i.e. inshore-offshore and latitudinal).

   Develop a spatially explicit age-structured model to account for spatial and temporal differences in size/age distributions, size/age at maturity, and fishing effort and catchability rates.

   Develop statistical sampling methods to improve catch and effort statistics in the recreational fishery. Evaluate extent of recreational netting of menhaden for bait purposes.

   Monitor landings, size, age, gear, and harvest area in the reduction and bait fisheries, and determine age composition by area. Maintain biostatistical sampling of bait samples in purse seine fisheries for Virginia and New Jersey and enhance this sampling in Maryland, the Potomac, and North Carolina to improve stock assessment (ongoing).

   Study the ecological role of menhaden (predator/prey relationships, nutrient enrichment, oxygen depletion, etc.) in major Atlantic coast embayments and estuaries (predator/prey interactions being evaluated through ASMFC multispecies efforts). Re-evaluate menhaden natural mortality by age and the response to changing predator population sizes (evaluated through MS model, incorporated variable *M* in assessment).

   Maintain and expand seine indices estimating size of recruiting year-classes of juveniles using fishery-independent survey techniques, particularly needed in mid-Atlantic region (ongoing research).

   Periodically monitor the economic structure and sociological characteristics of the menhaden reduction industry (Committee on Economic and Social Sciences - CESS). Determine the effects of regulations on the fishery, the participants and the stock (CESS ongoing project).

   Define local depletion in qualitative and quantitative terms. Determine environmental influences. Studies should not be limited to Chesapeake Bay.

2. Evaluate effects of selected environmental factors on growth, survival and abundance of juvenile and adult menhaden, particularly in Chesapeake Bay and other coastal nursery areas (NMFS/CBO ongoing project).

   Determine how loss/degradation of critical estuarine and nearshore habitat affects growth, survival, and abundance of juvenile and adult menhaden abundance.

Evaluate use of coastal power plant impingement data as a possible means to estimate young-of-the-year menhaden abundance (ASMFC MSC project).

3. Determine the causes of fish diseases (such as ulcerative mycosis and toxic dinoflagellates) on the menhaden stock (ongoing research in MD/VA).

   Monitor fish kills along the Atlantic coast and use the NMFS Beaufort Laboratory as a repository for these reports (ongoing).

   Investigate the amount or extent of bycatch in the menhaden fishery. Evaluate whether a statistically valid observer program is needed to document possible sea turtle interactions with the various gear types. Develop bycatch studies of menhaden by other fisheries.

   Alternative measures of effort, including spotter pilot logbooks, trip length, or other variables, should be evaluated. Spotter pilot logbooks should be evaluated for spotter plane search time, GPS coordinates, and estimates of school sizes observed by pilots.

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11.0 Tables

Table 2.1 Estimated fork lengths and weights for Atlantic menhaden ages 0-6 calculated at middle of fishing year.

Age	Fork Length (mm)	Weight (g)
0	133.8	39.5
1	199.8	137.7
2	253.8	290.1
3	284.6	414.1
4	302	498.6
5	312	551.5
6	317.6	583.2

Table 2.2 Annual parameter estimates of weight-length and length at age regressions from biological sampling of Atlantic menhaden.

Year	Weight-Length				Von Bertalanffy Curve			
	n	a	b	RMSE	n	L_∞	K	t_0
1955	16037	-11.808	3.157	0.0097	15673	345.99	0.418	-0.319
1956	19873	-11.823	3.161	0.0152	18912	336.83	0.549	0.046
1957	19674	-12.262	3.242	0.0091	19139	340.73	0.442	-0.340
1958	15315	-12.348	3.263	0.0083	15309	341.70	0.497	-0.021
1959	17935	-12.359	3.262	0.0060	17958	353.73	0.351	-0.765
1960	13505	-12.736	3.332	0.0078	13512	348.07	0.401	-0.360
1961	13184	-12.688	3.323	0.0092	12899	353.53	0.342	-0.747
1962	15771	-11.378	3.083	0.0073	15458	358.28	0.345	-0.841
1963	13001	-11.959	3.194	0.0159	12756	362.98	0.338	-0.788
1964	10438	-11.830	3.169	0.0635	10287	366.37	0.367	-0.633
1965	19518	-11.970	3.193	0.0121	19236	379.71	0.338	-0.692
1966	15633	-11.541	3.110	0.0148	15492	363.44	0.323	-0.981
1967	15426	-12.232	3.238	0.0146	14868	320.76	0.515	-0.582
1968	26830	-11.869	3.176	0.0142	25908	336.33	0.383	-0.937
1969	15114	-11.797	3.167	0.1100	14881	398.14	0.280	-1.147
1970	8426	-11.651	3.139	0.0078	8239	449.11	0.221	-1.082
1971	8269	-11.364	3.079	0.0129	8118	334.79	0.511	-0.391
1972	6552	-11.673	3.130	0.0107	6198	361.82	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

Table 2.2 (*continued*)

Year	Weight-Length				Von Bertalanffy Curve			
	n	*a*	*b*	RMSE	*n*	L_∞	*K*	t_0
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
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

Table 5.1 Estimated reduction landings of Atlantic menhaden in numbers by age (in millions), 1955-2002.

	Age						
Year	**0**	**1**	**2**	**3**	**4**	**5**	**6-8**
1955	761.0	674.2	1057.7	267.3	307.2	38.1	13.0
1956	36.4	2073.3	902.7	319.6	44.8	150.7	37.4
1957	299.6	1600.0	1361.8	96.7	70.8	40.5	42.3
1958	106.1	858.2	1635.4	72.1	17.3	15.9	14.4
1959	11.4	4038.7	851.3	388.3	33.4	11.9	18.7
1960	72.2	281.0	2208.6	76.4	102.2	23.8	11.0
1961	0.3	832.4	503.6	1209.6	19.2	29.4	3.9
1962	51.6	514.1	834.5	217.3	423.4	30.8	28.3
1963	96.9	724.2	709.2	122.5	45.0	52.4	14.3
1964	302.6	704.0	605.0	83.5	17.9	7.9	8.3
1965	259.1	745.2	421.4	77.8	12.2	1.8	2.0
1966	349.5	550.8	404.1	31.7	3.9	0.4	0.3
1967	7.0	633.2	265.7	72.8	5.1	0.5	0.0
1968	154.3	377.4	539.0	65.7	10.7	1.0	0.1
1969	158.1	372.3	284.3	47.8	5.4	0.2	0.0
1970	21.4	870.9	473.9	32.6	4.0	0.1	0.0
1971	72.9	263.3	524.3	88.3	17.8	2.5	0.0
1972	50.2	981.3	488.5	173.1	19.1	1.9	0.0
1973	56.0	588.5	1152.9	38.6	7.0	0.3	0.0
1974	315.6	636.7	986.0	48.6	2.5	1.4	0.0
1975	298.6	720.0	1086.5	50.2	6.6	0.2	0.1
1976	274.2	1612.0	1341.1	48.0	8.0	0.3	0.0
1977	484.6	1004.5	2081.8	83.5	17.8	1.4	0.1
1978	457.4	664.1	1670.9	258.1	31.2	3.5	0.0
1979	1492.5	623.1	1603.3	127.9	21.8	1.5	0.1
1980	88.3	1478.1	1458.2	222.7	69.2	14.4	1.4
1981	1187.6	698.7	1811.5	222.2	47.5	15.4	1.3
1982	114.1	919.4	1739.6	379.7	16.3	5.8	0.9
1983	964.4	517.2	2293.1	114.4	47.4	5.0	0.7
1984	1294.2	1024.2	892.1	271.5	50.3	15.2	0.5
1985	637.2	1075.9	1224.6	44.1	35.6	6.3	1.7
1986	98.4	224.2	1523.1	49.1	10.5	6.1	1.1
1987	42.9	504.7	1587.7	151.9	25.2	2.2	0.7
1988	338.8	282.7	1157.7	301.4	69.8	7.1	0.6
1989	149.7	1154.6	1158.5	108.4	47.5	11.6	0.2
1990	308.1	132.8	1553.1	109.0	42.2	12.3	0.4
1991	881.8	1033.9	946.1	254.0	38.0	10.7	2.2
1992	399.7	727.2	795.4	66.1	51.3	10.9	1.9
1993	67.9	379.0	983.1	148.9	10.9	3.9	0.3
1994	88.6	274.5	888.9	165.1	67.2	7.5	0.2
1995	56.8	533.7	671.9	309.1	67.5	4.4	0.0
1996	33.7	209.1	679.1	139.0	29.0	2.0	0.0
1997	25.2	246.9	424.5	237.4	51.6	9.0	1.2
1998	72.8	185.0	540.6	126.3	73.0	9.0	0.8
1999	193.9	301.1	450.8	81.8	25.0	3.2	0.4
2000	77.8	114.2	340.6	111.9	11.1	1.9	0.0
2001	23.0	43.5	369.5	217.6	14.9	0.7	0.0
2002	178.2	211.7	259.8	135.8	17.1	0.5	0.0

Table 5.2 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, 1955-2002.

Year	Sample Size (n)	Landings (millions)	Landings (1000 mt)	Intensity (C/100n)	Mean Weight (g)
1955	16136	3118.4	641.4	3975.0	205.7
1956	19875	3564.8	712.1	3582.9	199.8
1957	19698	3511.7	602.8	3060.2	171.7
1958	15324	2719.2	510.0	3328.1	187.6
1959	17960	5353.6	659.1	3669.8	123.1
1960	13513	2775.1	529.8	3920.7	190.9
1961	13189	2598.3	575.9	4366.5	221.6
1962	15793	2099.9	537.7	3404.7	256.1
1963	13033	1764.5	346.9	2661.7	196.6
1964	10443	1729.1	269.2	2577.8	155.7
1965	19550	1519.5	273.4	1398.5	179.9
1966	15670	1340.6	219.6	1401.4	163.8
1967	15435	984.2	193.5	1253.6	196.6
1968	26838	1148.0	234.8	874.9	204.5
1969	15121	868.2	161.6	1068.7	186.1
1970	8435	1403.0	259.4	3075.3	184.9
1971	8269	969.1	250.3	3027.0	258.3
1972	6553	1713.9	365.9	5583.7	213.5
1973	6353	1843.4	346.9	5460.4	188.2
1974	5421	1990.6	292.2	5390.1	146.8
1975	7283	2162.3	250.2	3435.4	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	6366	3870.1	375.7	5901.7	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	7718	3025.3	306.7	3973.8	101.4
1986	5408	1912.4	238.0	4400.9	124.5
1987	7398	2315.2	327.0	4420.1	141.2
1988	7339	2158.0	309.3	4214.5	143.3
1989	6997	2630.5	322.0	4602.0	122.4

Table 5.2 (*continued*)

Year	Sample Size (n)	Landings		Intensity (C/100n)	Mean Weight (g)
		(millions)	(1000 mt)		
1990	6828	2157.9	401.2	5875.8	185.9
1991	7690	3166.6	381.4	4959.7	120.4
1992	5610	2052.5	297.6	5304.8	145.0
1993	5318	1594.0	320.6	6028.6	201.1
1994	4708	1492.0	260.0	5522.5	174.3
1995	4606	1643.3	339.9	7379.5	206.8
1996	4218	1091.9	292.9	6944.0	268.2
1997	4125	995.9	259.1	6281.2	260.2
1998	3808	1007.5	245.9	6457.5	244.1
1999	3620	1056.3	171.2	4729.3	162.1
2000	3040	657.4	167.2	5500.0	254.3
2001	3923	669.2	233.7	5957.2	349.2
2002	3580	803.1	174.0	4860.3	216.7

Table 5.3 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 bait fishery, 1985-2002.

Year	Sample Size (n)	Landings (millions)	Landings (1000 mt)	Intensity ($C/100n$)	Mean Weight (g)
1985	800	99.2	26.7	3332.7	268.8
1986	420	92.3	28.0	6658.0	303.0
1987	220	101.4	30.6	13916.7	301.8
1988	10	116.3	36.2	362370.0	311.7
1989	30	109.1	30.9	103161.6	283.6
1990	10	115.2	30.7	306852.2	266.3
1991	78	125.8	36.2	46439.9	287.9
1992	70	125.2	38.7	55316.9	309.4
1993	169	105.7	34.7	20555.8	328.6
1994	539	91.2	28.1	5218.8	308.4
1995	362	111.5	31.1	8593.1	279.1
1996	357	65.2	23.3	6532.2	357.7
1997	313	70.8	25.6	8173.8	361.2
1998	636	111.6	40.1	6298.6	359.0
1999	538	126.3	36.0	6683.9	284.7
2000	543	111.7	35.0	6440.6	313.0
2001	962	102.5	36.5	3794.6	356.1
2002	702	96.1	36.8	5241.3	382.7

Table 5.4 Years of activity for individual menhaden reduction plants along the U.S. Atlantic coast.

Year/ Plant	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	32	33	34	35	36	Total Plants	Number 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

Table 5.4 (*continued*)

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

Table 5.5 Sample size of biological samples from the Atlantic menhaden bait fishery by region, 1985-2002.

Year	Region			
	New England	Middle Atlantic	Chesapeake Bay	South Atlantic
1985	600	0	0	200
1986	40	0	0	380
1987	0	0	0	220
1988	0	0	0	10
1989	20	0	0	10
1990	0	0	0	10
1991	0	0	0	78
1992	0	0	30	40
1993	0	0	39	130
1994	80	320	0	139
1995	130	59	96	77
1996	15	187	137	18
1997	0	110	136	67
1998	0	225	295	116
1999	0	201	299	38
2000	0	265	239	39
2001	0	677	275	10
2002	0	523	103	76

Table 5.6 Estimated bait landings of Atlantic menhaden in numbers by age (in millions), 1985-2002.

	Age						
Year	**0**	**1**	**2**	**3**	**4**	**5**	**6-8**
1985	0.52	8.71	62.74	18.78	6.84	1.35	0.25
1986	0.33	5.08	39.27	31.23	14.84	1.23	0.30
1987	0.43	4.81	48.02	31.64	14.96	1.28	0.30
1988	0.40	6.13	46.02	41.06	20.56	1.70	0.41
1989	0.52	7.87	56.65	30.18	12.44	1.22	0.25
1990	0.61	23.27	44.46	30.89	14.37	1.34	0.29
1991	0.34	15.53	49.15	39.42	19.16	1.81	0.39
1992	0.54	18.46	41.80	41.87	20.00	2.06	0.42
1993	0.76	21.29	23.27	38.88	19.13	1.99	0.40
1994	0.21	8.46	37.05	27.50	15.58	2.24	0.16
1995	0.00	23.41	26.66	36.48	24.84	0.07	0.00
1996	0.04	2.77	34.99	21.69	5.52	0.21	0.00
1997	0.00	2.25	25.36	20.57	16.95	4.86	0.84
1998	3.22	4.91	45.12	32.39	21.80	3.49	0.66
1999	0.14	5.19	74.70	30.46	13.75	1.78	0.29
2000	0.57	17.64	63.40	20.48	8.33	1.04	0.28
2001	0.20	4.63	54.87	37.29	4.76	0.63	0.14
2002	0.00	4.84	36.76	44.13	9.43	0.93	0.06

Table 5.7 Number of hauls per year for state seine surveys used in assessment, 1959-2002.

Year	North Carolina	Virginia	Maryland	Connecticut	Rhode Island
1959			34		
1960			36		
1961			46		
1962			88		
1963			88		
1964			88		
1965			88		
1966			132		
1967			132		
1968		55	132		
1969		60	132		
1970		66	132		
1971		70	132		
1972	65	110	132		
1973	136	70	132		
1974	247		130		
1975	185		132		
1976	136		132		
1977	182		132		
1978	160		132		
1979	61		132		
1980	68	87	132		
1981	69	94	132		
1982	84	64	132		
1983	92	54	132		
1984	91	58	132		
1985	82	78	132		
1986	88	72	132		
1987	94	72	132	56	
1988	86	90	132	56	74
1989	91	123	132	56	74
1990	91	125	132	56	80
1991	93	121	132	56	80
1992	67	125	132	56	80
1993	101	123	132	56	84
1994	96	125	132	56	85
1995	120	124	132	56	89
1996	117	124	132	56	90
1997	118	124	132	56	90
1998	122	125	132	56	90
1999	118	124	132	56	90
2000	134	125	132	56	90
2001	132	128	132	56	90
2002	133	125	132	56	90

Table 5.8 Pair-wise correlations among the five state seine indices from delta-lognormal GLM that were combined to create the coastwide juvenile abundance index for Atlantic menhaden. Top value is correlation coefficient (r), second value is $\propto$ = Pr {H_0: r=0}, and third value is sample size.

Juvenile Abundance Index	NC Seine Index	VA Seine Index	MD Seine Index	CT Seine Index	RI Seine Index
NC Seine Index	1.0 - 31	0.773 0.0001 25	0.735 0.0001 31	-0.215 0.424 16	-0.319 0.246 15
VA Seine Index		1.0 - 29	0.455 0.0131 29	-0.120 0.658 16	-0.387 0.154 15
MD Seine Index			1.0 - 44	-0.341 0.196 16	-0.344 0.209 15
CT Seine Index				1.0 - 16	0.445 0.096 15
RI Seine Index					1.0 - 15

Table 6.1 General definitions, input data, population model, and negative log-likelihood components of the forward-projecting statistical age-structured model used for Atlantic menhaden.

General Definitions	**Symbol**	**Description/Definition**
Year index: y = {1955,..,2002}	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 Lewis et al. (1987)
Fecundity-at-age	γ_a	From Lewis et al. (1987)
Observed age-0 CPUE y = {1959,...,2002}	$U_{1,y}$	Based on numbers of age-0 fish from various seine samples (selected/combined Assessment Workshop)
Observed pound net CPUE y = {1964,...,2002}	$U_{2,y}$	Based on pound net landings of menhaden per license 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	Fixed at 0.2 for U_1 and 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 age samples collected 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 0.01 for L_1 and 0.3 for L_2
Observed natural mortality	M_a	From MSVPA model

Table 6.1 (*continued*)

Population Model	**Symbol**	**Description/Definition**
Fishery selectivity	$s_{f,a}$	Assumed constant for all years (y) $s_{1,a} = \frac{1}{1+\exp(-\eta_1[a-\alpha_1])}$ $s_{2,a} = \left[\frac{1}{1+\exp(-\eta_{1,2}[a-\alpha_{1,2}])}\right]\left[1-\frac{1}{1+\exp(-\eta_{2,2}[a-\alpha_{2,2}])}\right]\left[\frac{1}{\max(s_{2,a})}\right]$ where η's and α's are estimated parameters
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
Natural mortality	M_a	$M_a = \delta M_a$ where δ is an estimated parameter
Total mortality	$Z_{a,y}$	$Z_{a,y} = M_a + \sum_{f=1}^{2} F_{f,a,y}$
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	$N_{a+1,1947} = N_{a,1947}\exp(-Z_{a,1947})$ $N_{8+,1947} = N_{7,1947}\exp(-Z_{7,1947})/[1-\exp(-Z_{8+,1947})]$ $\varepsilon_y = \sum_{a=0}^{8+} N_{a,y} m_a \gamma_a 0.5$ $N_{0,y} = \frac{\varepsilon_y}{\phi_y}\exp\left[h'\left(1-\frac{\varepsilon_y}{R_0\phi_y}\right)\right] + R_y$ (Ricker) $N_{0,y} = \frac{0.8R_0 h\varepsilon_y}{0.2\phi_y R_0(1-h)+(h-0.2)\varepsilon_y} + R_y$ (B-H) $N_{a+1,y+1} = N_{a,y}\exp(-Z_{a,y})$ $N_{A,y} = N_{A-1,y-1}\exp(-Z_{A-1,y-1}) + N_{A,y-1}\exp(-Z_{A,y-1})$ where R_0 and h, and $h'$are parameters of the stock-recruit curves related by $h' = \log\left(\frac{4h}{1-h}\right)$ and R_y are annual recruitment parameters.

Table 6.1 (*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 Estimates of natural mortality, *M*, at age in the base, sensitivity, and retrospective runs.

Base, Sensitivity and Retrospective Runs:		Natural Mortality Rate, *M*, at Age: 0	1	2	3+
Base Ricker		4.31	0.98	0.56	0.55
Fixed *M* Vector*		2.34	0.53	0.31	0.30
Fixed *M* at 0.45*		0.45	0.45	0.45	0.45
Knife-edge Maturity		4.31	0.98	0.56	0.55
Fixed steepness (*h*):	**0.7**	3.95	0.90	0.52	0.51
	0.8	3.09	0.70	0.41	0.40
	0.9	1.65	0.38	0.22	0.21
Retrospective:	**2001**	4.33	0.99	0.57	0.55
	2000	4.37	1.00	0.57	0.56
	1999	4.37	1.00	0.57	0.56
	1998	4.36	0.99	0.57	0.56
	1997	4.35	0.99	0.57	0.56
Base Beverton-Holt		4.30	0.98	0.56	0.55
Fixed *M* Vector*		2.34	0.53	0.31	0.30
Fixed *M* at 0.45*		0.45	0.45	0.45	0.45
Knife-edge Maturity		4.30	0.98	0.56	0.55
Fixed steepness (*h*):	**0.7**	3.71	0.85	0.49	0.48
	0.8	3.78	0.86	0.50	0.48
	0.9	1.99	0.45	0.26	0.25
Retrospective:	**2001**	4.32	0.98	0.57	0.55
	2000	4.37	1.00	0.57	0.56
	1999	4.37	1.00	0.57	0.56
	1998	4.36	0.99	0.57	0.56
	1997	4.35	0.99	0.57	0.56

* Fixed, not estimated.

Table 7.2 Historical performance based on percentiles (median and interquartile range) for output variables, 1955-2002.

Output Variables	Current Year Value (2002)	Percentiles		
		25th	50th	75th
Base Ricker Run:				
Fishing mortality, *F* (2+)	0.79	0.83	1.04	1.27
Exploitation rate, *u* (1+)	0.19	0.20	0.23	0.26
Spawning stock biomass (1000 t)	91.9	56.6	76.8	120.1
Population fecundity (billions)	40,632	23,196	30,137	48,636
Recruits Age-0 (billions)	406.8	240.5	360.9	573.3
Recruits Age-1 (billions)	2.5	3.22	4.8	7.7
Base Beverton-Holt Run:				
Fishing mortality, *F* (2+)	0.78	0.84	1.04	1.27
Exploitation rate, *u* (1+)	0.19	0.20	0.23	0.26
Spawning stock biomass (1000 t)	92.4	56.3	76.5	120.3
Population fecundity (billions)	40,862	23,180	30,020	48,572
Recruits Age-0 (billions)	402.7	237.6	356.2	565.9
Recruits Age-1 (billions)	2.5	3.2	4.8	7.6

Table 7.3 Estimated numbers of Atlantic menhaden (in billions) at start of fishing year from forward-projecting statistical age-structured model (base Ricker run), 1955-2002.

	Age								
Year	0	1	2	3	4	5	6	7	8
1955	809.17	5.11	2.24	0.56	0.796	0.099	0.0144	0.00111	0.00042
1956	765.61	10.83	1.58	0.49	0.110	0.155	0.0194	0.00308	0.00035
1957	446.46	10.23	2.98	0.20	0.054	0.012	0.0172	0.00235	0.00044
1958	1639.96	5.97	3.08	0.57	0.034	0.009	0.0021	0.00324	0.00055
1959	248.49	21.95	1.91	0.80	0.133	0.008	0.0022	0.00053	0.00102
1960	356.50	3.33	6.91	0.45	0.170	0.028	0.0017	0.00050	0.00038
1961	227.92	4.77	1.14	2.45	0.147	0.055	0.0092	0.00060	0.00033
1962	215.65	3.05	1.53	0.30	0.577	0.034	0.0129	0.00238	0.00025
1963	171.89	2.88	0.88	0.25	0.042	0.082	0.0049	0.00202	0.00043
1964	197.98	2.30	0.77	0.10	0.024	0.004	0.0080	0.00053	0.00028
1965	168.86	2.64	0.61	0.08	0.009	0.002	0.0004	0.00079	0.00008
1966	237.61	2.25	0.60	0.03	0.003	0.000	0.0001	0.00002	0.00004
1967	127.99	3.17	0.54	0.04	0.002	0.000	0.0000	0.00001	0.00000
1968	205.64	1.71	0.90	0.08	0.005	0.000	0.0000	0.00000	0.00000
1969	346.46	2.75	0.46	0.10	0.008	0.001	0.0000	0.00000	0.00000
1970	173.14	4.64	0.85	0.10	0.021	0.002	0.0001	0.00000	0.00000
1971	414.37	2.32	1.35	0.14	0.015	0.003	0.0002	0.00002	0.00000
1972	296.42	5.55	0.74	0.34	0.031	0.003	0.0007	0.00006	0.00000
1973	349.14	3.96	1.59	0.11	0.045	0.004	0.0004	0.00010	0.00001
1974	432.57	4.67	1.17	0.28	0.017	0.007	0.0006	0.00008	0.00002
1975	726.07	5.78	1.38	0.20	0.043	0.003	0.0011	0.00011	0.00002
1976	601.24	9.71	1.76	0.28	0.037	0.008	0.0005	0.00022	0.00003
1977	545.05	8.04	2.90	0.32	0.046	0.006	0.0013	0.00009	0.00005
1978	565.96	7.29	2.46	0.60	0.060	0.008	0.0011	0.00026	0.00003
1979	957.30	7.57	2.18	0.45	0.098	0.010	0.0014	0.00020	0.00006
1980	568.67	12.80	2.26	0.40	0.074	0.016	0.0016	0.00025	0.00005
1981	853.32	7.60	3.75	0.38	0.060	0.011	0.0024	0.00027	0.00005
1982	326.84	11.42	2.31	0.76	0.069	0.011	0.0020	0.00048	0.00007
1983	587.15	4.37	3.38	0.41	0.119	0.011	0.0017	0.00035	0.00010
1984	832.01	7.85	1.26	0.53	0.057	0.017	0.0015	0.00026	0.00007
1985	690.11	11.12	2.19	0.17	0.063	0.007	0.0020	0.00020	0.00005
1986	508.51	9.23	3.45	0.48	0.032	0.012	0.0013	0.00042	0.00006
1987	365.29	6.81	3.09	1.10	0.138	0.009	0.0034	0.00041	0.00016
1988	723.87	4.89	2.24	0.91	0.301	0.038	0.0025	0.00101	0.00017
1989	281.93	9.69	1.55	0.54	0.196	0.064	0.0082	0.00061	0.00030

Table 7.3 (*continued*).

Year	Age								
	0	1	2	3	4	5	6	7	8
1990	506.09	3.77	2.97	0.32	0.096	0.035	0.0116	0.00164	0.00019
1991	603.88	6.77	1.19	0.70	0.067	0.020	0.0074	0.00269	0.00045
1992	498.79	8.07	1.94	0.17	0.086	0.008	0.0025	0.00107	0.00049
1993	348.04	6.68	2.56	0.46	0.035	0.017	0.0016	0.00059	0.00040
1994	456.97	4.66	2.19	0.74	0.118	0.009	0.0044	0.00047	0.00030
1995	254.36	6.12	1.56	0.71	0.221	0.035	0.0027	0.00141	0.00026
1996	241.43	3.40	1.97	0.42	0.173	0.054	0.0087	0.00071	0.00046
1997	215.30	3.23	1.13	0.62	0.124	0.051	0.0161	0.00273	0.00038
1998	287.29	2.88	1.05	0.32	0.162	0.032	0.0135	0.00450	0.00090
1999	285.96	3.84	0.90	0.23	0.059	0.030	0.0060	0.00293	0.00129
2000	153.12	3.83	1.24	0.22	0.046	0.012	0.0060	0.00147	0.00116
2001	187.81	2.05	1.28	0.38	0.058	0.012	0.0031	0.00184	0.00088
2002	406.81	2.51	0.67	0.36	0.095	0.014	0.0030	0.00087	0.00082

Table 8.1 Biological reference points from base Ricker run: (a) historical performance (as percentiles), (b) static spawning stock per recruit (SPR for 10 and 20%), (c) static population fecundity per recruit (FPR for 10 and 20%) and (d) replacement F at F_{med} (for threshold) and $F_{75th\%}$ (for target). Fecundity targets and thresholds are obtained from F_{med}. Selectivity for static SPR, static FPR, and replacement is based on 2002 pattern.

	Biological Reference Points				
Approach	***F* (1/yr)**	**SSB/R_0 (t/millions)**	**SSB[a] (1000 t)**	**Fecundity/R_0 (thousands)**	**Fecundity[a] (trillions)**
Historical Performance (1955-2002):					
25th %	0.8	-	56.6	-	23.2
50th %	1.0	-	76.8	-	30.1
75th %	1.3	-	120.1	-	48.6
Static SPR (in biomass):					
10%	1.4	0.15	54.1	-	-
20%	0.8	0.30	108.3	-	-
Static FPR (in fecundity):					
10%	1.3	-	-	69.0	24.9
20%	0.8	-	-	139.6	50.4
Fecundity/R_0 (replacement)					
50th % (F-threshold)	1.18	0.19	68.6	73.8	26.6
(*B*-target)					
(*B*-threshold/MSST)	-	-	34.3	-	13.3
75th (*F*-target)	0.75	0.36	-	135.6	-

[a] Multiply SSB/R_0 or Fecundity/R_0 by median recruits to age-0 (360.9 billion) to obtain SSB or fecundity for static-SSB, static-FPR, and replacement values. Minimum spawning stock threshold (MSST) is calculated by multiplying target SSB or fecundity by (1-M), or by 0.5 if M > 0.5. With age-varying M, we use adult M (age > 2).

Table 9.1 Summary of terminal values (with approximate confidence intervals in parentheses) and benchmarks to determine status of stock.

	Ricker		Beverton-Holt
Terminal Year (2002)			
Full F (1/yr)	0.79 (0.60, 0.97)		0.78 (0.60, 0.97)
SSB (1000 t)	91.9 (74.3, 109.6)		92.4 (74.8, 110.1)
Fecundity (trillions)	40.6 (32.6, 48.5)		40.9 (33.0, 48.7)
Amendment 1 Benchmarks (not based on underlying spawner-recruit relationship):			
F-target (1/yr)		1.04	
F-threshold (1/yr)		1.33	
SSB-target (1000 t)		37.40	
SSB-threshold (1000 t)		20.57	
New Benchmarks from this Assessment:			
F-target (1/yr)	0.75		0.75
F-threshold (1/yr)	1.18		1.19
Fecundity-target (trillions)	26.6		26.5
Fecundity-threshold (trillions)	13.3		13.3

12.0 Figures

Figure 2.1 Weighted mean weight at age for Atlantic menhaden.

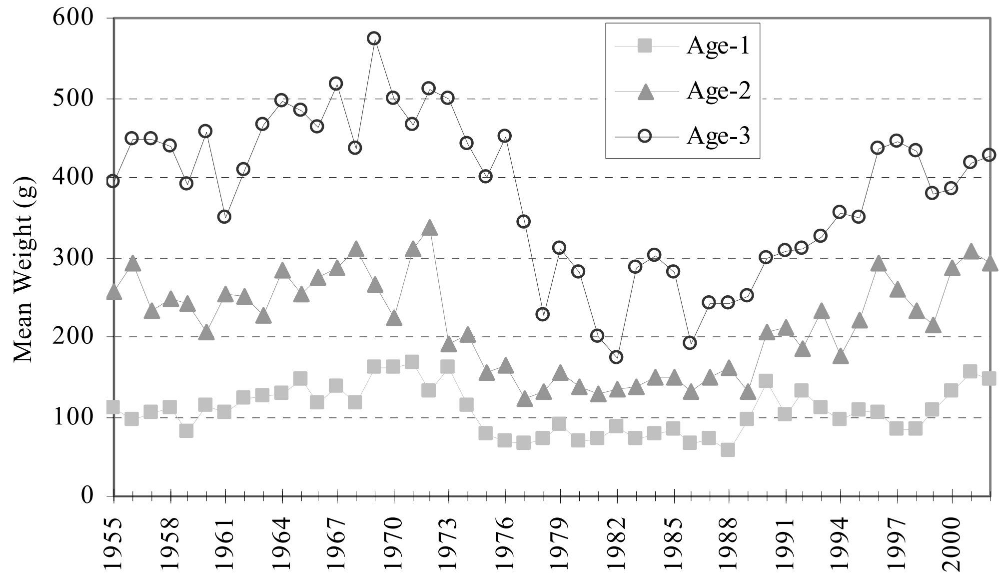


Figure 2.2 Fecundity (no. of maturing or ripe ova) as a function of fork length (mm) for Atlantic menhaden.

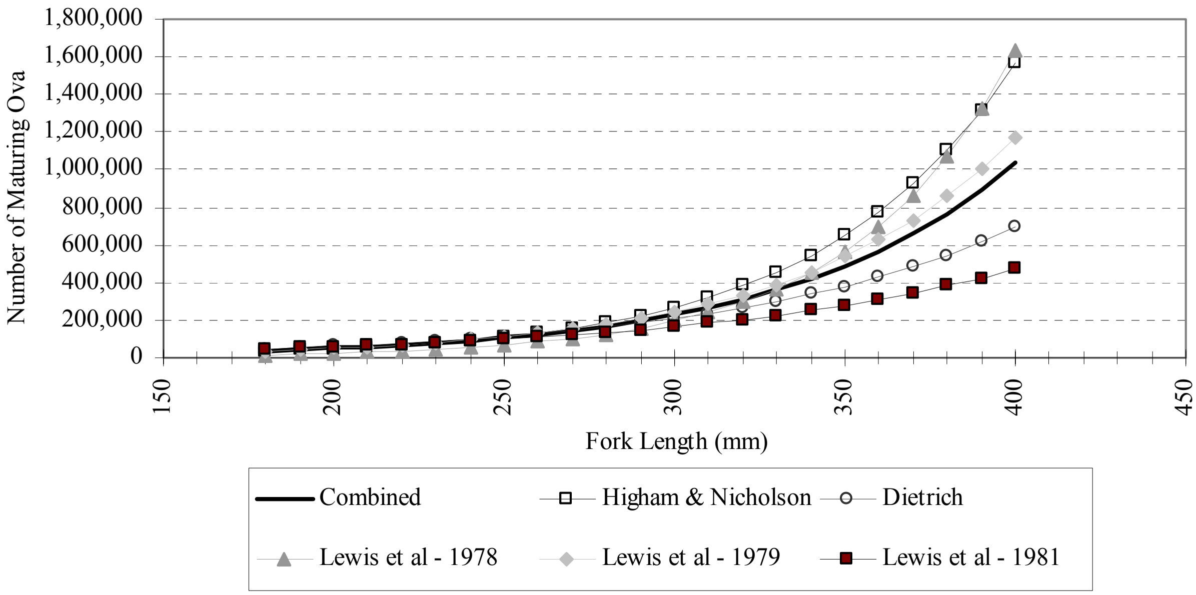


Figure 5.1 Landings and nominal effort from the reduction purse seine fishery for Atlantic menhaden, 1955-2002.

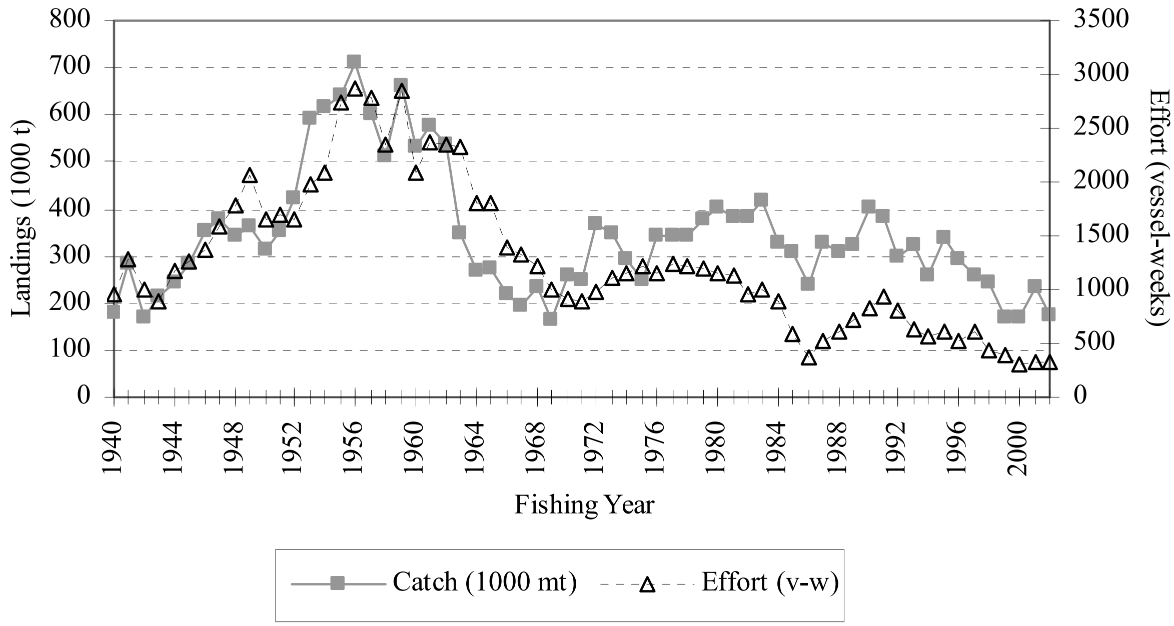


Figure 5.2 Landings vs. nominal effort from the reduction purse seine fishery for Atlantic menhaden.

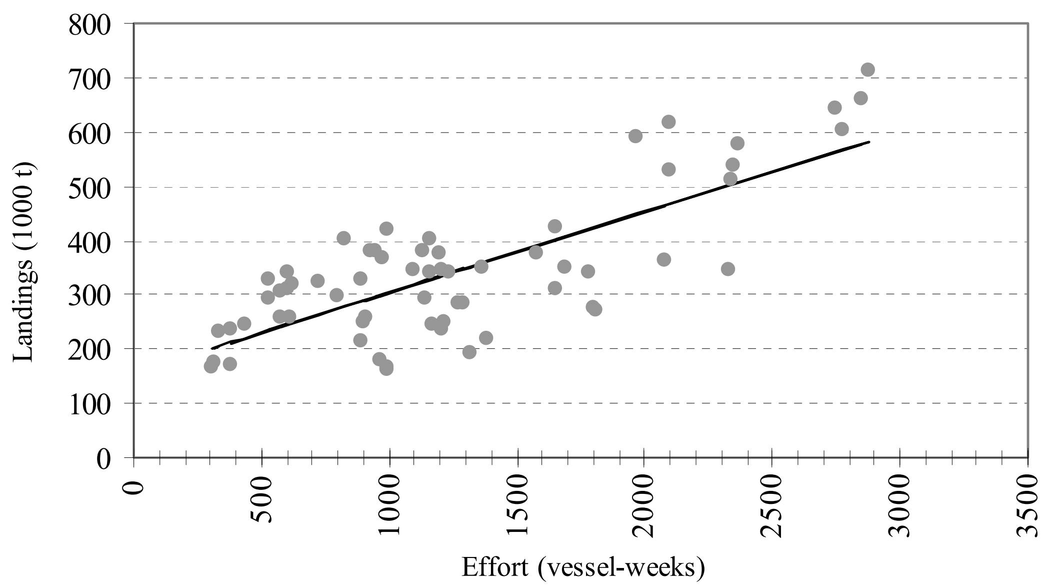


Figure 5.3 Mean landings by state from the bait fishery for Atlantic menhaden, 1998-2002.

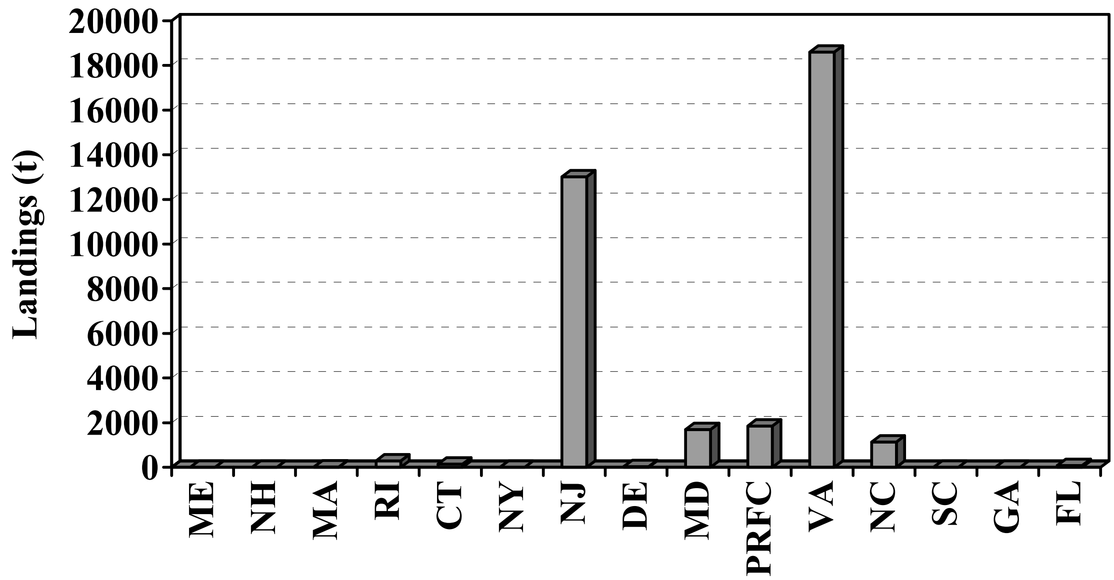


Figure 5.4 Annual landings by region from the bait fishery for Atlantic menhaden, 1985-2002.

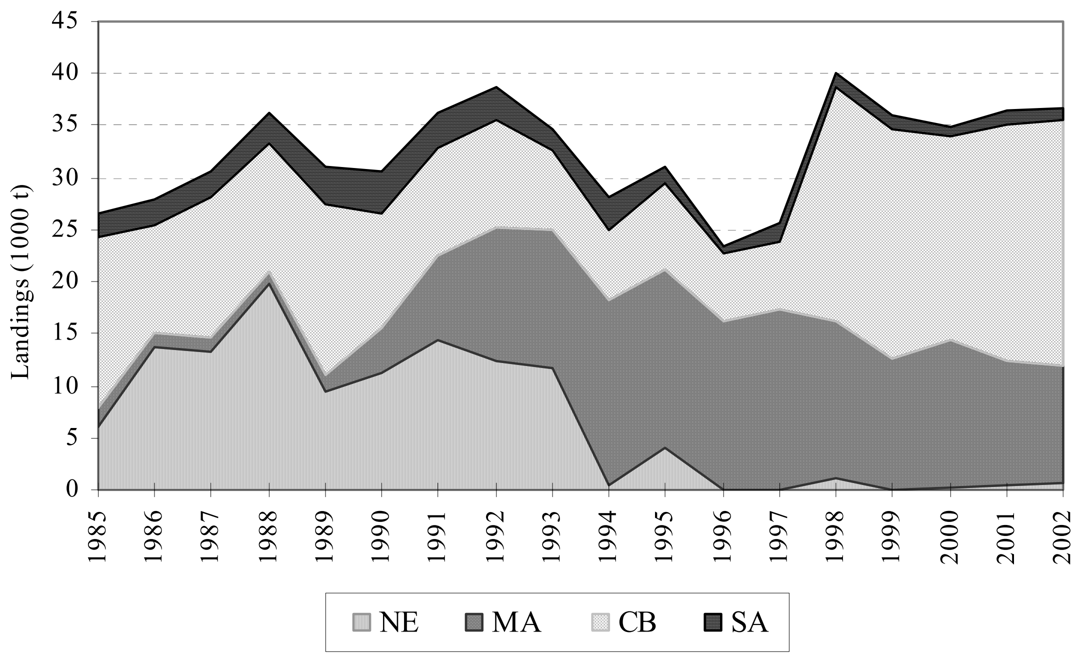


Figure 5.5 Mean weight of Atlantic menhaden caught by the reduction and bait fisheries.

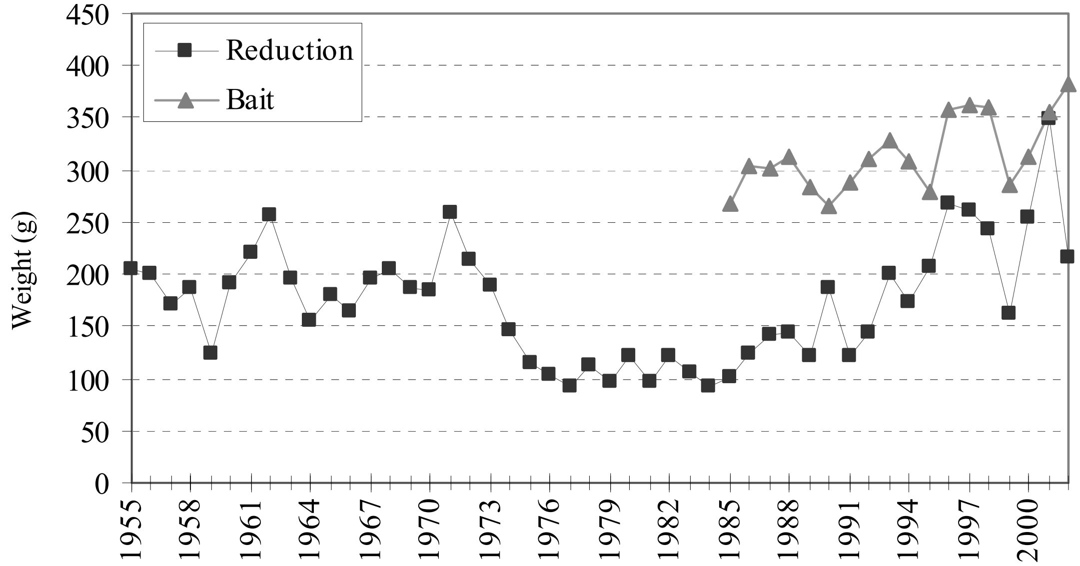


Figure 5.6 Annual landings in numbers from the reduction and bait fisheries, 1985-2002.

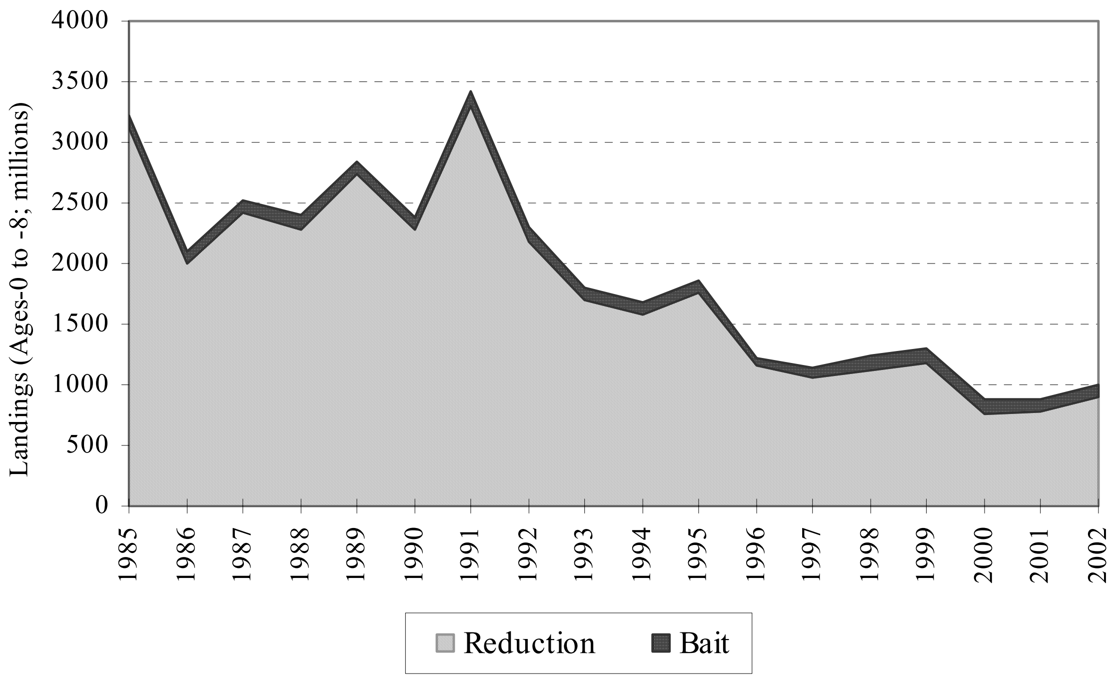


Figure 5.7 Delta-lognormal GLM mean and standard error of catch-per-haul from North Carolina alosid seine survey.

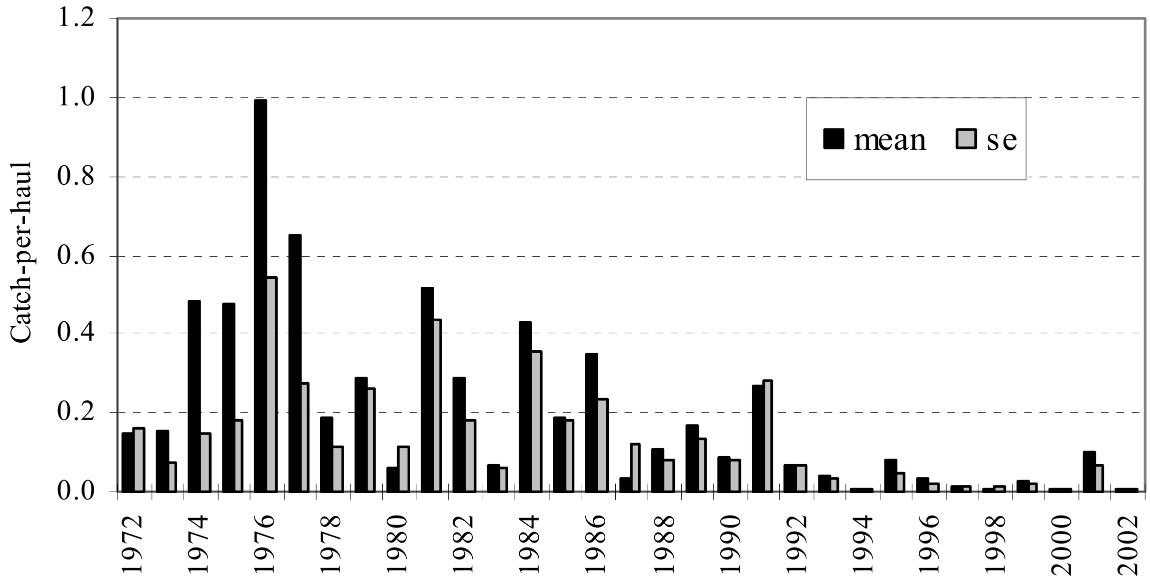


Figure 5.8 Delta-lognormal GLM mean and standard error of catch-per-haul from Virginia striped bass seine survey.

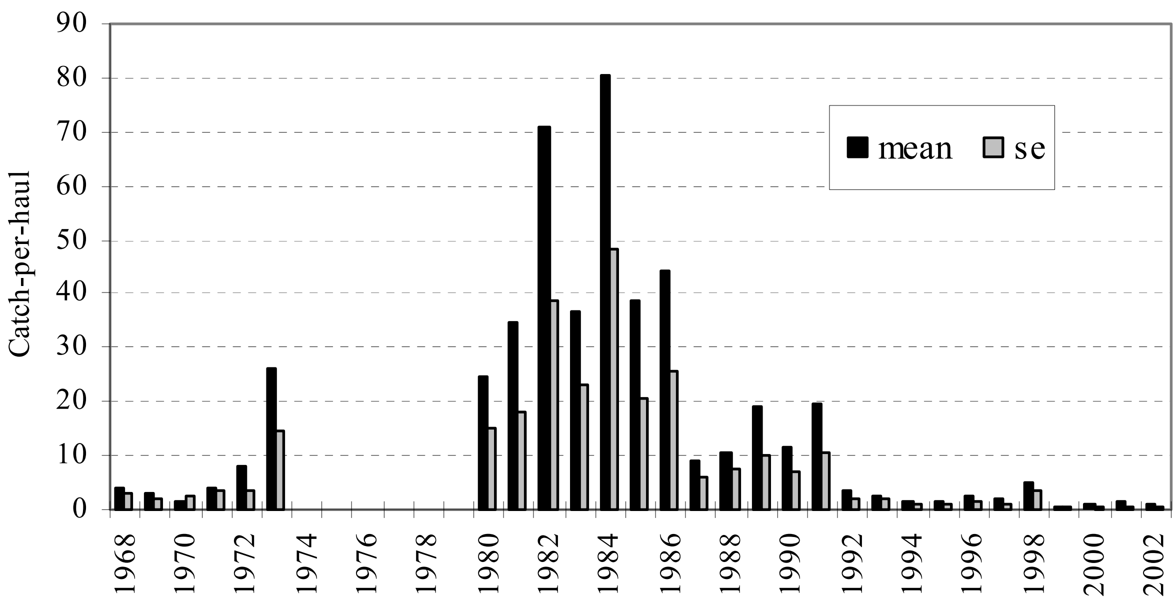


Figure 5.9 Delta-lognormal GLM mean and standard error of catch-per-haul from Maryland striped bass seine survey.

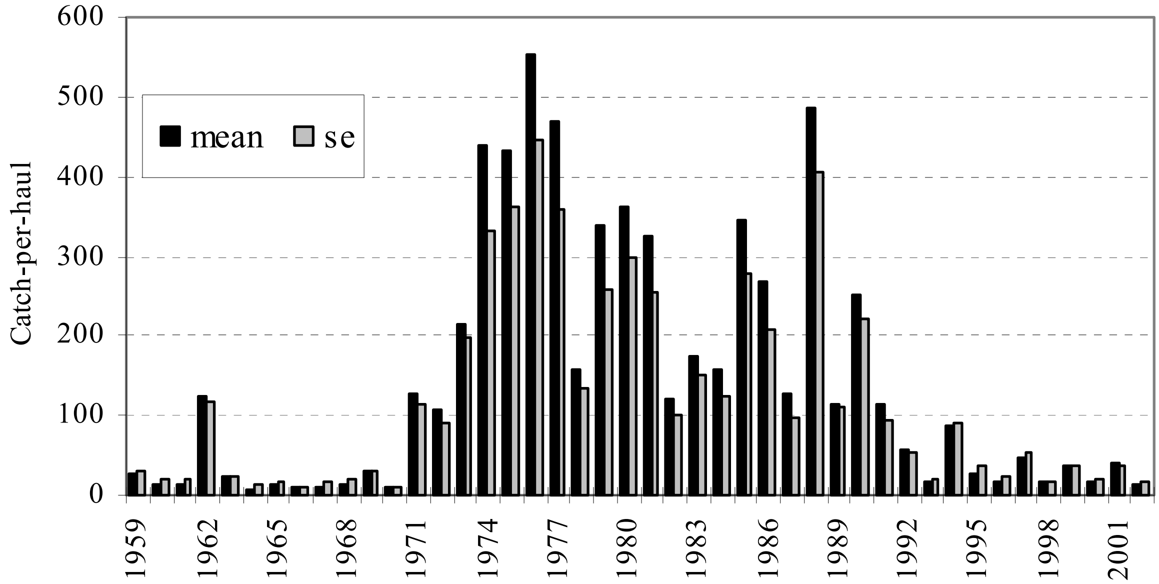


Figure 5.10 Delta-lognormal GLM mean and standard error of catch-per-haul from Connecticut River seine survey.

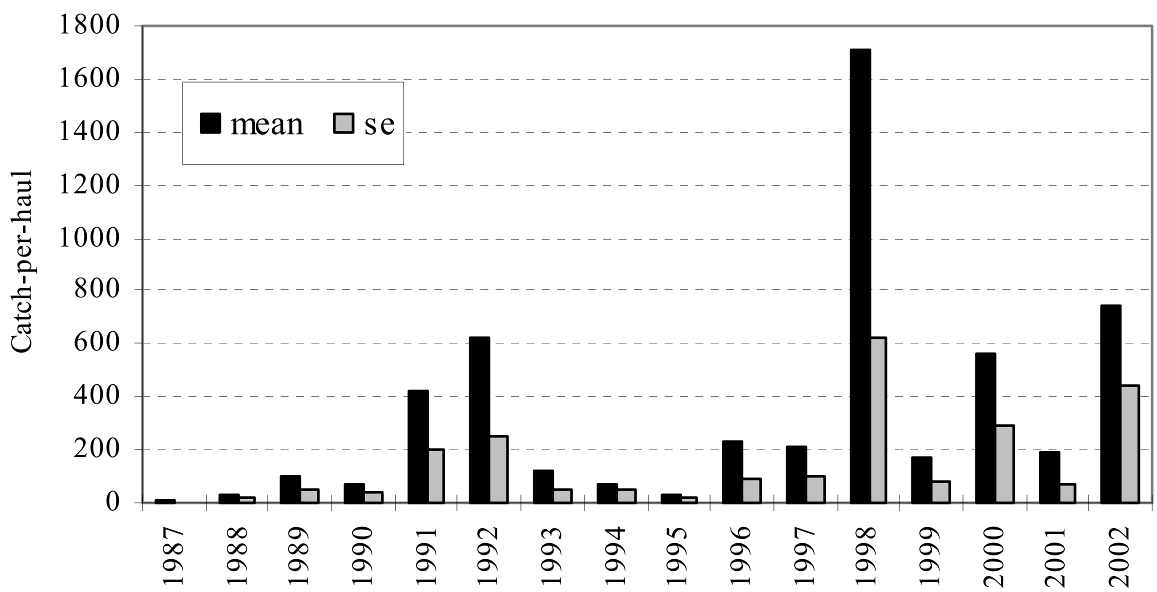


Figure 5.11 Delta-lognormal GLM mean and standard error of catch-per-haul from Rhode Island Narragansett Bay seine survey.

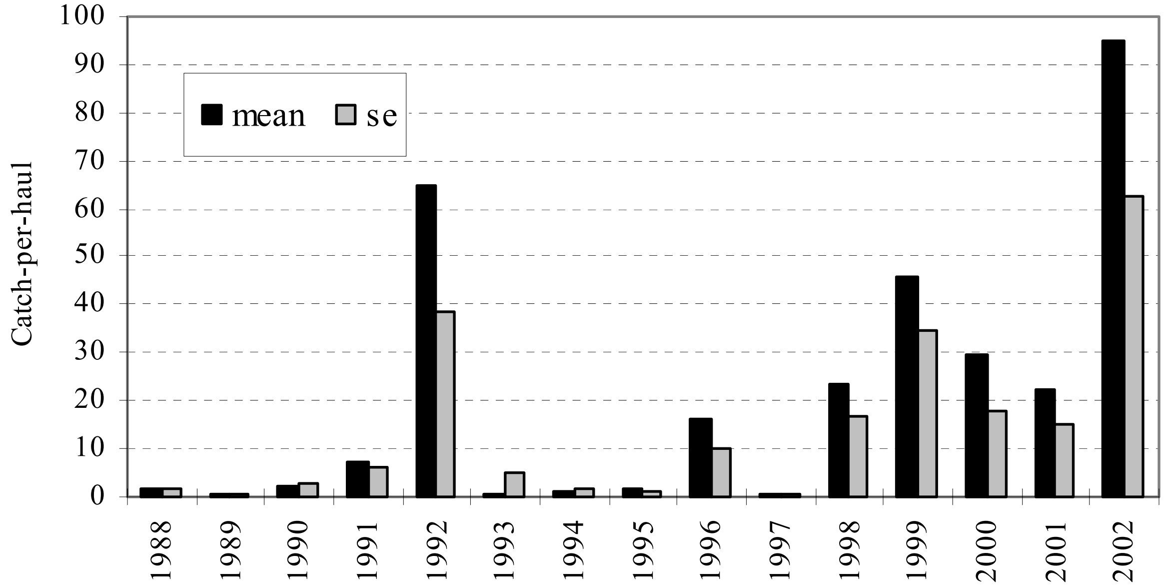


Figure 5.12 Coastwide juvenile abundance index from state seine surveys (based on % Estuarine Drainage Area adjusted for historic catch-per-tow).

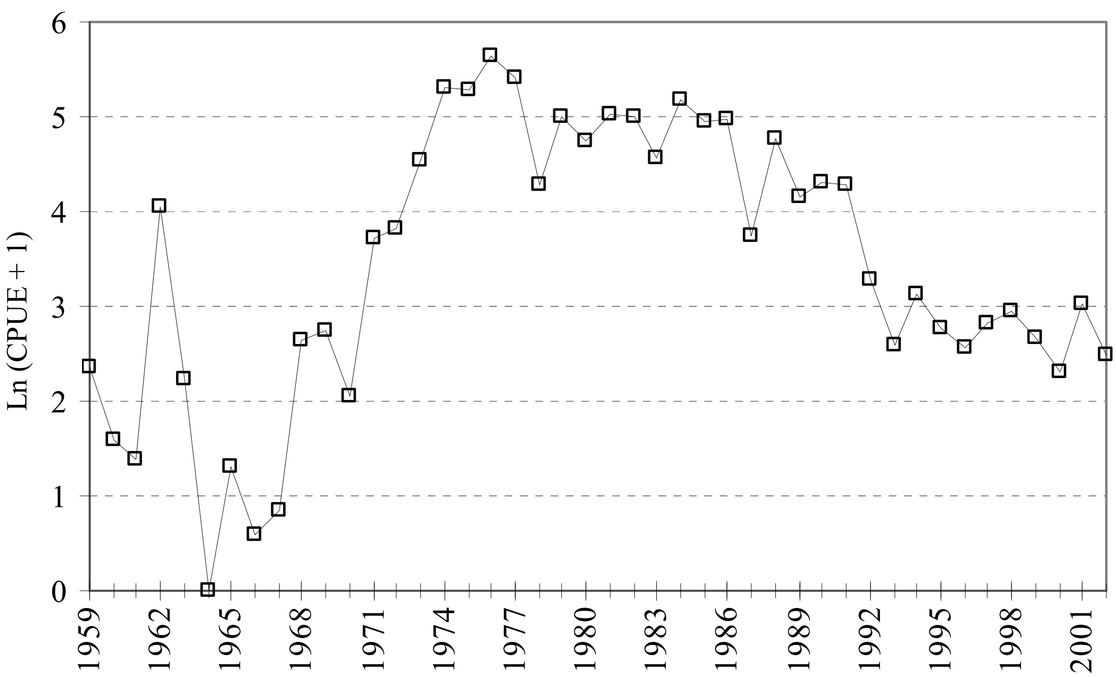


Figure 5.13 Pound net landings per license from the Potomac River Fishery Commission.

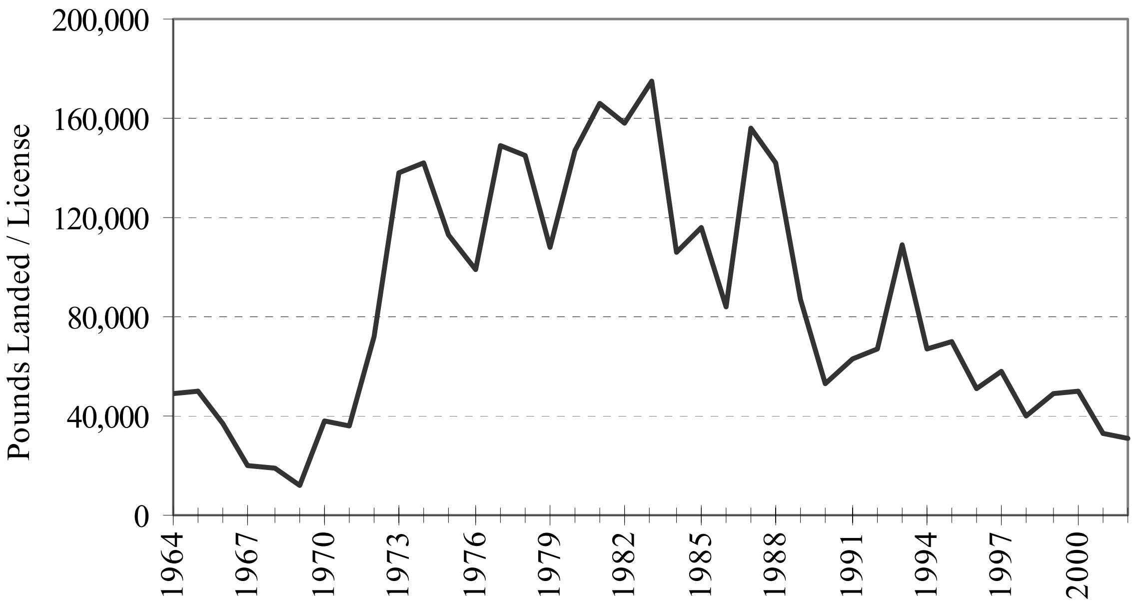


Figure 7.1 Observed and predicted landings of Atlantic menhaden by the reduction fishery (base Ricker model).

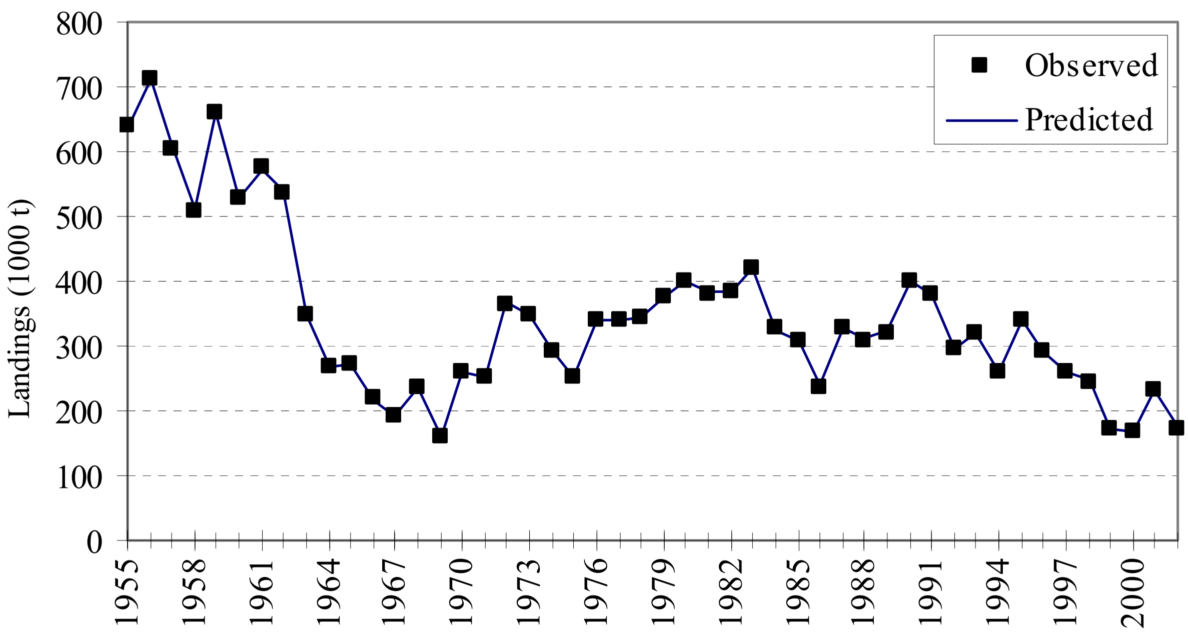


Figure 7.2 Observed and predicted landings of Atlantic menhaden by the bait fishery (base Ricker model).

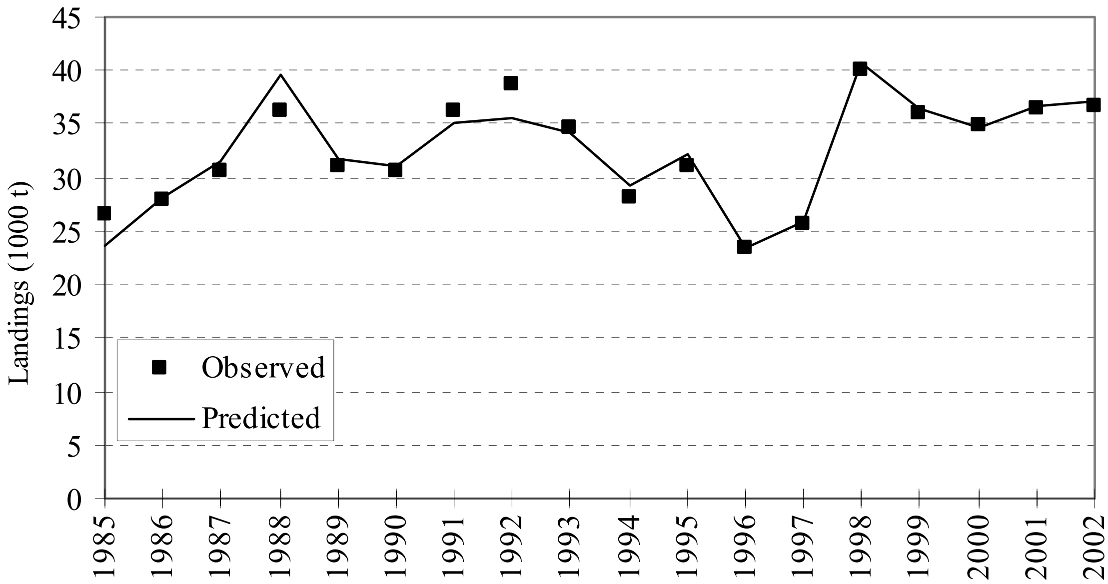


Figure 7.3 Bubble plot for Atlantic menhaden catch-at-age from the reduction fishery (base Ricker model).

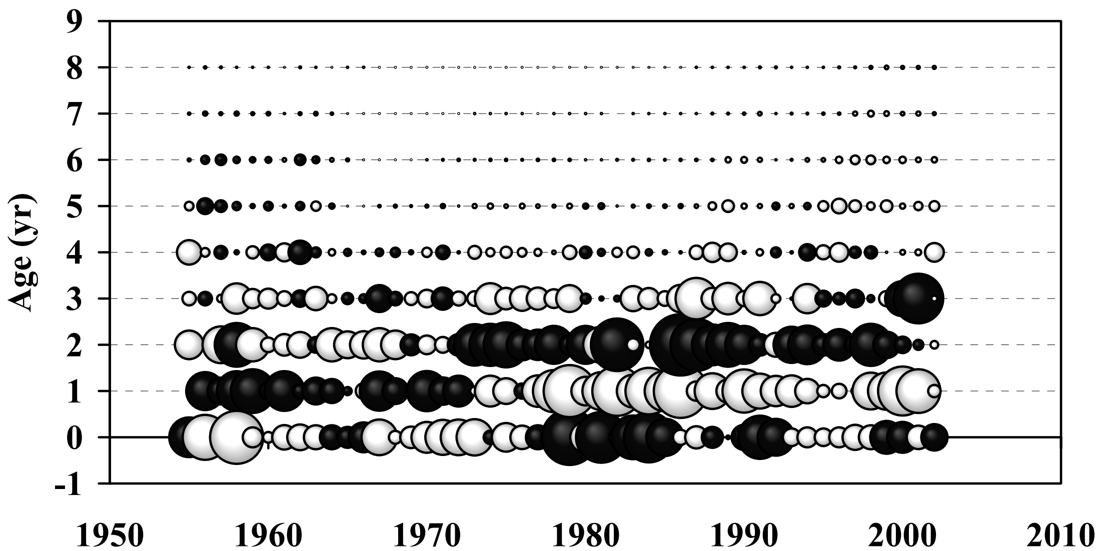


Figure 7.4 Bubble plot for Atlantic menhaden catch-at-age from the bait fishery (base Ricker model).

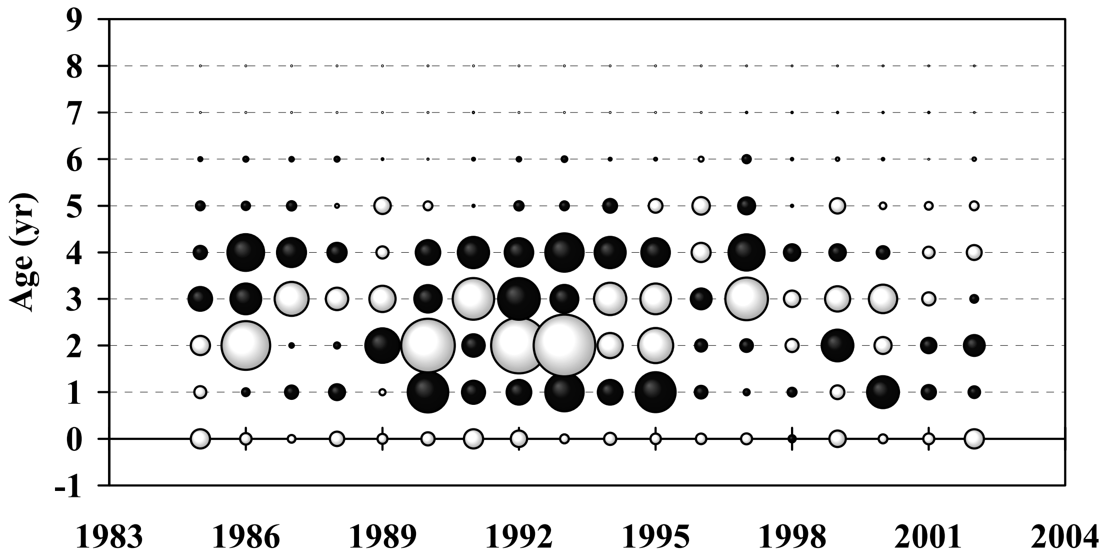


Figure 7.5 Observed and predicted coastwide juvenile abundance indices (logarithm) for Atlantic menhaden (base Ricker model).

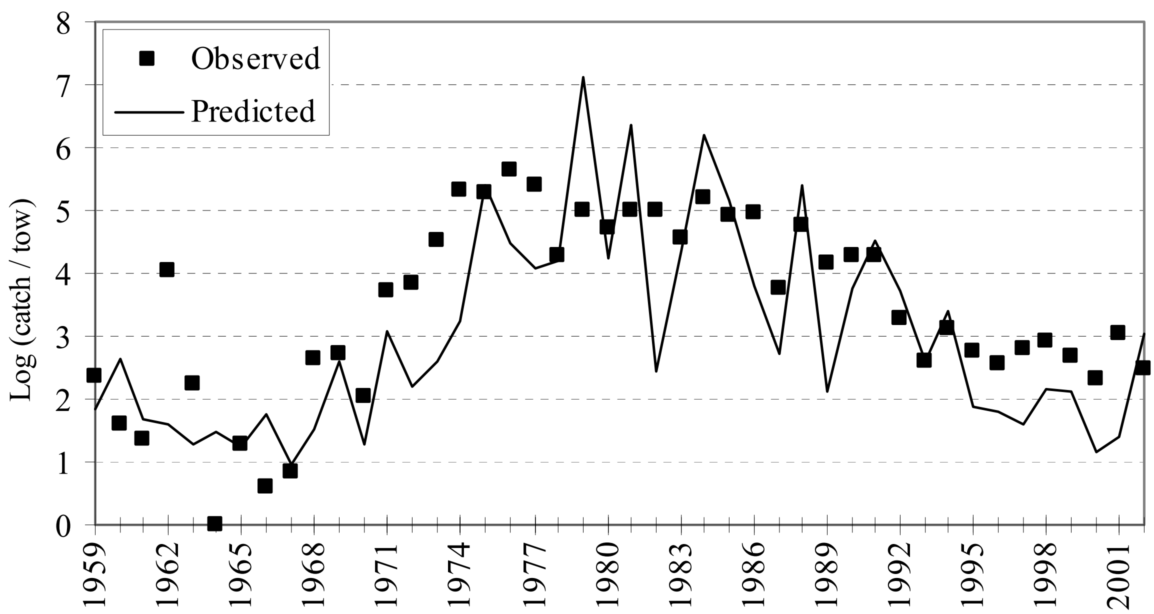


Figure 7.6 Observed and predicted PRFC pound net indices for Atlantic menhaden (base Ricker model).

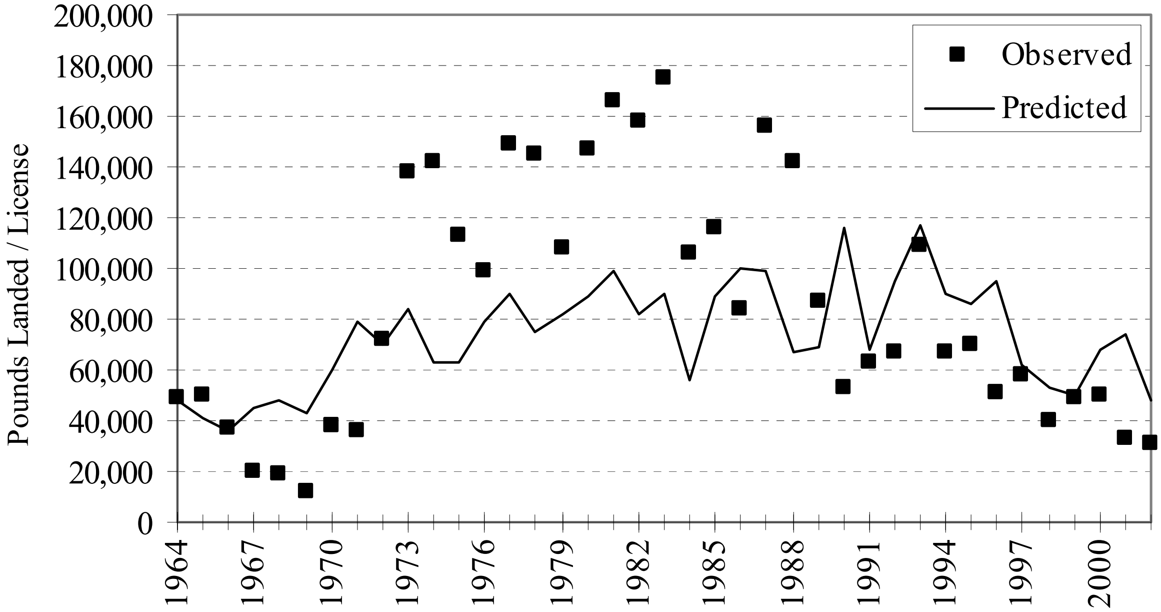


Figure 7.7 Selectivity of reduction and bait Atlantic menhaden fisheries and catch-weighted selectivity for current year (2002). Estimated in the base Ricker model run.

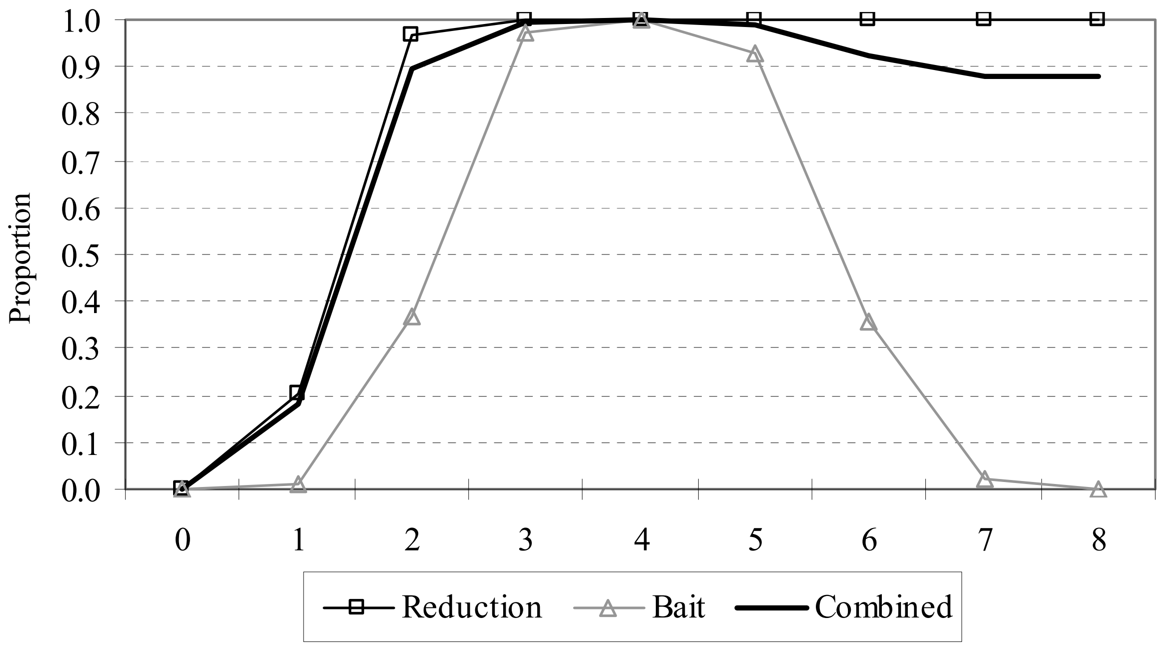


Figure 7.8 Atlantic menhaden fishing mortality rate, *F* (ages 2+) for both spawner-recruit models.

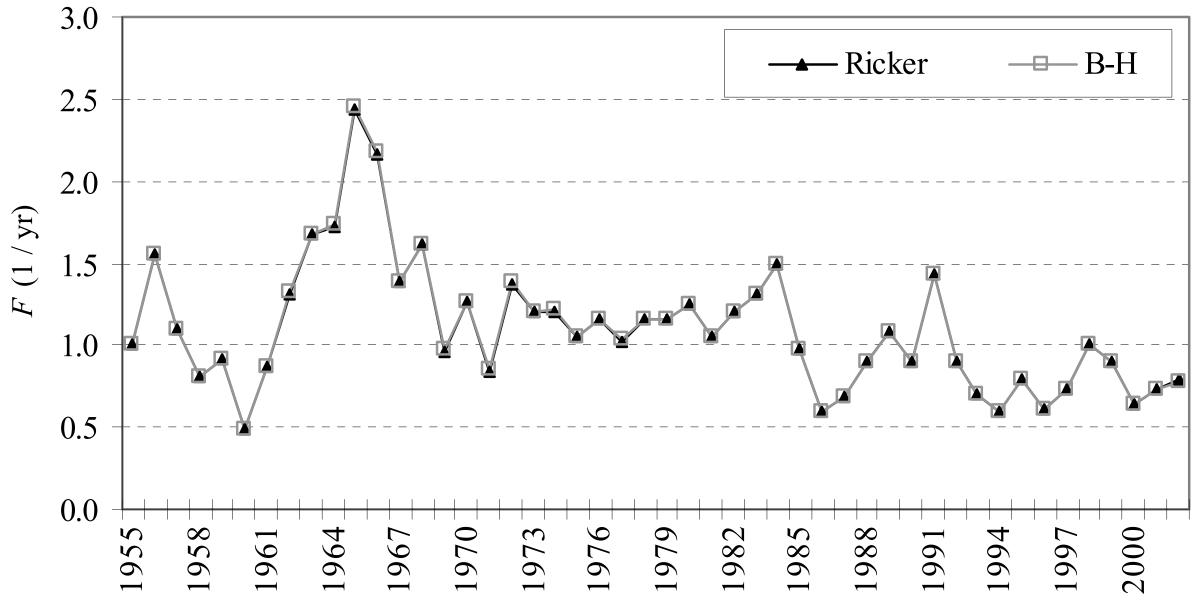


Figure 7.9 Atlantic menhaden exploitation rate, *u* (ages 1+) for both spawner-recruit models.

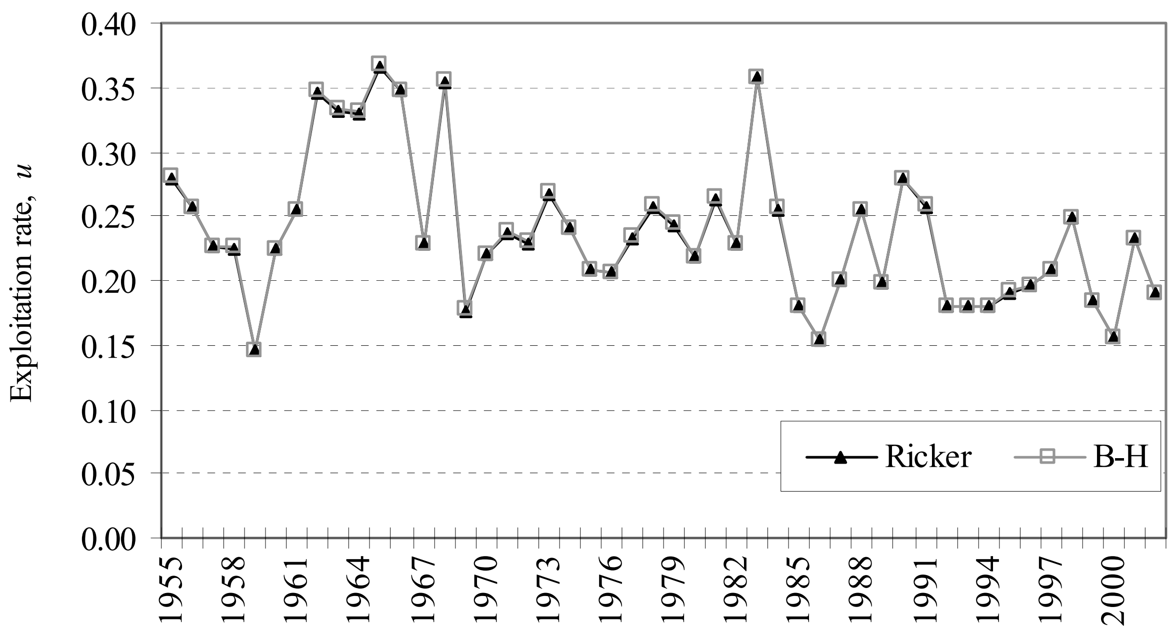


Figure 7.10 Atlantic menhaden spawning stock biomass for both spawner-recruit models.

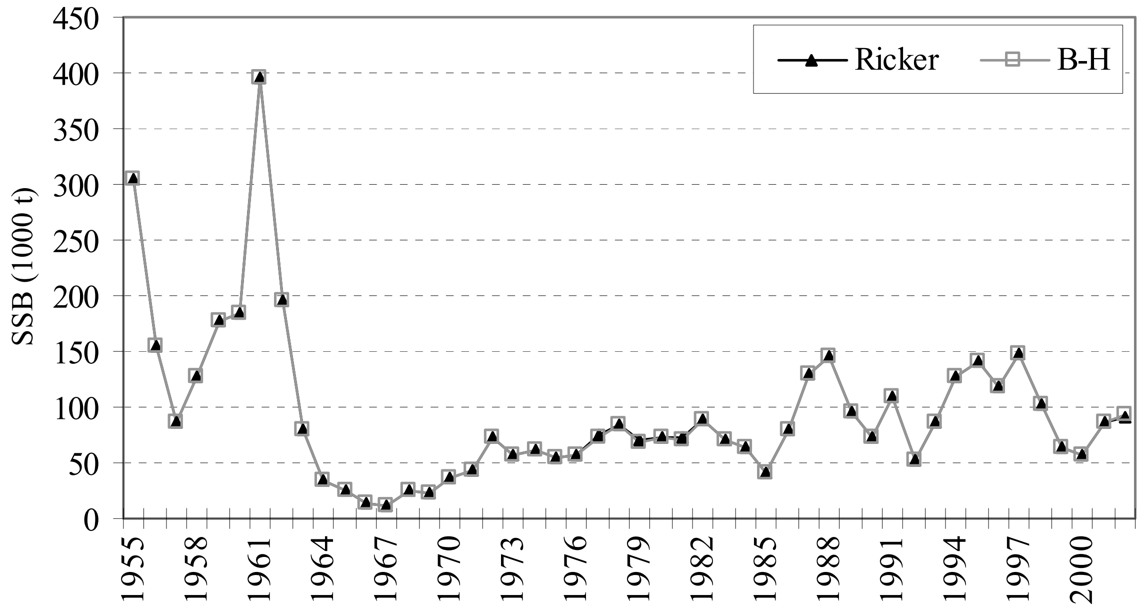


Figure 7.11 Atlantic menhaden population fecundity (# maturing ova) for both spawner-recruit models.

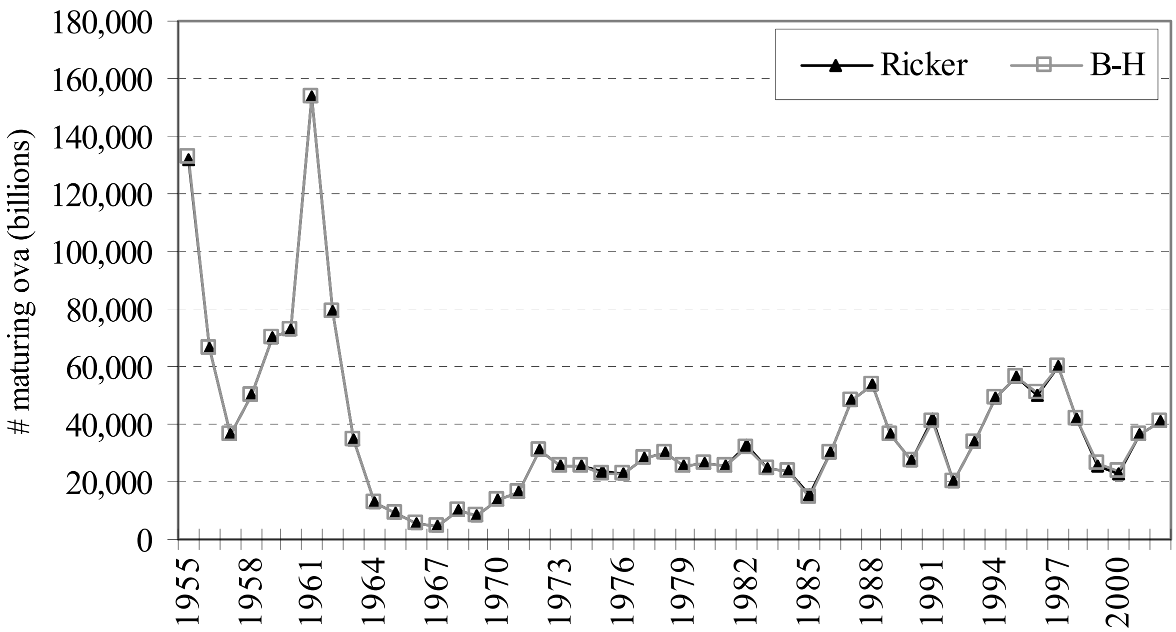


Figure 7.12 Atlantic menhaden recruitment to age-0 for both spawner-recruit models.

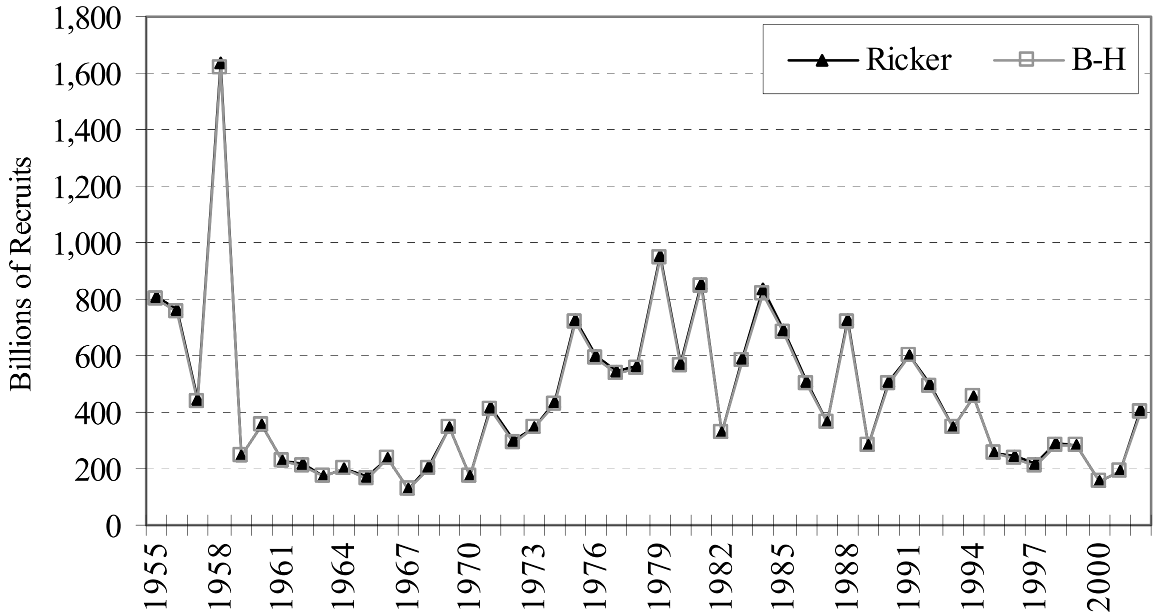


Figure 7.13 Atlantic menhaden recruitment to age-1 for both spawner-recruit models.

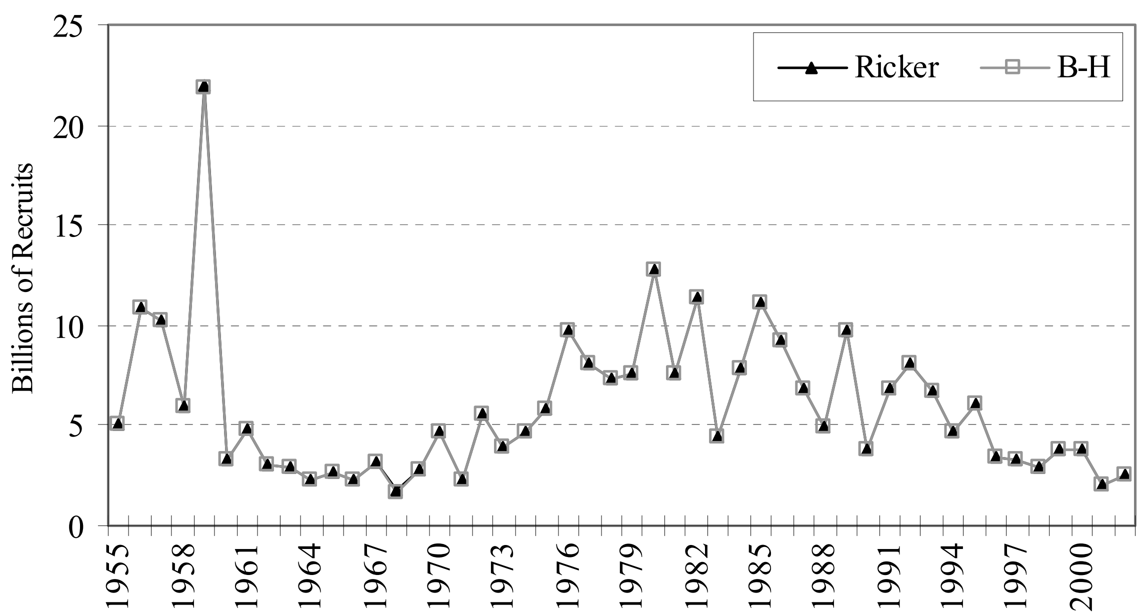


Figure 7.14 Atlantic menhaden natural mortality rate, *M* at age for both spawner-recruit models with plus/minus 2 standard errors from Ricker model.

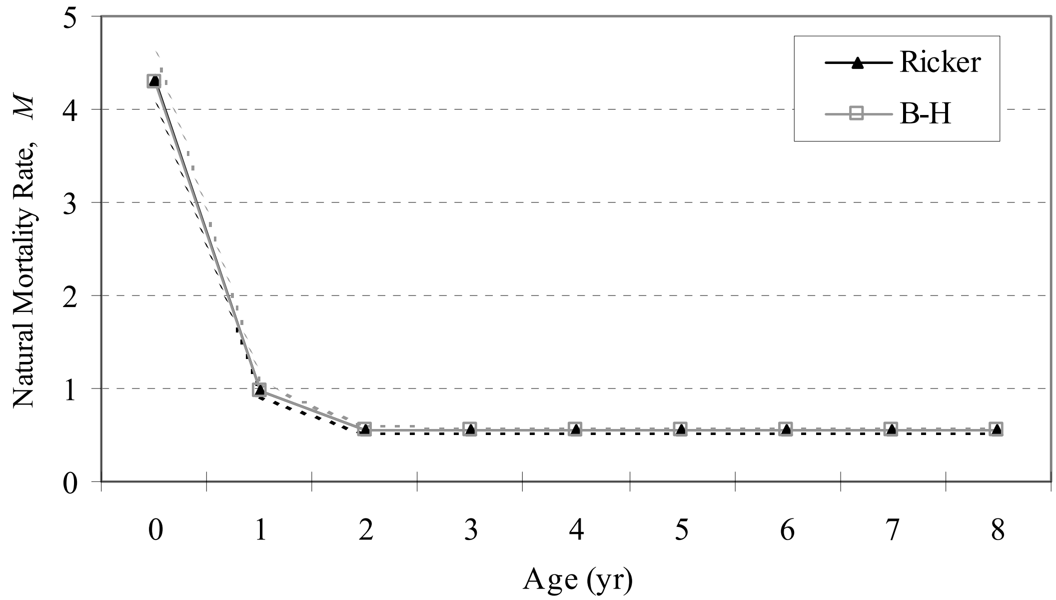


Figure 7.15 Atlantic menhaden fishing mortality rate, *F* (ages 2+) plus/minus 2 standard errors from Ricker model.

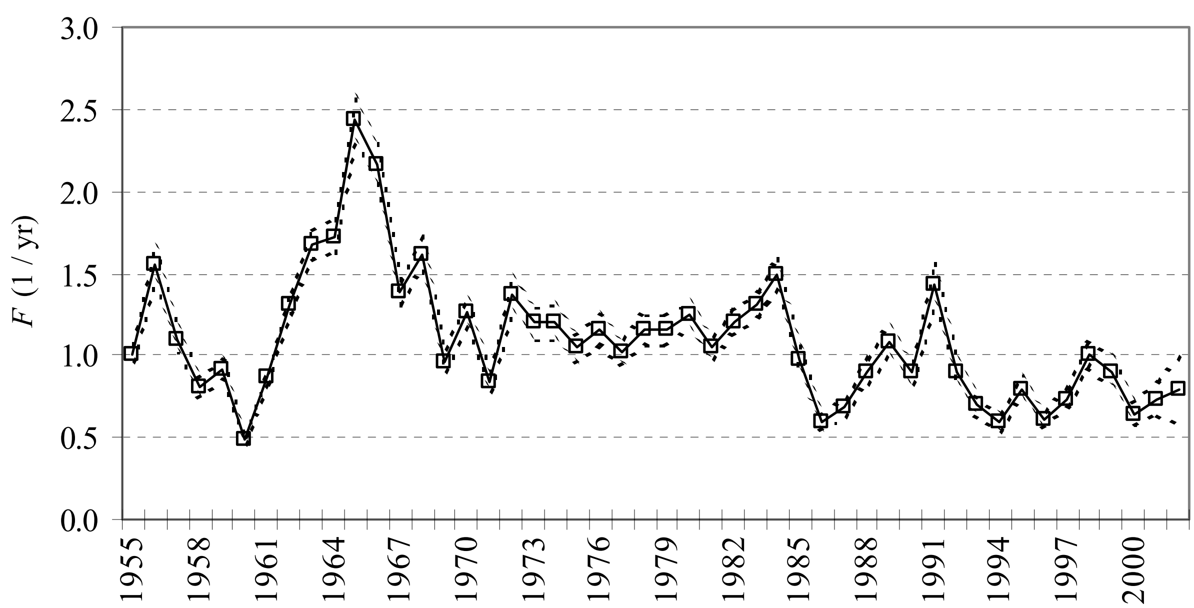


Figure 7.16 Atlantic menhaden population fecundity (# maturing ova) plus/minus 2 standard errors from Ricker model.

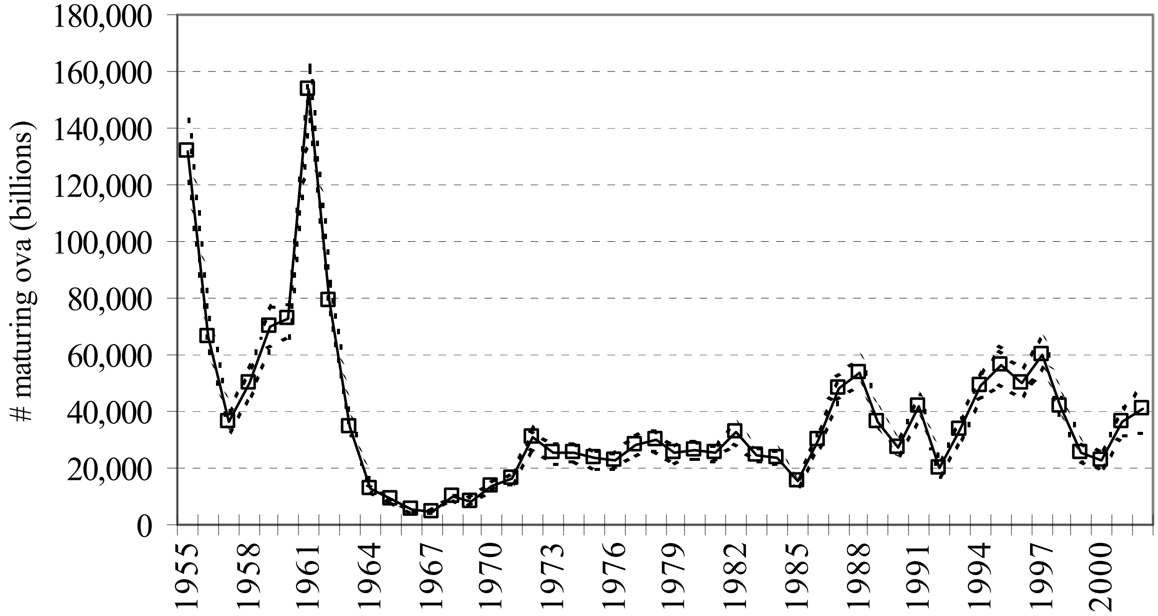


Figure 7.17 Atlantic menhaden recruitment to age-0 plus/minus 2 standard errors from Ricker model.

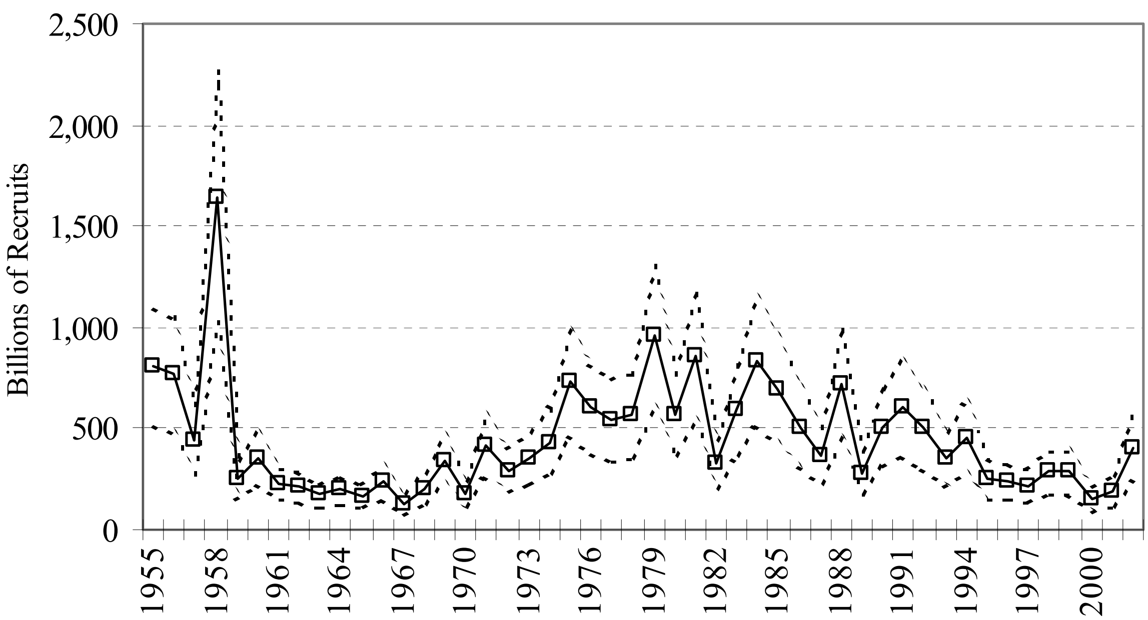


Figure 7.18 Atlantic menhaden fishing mortality rate, *F* (ages 2+) with decreasing steepness (*h*) from Ricker model.

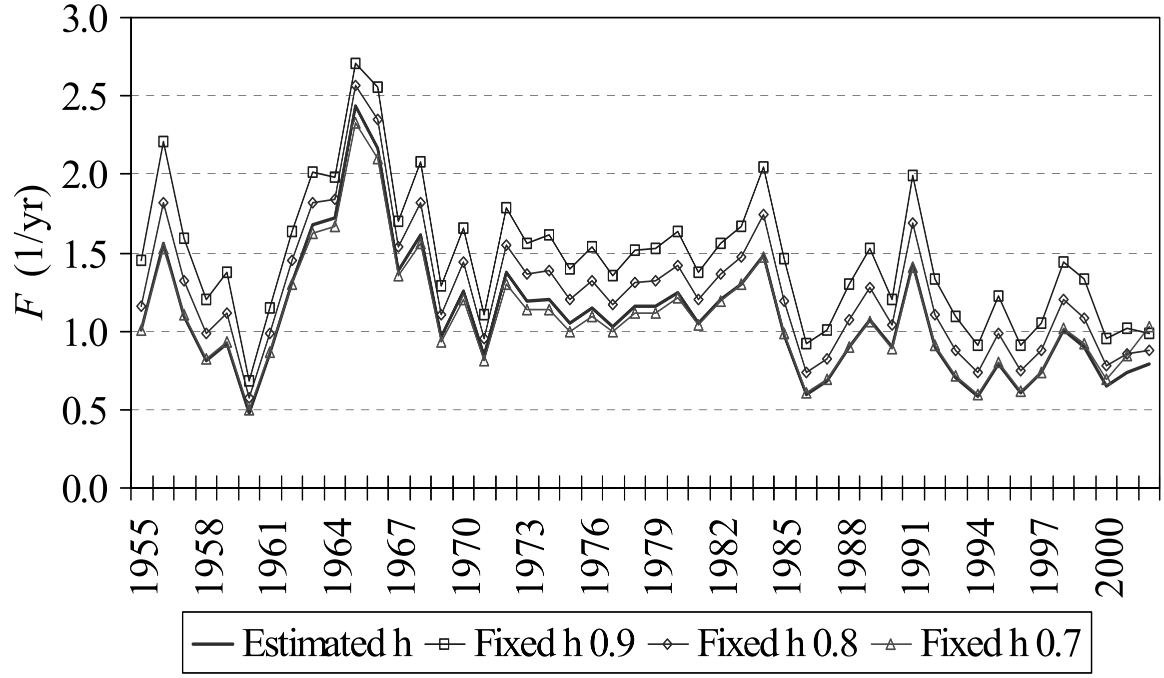


Figure 7.19 Atlantic menhaden population fecundity (# maturing ova) with decreasing steepness (*h*) from Ricker model.

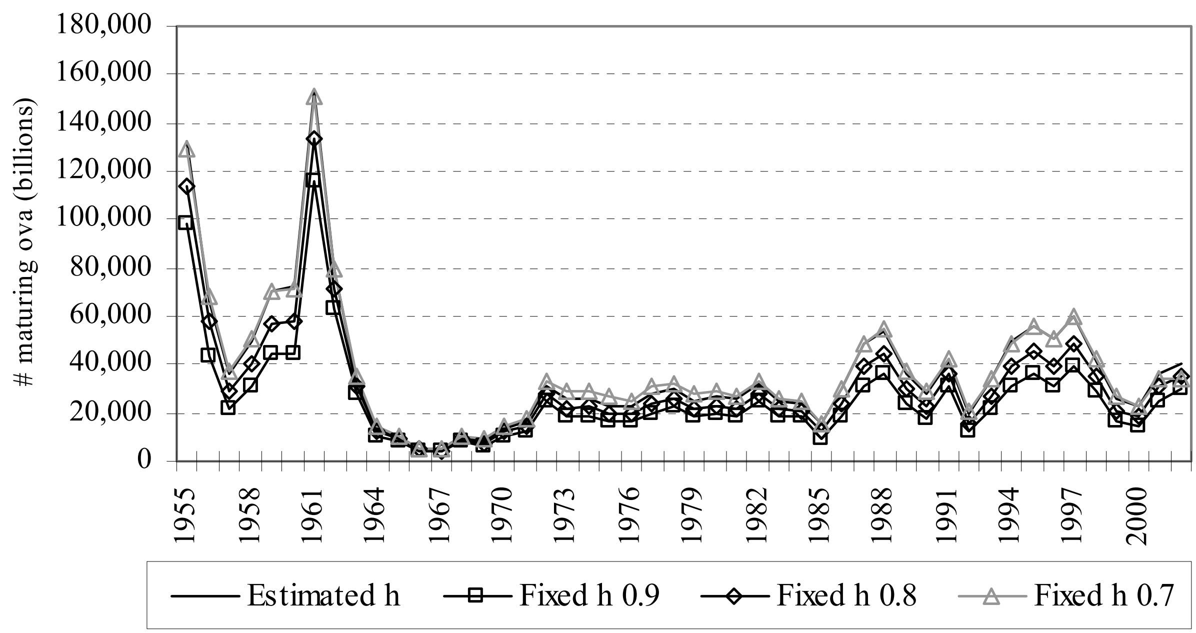


Figure 7.20 Atlantic menhaden recruitment to age-0 with decreasing steepness (*h*) from Ricker model.

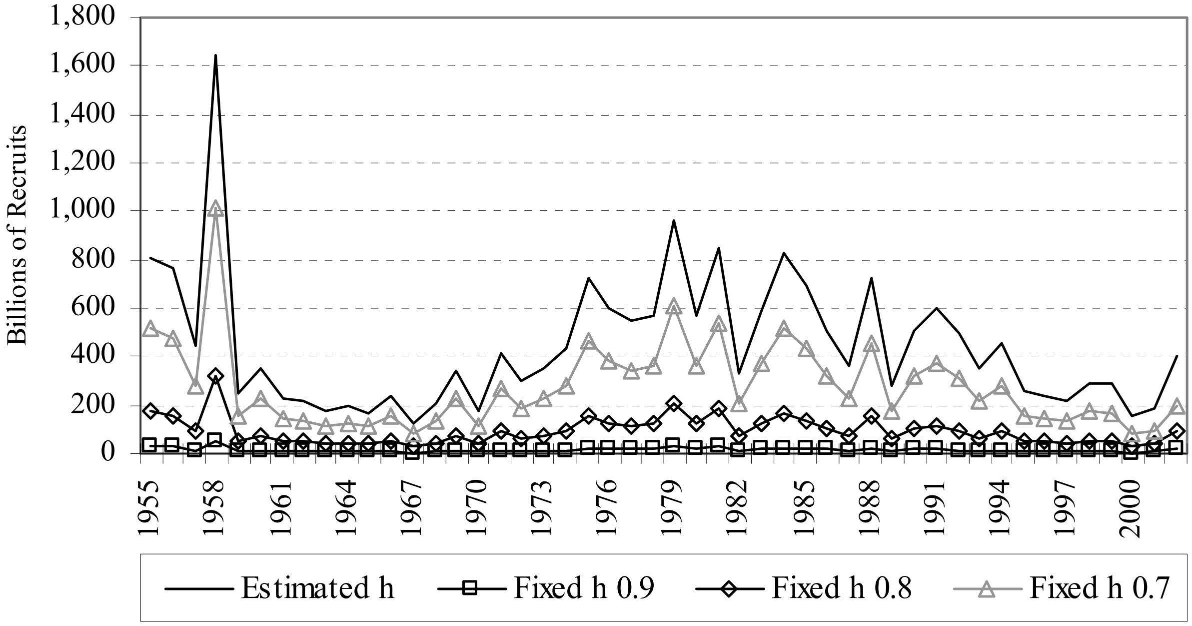


Figure 7.21 Atlantic menhaden fishing mortality rate, *F* (ages 2+) for alternative runs (*M*, maturity) from Ricker model.

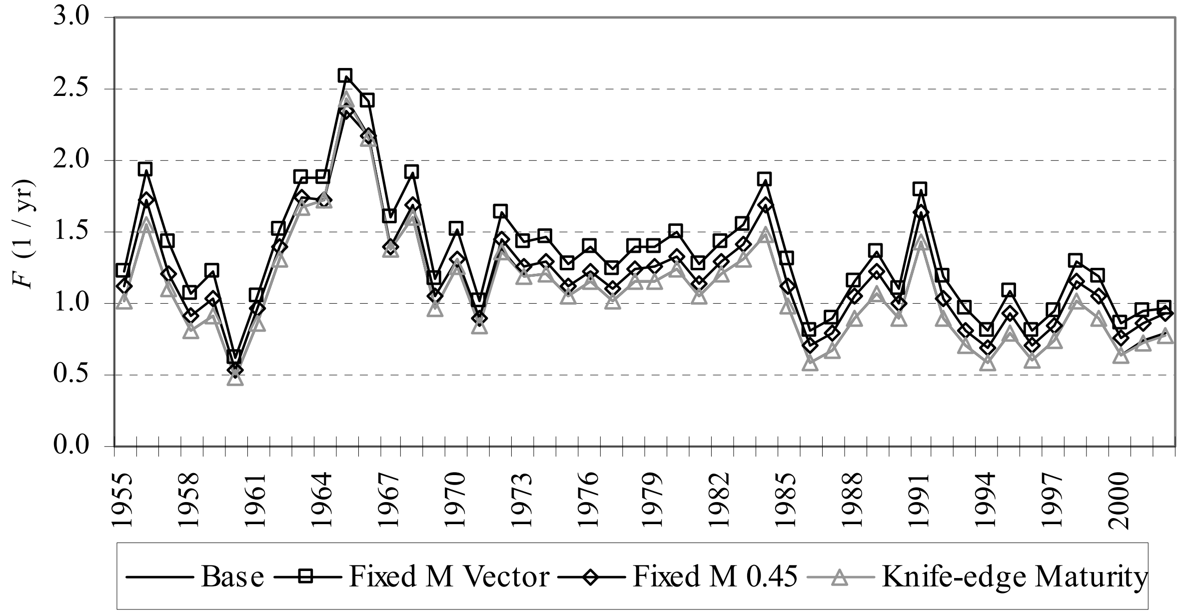


Figure 7.22 Atlantic menhaden population fecundity (# maturing ova) for alternative runs (*M*, maturity) from Ricker model.

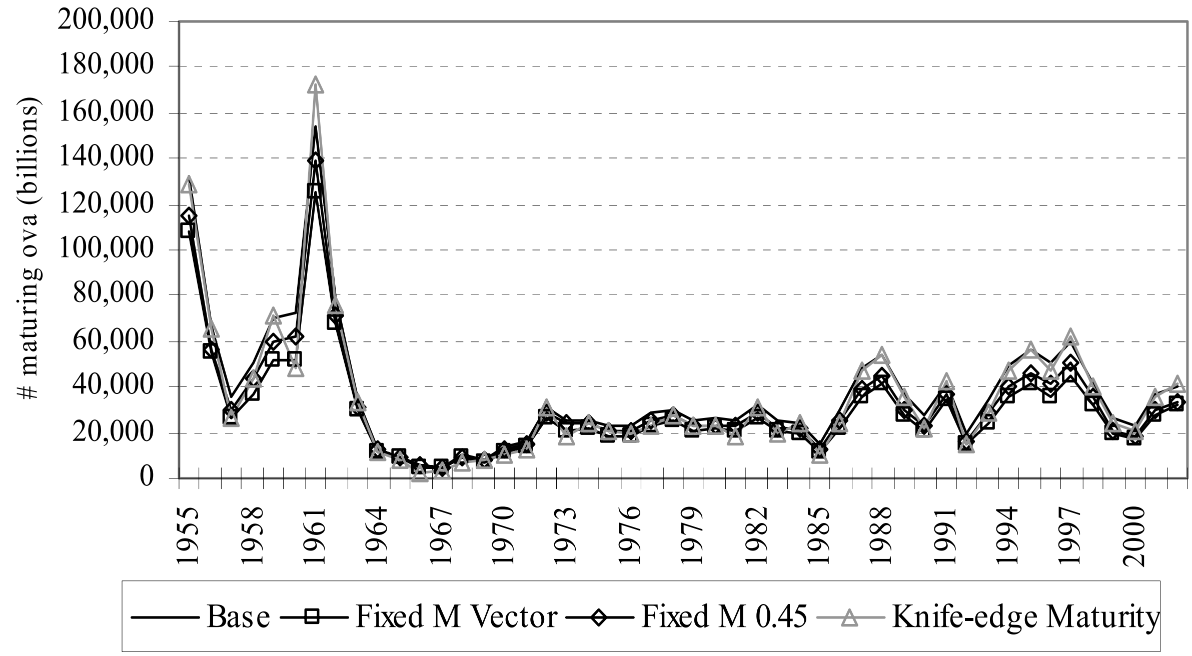


Figure 7.23 Atlantic menhaden recruitment to age-0 for alternative runs (*M*, maturity) from Ricker model.

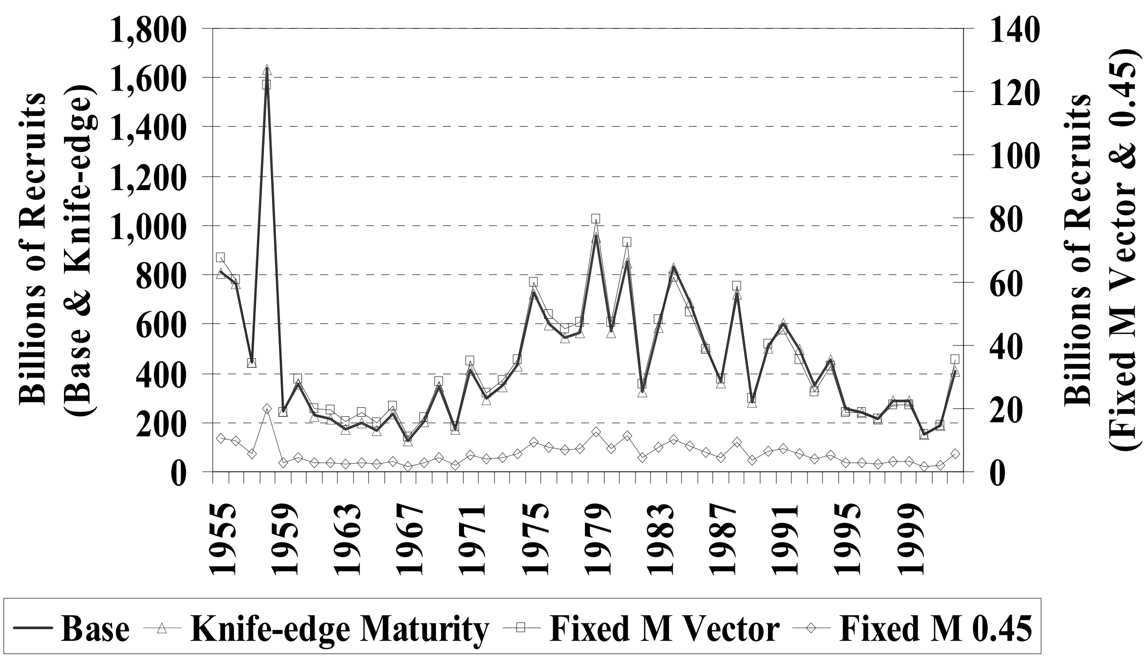


Figure 7.24 Retrospective comparison of Atlantic menhaden fishing mortality rate, *F* (ages 2+) from Ricker model.

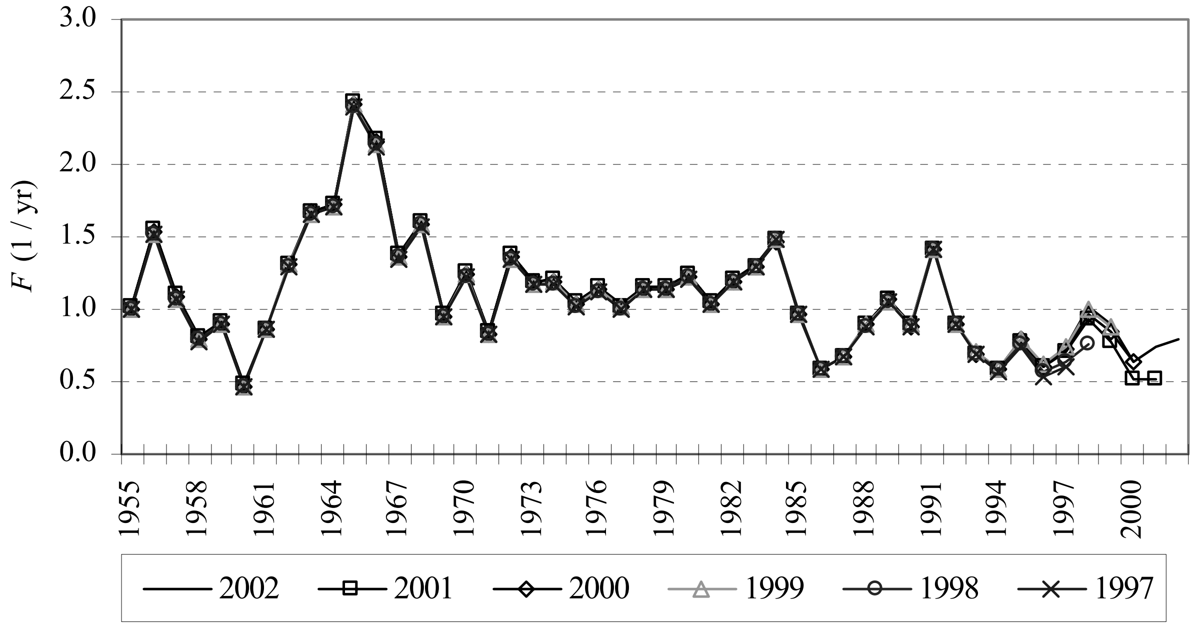


Figure 7.25 Retrospective comparison of Atlantic menhaden population fecundity (# maturing ova) from Ricker model.

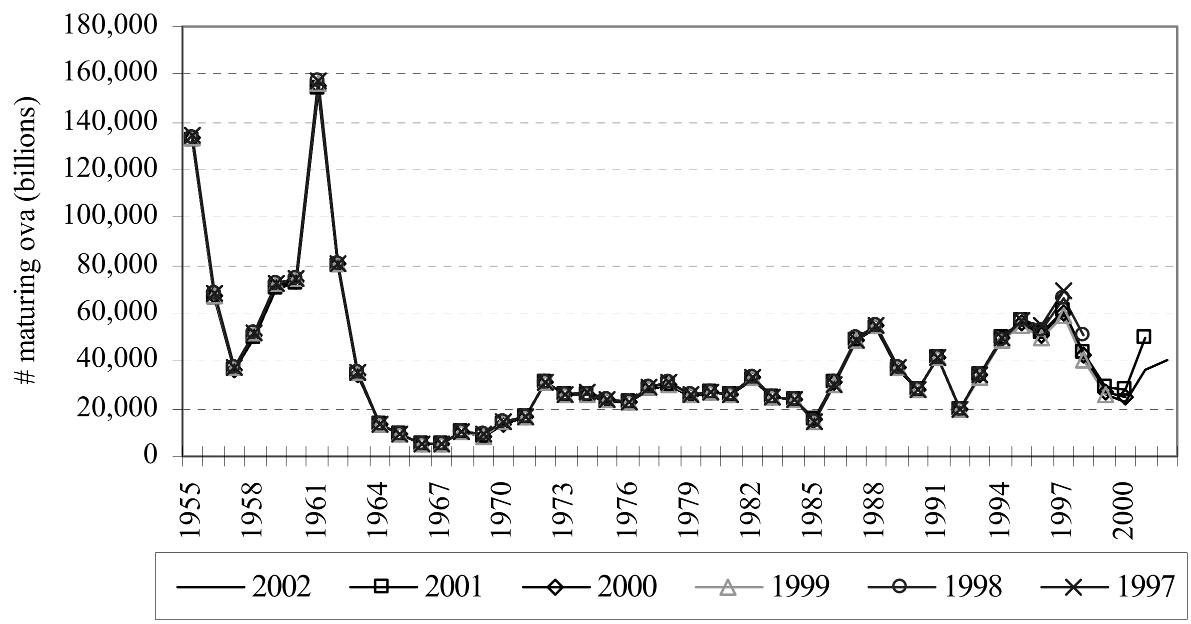


Figure 7.26 Retrospective comparison of Atlantic menhaden recruitment to age-0 from Ricker model.

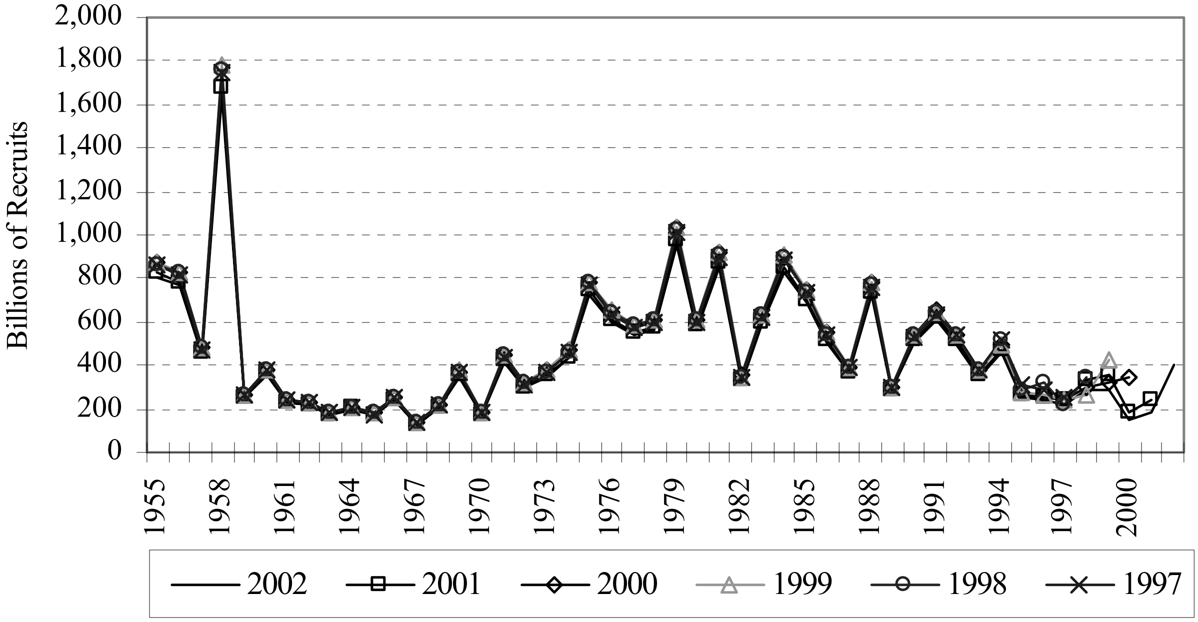


Figure 8.1 Schematic fisheries control rule (modified from Mace et al. 1996).

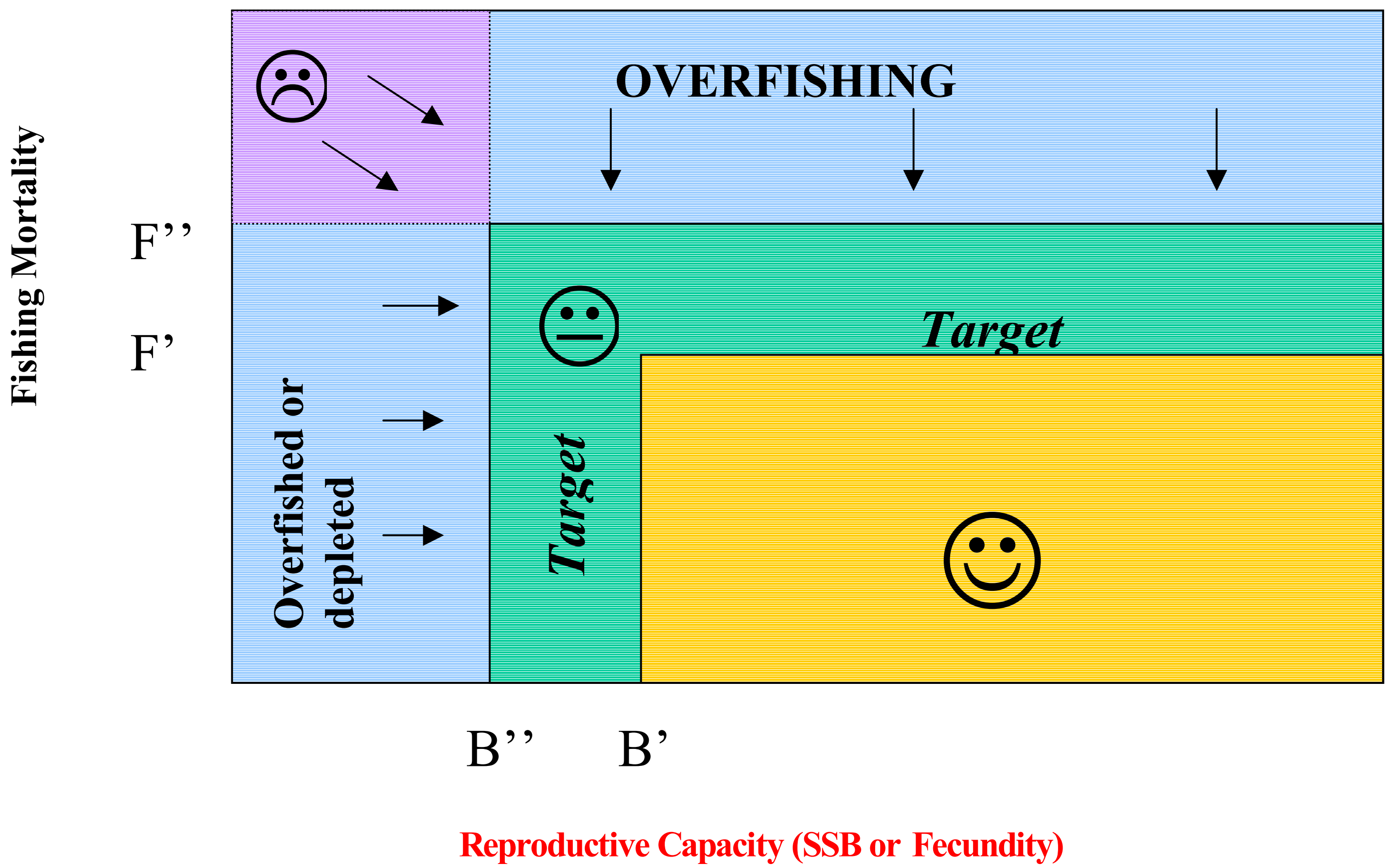


Figure 8.2 Spawner-recruit curves for Atlantic menhaden (Ricker and Beverton-Holt).

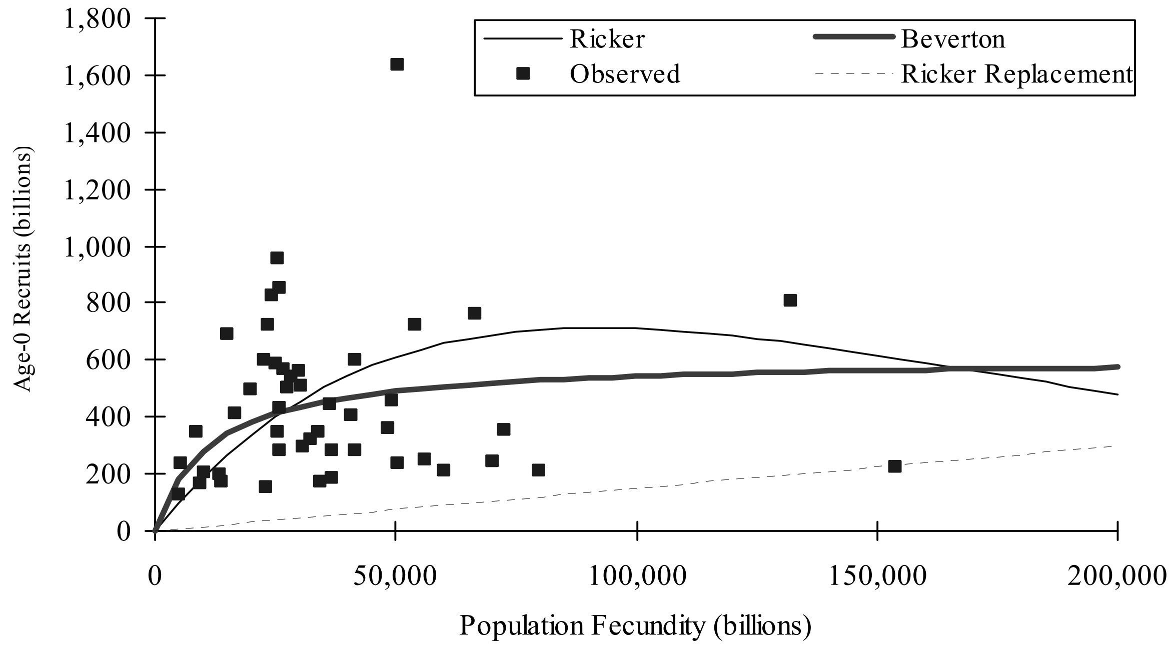


Figure 8.3 Atlantic menhaden fecundity-per-recruit (static FPR) and yield-per-recruit (YPR) from Ricker base run.

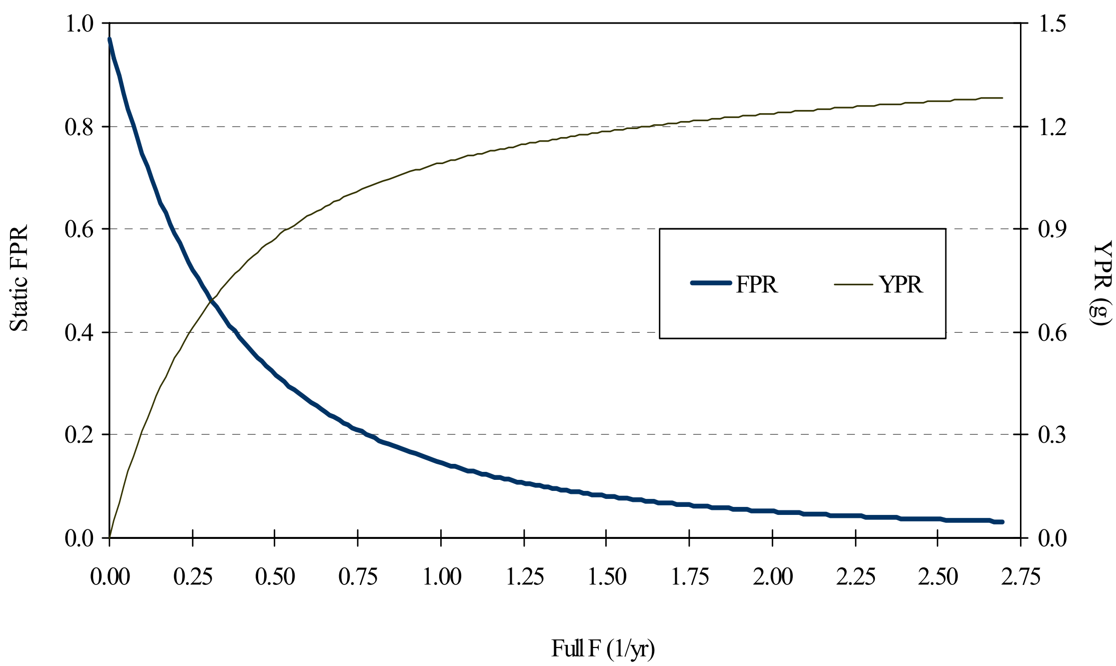


Figure 8.4 Atlantic menhaden fecundity-per-recruit (static FPR) and yield-per-recruit (YPR) from Beverton-Holt base run.

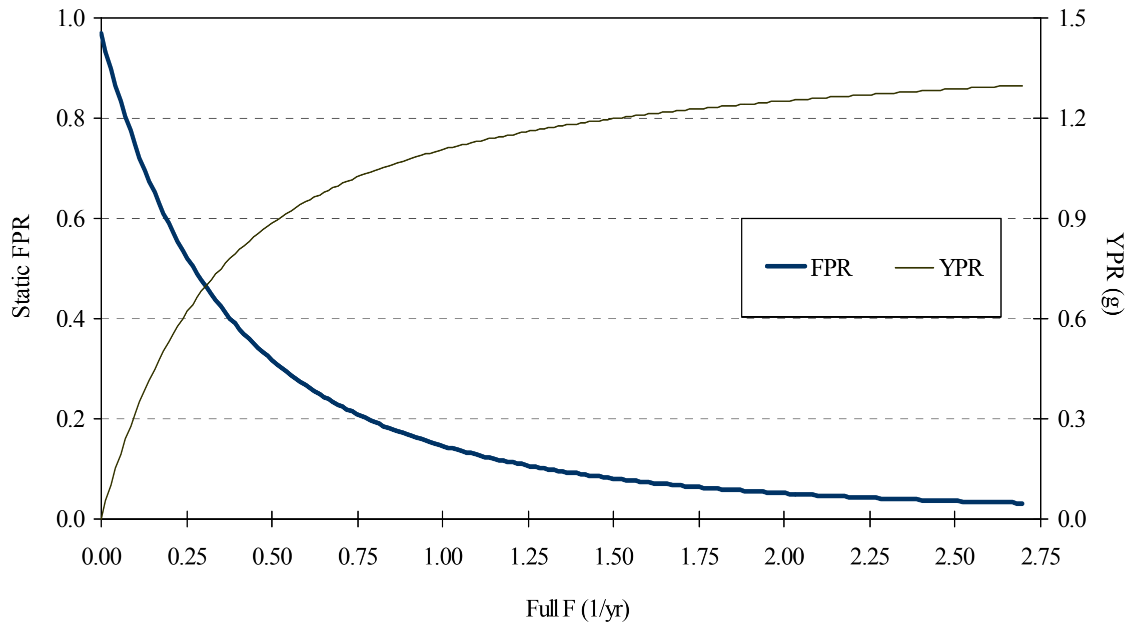


Figure 8.5 Atlantic menhaden spawner-per-recruit (static-SPR as SSB) for both spawner-recruit models.

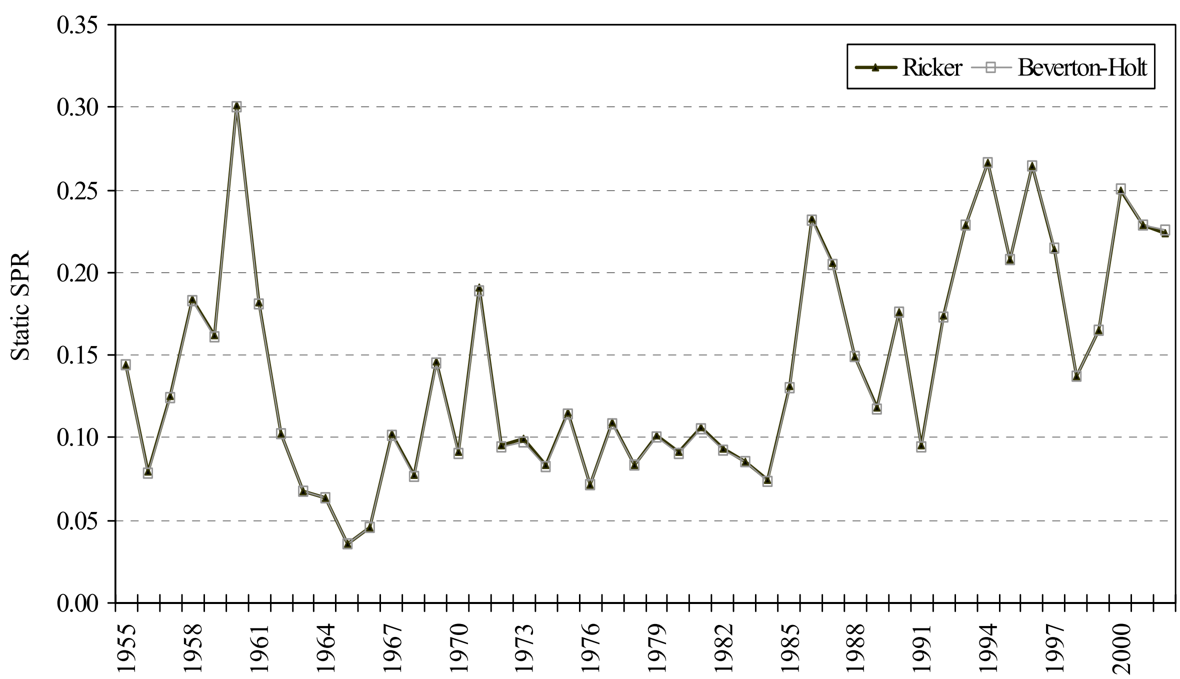


Figure 8.6 Atlantic menhaden spawner-per-recruit (static-FPR as fecundity) for both spawner-recruit models.

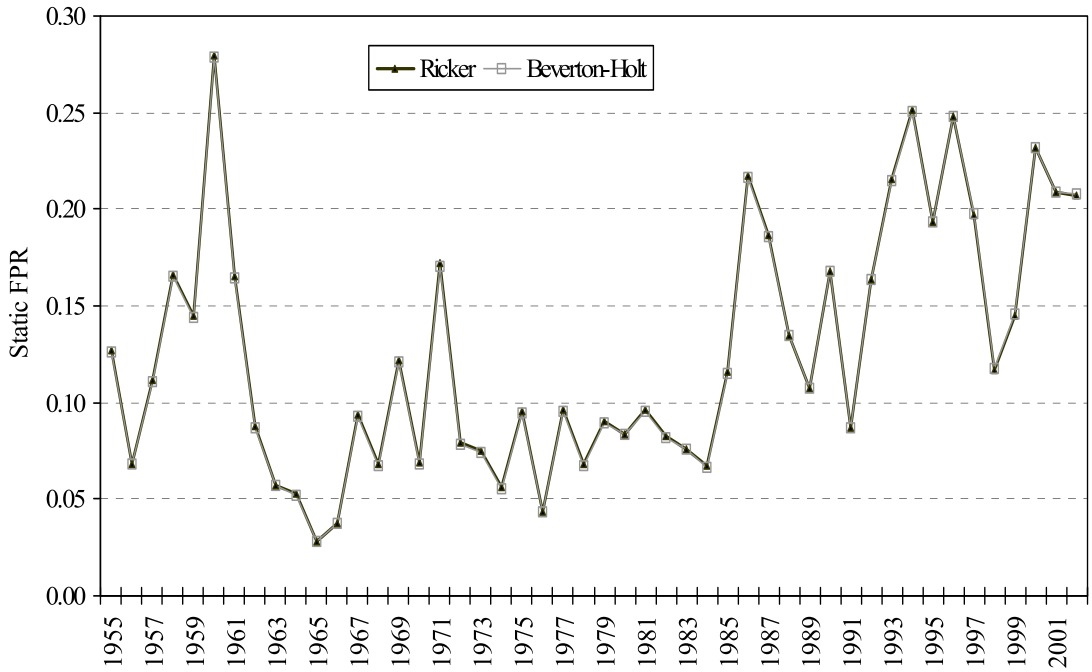


Figure 8.7 Atlantic menhaden population fecundity (# maturing ova) vs. recruits to age-0 for Ricker base run.

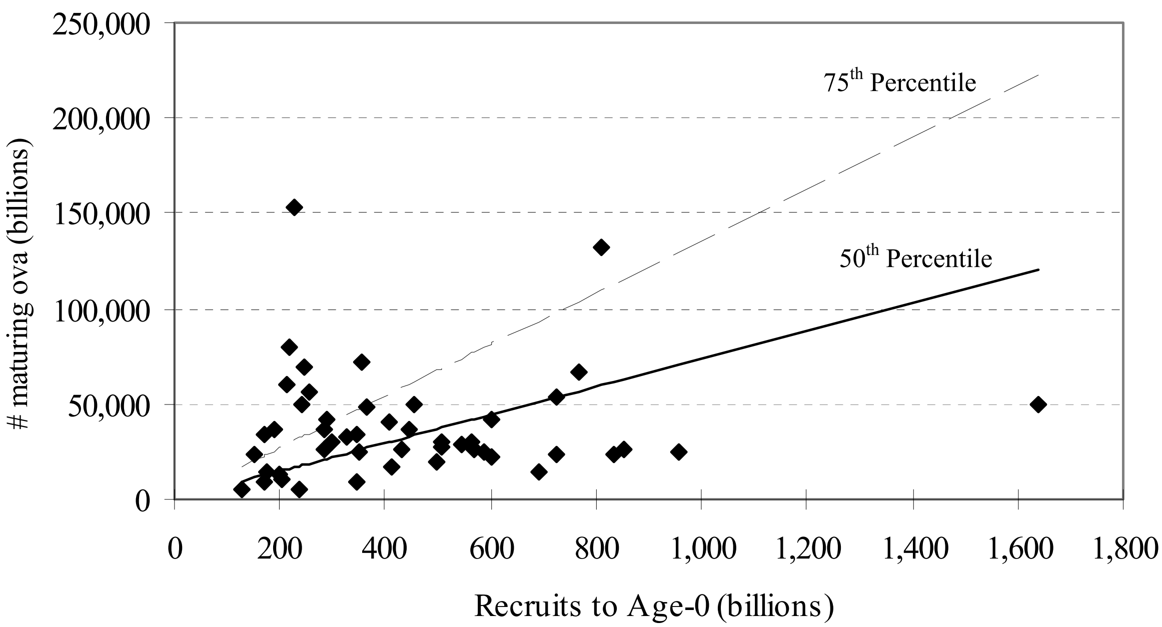


Figure 8.8 Atlantic menhaden population fecundity (# maturing ova) vs. recruits to age-0 for Beverton-Holt base run.

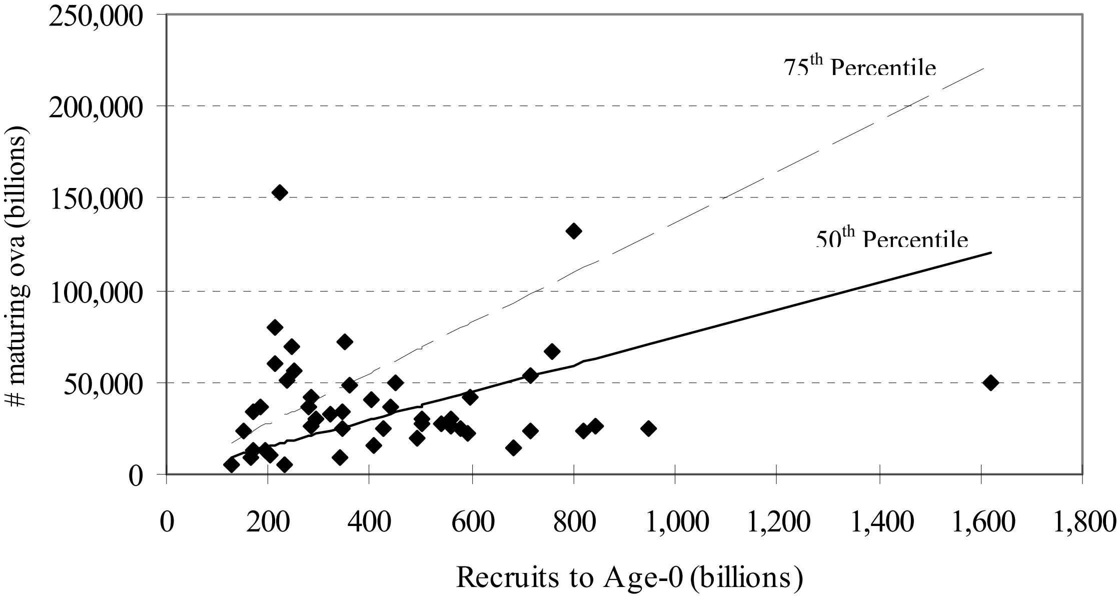


Figure 9.1 Atlantic menhaden fishing mortality rate, *F* (ages 2+) plus/minus 2 standard errors from Ricker model. Horizontal lines represent target (dashed) and threshold (solid).

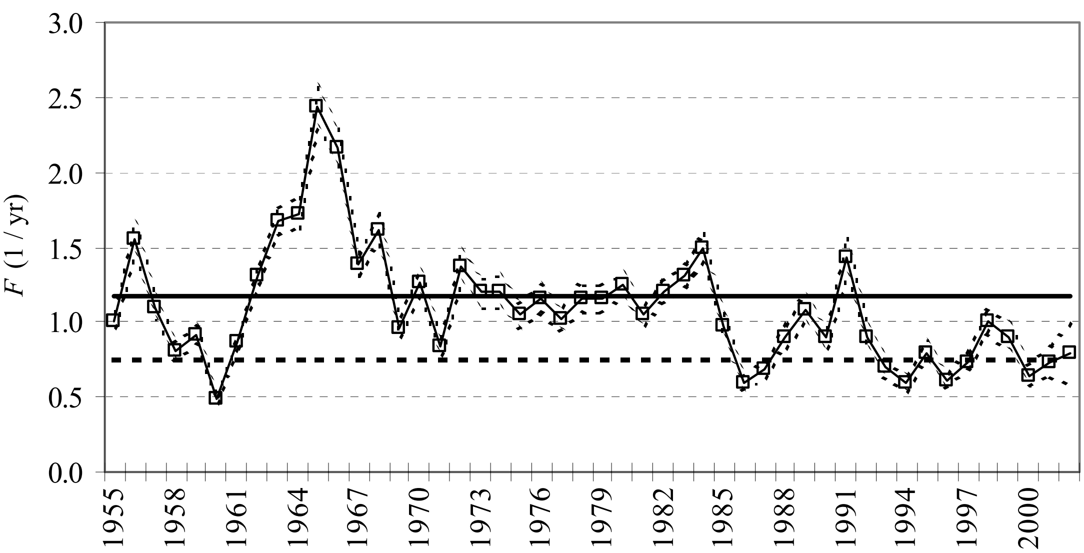


Figure 9.2. Atlantic menhaden population fecundity (# maturing ova) plus/minus 2 standard errors from Ricker model. Horizontal lines represent target (dashed) and threshold (solid).

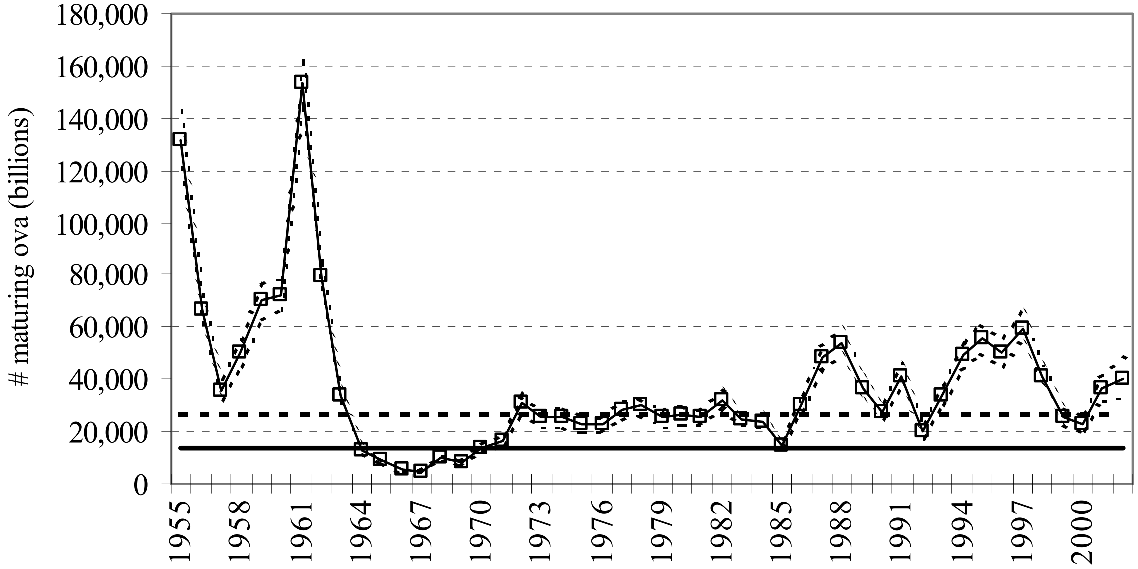


Figure 9.3. Atlantic menhaden spawning stock biomass (SSB) plus/minus 2 standard errors from Ricker model. Horizontal lines represent target (dashed) and threshold (solid) from Amendment 1.

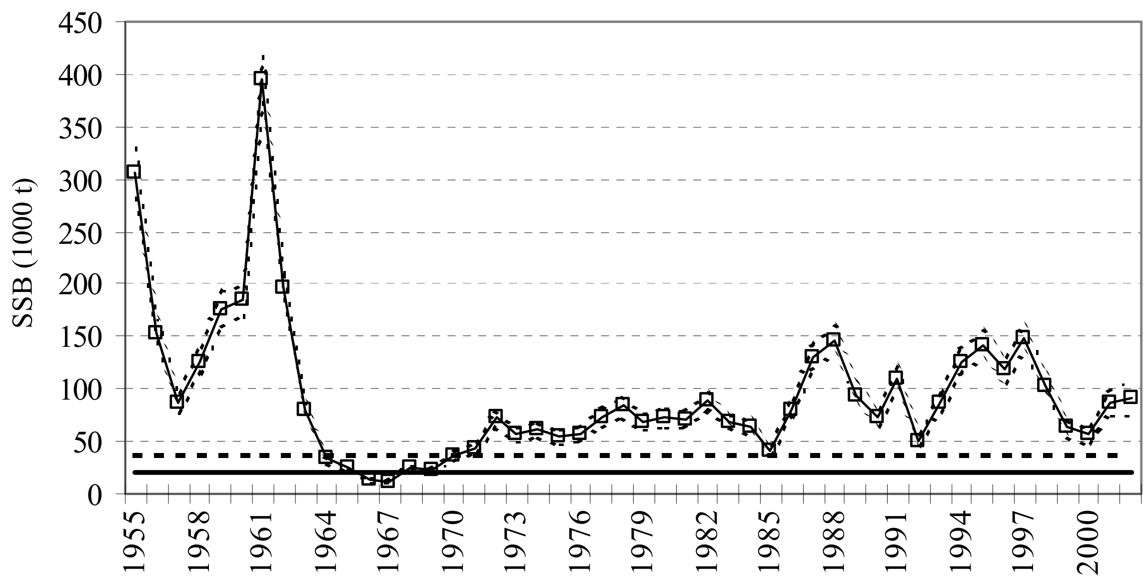


Figure 9.4 Control plot for Atlantic menhaden from base Ricker model (solid square is value for 2002).

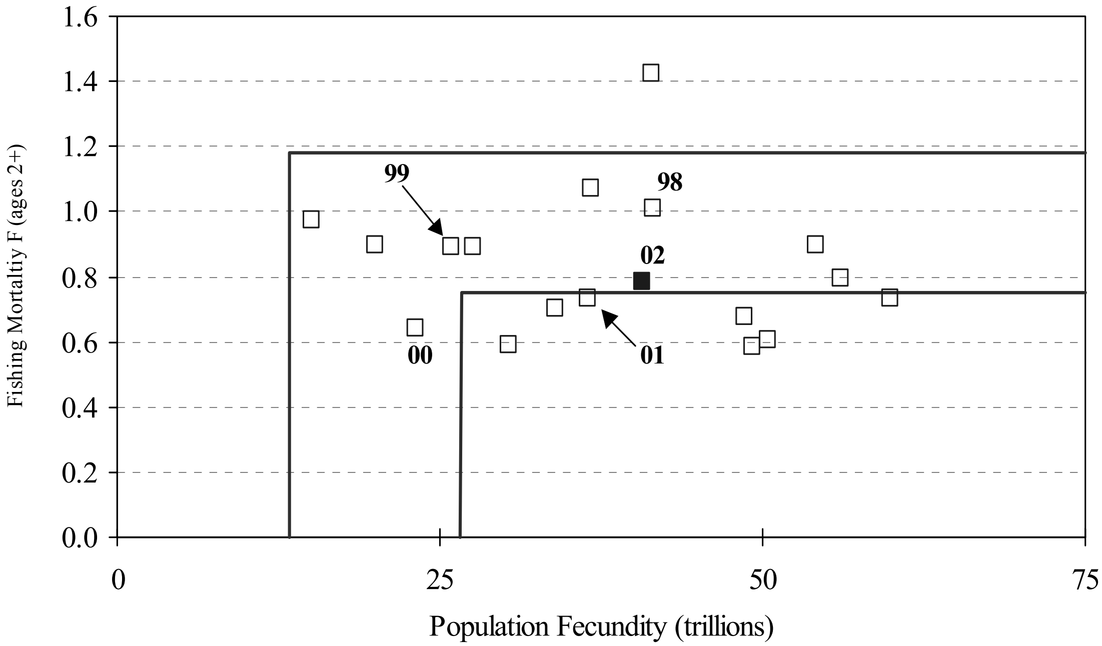
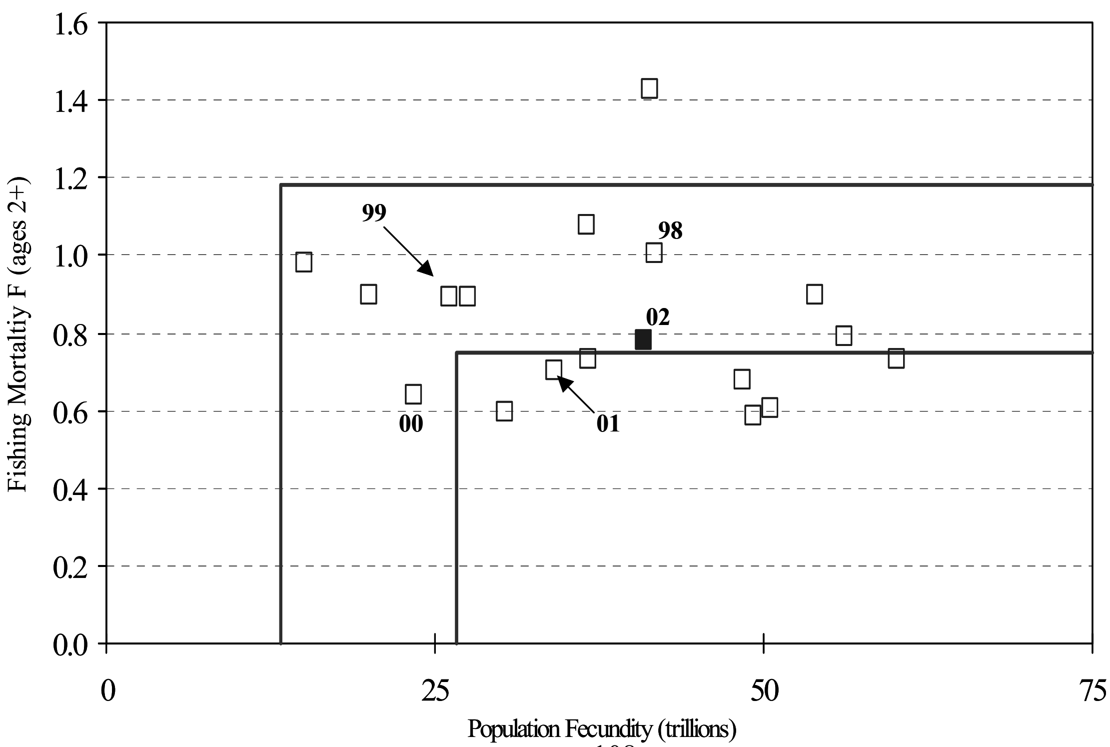


Figure 9.5 Control plot for Atlantic menhaden from base Beverton-Holt model (solid square is value for 2002).



APPENDICES

Appendix A. List of Participants

Appendix B. Stock Assessment Workshop Summary

Appendix C. Control File for Base Ricker Run

Appendix D. Corresponding Input File

Appendix E. ADMB Model Runs Description

Appendix A
Atlantic Menhaden Stock Assessment Workshop Participants

Dr. Matt Cieri
ME DMR
PO Box 8
194 McKown Point Rd.
West Boothbay Harbor, ME 04575
Matthew.Cieri@state.me.us
Tel: 207-633-9520
Fax:207-633-9579

Peter Himchak
NJ Fish and Wildlife
PO Box 418
Port Republic, NJ 08241
Peter.Himchak@dep.state.nj.us
Tel: 609-748-2020
Fax: 609-748-2032

Laura Lee
RI DFW Marine Fisheries
3 Fort Wetherwill Road
Jamestown, RI 02835
llee@asmfc.org
Tel: 401-423-1935
Fax:401-423-1925

Dr. Behzad Mahmoudi
FL MRI
J4S/FA
100 Eighth Ave SE
St. Petersburg, FL 33701
Behzad.Mahmoudi@FWC.state.fl.us
Tel: 727-896-8626

Jason McNamee
RI DFW Marine Fisheries
3 Fort Weatherwill Road
Jamestown, RI 02835
jmcnamee@dem.state.ri.us
Tel: 401-423-1943
Fax:401-423-1925

Dr. Alexi Sharov
MD DNR Fisheries Service
Tawes State Office Building
580 Taylor Avenue
Annapolis, MD 21401
ASHAROV@dnr.state.md.us
Tel: 410-260-8288
Fax:410-260-8279

Joseph Smith
NMFS Beaufort Lab
101 Pivers Island Road
Beaufort, NC 28516
Joseph.W.Smith@NOAA.gov
Tel: 252-728-8765
Fax: 252-728-8619

Dr. Douglas Vaughan
NMFS CCFHR
101 Pivers Island Road
Beaufort, NC 28516
Doug.Vaughan@NOAA.gov
Tel: 252-728-8761
Fax: 252-728-8619

Nancy Wallace
ASMFC
1444 Eye St., NW. Sixth Floor
Washington, DC 20005
nwallace@asmfc.org
Tel: 202-289-6400
Fax: 202-289-6051

Dr. Erik Williams
NMFS CCFHR
101 Pivers Island Road
Beaufort, NC 28516
Erik.Williams@NOAA.gov
Tel: 252-728-8603
Fax: 252-728-8619

Appendix B
Stock Assessment Workshop Summary:

Life History:

Natural Mortality - proportion at age from Multispecies VPA model
 Alternate Runs: 1) Constant M=0.45 for all ages
 2) Age-varying M from Multispecies VPA
Maturity - pooled proportions for age 2 and age 3 in Lewis et al. (1987)
 Alternate Run: knife edge maturity between ages 2 and 3
Fecundity - combined relationship in Lewis et al. (1987)

Landings:

Reduction Fishery - landings and catch at age (1955-2002)
Bait - landings and catch at age (1985-2002)

Indices:

Five Juvenile Abundance Indices using Seines (NC, VA, MD, CT, RI) - delta lognormal GLM, combine into single index as follows: average of standardized VA and MD, average of standardized CT and RI; weighted average of standardized NC, CB, and NE based on %EDA adjusted for productivity from Ahrenholz. Re-standardized by average mean and variance from individual indices.
PRFC Pound net Index (catch in numbers per license) - selectivity (age 1 - 25%, age 2 - 100%, age 3 - 25%)

Spawner-Recruit Relationship: Ricker, Beverton-Holt

Base Runs for each spawner-recruit relationship:

Estimate M using proportion at age from Multispecies VPA, pooled maturity estimates at age 2 and 3, fecundity basis for spawner-recruit relationship. Logarithm of coastwide JAI to reduce extremes in range, assume JAIs biased low in low abundance years and biased high in high abundance years due to schooling nature of menhaden.

Summary of ADMB runs for each spawner-recruit relationship (runs in parenthesis):

1. Base run with Hessian for error estimates (26, 32)
2. M fixed at age-varying values from Multispecies VPA (21, 24)
3. M constant at 0.45 (25, 31)
4. Knife Edge Maturity (0% age 2, 100% age 3) (37, 41)
5. Sensitivity to steepness (*h*): BH - 0.7, 0.8, 0.9 (fix R_0 at base run) (38-40, 42-44) (corresponding steepness values for Ricker used)
6. Retrospective on base runs (5 additional runs per spawner-recruit) (45-49, 50-54)

Benchmarks:

Modified approach from that used in the Amendment 1 to the FMP

F-based benchmarks:

Threshold: F_{rep} (=F_{med}) where F_{rep} corresponds to median Fecundity/R_0
(Same approach as in Amendment 1)

Target: F^{75th} corresponding to 75th percentile of Fecundity/R_0 (Parallels approach for threshold; this maintains consistency of approach between threshold and target)

Fecundity-based benchmarks:

(analog to SSB-based benchmarks in Amendment 1 but based on fecundity)

Target: Fecundity corresponding to F_{rep} (Fecundity/R_0 * R_0)
where R = med R (1955-2002)

Threshold: (1-M_A)*target where $M_A \cong 0.5$ for adult ages as estimated in base runs; if M>0.5 then Tech. Guidance suggests using threshold = 0.5*target.

Appendix C
Control File for Base Ricker Run (menhad058.tpl):

```
//--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//
//  Atlantic Menhaden Model
//
//  Erik H. Williams, NMFS, Beaufort Lab
//  (erik.williams@noaa.gov), March 2003
//
//--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
DATA_SECTION
// Starting and ending year of the model
init_int styr;
init_int endyr;
// Number of ages
init_int nages;
// Vector of ages for age bins
init_ivector agebins(1,nages);

//starting year for recruitment estimation (not being read in)
int styrR;
//this section MUST BE INDENTED!!!
 LOCAL_CALCS
   styrR=styr-(nages-1);
 END_CALCS

// Natural mortality vector
init_vector M_vec(1,nages);

// Stock-recruit function (1=Bev-Holt,2=Ricker)
init_number SRswitch;

//--><>--Biologicals--><>--><>--><>--><>--><>--><>--><>--><>--><>--
//weight-at-age in the fishery (g)
init_matrix wgt_fish(styr,endyr,1,nages);
//weight-at-age for the spawning population (g)
init_matrix wgt_spawn(styr,endyr,1,nages);

//maturity of females (%)
init_vector mat_f(1,nages);

//fecundity at age (eggs)
init_matrix fec_f(styr,endyr,1,nages);

//--><>--Recruitment Index--><>--><>--><>--><>--><>--><>--
init_int U_age0_styr;
init_int U_age0_endyr;
init_vector U_age0_obs(U_age0_styr,U_age0_endyr);

//--><>--Pound Net Index--><>--><>--><>--><>--><>--><>--
init_int U_pound_styr;
init_int U_pound_endyr;
init_vector U_pound_obs(U_pound_styr,U_pound_endyr);
```

```
init_vector U_pound_sel(1,nages);

//--><>--Reduction Fishery--><>--><>--><>--><>--><>--><>--><>--><
// Landings (1000mt)
init_int L_reduction_styr;
init_int L_reduction_endyr;
init_vector L_reduction_obs(L_reduction_styr,L_reduction_endyr);
// Age Compositions
init_int agec_reduction_styr;
init_int agec_reduction_endyr;
init_vector agec_reduction_nsamp(agec_reduction_styr,agec_reduction_endyr);
init_matrix agec_reduction_obs(agec_reduction_styr,agec_reduction_endyr,1,nages);

//--><>--Bait Fishery--><>--><>--><>--><>--><>--><>--><>--><
// Landings (1000mt)
init_int L_bait_styr;
init_int L_bait_endyr;
init_vector L_bait_obs(L_bait_styr,L_bait_endyr);
// Age Compositions
init_int agec_bait_styr;
init_int agec_bait_endyr;
init_vector agec_bait_nsamp(agec_bait_styr,agec_bait_endyr);
init_matrix agec_bait_obs(agec_bait_styr,agec_bait_endyr,1,nages);


// Indices for year(y) and age(a)
int y;
int a;

PARAMETER_SECTION
//stuff for R output
vector YEAR(styrR,endyr);
vector AGE(1,nages);

//Natural Mortality
//init_bounded_dev_vector M_dev(styrR,endyr,-0.99,0.99,2);
vector M_dev(styr,endyr);
init_bounded_number M_const(-0.99,0.99,3);
//number M_const;
matrix M(styrR,endyr,1,nages);
sdreport_vector M_vec_sd(1,nages);

//Population Numbers
init_bounded_number R1_log(-10,10,1);//log(Recruits) in styrR and first age
number R1_log_constraint;//constraint for first recruitment estimate
number R1;//Recruits in styrR and first age
init_bounded_dev_vector R_log_dev(styrR+1,endyr,-5,5,2);//recruitment deviations from SR curve
matrix N(styrR,endyr,1,nages);//Population numbers by year and age
matrix B(styrR,endyr,1,nages);//Population biomass by year and age
sdreport_vector R_age0(styrR,endyr);//Recruits at age 0 by year
sdreport_vector R_age1(styrR,endyr);//Recruits at age 1 by year
vector R_pred(styrR,endyr);//S-R curve predicted R's used only in report output
vector R_rep(styrR,endyr);//replacement R's used only in report output
vector B_sum(styrR,endyr);//Total biomass by year
sdreport_vector SSB(styrR,endyr);//Spawning biomass by year
```

```
sdreport_vector FEC(styrR,endyr);//Fecundity by year

//---Stock-Recruit Function (Beverton-Holt, steepness parameterization)----------
init_bounded_number R0_log(0,10,1);//log(virgin Recruitment)
init_bounded_number steep(0.21,0.99,1);//steepness
sdreport_number steep_sd;
sdreport_number R0;
number S0; //equal to spr*R0 = virgin SSB
number S1S0; //SSB(styr) / virgin SSB
number SendS0; //SSB(endyr) / virgin SSB
number FEC0; //equal to fpr*R0 = virgin SSB
number FEC1FEC0; //SSB(styr) / virgin SSB
number FECendFEC0; //SSB(endyr) / virgin SSB


//Catchability (CPUE q's)----------------------------------------------------
init_bounded_number q_log_U_age0(-5,0,1);
init_bounded_number q_log_U_pound(5,15,1);
//Survey and Index Predictions
vector U_age0_pred(U_age0_styr,U_age0_endyr);
vector U_age0_cv(U_age0_styr,U_age0_endyr);
vector U_pound_pred(U_pound_styr,U_pound_endyr);
vector U_pound_cv(U_pound_styr,U_pound_endyr);

//Catch (numbers), Landings (1000mt) (males = 1, females = 2)
matrix C_reduction(styrR,endyr,1,nages);
matrix C_bait(styrR,endyr,1,nages);
matrix C_total(styrR,endyr,1,nages);
matrix L_reduction(styrR,endyr,1,nages);
matrix L_bait(styrR,endyr,1,nages);
matrix L_total(styrR,endyr,1,nages);

//predicted age comps and landings
matrix agec_reduction_pred(agec_reduction_styr,agec_reduction_endyr,1,nages);
matrix agec_bait_pred(agec_bait_styr,agec_bait_endyr,1,nages);
vector L_reduction_pred(L_reduction_styr,L_reduction_endyr);
vector L_bait_pred(L_bait_styr,L_bait_endyr);
number L_reduction_cv;
number L_bait_cv;

//---Selectivity------------------------------------------------------------------
//---logistic and double logistic---------------------------------------------
init_bounded_number selpar_s_reduction(0.1,10.0,1);
init_bounded_number selpar_A50_reduction(1,5,1);
init_bounded_number selpar_s_bait(0.1,10.0,1);
init_bounded_number selpar_A50_bait(1,5,1);
//---logistic and double logistic (time varying)----------------------------------
//init_bounded_dev_vector selpar_A50_dev_reduction(agec_reduction_styr,agec_reduction_endyr,-2,2,3);
//init_bounded_dev_vector selpar_A50_dev_bait(agec_bait_styr,agec_bait_endyr,-2,2,3);
vector selpar_A50_dev_reduction(agec_reduction_styr,agec_reduction_endyr);
vector selpar_A50_dev_bait(agec_bait_styr,agec_bait_endyr);
//---double logistic selectivity--------------------------------------------
//init_bounded_number selpar_s2_reduction(0.01,5,3);
//init_bounded_number selpar_A502_reduction(5,10,3);
init_bounded_number selpar_s2_bait(0.01,5,3);
```

```
init_bounded_number selpar_A502_bait(2,10,3);
//---time-varying descending limb of double logistic selectivity-----------------
//init_bounded_vector selpar_s2_reduction(agec_reduction_styr,agec_reduction_endyr,0.01,10,3)
//---age-specific selectivity parameters----------------------------------------
//init_bounded_vector sel_p_reduction(1,nages,0.0,1.0,1);
//init_bounded_vector sel_p_bait(1,nages,0.0,1.0,1);
//number selpar_A50_reduction;
//number selpar_A50_bait;

matrix sel_reduction(styr,endyr,1,nages);

matrix sel_bait(styr,endyr,1,nages);

//Mortality--------------------------------------------------------------------
init_bounded_number F_log_avg_reduction(-4,1,1);
init_bounded_dev_vector F_log_dev_reduction(L_reduction_styr,L_reduction_endyr,-5,5,1);
matrix F_reduction(styrR,endyr,1,nages);

init_bounded_number F_log_avg_bait(-4,1,1);
init_bounded_dev_vector F_log_dev_bait(L_bait_styr,L_bait_endyr,-5,5,1);
matrix F_bait(styrR,endyr,1,nages);

matrix F_total(styrR,endyr,1,nages);
matrix F_DSV(styrR,endyr,1,nages);
sdreport_vector F_DSV_vec(styrR,endyr);
sdreport_vector E(styrR,endyr);//exploitation rate
sdreport_vector F_full(styrR,endyr);
matrix Z(styrR,endyr,1,nages);

//---MSY stuff------------------------------------------------------------
//vector of catches for last 3 years of each fishery (2 fisheries)
vector C_last3(1,6);
matrix sel_last3(1,6,1,nages);
matrix sel_msy(styrR,endyr,1,nages); //assumed selectivity for msy calcs
//Newton-Raphson stuff
matrix N_msy(1,3,1,nages);
vector SSB_msy(1,3);
vector FEC_msy(1,3);
vector EdE_msy(styrR,endyr);
vector FdF_msy(styrR,endyr);
vector SdSSB_msy(styrR,endyr);
vector SSB_msy_out(styrR,endyr);
number SdSSB_msy_end;
vector FECdFEC_msy(styrR,endyr);
vector FEC_msy_out(styrR,endyr);
number FECdFEC_msy_end;
vector F_msy_out(styrR,endyr);
vector F_DSV_msy_out(styrR,endyr);
number FdF_msy_end;
vector msy_out(styrR,endyr);
vector E_msy_out(styrR,endyr);
vector msy_outx(1,400);
vector xx(1,400);
vector F_msy(1,3);
matrix Z_msy(1,3,1,nages);
```

```
vector L_msy(1,3);
vector C_msy(1,nages);
vector spr_msy(1,3);
vector fpr_msy(1,3);
vector R_eq(1,3);
number df;
vector dmsy(styrR,endyr);
number ddmsy;

//Per-recruit stuff in report section
matrix N_spr_F0(styrR,endyr,1,nages);
vector N_spr(1,nages);
vector spr_F0(styrR,endyr);
vector spr_static(styr,endyr);
vector fpr_F0(styrR,endyr);
vector fpr_static(styr,endyr);
vector F_pr(1,201);//fishing mortality vector for per-recruit curve output
vector F_DSV_pr(1,201);
vector SSB_pr(1,201);//spawning biomass per-recruit output
vector FEC_pr(1,201);//fecundity per-recruit output
vector Y_pr(1,201);//yield per-recruit output
//Equilibrium stuff for per-recruit section in report section
vector Z_eq(1,nages);
vector N_eq(1,nages);
number spr_eq;
number fpr_eq;
number C_eq;
vector SSB_eq(1,201);
vector FEC_eq(1,201);
vector Y_eq(1,201);

//DUMMY parameter to hold off MSY calcs until last
init_number dummy(4);

//Likelihood weights and components
vector lambda(1,13);
number f_U_age0;
number f_U_pound;
number f_agec_reduction;
number f_L_reduction;
number f_agec_bait;
number f_L_bait;
number f_N_dev;
number f_N_last3;
number f_selpar_dev;
number f_F_dev_reduction;
number f_F_dev_bait;
number f_M_dev;
number f_dummy;
objective_function_value f;

INITIALIZATION_SECTION
//population numbers
R1_log 6;
R0_log 6;
```

```
steep 0.7;

//selectivity parameters
selpar_s_reduction 2.0;
selpar_A50_reduction 1.0;
selpar_s_bait 2.0;
selpar_A50_bait 2.0;

//double logistic selectivity parameters
//selpar_s2_reduction 5.0;
//selpar_A502_reduction 6.0;
selpar_s2_bait 5.0;
selpar_A502_bait 6.0;

q_log_U_age0 -3.0;
q_log_U_pound 6.0;

F_log_avg_reduction 0;
F_log_avg_bait 0;

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

RUNTIME_SECTION
maximum_function_evaluations 9000;
convergence_criteria 1e-9;

PRELIMINARY_CALCS_SECTION
  //stuff for R output
  YEAR.fill_seqadd(styrR,1);
  AGE.fill_seqadd(0,1);

  F_DSV.initialize();
  F_reduction.initialize();
  F_bait.initialize();
  C_reduction.initialize();
  C_bait.initialize();

  //Weights for likelihood components
  lambda(1)=1.0;   //CPUE age0 index
  lambda(2)=1.0;   //CPUE seamap index
  lambda(3)=0.1;   //Reduction fishery age comps sample size
  lambda(4)=1.0;   //Reduction fishery landings
  lambda(5)=0.5;   //Bait fishery age comps sample size
  lambda(6)=10.0;   //Bait fishery landings
  lambda(7)=1.0;   //Recruitment deviations (including R1_constraint)
  lambda(8)=1.0;   //additional constraint on last 3 years R's
  lambda(9)=1.0;   //selpar deviations
  lambda(10)=1.0;   //constraint on F deviations for reduction fishery
  lambda(11)=1.0;  //constraint on F deviations for bait fishery
  lambda(12)=1.0;   //M constraint
  lambda(13)=1.0;   //DUMMY

  //re-weight cv's
```

```
  U_age0_cv=0.2;
  U_pound_cv=0.2;
  L_reduction_cv=0.01;
  L_bait_cv=0.30;

  //Fixed or starting values for some parameters
  R_log_dev=0.0;
  selpar_A50_dev_reduction=0.0;
  selpar_A50_dev_bait=0.0;

  //difference for msy derivative approximations
  df=0.0000001;

  //fill in F's for per-recruit stuff
  F_pr.fill_seqadd(0,.015);

TOP_OF_MAIN_SECTION
  arrmblsize=2000000;
  gradient_structure::set_MAX_NVAR_OFFSET(1600);
  gradient_structure::set_GRADSTACK_BUFFER_SIZE(15000000);
  gradient_structure::set_CMPDIF_BUFFER_SIZE(100000000);
  gradient_structure::set_NUM_DEPENDENT_VARIABLES(1000);

PROCEDURE_SECTION
  steep_sd=steep;
  get_selectivity();
  //cout << "made it through selectivity" << endl;
  get_mortality();
  //cout << "made it through mortality" << endl;
  get_spr_F0();
  //cout << "made it through spr_F0" << endl;
  get_numbers_at_age();
  //cout << "made it through numbers-at-age" << endl;

  get_catch_at_age();

  //cout << "made it through catch-at-age" << endl;

  get_biomasses();
  //cout << "made it through biomasses" << endl;
  get_pred_agecomps();
  //cout << "made it through pred agecomps" << endl;
  if(last_phase())
  {
    get_msy();
  }
  //cout << "made it through msy" << endl;
  evaluate_the_objective_function();
  //cout << "made it through objective function" << endl;

  //M vector for getting std dev's
  M_vec_sd=M(endyr);

  //Compute the exploitation rate for ages 1+ and pop wgtd F for ages 2+
  for(y=styrR; y<=endyr; y++)
```

```
  {
   E(y)=sum(C_total(y)(2,nages))/sum(N(y)(2,nages));
   F_DSV_vec(y)=((F_bait(y)(3,nages)+F_reduction(y)(3,nages))*N(y)(3,nages))/sum(N(y)(3,nages));
  }

FUNCTION get_selectivity
  //--below needed for time varying logistic------------------------------------------
  for (y=styr; y<=endyr; y++)
  {
   for (a=1; a<=nages; a++)
   {
    //---logistic-----------------------------------------------------------------
    sel_reduction(y,a)=1./(1.+mfexp(-1.*selpar_s_reduction*(double(agebins(a))-selpar_A50_reduction)));
    //sel_bait(y,a)=1./(1.+mfexp(-1.*selpar_s_bait*(double(agebins(a))-selpar_A50_bait)));
    //---double logistic-----------------------------------------------------------
    //sel_reduction(y,a)=(1./(1.+mfexp(-1.*selpar_s_reduction*(double(agebins(a))-selpar_A50_reduction))))*(1-
(1./(1.+mfexp(-1.*selpar_s2_reduction*(double(agebins(a))-selpar_A502_reduction)))));
    sel_bait(y,a)=(1./(1.+mfexp(-1.*selpar_s_bait*(double(agebins(a))-selpar_A50_bait))))*(1-(1./(1.+mfexp(-
1.*selpar_s2_bait*(double(agebins(a))-selpar_A502_bait)))));
    //---logistic (time varying)---------------------------------------------------
    //if (y>=agec_reduction_styr)
    //{
     //sel_reduction(y,a)=1./(1.+mfexp(-1.*selpar_s_reduction*(double(agebins(a))-
(selpar_A50_reduction+selpar_A50_dev_reduction(y)))));
     //---double logistic------------------------------------------------------------
     //sel_reduction(y,a)=(1./(1.+mfexp(-1.*selpar_s_reduction*(double(agebins(a))-
(selpar_A50_reduction+selpar_A50_dev_reduction(y))))))*(1-(1./(1.+mfexp(-
1*selpar_s2_reduction*(double(agebins(a))-selpar_A502_reduction)))));
    //}
    //if (y>=agec_bait_styr)
    //{
     //sel_bait(y,a)=1./(1.+mfexp(-1.*selpar_s_bait*(double(agebins(a))-
(selpar_A50_bait+selpar_A50_dev_bait(y)))));
     //---double logistic------------------------------------------------------------
     //sel_bait(y,a)=(1./(1.+mfexp(-1.*selpar_s_bait*(double(agebins(a))-
(selpar_A50_bait+selpar_A50_dev_bait(y))))))*(1-(1./(1.+mfexp(-1*selpar_s2_bait*(double(agebins(a))-
selpar_A502_bait)))));
    //}
   }
   //---double logistic stuff-------------------------------------------------------
   //sel_reduction(y)=sel_reduction(y)/max(sel_reduction(y));
   sel_bait(y)=sel_bait(y)/max(sel_bait(y));
   //---age-specific selectivity parameters-------------------------------------------
   //sel_reduction(y)=sel_p_reduction/(max(sel_p_reduction)+0.0001);
   //sel_bait(y)=sel_p_bait/(max(sel_p_bait)+0.0001);
  }

FUNCTION get_mortality
  F_full=0.0;
  for (y=styr; y<=endyr; y++)
  {
   M(y)=M_vec*(M_const+1.0)*(M_dev(y)+1.0);
   if(y>=L_reduction_styr)
   {
    F_reduction(y)=sel_reduction(y)*mfexp(F_log_avg_reduction+F_log_dev_reduction(y));
```

```
    F_full(y)+=mfexp(F_log_avg_reduction+F_log_dev_reduction(y));
   }
   if(y>=L_bait_styr)
   {
    F_bait(y)=sel_bait(y)*mfexp(F_log_avg_bait+F_log_dev_bait(y));
    F_full(y)+=mfexp(F_log_avg_bait+F_log_dev_bait(y));
   }
   else //earlier years bait landings asssumed to have average F from first 3 years
   {
    F_bait(y)=sel_bait(y)*mfexp((3.0*F_log_avg_bait+sum(F_log_dev_bait(L_bait_styr,L_bait_styr+2)))/3);
    F_full(y)+=mfexp((3*F_log_avg_bait+sum(F_log_dev_bait(L_bait_styr,L_bait_styr+2)))/3);
   }
   F_total(y)=F_reduction(y)+F_bait(y);
   Z(y)=F_total(y)+M(y);
  }
  for(y=styrR; y<styr; y++)
  {
   M(y)=M(styr);
   Z(y)=Z(styr);
   F_reduction(y)=F_reduction(styr);
   F_bait(y)=F_bait(styr);
   F_full(y)=F_full(styr);
   F_total(y)=F_total(styr);
  }

FUNCTION get_spr_F0
  for(y=styrR; y<=endyr; y++)
  {
   N_spr_F0(y,1)=1.0;
   for(a=2; a<=nages; a++)
   {
    N_spr_F0(y,a)=N_spr_F0(y,a-1)*mfexp(-1.*M(y,a-1));
   }
   N_spr_F0(y,nages)=N_spr_F0(y,nages-1)*mfexp(-1.*M(y,nages-1))/(1-mfexp(-1.*M(y,nages)));//plus group
   if(y<styr)
   {
    spr_F0(y)=sum(elem_prod(elem_prod(N_spr_F0(y),wgt_spawn(styr)),mat_f))*0.5;
    fpr_F0(y)=sum(elem_prod(elem_prod(N_spr_F0(y),mat_f),fec_f(styr)))*0.5;
   }
   if(y>=styr)
   {
    spr_F0(y)=sum(elem_prod(elem_prod(N_spr_F0(y),wgt_spawn(y)),mat_f))*0.5;
    fpr_F0(y)=sum(elem_prod(elem_prod(N_spr_F0(y),mat_f),fec_f(y)))*0.5;
   }
  }

FUNCTION get_numbers_at_age
  R0=mfexp(R0_log);
//Initial age
  N(styrR,1)=mfexp(R1_log);
  for (a=2; a<=nages; a++)
  {
   N(styrR,a)=N(styrR,a-1)*mfexp(-1.*Z(styrR,a-1));
  }
//plus group calculation
```

```
  N(styrR,nages)=N(styrR,nages-1)*mfexp(-1.*Z(styrR,nages-1))/(1.-mfexp(-1.*Z(styrR,nages)));

//Biomass calcs
  SSB(styrR)=sum(elem_prod(elem_prod(N(styrR),wgt_spawn(styr)),mat_f))*0.5;
  FEC(styrR)=sum(elem_prod(elem_prod(N(styrR),mat_f),fec_f(styr)))*0.5;
  B(styrR)=elem_prod(N(styrR),wgt_fish(styr));
  B_sum(styrR)=sum(B(styrR));

//Constraint for first recruitment to follow S-R curve
  if(SRswitch<2)//Beverton-Holt stock-recruit function
  {
    //R1_log_constraint=log(((0.8*R0*steep*SSB(styrR))/(0.2*R0*spr_F0(styrR)*(1-steep)+(steep-
0.2)*SSB(styrR)))+0.00001);
    R1_log_constraint=log(((0.8*R0*steep*FEC(styrR))/(0.2*R0*fpr_F0(styrR)*(1-steep)+(steep-
0.2)*FEC(styrR)))+0.00001);
  }
  if(SRswitch>1)//Ricker stock-recruit function
  {
    //R1_log_constraint=log((SSB(styrR)/spr_F0(styrR))*mfexp(log((steep*4)/(1-steep))*(1-
SSB(styrR)/(R0*spr_F0(styrR))))+0.00001);
    R1_log_constraint=log((FEC(styrR)/fpr_F0(styrR))*mfexp(log((steep*4)/(1-steep))*(1-
FEC(styrR)/(R0*fpr_F0(styrR))))+0.00001);
  }

//Rest of years ages
  for (y=styrR; y<endyr; y++)
  {
    if(SRswitch<2)//Beverton-Holt stock-recruit function

    {

      //N(y+1,1)=mfexp(log(((0.8*R0*steep*SSB(y))/(0.2*R0*spr_F0(y)*(1-steep)+(steep-
0.2)*SSB(y)))+0.00001)+R_log_dev(y+1));
      N(y+1,1)=mfexp(log(((0.8*R0*steep*FEC(y))/(0.2*R0*fpr_F0(y)*(1-steep)+(steep-
0.2)*FEC(y)))+0.00001)+R_log_dev(y+1));
    }
    if(SRswitch>1)//Ricker stock-recruit function
    {
      //N(y+1,1)=mfexp(log((SSB(y)/spr_F0(y))*mfexp(log((steep*4)/(1-steep))*(1-
SSB(y)/(R0*spr_F0(y))))+0.00001)+R_log_dev(y+1));
      N(y+1,1)=mfexp(log((FEC(y)/fpr_F0(y))*mfexp(log((steep*4)/(1-steep))*(1-
FEC(y)/(R0*fpr_F0(y))))+0.00001)+R_log_dev(y+1));
    }
    N(y+1)(2,nages)=++elem_prod(N(y)(1,nages-1),(mfexp(-1.*Z(y)(1,nages-1))));
    N(y+1,nages)+=N(y,nages)*mfexp(-1.*Z(y,nages));//plus group
    if(y<styr)
    {
      SSB(y+1)=sum(elem_prod(elem_prod(N(y+1),wgt_spawn(styr)),mat_f))*0.5;
      FEC(y+1)=sum(elem_prod(elem_prod(N(y+1),mat_f),fec_f(styr)))*0.5;
      B(y+1)=elem_prod(N(y+1),wgt_fish(styr));
    }
    if(y>=styr)
    {
      SSB(y+1)=sum(elem_prod(elem_prod(N(y+1),wgt_spawn(y)),mat_f))*0.5;
      FEC(y+1)=sum(elem_prod(elem_prod(N(y+1),mat_f),fec_f(y)))*0.5;
```

```
    B(y+1)=elem_prod(N(y+1),wgt_fish(y));
   }
   B_sum(y+1)=sum(B(y+1));
  }

//Recruitment time series
  R_age0=column(N,1);
  R_age1=column(N,2);
  R1=mfexp(R1_log);

//Benchmark parameters
  S0=spr_F0(endyr)*R0;
  S1S0=SSB(styr)/S0;
  SendS0=SSB(endyr)/S0;
  FEC0=fpr_F0(endyr)*R0;
  FEC1FEC0=FEC(styr)/FEC0;
  FECendFEC0=FEC(endyr)/FEC0;

FUNCTION get_catch_at_age
  for (y=styrR; y<=endyr; y++)
  {
   for(a=1; a<=nages; a++)
   {
    C_reduction(y,a)=N(y,a)*F_reduction(y,a)*(1.-mfexp(-1.*Z(y,a)))/Z(y,a);
    C_bait(y,a)=N(y,a)*F_bait(y,a)*(1.-mfexp(-1.*Z(y,a)))/Z(y,a);
    C_total(y,a)=N(y,a)*F_total(y,a)*(1.-mfexp(-1.*Z(y,a)))/Z(y,a);
   }
  }

FUNCTION get_biomasses
  for (y=styrR; y<=endyr; y++)
  {
   if(y<styr)
   {
    L_reduction(y)=elem_prod(C_reduction(y),wgt_fish(styr));
    L_bait(y)=elem_prod(C_bait(y),wgt_fish(styr));
    B(y)=elem_prod(N(y),wgt_fish(styr));
   }
   if(y>=styr)
   {
    L_reduction(y)=elem_prod(C_reduction(y),wgt_fish(y));
    L_bait(y)=elem_prod(C_bait(y),wgt_fish(y));
    B(y)=elem_prod(N(y),wgt_fish(y));
   }
   L_total(y)=L_reduction(y)+L_bait(y);
   B_sum(y)=sum(B(y));
  }

//predicted landings
  for (y=L_reduction_styr; y<=L_reduction_endyr; y++)
  {
   L_reduction_pred(y)=sum(L_reduction(y));
  }
  for (y=L_bait_styr; y<=L_bait_endyr; y++)
  {
```

```
   L_bait_pred(y)=sum(L_bait(y));
  }

//Predicted CPUE age0 index
  for (y=U_age0_styr; y<=U_age0_endyr; y++)
  {
   U_age0_pred(y)=mfexp(q_log_U_age0)*N(y,1);
  }

//Predicted CPUE pound index
  for (y=U_pound_styr; y<=U_pound_endyr; y++)
  {
   U_pound_pred(y)=mfexp(q_log_U_pound)*sum(elem_prod(B(y),U_pound_sel));
  }

FUNCTION get_pred_agecomps
  //compute age comps by year
  for (y=agec_reduction_styr;y<=agec_reduction_endyr;y++)
  {
   agec_reduction_pred(y)=C_reduction(y)/sum(C_reduction(y));
  }
  for (y=agec_bait_styr;y<=agec_bait_endyr;y++)
  {
   agec_bait_pred(y)=C_bait(y)/sum(C_bait(y));
  }

FUNCTION get_msy
  for(y=styrR; y<=endyr; y++)
  {
  //computed weighted average selectivity from last 3 years of fisheries
  if(y>=styr)
  {

sel_msy(y)=(sum(C_reduction(y))*sel_reduction(y)+sum(C_bait(y))*sel_bait(y))/(sum(C_reduction(y))+sum(C_bai
t(y)));
  }
  if(y<styr)
  {

sel_msy(y)=(sum(C_reduction(y))*sel_reduction(styr)+sum(C_bait(y))*sel_bait(styr))/(sum(C_reduction(y))+sum(
C_bait(y)));
  }

  //use Newton's method to get Fmsy, MSY, and Smsy
  for (int i=1; i<=10; i++){
   F_msy(2)=F_msy(1)-df;
   F_msy(3)=F_msy(1)+df;
   L_msy=0.0;

   Z_msy(1)=sel_msy(y)*F_msy(1)+M(endyr);
   Z_msy(2)=sel_msy(y)*F_msy(2)+M(endyr);
   Z_msy(3)=sel_msy(y)*F_msy(3)+M(endyr);
   //Initial age
   N_msy(1,1)=1.0;
   N_msy(2,1)=1.0;
```

```
N_msy(3,1)=1.0;
for (a=2; a<=nages; a++)
{
  N_msy(1,a)=N_msy(1,a-1)*mfexp(-1.*Z_msy(1,a-1));
  N_msy(2,a)=N_msy(2,a-1)*mfexp(-1.*Z_msy(2,a-1));
  N_msy(3,a)=N_msy(3,a-1)*mfexp(-1.*Z_msy(3,a-1));
}
//last age is pooled
N_msy(1,nages)=N_msy(1,nages-1)*mfexp(-1.*Z_msy(1,nages-1))/(1.-mfexp(-1.*Z_msy(1,nages)));
N_msy(2,nages)=N_msy(2,nages-1)*mfexp(-1.*Z_msy(2,nages-1))/(1.-mfexp(-1.*Z_msy(2,nages)));
N_msy(3,nages)=N_msy(3,nages-1)*mfexp(-1.*Z_msy(3,nages-1))/(1.-mfexp(-1.*Z_msy(3,nages)));
spr_msy(1)=sum(elem_prod(elem_prod(N_msy(1),wgt_spawn(endyr)),mat_f))*0.5;
spr_msy(2)=sum(elem_prod(elem_prod(N_msy(2),wgt_spawn(endyr)),mat_f))*0.5;
spr_msy(3)=sum(elem_prod(elem_prod(N_msy(3),wgt_spawn(endyr)),mat_f))*0.5;
fpr_msy(1)=sum(elem_prod(elem_prod(N_msy(1),mat_f),fec_f(endyr)))*0.5;
fpr_msy(2)=sum(elem_prod(elem_prod(N_msy(2),mat_f),fec_f(endyr)))*0.5;
fpr_msy(3)=sum(elem_prod(elem_prod(N_msy(3),mat_f),fec_f(endyr)))*0.5;
if(SRswitch<2) //Beverton-Holt
{
  //R_eq(1)=(R0/((5*steep-1)*spr_msy(1)))*(4*steep*spr_msy(1)-spr_F0(endyr)*(1-steep));
  //R_eq(2)=(R0/((5*steep-1)*spr_msy(2)))*(4*steep*spr_msy(2)-spr_F0(endyr)*(1-steep));
  //R_eq(3)=(R0/((5*steep-1)*spr_msy(3)))*(4*steep*spr_msy(3)-spr_F0(endyr)*(1-steep));
  R_eq(1)=(R0/((5*steep-1)*fpr_msy(1)))*(4*steep*fpr_msy(1)-fpr_F0(endyr)*(1-steep));
  R_eq(2)=(R0/((5*steep-1)*fpr_msy(2)))*(4*steep*fpr_msy(2)-fpr_F0(endyr)*(1-steep));
  R_eq(3)=(R0/((5*steep-1)*fpr_msy(3)))*(4*steep*fpr_msy(3)-fpr_F0(endyr)*(1-steep));
}
if(SRswitch>1) //Ricker
{
  //R_eq(1)=(R0/(spr_msy(1)/spr_F0(endyr)))*(1+log(spr_msy(1)/spr_F0(endyr))/log((steep*4)/(1-steep)));
  //R_eq(2)=(R0/(spr_msy(2)/spr_F0(endyr)))*(1+log(spr_msy(2)/spr_F0(endyr))/log((steep*4)/(1-steep)));
  //R_eq(3)=(R0/(spr_msy(3)/spr_F0(endyr)))*(1+log(spr_msy(3)/spr_F0(endyr))/log((steep*4)/(1-steep)));
  R_eq(1)=(R0/(fpr_msy(1)/fpr_F0(endyr)))*(1+log(fpr_msy(1)/fpr_F0(endyr))/log((steep*4)/(1-steep)));
  R_eq(2)=(R0/(fpr_msy(2)/fpr_F0(endyr)))*(1+log(fpr_msy(2)/fpr_F0(endyr))/log((steep*4)/(1-steep)));
  R_eq(3)=(R0/(fpr_msy(3)/fpr_F0(endyr)))*(1+log(fpr_msy(3)/fpr_F0(endyr))/log((steep*4)/(1-steep)));
}
//Initial age
N_msy(1)=R_eq(1);
N_msy(2)=R_eq(2);
N_msy(3)=R_eq(3);
for (a=2; a<=nages; a++)
{
  N_msy(1,a)=N_msy(1,a-1)*mfexp(-1.*Z_msy(1,a-1));
  N_msy(2,a)=N_msy(2,a-1)*mfexp(-1.*Z_msy(2,a-1));
  N_msy(3,a)=N_msy(3,a-1)*mfexp(-1.*Z_msy(3,a-1));
}
//last age is pooled
N_msy(1,nages)=N_msy(1,nages-1)*mfexp(-1.*Z_msy(1,nages-1))/(1.-mfexp(-1.*Z_msy(1,nages)));
N_msy(2,nages)=N_msy(2,nages-1)*mfexp(-1.*Z_msy(2,nages-1))/(1.-mfexp(-1.*Z_msy(2,nages)));
N_msy(3,nages)=N_msy(3,nages-1)*mfexp(-1.*Z_msy(3,nages-1))/(1.-mfexp(-1.*Z_msy(3,nages)));
SSB_msy(1)=sum(elem_prod(elem_prod(N_msy(1),wgt_spawn(endyr)),mat_f))*0.5;
SSB_msy(2)=sum(elem_prod(elem_prod(N_msy(2),wgt_spawn(endyr)),mat_f))*0.5;
SSB_msy(3)=sum(elem_prod(elem_prod(N_msy(3),wgt_spawn(endyr)),mat_f))*0.5;
FEC_msy(1)=sum(elem_prod(elem_prod(N_msy(1),mat_f),fec_f(endyr)))*0.5;
FEC_msy(2)=sum(elem_prod(elem_prod(N_msy(2),mat_f),fec_f(endyr)))*0.5;
FEC_msy(3)=sum(elem_prod(elem_prod(N_msy(3),mat_f),fec_f(endyr)))*0.5;
```

```
   C_msy=0.0;
   for(a=1; a<=nages; a++){
     C_msy(a)=N_msy(1,a)*((Z_msy(1,a)-M(endyr,a))/Z_msy(1,a))*(1.-mfexp(-1.*Z_msy(1,a)));
     L_msy(1)+=N_msy(1,a)*((Z_msy(1,a)-M(endyr,a))/Z_msy(1,a))*(1.-mfexp(-
1.*Z_msy(1,a)))*wgt_fish(endyr,a);
     L_msy(2)+=N_msy(2,a)*((Z_msy(2,a)-M(endyr,a))/Z_msy(2,a))*(1.-mfexp(-
1.*Z_msy(2,a)))*wgt_fish(endyr,a);
     L_msy(3)+=N_msy(3,a)*((Z_msy(3,a)-M(endyr,a))/Z_msy(3,a))*(1.-mfexp(-
1.*Z_msy(3,a)))*wgt_fish(endyr,a);
   }
   dmsy(y)=(L_msy(3)-L_msy(2))/(2.*df);
   ddmsy=(L_msy(3)-2.*L_msy(1)+L_msy(2))/square(df);
   if(square(ddmsy)>1e-12){
     F_msy(1)-=(dmsy(y)/ddmsy);
   }
   if(F_msy(1)<=df){
     F_msy(1)=df;
   }
  }
  msy_out(y)=L_msy(1);
  E_msy_out(y)=sum(C_msy(2,nages))/sum(N_msy(1)(2,nages));
  F_msy_out(y)=F_msy(1);
  F_DSV_msy_out(y)=((Z_msy(1)-M(endyr))(3,nages)*N_msy(1)(3,nages))/sum(N_msy(1)(3,nages));
  SSB_msy_out(y)=SSB_msy(1);
  FEC_msy_out(y)=FEC_msy(1);
  }

  FdF_msy=elem_div(F_full,F_msy_out);
  SdSSB_msy=elem_div(SSB,SSB_msy_out);
  FECdFEC_msy=elem_div(FEC,FEC_msy_out);
  EdE_msy=elem_div(E,E_msy_out);
  SdSSB_msy_end=SdSSB_msy(endyr);
  FECdFEC_msy_end=FECdFEC_msy(endyr);
  FdF_msy_end=FdF_msy(endyr);

FUNCTION evaluate_the_objective_function
  f=0.;
  f_U_age0=0.;

  for (y=U_age0_styr; y<=U_age0_endyr; y++)
  {
   f_U_age0+=square(log(U_age0_obs(y)+.001)-log(U_age0_pred(y)+.001))/(2.0*square(U_age0_cv(y)));
  }
  f+=lambda(1)*f_U_age0;

  f_U_pound=0.;

  for (y=U_pound_styr; y<=U_pound_endyr; y++)
  {
   f_U_pound+=square(log(U_pound_obs(y)+.001)-log(U_pound_pred(y)+.001))/(2.0*square(U_pound_cv(y)));
  }
  f+=lambda(2)*f_U_pound;

  f_agec_reduction=0.;
  for (y=agec_reduction_styr; y<=agec_reduction_endyr; y++)
```

```
 {
   f_agec_reduction-
=lambda(3)*agec_reduction_nsamp(y)*sum(elem_prod((agec_reduction_obs(y)+.001),log(agec_reduction_pred(y)+
.001))-elem_prod((agec_reduction_obs(y)+.001),log(agec_reduction_obs(y)+.001)));
 }
 f+=f_agec_reduction;

 f_agec_bait=0.;
 for (y=agec_bait_styr; y<=agec_bait_endyr; y++)
 {
   f_agec_bait-
=lambda(5)*agec_bait_nsamp(y)*sum(elem_prod((agec_bait_obs(y)+.001),log(agec_bait_pred(y)+.001))-
elem_prod((agec_bait_obs(y)+.001),log(agec_bait_obs(y)+.001)));
 }
 f+=f_agec_bait;

 f_L_reduction=0.;
 for (y=L_reduction_styr; y<=L_reduction_endyr; y++)
 {
   f_L_reduction+=square(log(L_reduction_obs(y)+.001)-
log(L_reduction_pred(y)+.001))/(2.0*square(L_reduction_cv));
 }
 f_L_bait=0.;
 for (y=L_bait_styr; y<=L_bait_endyr; y++)
 {
   f_L_bait+=square(log(L_bait_obs(y)+.001)-log(L_bait_pred(y)+.001))/(2.0*square(L_bait_cv));
 }
 f+=lambda(4)*f_L_reduction+lambda(6)*f_L_bait;

 f_N_dev=lambda(7)*square(R1_log-R1_log_constraint);
 f_N_dev+=lambda(7)*norm2(R_log_dev);
 f+=f_N_dev;

 f_N_last3=lambda(8)*norm2(R_log_dev(endyr-2,endyr));
 f+=f_N_last3;

 f_selpar_dev=lambda(9)*(norm2(selpar_A50_dev_reduction)+norm2(selpar_A50_dev_bait));
 f+=f_selpar_dev;

 f_F_dev_reduction=lambda(10)*norm2(F_log_dev_reduction);
 f+=f_F_dev_reduction;

 f_F_dev_bait=lambda(11)*norm2(F_log_dev_bait);
 f+=f_F_dev_bait;

 f_M_dev=lambda(12)*norm2(M_dev);
 f+=f_M_dev;

 f_dummy=square(dummy);
 f+=lambda(13)*f_dummy;

REPORT_SECTION
 get_msy();

 report << "Likelihood " << "Value " << "Weight" << endl;
```

```
report << "age0_index " << f_U_age0 << " " << lambda(1) << endl;
report << "pound_index " << f_U_pound << " " << lambda(2) << endl;
report << "reduction_agec " << f_agec_reduction << " " << lambda(3) << endl;
report << "L_reduction " << f_L_reduction << " " << lambda(4) << endl;
report << "bait_agec " << f_agec_bait << " " << lambda(5) << endl;
report << "L_bait " << f_L_bait << " " << lambda(6) << endl;
report << "R_dev " << f_N_dev << " " << lambda(7) << endl;
report << "R_dev_last3 " << f_N_last3 << " " << lambda(8) << endl;
report << "selpar_dev " << f_selpar_dev << " " << lambda(9) << endl;
report << "F_dev_reduction " << f_F_dev_reduction << " " << lambda(10) << endl;
report << "F_dev_bait " << f_F_dev_bait << " " << lambda(11) << endl;
report << "M_dev " << f_M_dev << " " << lambda(12) << endl;
report << "DUMMY " << f_dummy << " " << lambda(13) << endl;

report << "TotalLikelihood " << f << endl;

report << "Error levels in model" << endl;
report << "U_age0_cv " << U_age0_cv << endl;
report << "U_pound_cv " << U_pound_cv << endl;
report << "L_reduction_cv " << L_reduction_cv << endl;
report << "L_bait_cv " << L_bait_cv << endl;

report << "NaturalMortality in last year " << endl;
report << "Age " << agebins << endl;
report << "M " << M(endyr) << endl;

report << "VirginSSB " << S0 << endl;
report << "SSB1/VirginSSB " << S1S0 << endl;
report << "SSB(end)/VirginSSB " << SendS0 << endl;
report << "VirginFEC " << FEC0 << endl;
report << "FEC1/VirginFEC " << FEC1FEC0 << endl;
report << "FEC(end)/VirginSSB " << FECendFEC0 << endl;

report << "SSB/R_F0" << endl;
report << "Year";
for(y=styrR; y<=endyr; y++)
{
 report << " " << y;
}
report << endl;
report << "SSB/R_F0 " << spr_F0 << endl;
report << "FEC/R_F0 " << fpr_F0 << endl;
report << "Steepness " << steep << endl;
report << "R0 " << R0 << endl;
if(SRswitch<2)
{
 report << "S-R_curve Beverton-Holt" << endl;
}
if(SRswitch>1)
{
 report << "S-R_curve Ricker" << endl;
}

report << "MSYstuff" << endl;
report << "N-R_convergence " << dmsy << endl;
```

```
report << "Emsy " << E_msy_out << endl;
report << "Fmsy " << F_msy_out << endl;
report << "Fmsy_DSV " << F_DSV_msy_out << endl;
report << "SSBmsy " << SSB_msy_out << endl;
report << "FECmsy " << FEC_msy_out << endl;
report << "MSY " << msy_out << endl;
report << "SSB2002/SSBmsy " << SdSSB_msy_end << endl;
report << "FEC2002/FECmsy " << FECdFEC_msy_end << endl;
report << "F2002/Fmsy " << FdF_msy_end << endl;
report << "F_DSV(2002)/Fmsy_DSV " << F_DSV_vec(endyr)/F_DSV_msy_out(endyr) << endl;

report << "Year";
for(y=styrR; y<=endyr; y++)
{
 report << " " << y;
}
report << endl;
report << "E/Emsy " << EdE_msy << endl;
report << "F/Fmsy " << FdF_msy << endl;
report << "F_DSV/Fmsy_DSV " << elem_div(F_DSV_vec,F_DSV_msy_out) << endl;
report << "SSB/SSBmsy " << SdSSB_msy << endl;
report << "FEC/FECmsy " << FECdFEC_msy << endl;

report << "Recruits" << endl;
report << "Year";
for(y=styrR; y<=endyr; y++)
{
 report << " " << y;
}
report << endl;
report << "Age-0_recruits " << R_age0 << endl;
report << "Age-1_recruits " << R_age1 << endl;
report << "SSB" << endl;
report << "Year";
for(y=styrR; y<=endyr; y++)
{
 report << " " << y;
}
report << endl;
report << "SSB " << SSB << endl;
report << "FEC " << FEC << endl;
report << "Lagged_R " << R_age0(styrR+1,endyr) << endl;

for(y=styrR; y<=endyr; y++)
{
   if(y<styrR+1)
   {
    if(SRswitch<2)
    {
     //R_pred(y)=(0.8*R0*steep*SSB(y))/(0.2*spr_F0(y)*R0*(1-steep)+(steep-0.2)*SSB(y));

     R_pred(y)=(0.8*R0*steep*FEC(y))/(0.2*fpr_F0(y)*R0*(1-steep)+(steep-0.2)*FEC(y));
    }
    if(SRswitch>1)
    {
```

```
      //R_pred(y)=(SSB(y)/spr_F0(y))*mfexp(log((steep*4)/(1-steep))*(1-SSB(y)/(R0*spr_F0(y))));

      R_pred(y)=(FEC(y)/fpr_F0(y))*mfexp(log((steep*4)/(1-steep))*(1-FEC(y)/(R0*fpr_F0(y))));
     }
    }
    else
    {
     if(SRswitch<2)
     {
      //R_pred(y)=(0.8*R0*steep*SSB(y-1))/(0.2*spr_F0(y-1)*R0*(1-steep)+(steep-0.2)*SSB(y-1));

      R_pred(y)=(0.8*R0*steep*FEC(y-1))/(0.2*fpr_F0(y-1)*R0*(1-steep)+(steep-0.2)*FEC(y-1));
     }
     if(SRswitch>1)
     {
      //R_pred(y)=(SSB(y-1)/spr_F0(y-1))*mfexp(log((steep*4)/(1-steep))*(1-SSB(y-1)/(R0*spr_F0(y-1))));

      R_pred(y)=(FEC(y-1)/fpr_F0(y-1))*mfexp(log((steep*4)/(1-steep))*(1-FEC(y-1)/(R0*fpr_F0(y-1))));
     }
    }


    //R_rep(y)=SSB(y)/spr_F0(y);
    R_rep(y)=FEC(y)/fpr_F0(y);
  }
  report << "S-R_R " << R_pred << endl;
  report << "Replacement " << R_rep << endl;


  report << "Reduction fishery selectivity A50 parameters" << endl;
  report << "Year";
  for(y=agec_reduction_styr; y<=endyr; y++)
  {
   report << " " << y;
  }
  report << endl;
  report << "A50_parameter " << selpar_A50_reduction+selpar_A50_dev_reduction << endl;
  report << "Reduction fishery selectivity" << endl;
  report << "Year/Age " << agebins << endl;
  for(y=agec_reduction_styr; y<=endyr; y++)
  {
   report << y << sel_reduction(y) << endl;
  }
  report << "Bait fishery selectivity A50 parameters" << endl;
  report << "Year";
  for(y=agec_bait_styr; y<=endyr; y++)
  {
   report << " " << y;
  }
  report << endl;
  report << "A50_parameter " << selpar_A50_bait+selpar_A50_dev_bait << endl;
  report << "Bait fishery selectivity" << endl;
  report << "Year/Age " << agebins << endl;
  for(y=agec_bait_styr; y<=endyr; y++)
  {
```

```
  report << y << sel_bait(y) << endl;
}

report << "Full F reduction fishery" << endl;
report << "Year";
for(y=L_reduction_styr; y<=endyr; y++)
{
  report << " " << y;
}
report << endl;
report << "FullF_reduction " << mfexp(F_log_avg_reduction+F_log_dev_reduction) << endl;
report << "Year";
for(y=L_bait_styr; y<=endyr; y++)
{
  report << " " << y;
}
report << endl;
report << "FullF_bait " << mfexp(F_log_avg_bait+F_log_dev_bait) << endl;
report << "Year";
for(y=styrR; y<=endyr; y++)
{
  report << " " << y;
}
report << endl;
report << "FullF_total " << F_full << endl;
report << "Doug's_F " << F_DSV_vec << endl;
report << "Exploitation_rate " << E << endl;

report << "CPUE_age0_index" << endl;
report << "age0_index_q " << mfexp(q_log_U_age0) << endl;
report << "Year";

for(y=U_age0_styr; y<=endyr; y++)
{
  report << " " << y;
}
report << endl;
report << "Observed " << U_age0_obs << endl;

report << "Predicted " << U_age0_pred << endl;

report << "CPUE_pound_index" << endl;
report << "pound_index_q " << mfexp(q_log_U_pound) << endl;
report << "Year";

for(y=U_pound_styr; y<=endyr; y++)
{
  report << " " << y;
}
report << endl;
report << "Observed " << U_pound_obs << endl;
report << "Predicted " << U_pound_pred << endl;

report << "reduction landings (1000mt)" << endl;
report << "Year";
```

```
for(y=L_reduction_styr; y<=endyr; y++)
{
  report << " " << y;
}
report << endl;
report << "Observed " << L_reduction_obs << endl;
report << "Predicted " << L_reduction_pred << endl;

report << "bait landings (1000mt)" << endl;
report << "Year";
for(y=L_bait_styr; y<=endyr; y++)
{
  report << " " << y;

}
report << endl;
report << "Observed " << L_bait_obs << endl;
report << "Predicted " << L_bait_pred << endl;

report << "NaturalMortality " << endl;
report << "Year/Age " << agebins << endl;
for(y=styrR; y<=endyr; y++)
{
  report << y << M(y) << endl;
}
report << "N (billions)" << endl;
report << "Year/Age " << agebins << endl;
for(y=styrR; y<=endyr; y++)
{
  report << y << N(y) << endl;
}
report << "B (1000mt)" << endl;
report << "Year/Age " << agebins << endl;
for(y=styrR; y<=endyr; y++)
{
  report << y << B(y) << endl;
}

report << "Catch reduction (billions)" << endl;
report << "Year/Age " << agebins << endl;
for(y=styrR; y<=endyr; y++)
{
  report << y << C_reduction(y) << endl;
}
report << "Catch bait (billions)" << endl;

report << "Year/Age " << agebins << endl;
for(y=styrR; y<=endyr; y++)
{
  report << y << C_bait(y) << endl;
}

for (y=agec_reduction_styr; y<=agec_reduction_endyr; y++){
  report << "Reduction Age Composition " << y << endl;
  report << "Age " << agebins << endl;
```

```
  report << "Observed" << agec_reduction_obs(y) << endl;
  report << "Predicted" << agec_reduction_pred(y) << endl;
}

for (y=agec_bait_styr; y<=agec_bait_endyr; y++){
  report << "Bait Age Composition " << y << endl;
  report << "Age " << agebins << endl;
  report << "Observed" << agec_bait_obs(y) << endl;
  report << "Predicted" << agec_bait_pred(y) << endl;
}

report << "Reduction age comp residuals" << endl;
report << "Year " << "Age " << "Residual " << endl;
for (y=agec_reduction_styr; y<=agec_reduction_endyr; y++){
  for(a=1; a<=nages; a++){
    report << y << " " << agebins(a) << " " << agec_reduction_obs(y,a)-agec_reduction_pred(y,a) << endl;
  }
}
report << " " << endl;
report << "Bait age comp residuals" << endl;
report << "Year " << "Age " << "Residual " << endl;
for (y=agec_bait_styr; y<=agec_bait_endyr; y++){
  for(a=1; a<=nages; a++){
    report << y << " " << agebins(a) << " " << agec_bait_obs(y,a)-agec_bait_pred(y,a) << endl;
  }
}

for(y=styr; y<=endyr; y++)
{
  N_spr(1)=1.0;
  for(a=2; a<=nages; a++)
  {
    N_spr(a)=N_spr(a-1)*mfexp(-1.*Z(y,a-1));
  }
  N_spr(nages)+=N_spr(nages)*mfexp(-1.*Z(y,nages));//plus group
  spr_static(y)=(sum(elem_prod(elem_prod(N_spr,wgt_spawn(y)),mat_f))*0.5)/spr_F0(y);
  fpr_static(y)=(sum(elem_prod(elem_prod(N_spr,mat_f),fec_f(y)))*0.5)/fpr_F0(y);
}
report << "Static SPR" << endl;
report << "Year";
for(y=styr; y<=endyr; y++)
{
  report << " " << y;
}
report << endl;
report << "static_SPR " << spr_static << endl;
report << "static_FPR " << fpr_static << endl;

//compute SSB/R and YPR as functions of F
for(int f=1; f<=201; f++)
{
  N_spr(1)=1.0;
  Z_msy(1)=sel_msy(endyr)*F_pr(f)+M(endyr);
  for (a=2; a<=nages; a++)
  {
```

```
   N_spr(a)=N_spr(a-1)*mfexp(-1.*Z_msy(1,a-1));
  }
  N_spr(nages)+=N_spr(nages)*mfexp(-1.*Z_msy(1,nages));
  SSB_pr(f)=sum(elem_prod(elem_prod(N_spr,wgt_spawn(endyr)),mat_f)*0.5);
  FEC_pr(f)=sum(elem_prod(elem_prod(N_spr,mat_f),fec_f(endyr))*0.5);

  Y_pr(f)=0.0;
  for (a=1; a<=nages; a++)
  {
   Y_pr(f)+=N_spr(a)*((Z_msy(1,a)-M(endyr,a))/Z_msy(1,a))*(1.-mfexp(-1.*Z_msy(1,a)))*wgt_fish(endyr,a);
  }
  F_DSV_pr(f)=((Z_msy(1)(3,nages)-M(endyr)(3,nages))*N_spr(3,nages))/sum(N_spr(3,nages));

  //Compute equilibrium values of SSB and Yield at each F
  //based on stock-recruit curve estimated above
  Z_eq=sel_msy(endyr)*F_pr(f)+M(endyr);
  N_eq(1)=1.0;
  for (a=2; a<=nages; a++)
  {
   N_eq(a)=N_eq(a-1)*mfexp(-1.*Z_eq(a-1));
  }
  //last age is pooled
  N_eq(nages)=N_eq(nages-1)*mfexp(-1.*Z_eq(nages-1))/(1.-mfexp(-1.*Z_eq(nages)));
  spr_eq=sum(elem_prod(elem_prod(N_eq,wgt_spawn(endyr)),mat_f))*0.5;
  fpr_eq=sum(elem_prod(elem_prod(N_eq,mat_f),fec_f(endyr)))*0.5;
  if(SRswitch<2) //Beverton-Holt
  {
   //R_eq(1)=(R0/((5*steep-1)*spr_eq))*(4*steep*spr_eq-spr_F0(endyr)*(1-steep));
   R_eq(1)=(R0/((5*steep-1)*fpr_eq))*(4*steep*fpr_eq-fpr_F0(endyr)*(1-steep));
  }
  if(SRswitch>1) //Ricker
  {
   //R_eq(1)=(R0/(spr_eq/spr_F0(endyr)))*(1+log(spr_eq/spr_F0(endyr))/log((steep*4)/(1-steep)));
   R_eq(1)=(R0/(fpr_eq/fpr_F0(endyr)))*(1+log(fpr_eq/fpr_F0(endyr))/log((steep*4)/(1-steep)));
  }
  //Initial age
  N_eq(1)=R_eq(1);
  for (a=2; a<=nages; a++)
  {
   N_eq(a)=N_eq(a-1)*mfexp(-1.*Z_eq(a-1));
  }
  //last age is pooled
  N_eq(nages)=N_eq(nages-1)*mfexp(-1.*Z_eq(nages-1))/(1.-mfexp(-1.*Z_eq(nages)));
  SSB_eq(f)=sum(elem_prod(elem_prod(N_eq,wgt_spawn(endyr)),mat_f))*0.5;
  FEC_eq(f)=sum(elem_prod(elem_prod(N_eq,mat_f),fec_f(endyr)))*0.5;
  C_eq=0.0;
  Y_eq(f)=0.0;
  for(a=1; a<=nages; a++)
  {
   C_eq+=N_eq(a)*((Z_eq(a)-M(endyr,a))/Z_eq(a))*(1.-mfexp(-1.*Z_eq(a)));
   Y_eq(f)+=N_eq(a)*((Z_eq(a)-M(endyr,a))/Z_eq(a))*(1.-mfexp(-1.*Z_eq(a)))*wgt_fish(endyr,a);
  }
 }
 SSB_pr=SSB_pr/spr_F0(endyr);
 FEC_pr=FEC_pr/fpr_F0(endyr);
```

```
  report << "F F_DSV SPR YPR SSB_eq Y_eq" << endl;
  for(a=1; a<=201; a++)
  {

    report << F_pr(a) << " " << F_DSV_pr(a) << " " << SSB_pr(a) << " " << Y_pr(a) << " " << SSB_eq(a) << " " <<
Y_eq(a) << endl;
  }

  report << "F F_DSV FPR YPR FEC_eq Y_eq" << endl;
  for(a=1; a<=201; a++)
  {

    report << F_pr(a) << " " << F_DSV_pr(a) << " " << FEC_pr(a) << " " << Y_pr(a) << " " << FEC_eq(a) << " " <<
Y_eq(a) << endl;
  }

  report << "selectivity (catch-weighted)" << endl;
  report << "Year/Age " << agebins << endl;
  for(y=styrR; y<=endyr; y++)
  {
    report << y << sel_msy(y) << endl;
  }

  #include "s-report4.cxx"   // ADMB code to write the S-compatible report
```

Appendix D
Corresponding Input File (menhad026.dat):

#starting and ending year of the model, respectively
1955
2002

#Number of ages
9
#Agebin vector
0 1 2 3 4 5 6 7 8

#Natural Mortality
2.343 0.534 0.307 0.3 0.3 0.3 0.3 0.3 0.3
#0.82 0.57 0.46 0.34 0.34 0.34 0.34 0.34 0.34
#0.45 0.45 0.45 0.45 0.45 0.45 0.45 0.45 0.45

#Stock-recruit switch (1=Bev-Holt,2=Ricker)
2

#weight-at-age in the fishery (g)

30.9	106.1	242.9	379.6	493.7	580.4	642.9	686.4	716.1
19.8	108.8	278.3	431.0	541.1	612.7	656.9	683.4	699.0
34.1	115.3	259.7	399.8	513.3	596.9	655.4	695.0	721.4
19.2	101.8	269.0	432.4	559.8	649.0	707.7	745.2	768.7
49.3	124.9	254.5	387.9	506.7	604.1	679.9	737.1	779.3
28.7	102.0	243.4	392.0	521.2	622.7	698.0	751.8	789.4
43.7	115.0	241.8	376.2	498.6	600.9	681.8	743.8	790.1
60.4	139.4	267.1	394.4	505.8	596.4	666.8	720.0	759.3
54.1	134.1	270.6	412.0	539.3	645.1	728.7	792.7	840.6
54.1	144.7	299.9	457.3	594.6	704.7	788.6	850.7	895.5
52.4	138.8	291.2	452.1	598.5	720.8	817.8	892.2	948.1
64.4	141.1	265.1	390.7	503.3	597.4	672.5	730.7	774.9
66.2	164.7	304.9	419.4	500.4	553.6	587.2	607.9	620.5
70.7	152.9	277.3	393.6	489.6	563.6	618.2	657.4	685.2
82.3	175.6	331.6	498.6	657.7	798.7	918.1	1016.0	1094.6
58.6	135.6	278.4	448.8	628.3	803.5	965.9	1111.2	1238.0
56.1	158.8	312.5	440.9	532.9	593.9	632.6	656.6	671.4

22.8	129.8	334.9	520.2	653.9	741.0	794.8	827.1	846.1
45.2	123.4	271.5	441.7	610.8	764.9	898.0	1009.0	1099.2
33.3	98.1	240.6	433.8	658.8	897.8	1136.6	1365.4	1578.0
25.0	83.6	205.6	352.2	500.3	635.7	752.2	848.4	925.8
21.2	68.8	190.9	386.5	653.2	982.9	1364.0	1784.1	2231.1
20.2	63.4	158.5	283.5	422.5	562.3	694.2	813.3	917.6
25.9	62.8	143.0	258.7	406.4	580.4	774.5	982.4	1198.3
23.4	72.9	174.6	297.4	422.5	538.3	639.0	723.1	791.4
21.6	67.0	159.7	270.9	383.5	486.9	576.4	650.7	710.6
20.0	58.7	141.8	250.2	371.0	493.3	609.8	716.0	810.0
32.6	68.6	136.9	224.1	324.2	431.6	541.5	650.1	754.6
28.2	70.1	149.3	243.4	341.2	434.8	519.9	594.4	658.0
22.9	69.8	160.5	262.8	360.8	446.4	517.1	573.3	617.0
23.1	74.3	174.9	289.1	398.6	494.1	572.7	635.0	683.1
23.6	64.6	144.7	240.0	337.3	428.3	508.6	576.7	633.1
30.6	73.4	154.0	250.7	352.7	452.0	543.7	625.4	696.4
22.9	63.4	142.5	236.4	332.3	422.1	501.5	569.2	625.5
36.1	78.6	157.2	252.0	353.8	455.3	551.4	639.4	717.7
41.6	111.8	218.6	310.8	379.1	425.7	456.2	475.6	487.8
46.4	103.6	194.2	283.1	360.1	422.1	469.8	505.5	531.6
31.5	102.9	216.1	312.0	380.2	424.7	452.4	469.3	479.4
54.9	119.0	215.6	305.0	378.1	433.8	474.5	503.5	523.8
23.5	87.0	203.3	316.8	408.3	475.1	521.4	552.4	572.8
25.9	103.2	231.7	340.3	416.0	464.3	493.6	511.0	521.1
18.4	101.9	259.9	399.6	498.2	560.9	598.7	620.9	633.7
28.2	104.3	243.3	378.3	486.8	565.8	620.3	656.8	680.7
51.3	116.6	232.5	363.1	492.7	611.9	716.3	804.6	877.5
36.7	107.4	233.5	363.7	478.0	569.8	639.8	691.3	728.6
24.4	112.8	266.8	398.0	488.9	546.1	580.4	600.5	612.0
58.3	155.3	298.4	418.5	505.2	563.4	600.8	624.3	638.8
35.3	139.0	296.7	417.2	493.6	538.2	563.3	577.0	584.5

#weight-at-age for the spawning population

15.6	51.6	172.1	313.2	440.0	540.4	614.3	666.6	702.7
6.1	42.3	191.9	359.5	491.4	581.0	637.6	671.9	692.2
17.3	56.6	185.5	332.3	460.4	558.6	628.9	677.2	709.6
6.5	39.9	182.0	354.2	501.2	608.8	681.5	728.6	758.3
31.2	71.3	187.5	322.2	449.8	558.2	644.5	710.6	759.9
14.3	48.4	169.2	319.0	459.9	575.5	663.4	727.2	772.3

27.1	64.1	175.7	309.6	439.6	552.4	643.9	715.0	768.7
40.3	84.0	201.8	332.1	452.5	553.7	634.0	695.3	741.1
34.8	77.5	200.0	342.2	478.1	595.1	689.5	762.9	818.4
32.9	80.3	219.9	380.2	529.2	653.1	749.7	822.1	875.0
32.3	77.2	211.8	372.4	528.0	662.8	772.3	857.6	922.2
44.4	87.4	201.5	328.8	449.1	552.8	637.2	703.6	754.4
40.7	96.3	236.5	366.4	463.9	529.9	572.3	598.8	615.0
48.7	95.8	214.8	337.5	444.4	529.2	593.1	639.5	672.5
58.2	110.2	250.6	415.2	580.0	730.8	861.1	969.6	1057.5
40.1	80.8	202.3	361.5	538.4	717.1	886.6	1040.8	1176.9
31.4	86.6	236.8	381.2	491.3	566.7	615.5	646.1	664.9
6.7	49.7	230.2	433.3	593.6	702.5	771.3	813.0	837.9
27.6	67.2	192.8	355.5	527.5	690.2	834.2	956.2	1056.5
20.0	50.7	161.9	332.0	543.5	777.5	1017.9	1252.7	1474.0
13.4	40.6	139.7	277.5	427.2	570.1	696.4	802.8	889.3
12.4	33.3	120.9	279.5	511.4	810.9	1167.8	1570.0	2005.0
11.6	31.6	106.2	218.3	352.2	493.0	629.6	755.6	867.4
17.7	36.1	98.4	196.6	328.9	490.5	675.4	877.1	1089.7
13.3	36.8	119.7	234.7	360.6	482.1	590.7	683.1	759.1
12.3	33.9	109.7	214.2	327.8	436.8	533.6	615.4	682.3
12.0	30.5	96.3	193.7	309.8	432.5	552.6	664.3	764.6
23.8	43.1	100.0	178.5	272.9	377.3	486.5	596.2	703.0
18.5	40.2	107.1	195.3	292.4	388.9	478.6	558.5	627.6
12.9	35.8	112.4	211.4	313.0	405.4	483.6	546.9	596.6
12.6	37.1	121.3	231.7	345.3	448.4	535.5	605.8	660.7
14.6	35.0	101.8	191.4	289.0	384.0	469.9	544.2	606.3
20.6	42.9	110.9	201.1	301.6	403.0	499.0	585.9	662.3
14.0	34.2	100.2	188.5	284.7	378.3	463.2	536.9	598.7
25.7	48.5	115.2	203.2	302.5	404.9	504.2	596.5	679.8
24.5	62.4	165.6	267.5	347.9	404.7	442.6	467.0	482.4
31.6	63.6	148.1	239.7	323.5	393.0	447.6	489.0	519.6
15.8	51.9	159.9	267.4	349.4	404.9	440.2	461.9	475.0
37.7	74.5	167.2	262.0	343.7	408.0	455.8	490.3	514.6
11.0	40.7	143.3	262.2	365.7	444.6	500.5	538.5	563.7
10.9	47.2	167.7	290.0	382.1	443.1	480.8	503.5	516.7
5.6	39.5	179.6	334.5	454.1	533.4	582.3	611.3	628.2
13.3	48.9	171.7	313.4	436.3	529.7	595.7	640.4	670.0
35.2	70.4	171.6	297.1	428.7	554.0	666.1	762.4	842.9
21.0	56.7	168.0	299.7	423.5	526.8	607.3	667.6	711.5

8.9	47.9	189.7	337.3	448.3	521.0	565.5	591.8	607.1
34.2	87.4	228.0	362.5	465.9	537.4	584.2	613.9	632.4
14.3	64.5	220.2	362.9	460.2	519.0	552.6	571.2	581.3

#percent maturity-at-age
0 0 0.118 0.846 1 1 1 1 1

#fecundity at age

11538.49018	23121.45806	64222.22775	125829.0837	195923.1655	262235.7971	317720.1121	360513.0558	391786.5058
7813.151736	20107.12512	71189.65018	147746.7147	225243.4768	287354.0258	330749.7092	358736.9282	375966.6164
12507.59081	25164.68468	69080.77784	132204.1778	200645.1024	262351.8417	311699.3396	348214.4801	373912.6161
8251.956372	19706.3267	65987.15456	137643.5072	215278.473	282598.6306	333471.5513	368801.3629	392101.1003
17177.4255	29708.62728	69183.91569	125445.0278	190720.2757	256142.7532	315247.7376	364863.2538	404406.1131
11752.39281	23010.14409	62531.53359	122137.0905	191226.1647	258183.2186	315673.01	361163.8082	395236.0055
16156.56428	27839.25344	64816.40163	118141.4028	180968.1401	244995.7836	303815.2187	353990.9947	394590.8753
18759.41139	32066.50647	73602.13131	132569.5348	201109.1408	270153.9061	332958.8325	386084.4232	428760.7273
17512.74003	30286.92042	71094.25797	130656.1973	201662.112	274825.8346	342716.2617	401156.5135	448829.6365
16622.16905	30527.49966	77150.59433	146655.2864	228856.2748	311500.5023	385676.4676	447189.0952	495469.2874
16944.79565	30627.39221	77011.35697	148644.9259	237593.9185	331972.9268	421411.7639	499570.2074	564019.919
20366.51634	33710.09081	74542.33426	132408.406	200704.0487	271228.416	337299.5825	394968.1666	442779.8167
20018.15818	37423.11221	88210.75809	147237.9674	199968.991	240102.1685	267829.0016	285901.1411	297276.0911
21682.92674	36003.34733	77328.43073	130226.26	185794.6941	236734.0474	279258.3276	312552.573	337501.1703
23279.19762	38073.56611	84692.34499	154977.2118	244682.7754	345543.0686	448531.8136	546281.8839	634059.0162
18705.10784	30741.39996	71432.59042	140431.0709	241446.3334	372829.7619	528185.4834	698339.911	873573.3665
16084.9619	32984.63616	88508.14627	160007.8637	228249.2048	282458.0144	320974.8447	346557.6155	362872.9807
8065.550535	22501.69754	88837.7824	196503.0478	310944.8867	405422.5369	472628.2884	516450.0599	543613.6495
14789.33629	26751.02157	70335.34446	146577.4796	256029.4728	391088.9829	539542.8354	688932.0646	829478.8849
12967.59135	22657.73212	59921.84248	134467.5871	263246.2464	460078.94	731729.1361	1076050.903	1482614.397
10722.64906	19511.5358	51290.35829	105786.2738	181934.036	273083.0968	370174.2796	464899.7434	551412.1879
10572.8715	17489.89121	44269.67906	101891.2467	215330.4492	421508.3698	770273.3133	1323361.357	2151052.903
10353.96305	17003.04636	39237.69417	76253.46807	129278.7476	196647.259	274423.1487	357615.1035	441350.2033
12425.54172	18237.74918	36925.04075	69332.59574	121707.7397	201181.0235	315162.0747	470598.9314	673230.2745
10884.48979	18433.25045	43339.1224	82589.62238	134324.8399	193857.3199	255656.8991	314994.2261	368700.5527
10472.89189	17469.08971	39976.01471	74456.11289	118800.1641	168756.5961	219677.725	267808.633	310786.4811
10580.26411	16799.34193	36818.26847	69066.14681	114365.6813	171354.7399	236961.5557	307287.5649	378470.8341
13726.81245	19471.15046	36367.77381	62232.1756	98767.93223	146927.2164	206735.0861	277293.6143	356937.7899
12268.95266	19110.49057	40164.66018	72126.75961	114419.1686	164610.0975	219259.8659	274847.9394	328428.9628
10146.3436	17279.64097	40211.10409	74572.15895	117144.0962	162986.0603	207507.4425	247587.9593	281717.1903
10251.54239	18175.11572	44961.45019	86963.85295	140606.1816	199517.9706	257437.6024	309949.4617	354820.0184

11448.19498	18226.94528	39114.75087	70228.31215	109981.4239	155105.4747	201865.666	247041.6474	288398.3689
12994.96256	19879.95123	40796.02035	72388.13265	114377.0067	164748.8765	220418.3797	278035.0776	334619.2225
10790.70796	17382.59506	38136.79887	69853.29625	111339.5846	159442.0043	210247.3255	260173.214	306576.0996
15411.51962	22615.02433	43649.81022	74502.15258	115064.3998	163838.6829	218371.0298	275830.6068	333519.4847
14936.39623	26858.61107	60942.8085	100724.9083	137073.8284	165583.3998	185926.2012	199618.6571	208509.5843
16790.80132	26828.37032	55259.35601	91855.09026	131315.2996	168839.0555	201484.3292	228155.4962	249000.8278
11981.48625	23901.64886	60880.20939	105438.846	145585.0705	175964.5364	196686.8984	209979.9301	218203.7208
18909.75844	30487.44563	62377.13584	101231.3409	140459.3567	175289.5678	203623.3089	225341.1508	241329.2924
10218.49176	20285.37398	54230.58883	101392.67	150988.4039	194532.7818	228572.0201	253271.9653	270361.9946
9928.604176	22234.50873	65011.6707	120287.5971	171189.2832	209589.0058	235382.6143	251583.4567	261372.9266
7854.058013	19707.48961	66284.77032	131710.5883	194282.2053	242100.7918	274216.5689	294250.9027	306234.309
10911.33286	22381.40622	62616.12152	120348.4117	182241.6989	237188.8988	280399.6198	311843.8459	333620.2803
18024.72265	28926.52686	63070.79225	114972.2478	182580.8072	260720.6116	343046.8357	423793.2126	498730.8478
13560.85919	24984.70757	63278.63142	120156.4113	187032.5508	253818.406	313348.0678	362383.77	400626.1547
9144.781619	22322.52095	72340.57672	140656.9374	204867.532	253413.7722	285798.8592	305913.0762	317908.6007
17519.25189	34529.8487	88394.02784	156324.0768	220904.5456	272453.6855	309414.2938	334233.3546	350246.8802
10549.88464	25887.08933	80846.26972	148907.9335	206625.7208	246312.5995	270651.2529	284681.0902	292503.0289

#CPUE Age0 Index starting and ending years, respectively
1959
2002
#CPUE Age0 values
2.347436353 1.590346927 1.377733914 4.048337875 2.223970201 0 1.297973762 0.590583313 0.835531432
2.636859407 2.735105069 2.047480692 3.706553395 3.822407252 4.532764032 5.307806391 5.290544626
5.629034102 5.407740136 4.277778761 5.001431444 4.730615055 5.015256541 5.005277318 4.553852787
5.189187812 4.936139278 4.962221449 3.743667069 4.773840085 4.149947991 4.297822507 4.27110137
3.284910754 2.584540119 3.118300651 2.765453407 2.572039276 2.817038263 2.938148004 2.66154895
2.308060963 3.020996179 2.480916439

#CPUE Pound Net Index starting and ending years, respectively
1964
2002
#CPUE Pound Net values
49144.87681 50248.79861 36791.0828 20385.97931 19285 11595.62431 38307.66964 35787.08081 72429.75294
137812.963 142479.3043 113355.7204 99307.16807 149023.1642 145365.4286 107737.3433 147402.874
165567.6179 157790.0614 174959.8655 105734.3306 116446.5486 84204.20769 156189.3452 142269.1398
86812.4375 52602.04651 63249.68235 66595.98684 109284.1111 67482.67677 70028.18 51113.7 57570.6
39568.06 48554.63 50069.82 33206.27 31135.85
#CPUE Pound Net selectivity at age

0 0.25 1 0.25 0 0 0 0 0

#Starting and ending year of commercial fishery
1955
2002

#Reduction fishery landings (1000 mt)
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
401.2 381.4 297.6 320.6 260 339.9 292.9 259.1 245.9 171.2 167.2 233.7 174.0

#Reduction fishery age comp data starting and ending years
1955
2002

#Reduction fishery age comp samples sizes
15673 18912 19139 15309 17958 13512 12899 15458 12756 10287 19236 15492 14868 25908 14881 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

#Reduction fishery age comp data

0.2440	0.2162	0.3392	0.0857	0.0985	0.0122	0.0034	0.0006	0.0002
0.0102	0.5816	0.2532	0.0897	0.0126	0.0423	0.0081	0.0019	0.0006
0.0853	0.4556	0.3878	0.0275	0.0202	0.0115	0.0105	0.0012	0.0003
0.0390	0.3156	0.6014	0.0265	0.0063	0.0059	0.0033	0.0018	0.0002
0.0021	0.7544	0.1590	0.0725	0.0062	0.0022	0.0023	0.0008	0.0003
0.0260	0.1013	0.7959	0.0275	0.0368	0.0086	0.0029	0.0009	0.0002
0.0001	0.3204	0.1938	0.4655	0.0074	0.0113	0.0011	0.0003	0.0001
0.0246	0.2448	0.3974	0.1035	0.2016	0.0146	0.0117	0.0014	0.0003
0.0549	0.4104	0.4019	0.0694	0.0255	0.0297	0.0059	0.0019	0.0003
0.1750	0.4071	0.3499	0.0483	0.0104	0.0045	0.0038	0.0008	0.0002
0.1705	0.4904	0.2773	0.0512	0.0080	0.0012	0.0008	0.0005	0.0000
0.2607	0.4109	0.3015	0.0236	0.0029	0.0003	0.0001	0.0001	0.0000
0.0071	0.6434	0.2699	0.0739	0.0052	0.0005	0.0000	0.0000	0.0000
0.1344	0.3287	0.4695	0.0572	0.0093	0.0009	0.0001	0.0000	0.0000
0.1821	0.4289	0.3275	0.0551	0.0063	0.0002	0.0000	0.0000	0.0000
0.0153	0.6207	0.3378	0.0233	0.0029	0.0001	0.0000	0.0000	0.0000
0.0752	0.2717	0.5410	0.0911	0.0184	0.0026	0.0000	0.0000	0.0000
0.0293	0.5725	0.2850	0.1010	0.0112	0.0011	0.0000	0.0000	0.0000

0.0304	0.3192	0.6255	0.0210	0.0038	0.0002	0.0000	0.0000	0.0000
0.1585	0.3198	0.4953	0.0244	0.0013	0.0007	0.0000	0.0000	0.0000
0.1381	0.3330	0.5025	0.0232	0.0031	0.0001	0.0000	0.0000	0.0000
0.0835	0.4909	0.4084	0.0146	0.0024	0.0001	0.0000	0.0000	0.0000
0.1319	0.2734	0.5667	0.0227	0.0048	0.0004	0.0000	0.0000	0.0000
0.1483	0.2153	0.5416	0.0837	0.0101	0.0011	0.0000	0.0000	0.0000
0.3856	0.1610	0.4143	0.0331	0.0056	0.0004	0.0000	0.0000	0.0000
0.0265	0.4436	0.4376	0.0668	0.0208	0.0043	0.0004	0.0000	0.0000
0.2981	0.1754	0.4547	0.0558	0.0119	0.0039	0.0003	0.0000	0.0000
0.0359	0.2895	0.5478	0.1196	0.0051	0.0018	0.0002	0.0001	0.0000
0.2446	0.1312	0.5817	0.0290	0.0120	0.0013	0.0001	0.0000	0.0001
0.3648	0.2887	0.2514	0.0765	0.0142	0.0043	0.0001	0.0000	0.0000
0.2106	0.3556	0.4048	0.0146	0.0118	0.0021	0.0006	0.0000	0.0000
0.0514	0.1172	0.7964	0.0257	0.0055	0.0032	0.0006	0.0000	0.0000
0.0185	0.2180	0.6858	0.0656	0.0109	0.0009	0.0003	0.0000	0.0000
0.1570	0.1310	0.5365	0.1397	0.0323	0.0033	0.0002	0.0001	0.0000
0.0569	0.4389	0.4404	0.0412	0.0180	0.0044	0.0001	0.0000	0.0000
0.1428	0.0615	0.7197	0.0505	0.0195	0.0057	0.0002	0.0000	0.0000
0.2785	0.3265	0.2988	0.0802	0.0120	0.0034	0.0006	0.0000	0.0000
0.1947	0.3543	0.3876	0.0322	0.0250	0.0053	0.0007	0.0002	0.0000
0.0426	0.2378	0.6167	0.0934	0.0068	0.0024	0.0002	0.0000	0.0000
0.0594	0.1840	0.5957	0.1106	0.0451	0.0050	0.0002	0.0000	0.0000
0.0345	0.3247	0.4088	0.1881	0.0411	0.0027	0.0000	0.0000	0.0000
0.0309	0.1915	0.6219	0.1273	0.0265	0.0019	0.0000	0.0000	0.0000
0.0253	0.2479	0.4263	0.2384	0.0518	0.0090	0.0012	0.0000	0.0000
0.0723	0.1836	0.5366	0.1254	0.0724	0.0089	0.0008	0.0000	0.0000
0.1835	0.2851	0.4268	0.0775	0.0237	0.0031	0.0003	0.0000	0.0000
0.1183	0.1736	0.5181	0.1702	0.0168	0.0030	0.0000	0.0000	0.0000
0.0343	0.0650	0.5521	0.3252	0.0223	0.0010	0.0000	0.0000	0.0000
0.2219	0.2637	0.3235	0.1691	0.0212	0.0006	0.0000	0.0000	0.0000

#Starting and ending year of bait fishery
1985
2002

#Bait fishery landings (1000 mt)
26.66149628 27.96349572 30.61668496 36.2370013 30.94847457 30.68522285 36.22310375 38.72180693 34.73928477 28.12927897 31.10698034 23.31996761 25.58411427 40.05899747 35.95948236 34.97223512 36.50433391 36.78283933

#Bait fishery age comp data starting and ending years
1985
2002

#Bait fishery age comp samples sizes

800	420	220	10	30	10	78	70	169	539	362	357	313	636	538	543	962	702

#Bait fishery age comp data

0.0053	0.0878	0.6324	0.1893	0.0690	0.0136	0.0025	0.0000	0.0000
0.0036	0.0550	0.4255	0.3384	0.1608	0.0134	0.0032	0.0000	0.0000
0.0042	0.0474	0.4734	0.3119	0.1475	0.0127	0.0030	0.0000	0.0000
0.0034	0.0527	0.3958	0.3531	0.1768	0.0146	0.0035	0.0000	0.0000
0.0048	0.0721	0.5191	0.2766	0.1140	0.0112	0.0023	0.0000	0.0000
0.0053	0.2020	0.3859	0.2681	0.1247	0.0116	0.0025	0.0000	0.0000
0.0027	0.1235	0.3907	0.3134	0.1523	0.0144	0.0031	0.0000	0.0000
0.0043	0.1475	0.3340	0.3346	0.1598	0.0165	0.0033	0.0000	0.0000
0.0072	0.2014	0.2201	0.3678	0.1809	0.0188	0.0038	0.0000	0.0000
0.0023	0.0928	0.4063	0.3015	0.1708	0.0246	0.0018	0.0000	0.0000
0.0000	0.2101	0.2392	0.3273	0.2229	0.0006	0.0000	0.0000	0.0000
0.0005	0.0424	0.5366	0.3326	0.0846	0.0031	0.0000	0.0000	0.0000
0.0000	0.0317	0.3581	0.2904	0.2393	0.0686	0.0119	0.0000	0.0000
0.0289	0.0440	0.4044	0.2903	0.1953	0.0313	0.0059	0.0000	0.0000
0.0011	0.0411	0.5914	0.2412	0.1088	0.0141	0.0023	0.0000	0.0000
0.0051	0.1579	0.5674	0.1833	0.0746	0.0093	0.0025	0.0000	0.0000
0.0020	0.0452	0.5352	0.3637	0.0464	0.0061	0.0013	0.0000	0.0000
0.0000	0.0502	0.3822	0.4592	0.0982	0.0097	0.0006	0.0000	0.0000

Appendix E.
ADMB Model Runs Description:

<u>Developmental Runs:</u>
menhad004 - only age0 index added, NO s-report
menhad005 - only age0 index, s-report added
menhad006 - same as 005, spring seamap index added
menhad007 - same as 006, DE index added
menhad008 - same as 007, cleaned up the s-report (BASE RUN before SA workshop)
menhad009 - same as 008, weight on age0 index increased to 2.0
menhad010 - same as 008, weight on age0 index increased to 4.0
menhad011 - same as 008, weight on age0 index increased to 8.0
menhad012 - same as 008, weight on age0 index increased to 16.0
menhad013 - same as 008, M_const estimated
menhad014 - same as 008, Lance's M vector used (constant M vector)
menhad015 - same as 014, M_const estimated
menhad016 - same as 014, bait cv increased to 30%, juvenile index changed to include only seines, seamap and DE indices removed, pound net index added, uses s-report2.cxx
menhad017 - same as 016, uses s-report3.cxx and go2.r
menhad018 - same as 017, increased wgt on F_dev=10.0, bait landings=10.0
menhad019 - same as 017, increased wgt on bait landings=10.0
menhad020 - same as 019, increased wgt on age0 index=20.0
menhad021 - same as 020, use log transformed age0 index (Ricker BASE)
menhad022 - same as 021, remove age0 index
menhad023 - same as 021, remove pound net index
menhad024 - same as 021, use Beverton-Holt curve (B-H BASE)
menhad025 - same as 021, fixed M=0.45
menhad026 - same as 021, M_const estimated *(*Base Ricker Run during AW*)*
menhad027 - same as 021, knife-edge maturity
menhad028 - same as 021, steepness fixed=0.7
menhad029 - same as 021, steepness fixed=0.8
menhad030 - same as 021, steepness fixed=0.9
menhad031 - same as 024, fixed M=0.45
menhad032 - same as 024, M_const estimated (Base Beverton-Holt Run during AW)
menhad033 - same as 024, knife-edge maturity
menhad034 - same as 024, steepness fixed=0.7
menhad035 - same as 024, steepness fixed=0.8
menhad036 - same as 024, steepness fixed=0.9
menhad037 - same as 026, knife-edge maturity
menhad038 - same as 026, steepness fixed=0.7, R0_log=5.18498 (from 026)
menhad039 - same as 026, steepness fixed=0.8, R0_log=5.18498 (from 026)
menhad040 - same as 026, steepness fixed=0.9, R0_log=5.18498 (from 026)
menhad041 - same as 032, knife-edge maturity
menhad042 - same as 032, steepness fixed=0.7, R0_log=5.95697 (from 032)
menhad043 - same as 032, steepness fixed=0.8, R0_log=5.95697 (from 032)
menhad044 - same as 032, steepness fixed=0.9, R0_log=5.95697 (from 032)
menhad045 - same as 026, minus 2002 data
menhad046 - same as 045, minus 2001 data
menhad047 - same as 046, minus 2000 data
menhad048 - same as 047, minus 1999 data
menhad049 - same as 048, minus 1998 data
menhad050 - same as 032, minus 2002 data
menhad051 - same as 050, minus 2001 data
menhad052 - same as 051, minus 2000 data
menhad053 - same as 052, minus 1999 data

menhad054 - same as 053, minus 1998 data
menhad055 - same as 026, using B for predicted poundnet index
menhad056 - same as 026, fecundity calculations changed, B used for pound net
menhad057 - same as 032, fecundity calculations changed, B used for pound net

Ricker:
menhad058 - same as 056, uses 3 yr (1985-87) average F for pre-1985 bait landings (Ricker Base)
menhad060 - same as 058, fixed M vector from MSVPA
menhad061 - same as 058, fixed constant M=0.45
menhad062 - same as 058, fixed steep=0.7, R0_log=5.89533 (from 058)
menhad063 - same as 058, fixed steep=0.8, R0_log=5.89533 (from 058)
menhad064 - same as 058, fixed steep=0.9, R0_log=5.89533 (from 058)
menhad065 - same as 058, minus 2002 data
menhad066 - same as 065, minus 2001 data
menhad067 - same as 066, minus 2000 data
menhad068 - same as 067, minus 1999 data
menhad069 - same as 068, minus 1998 data
menhad081 - same as 058, knife-edge maturity

Beverton-Holt:
menhad059 - same as 057, uses 3 yr (1985-87) average F for pre-1985 bait landings (B-H Base)
menhad070 - same as 059, fixed M vector from MSVPA
menhad071 - same as 059, fixed constant M=0.45
menhad072 - same as 059, fixed steep=0.7, R0_log=6.38033 (from 059)
menhad073 - same as 059, fixed steep=0.8, R0_log=6.38033 (from 059)
menhad074 - same as 059, fixed steep=0.9, R0_log=6.38033 (from 059)
menhad075 - same as 059, minus 2002 data
menhad076 - same as 075, minus 2001 data
menhad077 - same as 076, minus 2000 data
menhad078 - same as 077, minus 1999 data
menhad079 - same as 078, minus 1998 data
menhad082 - same as 059, knife-edge maturity