2006 Stock Assessment Report
for
Atlantic Menhaden

A report prepared by the

Atlantic Menhaden Technical Committee
For the Atlantic Menhaden Management Board

September 26, 2006

EXECUTIVE SUMMARY

The Atlantic States Marine Fisheries Commission (ASMFC) convened a stock assessment workshop (AW) at the NOAA Center for Coastal Fisheries and Habitat Research, Beaufort, North Carolina, on Tuesday, July 18, 2006. The workshop's objective was to conduct an update of the benchmark assessment of the Atlantic menhaden (*Brevoortia tyrannus*) stock off the U.S. Atlantic coast (ASMFC 2004a). Participants in this update assessment included state, commission, federal and university scientists, as well as several observers (Appendix A). The AW worked at Beaufort through July 19, 2006. All decisions regarding stock assessment methods and acceptable data were made by consensus.

Following a scoping conference call in January 17, 2006, available data on the species were evaluated during a subsequent Data Workshop (March 16–17, 2006) in Providence, RI. These data were then finalized for inclusion in the assessment model. Data included abundance indices, recorded landings, and samples of annual size and age compositions from the landings. Six state juvenile abundance seine indices were developed; five of which were updated from the 2003 peer-reviewed assessment or benchmark assessment (ASMFC 2004a). The new seine index (New Jersey) was only used in an alternate model run. The pound net index from the PRFC was improved to reflect a better unit of fishing effort (from per license which has been fixed at 100 since 1994 to days fished). Landings and catch-in-numbers-at-age data were updated from the reduction and bait fisheries. A new vector of natural mortality at age was obtained from the recently peer-reviewed MSVPA-X model to replace the vector used in the benchmark assessment (SARC 2005).

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

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

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1.0 INTRODUCTION

Addendum 1 to the Atlantic menhaden Fishery Management Plan (FMP) calls for an updated assessment of Atlantic menhaden to be held three years following the 2003 peer-reviewed or benchmark assessment (ASMFC 2004b). The Atlantic States Marine Fisheries Commission (ASMFC) convened the review of this assessment at the NOAA Center for Coastal Fisheries and Habitat Research, Beaufort, North Carolina during July 18-19, 2006. Participation in the workshop included representation by the Commission, the Atlantic Menhaden Stock Assessment Subcommittee, and several observers (Appendix A).

The AW's major objective was to conduct an update to the last benchmark assessment of Atlantic menhaden, *Brevoortia tyrannus*, along the US Atlantic coast. In support of this task, the AW received data and recommendations resulting from a scoping workshop (SW) via conference call that was held on January 19, 2006, and a data workshop (DW) held in Providence, RI, on March 16-17, 2006. The SW and DW were charged with recommending any data or model changes to be made in this assessment, which was otherwise based on the benchmark assessment of Atlantic menhaden (ASMFC 2004a).

Scoping Workshop: The SW discussed data requirements for updating from the benchmark assessment and identified responsibility for obtaining these data. Fishery-dependent data included reduction landings and age compositions, bait landings and age composition, and the pound net CPUE from the PRFC. Fishery-independent data included the five-state juvenile abundance seine surveys used in the benchmark assessment, and consideration of additional state seine or other indices that may have recently been developed. New age-specific natural mortality rates would be derived from the recently peer-reviewed MSVPA-X (SARC 2005).

Data Workshop: Pertaining to the update assessment, the DW reviewed fishery-dependent and fishery-independent data and natural mortality. Reduction landings, catch in numbers at age, and biostatistical samples were available through the 2005 fishing year. Bait data were incomplete for the 2005 fishing year, but was available by May 2006 . Bait age-length keys and estimated catch in numbers at age were developed after the DW in preparation for the Assessment Workshop (AW). It was noted that there were unreported landings for the Virginia purse-seine bait vessels (= snapper boats) during 1993-1997. An alternate model run was recommended using a linear interpolation of VA bait landings from 1993-1997 based on the reported VA bait landings in 1992 and 1998. Data updates and analyses of the pound net CPUE from PRFC were discussed by the DW and recommended for use in the AW. In addition to updating of the five-state seine surveys from the benchmark assessment, a new seine survey from New Jersey was presented. It was recommended that an alternate model run would include the NJ seine survey in the coastwide juvenile abundance index used in the benchmark assessment. Age-specific estimates of natural mortality (M) from the peer-reviewed MSVPA-X were presented and discussed by the DW. Average annual values of age-specific M (1982-2002) were recommended for the base model run at the assessment workshop and average values of age-specific M for the last five years (1998-2002) were recommended as an alternate model run for the AW. Finally, there was considerable concern about changing selectivity in the reduction fishery. A constant selectivity for the reduction fleet was used in the benchmark assessment. The DW recommended that an alternate model run be made based on two selectivity periods: an early flat-topped selectivity and a late dome-shaped selectivity.

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 230 mm in the north and middle Atlantic regions because of latitudinal differences in size-at-age and the fact that larger fish of a given age are distributed 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 decline below 15^{o} C (Kroger et al. 1974). Atlantic menhaden reach lengths of about 500 mm total length (TL) and weights of over 1.5 kg (Cooper 1965). 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 almost 475,000 Atlantic menhaden aged between 1955 and 2005. Smith and O'Bier (1996) described an exceptionally large (433 mm FL; 1,551g; age-7) Atlantic menhaden caught in Chesapeake Bay during 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 by 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 (2001–2005 ????) 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 1955–2005 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 C).

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 and, thus, would not have produced any evidence for spawning in the Gulf of Maine (Judy and Lewis 1983).

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) when maintained at 16° and 24°C; they 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 at a size of 14–34 mm FL (Reintjes 1961; 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 also show young menhaden are more abundant in shallow, low salinity (< 5‰) estuarine zones (Weinstein 1979; Weinstein et al. 1980; Rogers et al. 1984). 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 salt marshes (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 NATURAL MORTALITY

Age-structured models attempt 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 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 mouth gape 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-varying 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 natural 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 suggest greater mortality on the youngest 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, but lower for older ages. 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 than empirically derived.

To address the concerns of menhaden as an important forage species and explore the role of M_2 in the population dynamics of this stock, the Commission began developing a Multispeices Virtual Population Assessment model (MSVPA) in 2001. The MSVPA model initially focused on the effects of predation by bluefish, striped bass, and weakfish on the Atlantic menhaden population, and has since been extended to adjust the population estimates of the predators and other prey species. The Commission also hosted several workshops to verify the data used in the model and obtain feedback from various technical committees on features to include in the model. Early versions of the MSVPA model were used by the Atlantic Menhaden Technical Committee to explore some basic questions about the abundance of age 0 and 1 menhaden. Additionally, an age-varying natural mortality was derived in some part by that version of the MSVPA. These results were then used as a vector in the single species formulation for menhaden during the most recent benchmark assessment (ASMFC 2004a).

Further development of the model has progressed and a new version (MSVPA-X) was reviewed through both an internal ASMFC peer review process and an external peer review.

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

- *Sciaenids* (spot, croaker)
- Small Forage Fish (anchovy, silversides, and sand lance)
- Medium Forage species (butterfish, squid)
- Clupeids (Atlantic herring, Atlantic thread herring, and others)
- Benthic invertebrates (worms)
- Benthic crustaceans (lobsters, blue crabs, and jonah crabs)
- Macrozooplankton (shrimps, mysids, and amphipods)

This new revision of the MSVPA was reviewed by the 42nd SAW (Stock Assessment Working-group; http://www.nefsc.noaa.gov/nefsc/publications/crd/crd0609) in December 2005. At that meeting the SAW suggested improvements to the model; however, overall the SAW approved model formation, inputs, and its use in providing ancillary management advice on the predator prey interactions of these stocks.

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 DEPENDENT DATA

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

Landings at the menhaden reduction plants have been reported since 1940 (Figure 3.1) and biostatistical samples of the catches have been continuously collected since 1955. A chronology of menhaden plant activity is shown in Table 3.1. As the directed bait fishery for menhaden has grown in recent years, greater emphasis has been placed on acquiring more representative port samples and more accurate landings records from this segment of the fishery (Figure 3.1). 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.

3.1 REDUCTION FISHERY

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

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

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. Commercial catch and effort data (Table 3.2) for the reduction fishery are available from 1940 through 2005. Contemporary landings data are supplied to the Beaufort Laboratory by the menhaden industry on a monthly basis; catches are enumerated as daily vessel unloads. The biostatistical data, or port samples, for length and weight at-age are available from 1955 through 2005, and represent one of the longest and most complete time series of fishery data sets in the nation. The CDFRs (daily logbooks) itemize purse-seine set locations and estimated catch, and vessel compliance is 100%. CDFR data for the Atlantic menhaden fleet are available for 1985–2005.

3.1.1 Reduction Fishery Overview

Some fishing for Atlantic menhaden has occurred since colonial times, but the use of purse-seine gear began in New England about 1850 (Ahrenholz et al. 1987). No longer bound to shore-based seining sites, the purse-seine fishery spread south to the Mid-Atlantic states and the Carolinas by the late 1800s. Purse-seine landings reached their zenith in the 1950s, and peak landings of 712,100 metric tons occurred in 1956; extant menhaden factories at the time, over 20 (ASMFC 2004a), ranged from northern Florida to southern Maine (Table 3.1). In the 1960s, the Atlantic menhaden stock contracted geographically, and many of the fish factories north of Chesapeake Bay closed because of a scarcity of fish (Table 3.1 and Nicholson 1975).

During the 1970s and 1980s, the menhaden population began to expand primarily because of a series of above average year-classes entering the fishery. Adult menhaden were again abundant in the northern half of their range, that is, Long Island Sound north to the southern Gulf of Maine. By the mid-1970s, reduction factories in Rhode Island, Massachusetts, and Maine began processing menhaden again (Table 3.1). In 1987, a reduction plant in New Brunswick, Canada, processed menhaden harvested in southern Maine, but transported by steamer to Canada. Beginning in 1988, Maine entered into an Internal Waters Processing venture (IWP) with the Soviet Union, which brought up to three foreign factory ships into Maine territorial waters (< 3 miles from the coast). American vessels harvested the menhaden and unloaded the catch for processing on the factory ships. By 1989 all shore-side reduction plants in New England had closed mainly because of odor abatement issues with local municipalities. A second Canadian plant in Nova Scotia also processed Atlantic menhaden caught in southern Maine in 1992–1993. The Russian-Maine IWP and the Canadian plants last processed menhaden during summer 1993.

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

A major change in the industry took place following the 1997 fishing season, when the two reduction plants operating in Reedville, VA, consolidated into a single company and a single factory; this significantly reduced effort and overall production capacity. Seven of the 20 vessels operating out of Reedville, VA, were removed from the fleet prior to the 1998 fishing year and 3 more vessels were removed prior to the 2000 fishing year, reducing the Virginia fleet to 10 vessels during 2000 through most of 2005. In November 2005, an eleventh vessel was added at Reedville, but it fished sparingly until the factory 'cut out' for the fishing season in early January. One bait purse-seine vessel in Northern Neck, VA, unloaded its catch for reduction sporadically at the Reedville fish factory in 2005.

Another major event within the industry occurred in Spring 2005 when the fish factory at Beaufort, NC, chose not to operate, and idled its two vessels. Thus, in 2005 the lone, surviving menhaden plant was in Reedville, VA, with about ten vessels.

Summer 2005 was also noteworthy in that it was the first time in twelve years (since 1993 when the IWP last operated) that adult Atlantic menhaden were abundant in north of Long Island Sound. Indeed, several New England states (see Section 3.2.1) recorded significant menhaden-for-bait landings for the first time in over a decade.

The regulatory trend of Atlantic coastal states relative to reduction purse-seine fishing for menhaden has been one of progressive area closures. Since New Jersey closed its territorial sea to reduction purse-seine vessels in 2002, the Atlantic menhaden reduction fishery has essentially become a two-state fishery. Within the geographic range of the current menhaden reduction fleet, Virginia and North Carolina are the only states that permit menhaden reduction purse-seine fishing. The Virginia fleet catches Atlantic menhaden off the coasts of Maryland, Delaware, and New Jersey; however, these catches are beyond three miles from shore and in the U.S. EEZ.

3.1.2 Reduction Fishery Landings

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 2003-05 the entire reduction fleet (10-12 vessels) unloaded an average of 776 times during each fishing year; the average unload per vessel was 213 t. In 2005 the reduction purse-seine fishery accounted for 79% of the total coastwide landings of Atlantic menhaden (Figure 3.2).

Landings and nominal fishing effort (vessel-weeks, measured as number of weeks a vessel unloaded during the fishing year) are available since 1940 (Table 3.2). Landings rose during the 1940s (from 167,000 to 376,000 t), peaked during the late 1950s (> 600,000 t for four of five years), and then declined to low levels during the 1960s (from 576,000 t in 1961 to 162,000 t in 1969). During the 1970s the stock rebuilt (landings rose from 250,000 t in 1971 to 376,000 t in 1979) and then maintained intermediate levels during the 1980s (varying between 238,000 t in

1986 when fish meal prices were extremely low to 418,600 t in 1983). Landings during the 1990s declined from 401,200 t in 1990 to 171,200 t in 1999.

By 1998, the fishery had contracted to only two factories, one in VA and one in NC. Landings dipped to 167,200 t in 2000, rose to 233,700 t in 2001, and then varied annually from 174,000 t to 166,100 to 183,400 t through 2004. Landings during 2000-04 when the fishery was relatively stable with two plants and about twelve vessels averaged 184,900 t. In 2005, only the factory in Virginia operated and landings declined again to 146,900 t. Reduction landings in 2005 accounted for 79% of total coastwide landings of Atlantic menhaden (bait and reduction combined); this down from 84% in 2004 and 83% in 2003.

During the 1980s, the menhaden industry suggested that a "topping off" bias occurred in the NOAA Fisheries' 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 1985–2005 were used to better apportion weekly-plant catches by fishing area and to correct for this bias. Coastwide, only minor differences were found in catch-at-age estimates used for management. Thus, based on temporal and areal distribution of current and historical port samples for the reduction fishery, and the complete accounting of landings by the menhaden companies, biases in the reduction fishery sampling data set are believed to be minimal.

Smith (1999) 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.

In recent years, median catches in Chesapeake Bay have been 22 t in 2003, and 21 t in 2004 and 2005. Since 2000 when the reduction fishery contracted to only one fish plant and about ten vessels in Virginia, removals from Chesapeake Bay by the reduction fleet have averaged 104,400 t annually (2000–2005), a 28% decline versus 1990–1999 when removals from the Bay averaged 145,700 t per year.

3.1.3 Age and Length Composition

Biological sampling for the menhaden purse-seine fishery 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) performed detailed examinations (validation and verification) of Atlantic menhaden scales and determined that rings on the scales are reliable age marks.

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.

About 3,700 Atlantic menhaden from the reduction fishery have been processed annually for size and age composition over the past three fishing seasons, 2003–2005 (Table 3.3). In comparing menhaden sampling intensity to the rule-of-thumb criteria used by the Northeast Fisheries Science Center (e.g. <200 t/100n), this sampling level might be considered low, although the results of Chester (1984) suggest this sampling level is relatively high.

In recent years, age-2 Atlantic menhaden have comprised almost 60% or more of the total numbers of fish landed (Table 3.4). In 2003 the age composition of the coastwide landings for reduction was 8.7% age-0s, 18.3% age-1s, 64.1% age-2s, and 8.9% age-3+s; in 2004, it was 1.8% age-0s, 21.9% age-1s, 66.7% age-2s, and 9.6% age-3+s; and in 2005, it was 1.9% age-0s, 12.2% age-1s, 59.0% age-2s, and 26.9% age-3+s. Overall mean weights of Atlantic menhaden in port samples from the reduction fishery 2003 through 2005 were 278 g, 214 g, and 251 g, respectively.

3.2 BAIT FISHERY

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

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

Between 1985–2005 reported annual landings of Atlantic menhaden for bait along the Atlantic coast averaged 34,220 metric tons (Table 3.2); for the same period, bait landings annually averaged 11% of total coastwide landings of Atlantic menhaden (bait and reduction landings combined). Although total landings for bait since 1999 have remained fairly level ranging 35,000–38,000 mt per year, in recent years (since 2001) reported bait landings have averaged 17% of the total coastwide Atlantic menhaden landings (Figure 3.1). The relative increase of bait in percent of coastal landings is attributed to better data collection in the Virginia 'snapper rig' bait seine fishery, but moreover the decline in coastal reduction landings due to reductions in processing plants and fleet size.

3.2.1 Bait Fishery Overview

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

As mentioned earlier, the presumed growth of the Atlantic coast bait fishery must be tempered by the knowledge that systems for reporting bait landings have historically been incomplete, particularly for Atlantic menhaden. In most cases, recent landings estimates are more accurate, although for some states bait landings 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 small-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 underreported (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.

In the New England region, purse-seine landings in Maine, Massachusetts, and Rhode Island account for the majority of the recorded bait landings. An ocean trap net fishery has historically operated off Rhode Island and Massachusetts. In New Hampshire and Connecticut, smaller directed gill net fisheries are well-regulated and monitored. The bulk of menhaden landings for bait in New England are utilized in the lobster fishery. Schools of large menhaden have been scarce in the New England region since the early 1990s (ASMFC 2001). Interestingly, in spring 2005, the purse-seine bait fishery in Massachusetts landed over 2.1 million pounds (953 mt) of menhaden—the highest landings for Massachusetts since 1995.

New Jersey dominates current menhaden bait landings in the mid-Atlantic region. New Jersey requires reports of catch by fishing area for licensed bait purse-seine vessels. Pound nets and gill nets also 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). Purse-seine landings in New Jersey from 2003–2005 were the lowest since the late 1980s and early 1990s, and only half of peak landings during the mid- to late 1990s; however, they continue to account for about 95% of the bait landings in the Mid-Atlantic region.

Virginia snapper rigs (small purse seines) dominate the reported menhaden bait landings in the Chesapeake Bay region, as documented by 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). Bait landings in the Chesapeake Bay region, all gears combined, have steadily increased since 1985, with landings during 2003–2005 the highest in the time series.

Bait landings from the South Atlantic region peaked in 1990 (over 4,000 mt) and have steady declined to an average of 650 mt during 2003–2005, with North Carolina accounting for 98% of the landings. Some landings in North Carolina are reported directly, while the rest are estimated from fishery-dependent sampling. The principal use for menhaden as bait in North Carolina is in the blue crab pot fishery. South Carolina and Georgia have no directed menhaden fisheries; shrimp trawl bycatch and cast nets supply menhaden to crab potters and sport fishermen in those states. Florida's east coast had substantial menhaden landings for bait from gill nets and purse seines prior to the implementation of a net ban in 1995 (ASMFC 2001).

Regionally and over the past two decades, the bait harvest in the Chesapeake Bay region has averaged 42% of all coastal bait landings. On the contrary, since 2000 bait landings in other regions have declined; consequently, between 2001–2005 bait landings in the Chesapeake Bay region accounted for 70% of coastal menhaden-for-bait landings. Over the same period, landings of menhaden-for-bait in the Mid-Atlantic, South Atlantic, and New England regions accounted for 27%, 2%, and 1% of the total coastwide bait landings, respectively (Figure 3.3).

3.2.2 Bait Landings

Bait landings rose throughout the 1980s and early 1990s as the bait purse seine fishery expanded (Table 3.2). Between 1985–2000 bait landings from all gears averaged 33,370 mt with landings modestly higher over the last five years, averaging 36,620 mt (Table 3.5).

Although the overall coastwide bait landings have remained relatively stable, the contribution by individual states has changed dramatically in recent years (Figure 3.2). From 1985–2000, eight states (including PRFC) accounted for nearly 98% of the coastwide bait landings. In recent years only four states, three of which are in the Chesapeake Bay region, account for over 96% of the coastwide bait landings. The purse-seine fisheries for bait account for nearly 80% (2001–2005) of all bait landings. Purse-seine fisheries for bait currently operate predominately in New Jersey and Virginia. A small purse-seine fishery for bait existed in North Carolina, but it has not operated since 2003. Pound net and small scale directed gill net fisheries for menhaden as bait exist in many states. These fisheries account for the majority of the remaining bait landings coastwide (18.5% of total bait landings). Additionally, menhaden for bait are taken as an aggregate bycatch in other coastal states by a variety of gears such as trawls, haul seines, traps, and cast nets (Figure 3.4).

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, were required to report their daily catches on CDFR forms, which are compiled at the Beaufort Laboratory. Bait vessels in New Jersey comply with Amendment 1 by requiring licensees to complete and submit daily logs documenting the amount and location of menhaden harvested to the NJ Division of Fish and Wildlife. Likewise, the bait purse seine fishery in North Carolina reported daily catch activity on a state trip ticket to the NC Division of Marine Fisheries.

During the AMTC Data Workshop in March 2006, concern was raised about unreported landings from Virginia bait purse seines during 1993–1997 (Figure 3.4). As an alternate data input for subsequent model runs, Virginia bait landings for 1993–1997 were linearly interpolated from estimated values for 1992 and 1998. Thus, a second set of bait landings (alternate) was developed for analysis (Figure 3.5).

3.2.3 Age and Length Composition

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 3.5). Protocols for acquiring size-at-age data from the bait fisheries are similar to sampling procedures for the reduction fishery. In 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. The number of age samples from the bait fishery has declined since 2003 due to decreased sampling in New Jersey.

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 3.5). 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) Mid-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 (Figure 3.3). When the number of samples for a given region and year was less than 50, data were pooled across the years available and substituted for that year. For the New England region, data for 1986–1996 were pooled and used for individual years 1986–1993 and 1996–2005. Data for 1985 were kept separate because these were particularly small fish. For the Mid-Atlantic region, data for 1994-2002 were pooled and substituted for individual years 1985–1993. The annual value for 2003 was used and then repeated for 2004–2005 due to insufficient sampling. For the Chesapeake Bay region, data for 1992–2005 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) 1997–2005. 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 3.6. In recent years, the bait catch-at-age has contracted from both ends (i.e., fewer younger and older ages being landed) due to the greater contribution of bait landings from Chesapeake Bay. From 1985–2000, 73% of the bait landings were age-2 and -3 menhaden (44% and 29%, respectively), with ages-1, -4, and

-5 significantly contributing to the landings (10%, 15%, and 2%, respectively). Recently (2001–2005), age-2 and -3 menhaden comprise over 88% of the bait landings (53% and 35%, respectively), with age-1's comprising 5% and age-4's comprising 6%. In 2005, 92% of the bait landings were age-2 and 3 fish.

3.3 RECREATIONAL FISHERY

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.

4.0 INDICES OF ABUNDANCE

Two types of indices of abundance were used in the recent peer-reviewed assessment (ASMFC 2004a). A series of fishery-independent seine surveys from five states were combined as a coastwide index of juvenile abundance (age-0). In addition, a fishery-dependent index was developed from commercial poundnet landings and effort from the Potomac River Fisheries Commission (PFRC) representing ages 1–3.

4.1 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 coastwide index was restricted to state seine indices and removed state trawl and gillnet surveys from consideration (ASMFC 2004). These surveys, as recently updated, include:

North Carolina Alosid seine survey (Program 100S; 1972–2005)
Virginia Striped Bass seine survey (1968–1973, 1980–2005)
Maryland Striped Bass seine survey (1959–2005)
Connecticut River seine survey (1987–2005)
Rhode Island Narragansett Bay seine survey (1988–2005)

Since the 2003 peer-reviewed assessment, the following seine survey has become available:

New Jersey seine survey (1980–2005)

4.1.1 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. Sample size and number of menhaden caught annually are summarized in Table 4.1 and 4.2.

During the data workshop for this updated assessment, the decision was made to restrict the data from this survey to stations that were relatively consistent over the duration of the survey (1972–2005). The codes for these stations are:

Waterbody	Location
0200020000	Black Walnut Point
0200030000	Cape Colony
0200040000	Albemarle Beach
0200050000	Brickhouse Point
0200060000	Bateman's Beach
0200070000	Bull Bay
0200080000	Soundview
0200090000	Harvey Point
200100000	Laural Pt to Bull Bay
200110000	Harvey Pt to Little River
200120000	Bull Bay to Ship Pt
200130000	Little River to Wade Pt
200160000	Long Shoal Pt to Ned Bees Pt
200180000	Ned Bees Pt to Caroon Pt
202000000	Pasquatank River
204000000	Little River
205000000	Perquimans River
206000000	Yeopin River
207000000	Edenton Bay
208000200	Mt Gld L./Harr.L. -Coler./Chow. B.
208000300	Coler./Chow.B./N.Holiday Is
208000500	Mouth Barnes Ck-Hwy 158/13 Br
209000000	Batchelor Bay
213000000	Bull Bay
213010000	Scuppernong River
300000000	Croatan Sound
400000000	Roanoke Sound

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. Rivers sampled include the James, Mattaponi, Pamunkey, Rappahannock, and York. Menhaden were caught predominantly in the Rappahannock River (73%), with smaller but significant quantities caught in the James (17%) and York (8%). The remaining 1% was caught in the Mattaponi and Pamunkey rivers. Sample size and number of menhaden caught annually are summarized in Table 4.1 and 4.2.

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. Permanent stations were sampled in four regions (Choptank River, Head of Bay, Nanticoke River, and Potomac River). The proportion of menhaden caught by region was 23% in CT, 30% in HB, 36% in NT, and 11% in PT. Sample size and number of menhaden caught annually are summarized in Table 4.1 and 4.2.

New Jersey's Delaware River seine survey has been conducted as a striped bass young-of-year seine survey since 1980 by the New Jersey Bureau of Marine Fisheries. This survey catches a variety of other species of fish and invertebrates, with significant numbers of age-0 Atlantic menhaden caught - over 150,000 since its inception. The sampling scheme has been modified over the years but the core survey area, station locations and field time frame (June–November) have remained consistent. The current sampling protocol, since 1998, consists of 32 fixed stations sampled twice a month from June through November within three distinct habitats: Region 1 – brackish tidal water; Region 2 – brackish to fresh tidal water; Region 3 – tidal freshwater.

Field sampling utilizes a 100-foot long, by 6-foot deep by 1/4-inch mesh bag beach seine. All fish are identified to species, quantified and a sub-sample of up to 30 lengths is recorded for each species from each seine haul. Basic water quality parameters such as water temperature, salinity and dissolved oxygen are also recorded. Those stations farthest up river, in the tidal fresh portion of the survey area (Region 3), were excluded from the index calculation because very few (less than 0.1%) of the menhaden caught came from this region. The catch of menhaden was approximately even between the two regions retained from this survey (49% in Region 1 and 51% in Region 2). Also, not all menhaden caught in a given year are age-0. To account for this, length frequency data was analyzed and all older (i.e. larger) menhaden were removed from the data set based on convention cut-off sizes by month described in the 2003 assessment report. Sample size and number of menhaden caught annually are summarized in Table 4.1 and 4.2.

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. Approximately 14 tows are taken annually in Deep, Essex, Glastonbury, and Salmon rivers. Almost half of the menhaden caught were in Deep River (49%), with 31% caught in Essex River, 3% in Glastonbury River, and 17% in Salmon River. Sample size and number of menhaden caught annually are summarized in Table 4.1 and 4.2.

Rhode Island's Narragansett Bay seine survey has been continuous since 1988 and stations (18) are sampled from June through October; the seine's dimensions are 3.05 m x 61 m. The number of menhaden caught was highly variable by station and year, with greater that 100,000 menhaden caught in 2000 at station 1 and in 2002 at station 4. Sample size and number of menhaden caught annually are summarized in Table 4.1 and 4.2.

4.1.2 Sampling Intensity

The numbers of hauls per year for each state seine survey are summarized in Table 4.1. The number of Atlantic menhaden caught by these seine surveys are summarized in Table 4.2. From 1959–1967, only seine data from Maryland are 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.

4.1.3 Biases

Because of the schooling nature of Atlantic menhaden and the fact that state surveys were designed originally 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.

4.1.4 Biological Sampling

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

4.1.5 Ageing Methods

For state seine surveys (North Carolina, Virginia, Maryland, and New Jersey) 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.

4.1.6 Development of Estimates

Catch-per-unit-effort (CPUE) indices were developed from the six 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 (standard deviations) 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 deviation of the delta-lognormal GLM are summarized for the six state seine surveys in a series of figures (Figures 4.1 –4.6).

Pairwise correlations were estimated for each of the state seine indices that were developed using the delta-lognormal GLM (Table 4.3). In particular, we found positive correlations for the NC seine index with the MD and NJ seine indices ($\alpha < 0.0001$), the two Chesapeake Bay indices with each other (MD & VA at $\alpha = 0.004$), and the two Chesapeake Bay indices with NJ seine index ($\alpha = 0.069$ and 0.042). Negative correlations were found between NJ and CT seine indices at $\alpha = 0.097$, and Chesapeake Bay seine indices with the RI seine index ($\alpha = 0.080$ for VA and a marginal $\alpha = 0.119$ for MD). The other pairwise correlations are not considered statistically significant.

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 according to the duration of the shorter series (VA) and averaged; similarly the two indices from southern New England were also standardized according to the shorter series (RI) and averaged. The North Carolina, Chesapeake Bay, New Jersey, and New England indices were then standardized to the time period 1987–2005 (shortest time period of the four regions). 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 for the peer-reviewed assessment, 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 (Figure 4.7). Varying state seine indices were represented in the coastwide index from 1968 to 1987. For this updated assessment, an alternate coastwide index was developed that included the standardized New Jersey seine index for the Middle Atlantic region (Figure 4.7).

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 the value of 1 added [*ln*(CPUE+1)].

4.1.7 Length/Weight/Catch-at-Age

See 4.1.4. Age-0s only used to calculate the indices of juvenile abundance.

4.2 FISHERY-DEPENDENT INDEX

A Potomac River Fisheries Commission fishery-dependent CPUE index was used in the 2003 peer-reviewed stock assessment. The pound net is a stationary nonselective fishing gear and it was believed to produce an index of relative abundance of menhaden (primarily ages-1 through 3) in Potomac River and Chesapeake Bay. 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), raising concerns about the validity of this index since 1994.

Recent efforts by the PRFC to obtain and computerize more detailed data on pound net landings and effort were presented to the ASMFC Menhaden Technical Committee on June 2005 (Carpenter 2005). An accompanying excel file was provided to the Menhaden Technical Committee and updated on March 3, 2006 with data through 2005 (Menhaden Harvest With Charts 2006.xls). Included in this file are published menhaden landings and number of pound net licenses from 1964–2005 (as used in the previous stock assessment with data through 2002), and pound net landings and number of pound net fishing days from 1976–1980 and 1988–2005 (Table 4.4). To develop an improved index based on pound net landings divided by pound net fishing days, regressions were done to fill in for missing years of the more refined data (1964–1975 and 1981–1987). The regression of pound net landings (PN) on published landings (PB) had an R^2 values of 0.996 and was highly significant:

$$PN = 224738 + 0.953*PB,$$

where PN and PB are in pounds (N = 23). The regression of pound net days fished (DF) on licenses (L; not including 1994–2005 when the number of licenses were fixed) had an R^2 of 0.485 and was significant at an α-level of 0.104 (N = 11):

$$DF = 3094.2 + 17.944*L.$$

The shorter period of overlap and greater variability increases the uncertainty of our composite index for the reconstructed years, but not for the most recent years (1988–2005). The pound net index used in this update assessment is based on estimated pound net landings per days fished, which includes the predicted values for the reconstructed years (1964–1975 and 1981–1987). We compare this newly developed PRFC pound net index with that used in the 2003 peer-reviewed assessment (Figure 4.8).

5.0 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. As an update assessment, this approach was maintained.

5.1 MODELS

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, 2006), South Atlantic black sea bass (Anonymous 2003, 2005), and South Atlantic snowy grouper and tilefish (Anonymous 2004). Forward-projecting age-structured models share many attributes with ADAPT-style tuned and untuned VPAs. The control file for the base model run is given in Appendix B, the corresponding input file in Appendix C, and a listing of ADMB model runs in Appendix D.

5.2 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 5.1. 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. There was a juvenile (age-0) index series (years 1959–2005) and a pound net CPUE index series (years 1964–2005).

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.

6.0. OUTPUTS/RESULTS

This section describes the output and results of the forward-projecting statistical age-structured model described in Section 5 on Methods. Development of the base run is described in Section 6.1. The base run with underlying spawner-recruit relation for the Ricker model developed by the Assessment Workshop was used. 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 6.2). Parameter estimates for the base run are shown with model uncertainty, represented by estimates of standard deviation from the Hessian matrix. These parameters include fishing mortality rate (*F* for ages 2+), population fecundity (number of maturing or ripe ova), and recruits to ages-0 (Section 6.3). Sensitivity of the model was tested for data input (alternate bait landings, alternate coastwide JAI, and alternate PRFC CPUE; Section 6.4.1) and for model configuration (allowing for time-varying selectivity for the reduction fishery; Section 6.4.2). 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 1999 (Section 6.5).

6.1. DEVELOPMENT OF BASE RUN

Selection of *M* at age

In the most recent benchmark assessment (ASMFC, 2004a) the then current MSVPA provided vector of age-specific *M* which was used as a starting estimate. The age-specific *M* vector was then multiplied by a model-estimated scaling parameter, resulting in an age specific *M* that was static across years. Since that benchmark assessment, the MSVPA-X model has undergone significant changes and peer reviews by both ASMFC internal and SARC external panels (see section 2.7).

For this update, an attempt was made to use the new *M* vector scaled by the current model as was previously done during the most recent benchmark assessment. However, results from this attempt were highly unrealistic, and suggested an $M > 1$ for the older age classes (Table 6.1). This behavior in estimating a large *M* for the older aged menhaden (>1) results from the lower values for *M* in the younger ages relative to the older ages. The data in the model suggest a high mortality rate for the younger ages (ages 0 and 1), resulting in higher estimates for the older ages.

To solve this problem of unrealistic *M* at the older age classes a number of sensitivity runs were conducted. These included:

1) using the previous *M* at age given in ASMFC, 2003
2) using the previous *M* vector provided by the earlier MSVPA scaled by the menhaden model
3) using the current MSVPA-X vector scaled such that *M* of age 6+ could not exceed (0.50) based on tagging estimates from Reish et al. 1985.

Runs 1 and 2 (above) were rejected because both relied on a preliminary MSVPA formulation. That formulation was not peer reviewed, used a more simplistic model that did not account of other prey items in its calculations, and was replaced by a more recent MSVPA-X. As such, Run 3 was selected for the base run. This analysis also has the benefit of utilizing observed tagging data (Reish et al. 1985), which was the basis for selecting the base run in the peer-reviewed assessment (ASMFC 2004a). The behavior and the interactions between MSVPA-X and the current menhaden assessment will be explored fully before the next benchmark assessment.

Base Run Configuration

For this updated assessment the base run was configured as follows:

- Age-varying *M* from MSVPA-X scaled to historical tagging estimate for oldest menhaden (age 6+).
- Life history relationships (maturity and fecundity) identical to previous assessment.
- Bait and reduction landings and catch-at-age from last assessment updated for 2003–2005.
- Five state seine juvenile abundance indices combined into single coastwide JAI updated for 2003–2005. Minor changes were made as follows: (1) reduced NC seine data to consistent stations, (2) normalizing to common years before combining state indices within regions.
- Improved PRFC poundnet index based on effort measured as days fished rather than number of licenses (which were fixed since 1994).
- Underlying Ricker spawner-recruit relationship (model benchmarks were found to be insensitive to this assumption during the previous assessment).
- Continued the assumption of constant flat-topped selectivity for the reduction fishery.

Alternate hypotheses for input data and model formulation are described with model output in section 6.4.

6.2. GOODNESS-OF-FIT

Goodness-of-fit is governed in the assessment model by the likelihood components in the objective function (Table 5.1). 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 (1955–2005; Figure 6.1) and the bait fishery (1985–2005; Figure 6.2) are compared for the base Ricker run. Reduction fishery landings, which are known very precisely, fit almost perfectly. The more poorly estimated bait landings show some deviations, but overall represent a good fit. Bubble plots and annual comparisons of observed and predicted proportion catch-at-age are presented for the reduction fishery (Figures 6.3 and 6.4) and bait fishery (Figures 6.5 and 6.6).

Observed and predicted coastwide juvenile abundance indices are compared for the base Ricker run (1959–2005; Figure 6.7). The model predicted greater year-to-year variability in recruitment to age-0 than the observed index. Finally, the observed and predicted pound net index (pounds landed per days fished for 1964–2005; Figure 6.8) fit poorly. Improved fit is apparent in the most recent years, coinciding with the improvement in the unit of effort from number of licenses (fixed at 100 since 1994) to days fished.

6.3. BASE RUN RESULTS

Results from the base (preferred) run are described in this section. These results are developed from an underlying Ricker spawner-recruit relation, and they include annual estimates of fishing mortality rate, population fecundity, and recruits to age-0, including precision of these estimates based on model-fitting error. In addition a comparison of these same estimates is made with results from the base Ricker run presented in the peer-reviewed assessment (ASMFC 2004a).

As noted earlier, an important element of this model approach is that M was specified as an age-specific set of values obtained from the results of the recent peer-reviewed MSVPA-X (Table 6.1). The absolute values were scaled so that M for the oldest ages matched historical tagging study results. Values of M for ages-3 and older from the base run (0.5) are similar to those obtained from historical tagging studies (M = 0.52 from Dryfoos et al. 1973; M = 0.50 from Reish et al. 1985).

6.3.1. Base Parameter Estimates and Precision

Precision of model estimates from each model run is based on the use of the delta-method to approximate variances. 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. For example, there is no attempt to model the error in 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.

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 Figure 6.9. 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 (77%). The bait fishery was modeled with a dome-shaped double-logistic equation (see Section 5), with age-4 fully recruited and ages-3 and -5 almost fully recruited (94% and 92%, respectively). The catch-weighted selectivity for the final fishing year (2005) shows ages-3 to -5 as fully recruited (>97%), with age-2 (70%) and ages-6 to -8 (83–89%) almost fully recruited.

Fishing mortality rates on ages-2 to 8+ (referred to as *F*) were calculated as the weighted average of age-specific *F*s for those ages and population number at age (Figure 6.10). High 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 peak in the mid-1960s, fishing mortality has declined and has generally been below 1.0 for the last 14 years. The time period 1955-2005 produced a median *F* of 1.04 with an interquartile range between 0.83 and 1.25 (Table 6.2). Age-specific estimates of F are summarized in Table 6.4 (base Ricker run). Estimates of F for 1955-1984 are based on the reduction fishery only, while those estimates for 1985-2005 are based on both the reduction and bait fisheries.The estimate of fishing mortality rate for 2005 of 0.50 is below the 25th percentile of the historical estimates.

The forward-projecting statistical age-structured model estimates population numbers at age (0-8) for 1955–2005 (Table 6.3 for base Ricker run). From these estimates, along with growth and reproductive data (Section 2), different estimates of reproductive capacity can be computed. Addendum 1 (ASMFC 2004b) adopted population fecundity as the preferred measure of reproductive output. Population fecundity (FEC, number of maturing ova) was high in the late 1950s and early 1960s, low in the late 1960s, and generally increasing since then (Figure 6.11). The largest values of population fecundity were present in 1955 and 1961, resulting from two very strong recruitment events in 1951 and 1958 as noted in earlier stock assessments (Ahrenholz et al. 1987b; Vaughan and Smith 1988; Vaughan et al. 2002b; ASMFC 2004a). The time period 1955-2005 produced a median population fecundity of 28.3 x 10^{12} ova with an interquartile range between 21.8 x 10^{12} and 43.1 x 10^{12} (Table 6.2). The estimate for population fecundity in 2005 was 41.7 x 10^{12}, between the median and the 75th percentile.

Age-0 recruits of Atlantic menhaden (Figure 6.12) were high during the late 1950s, especially the 1958 year-class. Median and interquartile values for age-0 recruits are summarized in Table 6.2. Recruitment was generally poor during the 1960s, with values below the 25th percentile (9.1 billion) for the recruitment time series. High recruitment occurred during the 1970s to levels above the 75th percentile (21.5 billion). These values are comparable to the late 1950s (with the exception of the extraordinary 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 2005 is likely to be modified in the future as more data from the cohort (age-1 in 2006, age-2 in 2007, etc.) are added to the analysis. The current estimate of recruits to age-0 in 2005 (8.8 billion for the Ricker model) is below the 25th percentile (9.1 billion).

Based on the delta method, annual estimates of fishing mortality rate *F* (Figure 6.10), population fecundity (Figure 6.11), and recruits to age-0 (Figure 6.12) are presented for the base Ricker run, with dashed lines showing plus or minus twice the standard error. Estimates of *F*, population fecundity, and recruits to age-0 appear to be quite precise.

6.3.2 Comparison of Update Base Run with Peer-Review Base Run

Results from this updated assessment compare very closely to those of the recent peer-reviewed assessment (ASMFC 2004a) (Figures 6.13–6.15).

6.4 SENSITIVITY ANALYSES

Sensitivity of the forward-projecting statistical age-structured model was investigated in two fundamental ways. First, sensitivity to input data was investigated by using alternate input data for (1) bait landings (and corresponding catch at age), (2) coastwide juvenile abundance index, and (3) old version of the PRFC CPUE based on number of licenses as the unit of fishing effort. Secondly, sensitivity to model configuration was investigated through time-varying selectivity in the reduction fishery.

6.4.1 Sensitivity to Input Data

Sensitivity runs were made to investigate the alternate configurations for bait landings, coastwide juvenile abundance index, and PRFC CPUE using the previous unit of effort based on number of licenses (Figures 6.16–6.18). Base bait landings were based on reported data, while an alternate set of landings included linearly interpolated VA purse seine landings for 1993–1997. The base coastwide JAI used the five state seine indices used in the original peer-reviewed assessment, which included NC, VA, MD, CT, and RI (ASMFC 2004). The alternate coastwide index included a new seine index developed for NJ. The base run used a new PRFC CPUE based on days fished as the unit of effort, rather than the previous number of licenses. An alternate run used the old unit of effort, an inappropriate unit of effort since it has been fixed at 100 licenses since 1994. Generally these results showed little variation from the base Ricker run. However, the alternate run based on the alternate PRFC CPUE estimated higher F and lower population fecundity in the terminal year.

6.4.2 Sensitivity to Selectivity

Because of the geographic contraction of the reduction fishery historically, concerns have been raised about the assumption of constant selectivity for the reduction fishery. Menhaden are known to roughly stratify by size and age with latitude along the East Coast. The closures of many reduction facilities to the north and increasing state regulations have contracted the fishery to primarily the mid-Atlantic region of the coast. The contraction of the fishery may affect the availability and hence the selectivity being applied to the reduction fishery in the stock assessment model.

In order to correct for the potential shift in selectivity, three time periods were defined. An early time period (1955–1981) continued the assumption of flat-top selectivity. The period 1982–1993 was considered a period of transition, during which both plants to the north (middle and north Atlantic) and to the south (North Carolina through Florida) closed operations. Annual selectivity parameters were estimated for this transition period. Since 1994, reduction plants have only operated in Virginia (two then one) and North Carolina (one then none). Therefore, 1994–2005 reduction fishery landings were assumed to have domed-shape selectivity. Results are summarized in Figures 6.16–6.18. Little difference is noted from the base Ricker run, except for lower F and higher population fecundity in the terminal year.

6.5. RETROSPECTIVE ANALYSIS

A series of five runs were made dropping the latest year of data from the base Ricker run. In the first run, the last year of data was 2004, in the second run the last year of data was 2003, and so forth through 1999. Little, if any, retrospective bias was noted in estimates of fishing mortality

(F), population fecundity, or recruits to age 0 (Figures 6.19-6.21). Annual estimates of F (Figure 6.19), population fecundity (Figure 6.20), and recruits to age-0 (Figure 6.21) were compared to the base run and the sequence of reduced data sets. The retrospective pattern suggests very little bias for full F, population fecundity, and age-0 recruits. There is greater variability in terminal year estimates of recruits and this is to be expected given the limited data available for estimating this value.

7.0 BIOLOGICAL REFERENCE POINTS

7.1 OVERFISHING DEFINITIONS

The limit reference points (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; the rate of removal of fish by the fishery exceeds the ability of the stock to replenish itself. When the reproductive output (measured as spawning stock biomass or population fecundity) falls below the biomass-limit or threshold, then the stock is overfished, meaning there is insufficient mature female biomass (SSB) or egg production (population fecundity) to replenish the stock.

Ideally, F-based and SSB-based reference points should be based on an underlying population dynamics model (e.g., F_{MSY} and B_{MSY} from Ricker or Beverton-Holt spawner-recruit models). However, traditional methods of specifying these reference points perform poorly when applied to historical Atlantic menhaden. There is considerable scatter in the spawner-recruit relationship (Figure 7.1). Hence, the reference points in Amendment 1, adopted in 2001 (ASMFC 2001), were developed from the historic spawning stock per recruit (SSB/R) relationship (Figure 7.2). As such, F_{MED} or $F_{threshold}$ (representing replacement level of stock, also known as F_{REP}) was based on median values of SSB/R. The corresponding spawning stock biomass to $F_{threshold}$ became the SSB_{target} (Figure 7.3). The limit (threshold) for SSB was calculated to account for natural mortality [(1-M)*SSB-target, where M=0.45]. In amendment 1, the F_{target} was based on F_{MAX} (maximum fishing mortality before the process of recruitment overfishing begins). The values calculated for these reference points were 1.04 and 1.33 for the F_{target} and $F_{threshold}$, respectively, while 37,400 mt and 20,570 mt were the SSB_{target} and $SSB_{threshold}$, respectively (Table 13 in ASMFC 2001).

7.2 ADDENDUM 1 BENCHMARKS

In 2003, a new benchmark stock assessment for Atlantic menhaden was completed by the Technical Committee (TC) and peer reviewed through the Southeast Data and Assessment Review (SEDAR) process (ASMFC 2004a). Based on SEDAR recommendations, the benchmarks were modified by the ASMFC in Addendum 1 as recommended by the Technical Committee (ASMFC 2004a, 2004b). The TC recommended using population fecundity (number of maturing or ripe eggs) (FEC) as a better measure of reproductive output of the population compared to spawning stock biomass (the weight of mature females) (SSB). For Atlantic menhaden, older menhaden release more eggs than younger menhaden per unit of female biomass. By using the number of eggs released, more reproductive importance is given to older fish in the population than accounted for simply by female biomass. Population fecundity is a more direct measure of reproductive potential. They also recommended changing the fishing mortality (*F*) target and threshold. The TC continued to use F_{MED} to represent F_{REP} as the $F_{threshold}$, but estimated it using fecundity per recruit rather the SSB per recruit. Because the analysis calculated an F_{MAX} that was greater than F_{MED} (and may be infinite), they recommended instead that F_{target} be based on the 75th percentile. This approach was consistent with the approach used for the $F_{threshold}$ (Figure 7.4). For biomass (or egg) benchmarks, the TC recommended following the approach of Amendment 1. The following biological reference points were estimated for the terminal year of the benchmark assessment: $F_{target} = 0.75$, $F_{threshold} = 1.18$, fecundity target (FEC_{target}) = 26.6 trillion eggs and fecundity threshold ($FEC_{threshold}$) = 13.3 trillion eggs (ASMFC 2004a).

7.3. EVALUATION OF CURRENT STATUS BASED ON BIOLOGICAL REFERENCE POINTS

Because growth and fecundity at age vary annually (see Appendix C), benchmarks will also vary annually. To provide consistency in presenting the historical pattern in estimated reference point values, we have calculated the ratio of $F/F_{threshold}$ (i.e., F/F_{rep} analogous to F/F_{msy}) and FEC/FEC_{target} (FEC/FEC_{msy} analogous to SSB/SSB_{MSY}) (Fig. 7.5). Overfishing occurred ($F/F_{rep} > 1$) from during the 1960s and again during the late-1970s and 1980s. Meanwhile population fecundity was very high in the 1950s (from two exceptionally strong recruitment events), below its target from 1964 through about 1970 (when an extended period of poor recruitment occurred), and generally noisy but rising population fecundity since then. With the recent decline in size at age (e.g., Figure 2.1), the benchmarks for *F* also declined from those calculated in the 2003 peer reviewed assessment ($F_{threshold}$ from 1.18 to 0.91 and F_{target} from 0.75 to 0.55). Sensitivity of the benchmarks to the alternate data and model formulations are also summarized in Table 7.1. The sensitivity run based on time-varying selectivity showed the greatest deviation in *F*-based benchmarks from the base run. The population fecundity benchmarks, both base and sensitivity varied little among them or from the peer-reviewed assessment (ASMFC 2004a).

Depending on the interpretation of the benchmarks presented in Addendum 1 (ASMFC 2004b), we can compare recent estimated values of fishing mortality rate (*F*) and population fecundity to the benchmark values or to model-consistent values updated with this assessment. First we compare these values to the estimated values given in Addendum 1 (Fig. 7.6). Estimates of *F* and population fecundity for the terminal year (2005, solid square) fall in the region where a stock is typically considered healthy (i.e., *F* is below its target, and population fecundity is above its target) based on these benchmarks. Alternatively, benchmarks are calculated from the update assessment for the base Ricker run (Table 7.1). Recent values of *F* and population fecundity are now compared to benchmarks based on the process defined in Addendum 1 (Fig. 7.7). Again, estimates of *F* and population fecundity for the terminal year (2005, solid square) fall in the region where a stock is typically considered to be healthy based on updated benchmark values.

The changes in the biological reference points, while seemingly large for F, are a re-estimation of benchmarks based on updated population parameters, but using the same process defined in the 2003 peer-reviewed assessment (ASMFC 2004a). These changes primarily reflect annual growth patterns for the terminal year, and are neither more nor less conservative than the previous estimates.

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Table 2.1 Estimated fork lengths and weights for Atlantic menhaden calculated at middle of fishing year averaged over 2001–2005.

Age	Fork Length (mm)	Weight (g)
0	134.0	41.6
1	191.1	124.2
2	242.5	258.6
3	275.6	382.5
4	297.1	481.5
5	311.2	555.8
6	320.6	609.7

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

	Weight-Length				*Von Bertalanffy Curve*			
Year	**n**	**a**	**b**	**RMSE**	**n**	**Linf**	**K**	**t0**
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
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
2003	3945	-12.031	3.211	0.0052	3108	346.20	0.418	-0.556
2004	4600	-11.603	3.120	0.0049	3759	370.20	0.303	-0.609
2005	3940	-11.012	3.007	0.0041	3102	336.90	0.382	-0.412

Table 3.1 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
2004										+																										1	10
2005										+																										1	11

Table 3.1 (*continued*)

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

Table 3.2 Landings and effort (vessel-weeks) of Atlantic menhaden in the reduction purse-seine fishery, 1940–2005, landings of Atlantic menhaden in the bait fisheries, 1985–2005, and total landings for both fisheries.

	Reduction Fishery		Bait Fishery	Total Landings
Year	Landings (1000 t)	Effort (v-w)	Landings (1000 t)	(1000 t)
1940	217.7	967		217.7
1941	277.9	1291		277.9
1942	167.2	991		167.2
1943	237.2	889		237.2
1944	257.9	1167		257.9
1945	295.9	1271		295.9
1946	362.4	1365		362.4
1947	378.3	1582		378.3
1948	346.5	1781		346.5
1949	363.8	2076		363.8
1950	297.2	1650		297.2
1951	361.4	1686		361.4
1952	409.9	1653		409.9
1953	593.2	1972		593.2
1954	608.1	2094		608.1
1955	641.4	2748		641.4
1956	712.1	2878		712.1
1957	602.8	2775		602.8
1958	510.0	2343		510.0
1959	659.1	2747		659.1
1960	529.8	2097		529.8
1961	575.9	2371		575.9
1962	537.7	2351		537.7
1963	346.9	2331		346.9
1964	269.2	1807		269.2
1965	273.4	1805		273.4
1966	219.6	1386		219.6
1967	193.5	1316		193.5
1968	234.8	1209		234.8
1969	161.6	995		161.6
1970	259.4	906		259.4
1971	250.3	897		250.3
1972	365.9	973		365.9
1973	346.9	1099		346.9
1974	292.2	1145		292.2
1975	250.2	1218		250.2
1976	340.5	1163		340.5
1977	341.1	1239		341.1
1978	344.1	1210		344.1
1979	375.7	1198		375.7
1980	401.5	1158		401.5
1981	381.3	1133		381.3
1982	382.4	948		382.4
1983	418.6	995		418.6
1984	326.3	892		326.3
1985	306.7	577	28.3	335.0
1986	238.0	377	31.1	269.1
1987	327.0	531	34.1	361.1
1988	309.3	604	36.2	345.5
1989	322.0	725	34.8	356.8
1990	401.2	826	33.6	434.8
1991	381.4	926	39.7	421.1
1992	297.6	794	42.4	340.0
1993	320.6	626	34.9	355.5
1994	260.0	573	27.2	287.2
1995	339.9	600	30.5	370.4
1996	292.9	528	23.3	316.2
1997	259.1	618	26.9	286.0
1998	245.9	437	40.4	286.3
1999	171.2	382	37.1	208.3
2000	167.2	311	35.0	202.2
2001	233.7	334	37.4	271.1
2002	174.0	318	37.2	211.2
2003	166.1	302	35.0	201.1
2004	183.4	345	35.3	218.7
2005	146.9	291	38.2	185.1

Table 3.3 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 reduction fishery, 1955–2005.

Year	Sample Size (n)	Landings (millions)	Landings (1000 t)	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
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
2003	3415	698.3	166.1	4863.7	237.9
2004	4170	978.0	183.4	4398.1	187.5
2005	3520	648.5	146.9	4173.3	226.5

Table 3.4 Estimated reduction landings of Atlantic menhaden in numbers by age (in millions), 1955–2005. Note that age 6 is a plus group.

Year	Age 0	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6	Total
1955	761.0	674.2	1057.7	267.3	307.2	38.1	13.0	3118.4
1956	36.4	2073.3	902.7	319.6	44.8	150.7	37.4	3564.8
1957	299.6	1600.0	1361.8	96.7	70.8	40.5	42.3	3511.7
1958	106.1	858.2	1635.4	72.1	17.3	15.9	14.4	2719.2
1959	11.4	4038.7	851.3	388.3	33.4	11.9	18.7	5353.6
1960	72.2	281.0	2208.6	76.4	102.2	23.8	11.0	2775.1
1961	0.3	832.4	503.6	1209.6	19.2	29.4	3.9	2598.3
1962	51.6	514.1	834.5	217.3	423.4	30.8	28.3	2099.9
1963	96.9	724.2	709.2	122.5	45.0	52.4	14.3	1764.5
1964	302.6	704.0	605.0	83.5	17.9	7.9	8.3	1729.1
1965	259.1	745.2	421.4	77.8	12.2	1.8	2.0	1519.5
1966	349.5	550.8	404.1	31.7	3.9	0.4	0.3	1340.6
1967	7.0	633.2	265.7	72.8	5.1	0.5	0.0	984.2
1968	154.3	377.4	539.0	65.7	10.7	1.0	0.1	1148.0
1969	158.1	372.3	284.3	47.8	5.4	0.2	0.0	868.2
1970	21.4	870.9	473.9	32.6	4.0	0.1	0.0	1403.0
1971	72.9	263.3	524.3	88.3	17.8	2.5	0.0	969.1
1972	50.2	981.3	488.5	173.1	19.1	1.9	0.0	1713.9
1973	56.0	588.5	1152.9	38.6	7.0	0.3	0.0	1843.4
1974	315.6	636.7	986.0	48.6	2.5	1.4	0.0	1990.6
1975	298.6	720.0	1086.5	50.2	6.6	0.2	0.1	2162.3
1976	274.2	1612.0	1341.1	48.0	8.0	0.3	0.0	3283.5
1977	484.6	1004.5	2081.8	83.5	17.8	1.4	0.1	3673.7
1978	457.4	664.1	1670.9	258.1	31.2	3.5	0.0	3085.2
1979	1492.5	623.1	1603.3	127.9	21.8	1.5	0.1	3870.1
1980	88.3	1478.1	1458.2	222.7	69.2	14.4	1.4	3332.3
1981	1187.6	698.7	1811.5	222.2	47.5	15.4	1.3	3984.0
1982	114.1	919.4	1739.6	379.7	16.3	5.8	0.9	3175.7
1983	964.4	517.2	2293.1	114.4	47.4	5.0	0.7	3942.1
1984	1294.2	1024.2	892.1	271.5	50.3	15.2	0.5	3548.0
1985	637.2	1075.9	1224.6	44.1	35.6	6.3	1.7	3025.3
1986	98.4	224.2	1523.1	49.1	10.5	6.1	1.1	1912.4
1987	42.9	504.7	1587.7	151.9	25.2	2.2	0.7	2315.2
1988	338.8	282.7	1157.7	301.4	69.8	7.1	0.6	2158.0
1989	149.7	1154.6	1158.5	108.4	47.5	11.6	0.2	2630.5
1990	308.1	132.8	1553.1	109.0	42.2	12.3	0.4	2157.9
1991	881.8	1033.9	946.1	254.0	38.0	10.7	2.2	3166.6
1992	399.7	727.2	795.4	66.1	51.3	10.9	1.9	2052.5
1993	67.9	379.0	983.1	148.9	10.9	3.9	0.3	1594.0
1994	88.6	274.5	888.9	165.1	67.2	7.5	0.2	1492.0
1995	56.8	533.7	671.9	309.1	67.5	4.4	0.0	1643.3
1996	33.7	209.1	679.1	139.0	29.0	2.0	0.0	1091.9
1997	25.2	246.9	424.5	237.4	51.6	9.0	1.2	995.9
1998	72.8	185.0	540.6	126.3	73.0	9.0	0.8	1007.5
1999	193.9	301.1	450.8	81.8	25.0	3.2	0.4	1056.3
2000	77.8	114.2	340.6	111.9	11.1	1.9	0.0	657.4
2001	23.0	43.5	369.5	217.6	14.9	0.7	0.0	669.2
2002	178.2	211.7	259.8	135.8	17.1	0.5	0.0	803.1
2003	60.7	127.5	447.3	53.8	7.8	0.9	0.3	698.3
2004	18.0	213.9	652.1	75.7	17.4	0.9	0.0	978.0
2005	12.1	78.9	382.9	154.2	18.7	1.8	0.0	648.5

Table 3.5 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, 1985–2005.

Year	Sample Size	Landings		Intensity	Mean
	(n)	(millions)	(1000 mt)	(C/100n)	Weight (g)
1985	800	105.6	28.3	3537.0	267.9
1986	420	103.6	31.1	7415.8	300.6
1987	220	114.0	34.1	15504.3	299.2
1988	10	116.8	36.2	361872.1	309.8
1989	30	123.0	34.8	115914.7	282.8
1990	10	125.7	33.6	336100.8	267.3
1991	78	138.3	39.7	50943.4	287.4
1992	70	138.3	42.4	60610.8	306.8
1993	169	106.9	34.9	20676.6	327.0
1994	539	88.3	27.2	5037.3	307.6
1995	362	108.3	30.5	8414.0	281.2
1996	357	65.1	23.3	6525.0	357.7
1997	313	75.3	26.9	8596.8	357.2
1998	636	113.3	40.4	6355.1	356.9
1999	538	130.6	37.1	6889.6	283.8
2000	543	112.0	35.0	6454.2	312.9
2001	962	105.3	37.4	3889.2	355.4
2002	702	97.2	37.2	5301.7	382.7
2003	427	109.2	35.0	8191.5	320.4
2004	354	131.2	35.3	9977.8	269.2
2005	322	113.4	38.2	11854.4	336.7

Table 3.6 Estimated bait landings of Atlantic menhaden in numbers at age (in millions), 1985–2005. Note that age 6 is a plus group.

	Age							
Year	0	1	2	3	4	5	6	Total
1985	0.6	9.4	66.5	20.3	7.2	1.4	0.3	105.6
1986	0.4	6.2	45.9	33.9	15.5	1.3	0.3	103.6
1987	0.5	6.1	55.4	34.6	15.6	1.4	0.3	114.0
1988	0.4	6.2	46.3	41.2	20.6	1.7	0.4	116.8
1989	0.7	9.3	64.8	33.5	13.2	1.3	0.3	123.0
1990	0.7	24.4	50.6	33.4	14.9	1.4	0.3	125.7
1991	0.5	16.8	56.5	42.4	19.8	1.9	0.4	138.3
1992	0.7	19.8	49.5	45.0	20.7	2.2	0.4	138.3
1993	0.8	21.4	23.9	39.2	19.2	2.0	0.4	106.9
1994	0.2	8.2	35.3	26.8	15.4	2.2	0.2	88.3
1995	0.0	22.2	25.5	35.7	24.9	0.1	0.0	108.3
1996	0.0	2.8	34.9	21.7	5.5	0.2	0.0	65.1
1997	0.0	2.6	27.1	22.2	17.6	5.0	0.9	75.3
1998	3.4	5.1	47.0	32.2	21.5	3.5	0.7	113.3
1999	0.1	5.4	77.6	31.4	14.1	1.8	0.3	130.6
2000	0.6	17.7	63.5	20.5	8.4	1.0	0.3	112.0
2001	0.2	4.8	57.1	37.9	4.6	0.6	0.1	105.3
2002	0.0	4.9	37.2	44.6	9.5	0.9	0.1	97.2
2003	0.5	8.8	69.4	25.2	5.0	0.2	0.0	109.2
2004	0.0	7.5	83.1	32.2	7.9	0.5	0.0	131.2
2005	0.0	1.4	51.3	52.9	7.3	0.5	0.0	113.4

Table 4.1 Number of hauls per year by state seine surveys available for this updated assessment. The New Jersey seine survey only used for alternate run.

Year	NC	VA	MD	NJ	CT	RI	Total
1959			34				34
1960			36				36
1961			46				46
1962			88				88
1963			88				88
1964			88				88
1965			88				88
1966			132				132
1967			132				132
1968		55	132				187
1969		60	132				192
1970		66	132				198
1971		70	132				202
1972	591	110	132				833
1973	951	70	132				1153
1974	548	0	130				678
1975	430	0	132				562
1976	308	0	132				440
1977	297	0	132				429
1978	323	0	132				455
1979	127	0	132				259
1980	190	87	132	21			430
1981	161	94	132	13			400
1982	213	64	132	21			430
1983	264	54	132	16			466
1984	203	58	132	31			424
1985	203	78	132	46			459
1986	177	72	132	36			417
1987	214	72	132	80	52		550
1988	191	90	132	80	55	74	622
1989	209	123	132	80	56	74	674
1990	192	125	132	80	56	80	665
1991	194	121	132	193	55	80	775
1992	194	125	132	193	53	80	777
1993	227	123	132	153	56	84	775
1994	223	125	132	153	53	85	771
1995	251	124	132	153	56	89	805
1996	243	124	132	153	56	90	798
1997	238	124	132	153	56	90	793
1998	242	125	132	142	56	90	787
1999	244	124	132	168	55	90	813
2000	259	125	132	168	56	90	830
2001	258	128	132	168	56	90	832
2002	259	125	132	239	55	90	900
2003	259	124	132	240	54	90	899
2004	411	125	132	238	55	90	1051
2005	334	127	132	238	55	90	976
Total N:	9628	3217	5746	3256	1046	1546	24439

Table 4.2 Number of Atlantic menhaden caught per year by state seine surveys used in this update assessment, 1959–2005. The New Jersey seine survey only used for alternate run.

Year	NC	VA	MD	NJ	CT	RI	Total
1959			179				179
1960			59				59
1961			142				142
1962			8,817				8,817
1963			4,754				4,754
1964			718				718
1965			161				161
1966			983				983
1967			859				859
1968		655	1,042				1,697
1969		935	7,946				8,881
1970		157	239				396
1971		1,799	23,085				24,884
1972	383	8,294	10,999				19,676
1973	4,064	20,837	59,624				84,525
1974	11,529	0	44,043				55,572
1975	13,983	0	55,273				69,256
1976	16,010	0	62,193				78,203
1977	5,216	0	86,874				92,090
1978	6,179	0	18,100				24,279
1979	293	0	58,716				59,009
1980	574	8,744	33,467	3,280			46,065
1981	2,644	3,674	39,066	10,642			56,026
1982	1,584	8,984	25,906	2,136			38,610
1983	4,888	3,408	24,375	1,625			34,296
1984	1,103	5,621	18,925	4,882			30,531
1985	483	9,721	47,615	2,901			60,720
1986	968	13,978	27,575	1,315			43,836
1987	292	2,504	10,819	475	137		14,227
1988	1,081	2,068	40,492	6,382	708	42	50,773
1989	535	5,645	18,855	6,641	14,840	11	46,527
1990	377	6,058	22,148	11,889	2,741	6,977	50,190
1991	2,985	9,904	11,622	8,818	22,987	517	56,833
1992	605	1,458	6,098	5,259	59,948	27,556	100,924
1993	2,749	892	920	1,162	9,452	0	15,175
1994	269	520	7,553	6,539	6,238	34	21,153
1995	4,763	544	1,187	9,337	929	43	16,803
1996	2,054	1,852	1,293	1,351	33,663	2,152	42,365
1997	2,373	1,332	6,702	9,977	7,808	7	28,199
1998	205	1,408	2,599	1,349	34,364	30,036	69,961
1999	297	60	6,803	35,628	57,179	8,267	108,234
2000	25	108	983	1,046	36,599	402,190	440,951
2001	9,225	302	3,432	516	14,108	12,529	40,112
2002	134	205	8,668	2,807	154,374	327,732	493,920
2003	2,930	178	1,038	3,669	158,953	994	167,762
2004	1,891	418	1,814	623	26,520	32,420	63,686
2005	3,850	4,555	21,947	25,079	392	11,105	66,928
Total N:	106,541	126,818	836,708	165,328	641,940	862,612	2,739,947

Table 4.3 Pairwise correlations among six state seine indices from the delta-lognormal GLM for Atlantic menhaden. Top value is the correlation coefficient (r), second value is $\alpha = \Pr\{H_0: r=0\}$, and third value is sample size (number of years of overlap). All but the New Jersey seine index were available and incorporated into the coastwide index for the base run for this updated assessment. The New Jersey seine index was incorporated into the coastwide index for an alternate run.

Correlations among JAI Seines	Seine Indices	South Atlantic	Chesapeake Bay		Middle Atlantic	New England	
		NC100S	VA CB	MD CB	NJ	CT RIVER	RI NB
South Atlantic	NC100S	1.0 34	0.198 0.313 28	0.648 <0.0001 34	0.722 <0.0001 26	-0.268 0.267 19	-0.289 0.261 17
Chesapeake Bay	VA CB	.	1.0 30	0.491 0.004 32	0.363 0.069 26	-0.146 0.552 19	-0.436 0.080 17
	MD CB	.	.	1.0 45	0.402 0.042 26	-0.362 0.128 19	-0.392 0.119 17
Middle Atlantic	NJ				1.0 26	-0.392 0.097 19	-0.230 0.374 17
New England	CT RIVER	.	.	.		1.0 19	0.289 0.261 18
	RI NB	.	.	.		.	1.0 17

Table 4.4 Estimated Atlantic menhaden landings and poundnet fishing effort from the Potomac River Fishing Commission, including published menhaden landings (pounds), poundnet landings (pounds), and poundnet effort as licenses and days fished. Regressions used to predict poundnet (PN) landings and days fished for 1964–1975 and 1981–1987. Licenses fixed at 100 from 1994 to present. CPUE(1) is based on published menhaden landings per license and CPUE(2) is poundnet landings per days fished.

Year	Pub Landings	Obs PN Landings	Pred PN Landings	Licenses	Obs DaysF	Pred DaysF	CPUE(1)	CPUE(2)
1964	6781993		6687470	138		5570	49145	1201
1965	7235827		7119940	144		5678	50249	1254
1966	5776200		5729025	157		5911	36791	969
1967	2955967		3041553	149		5768	19839	527
1968	2622760		2724032	136		5535	19285	492
1969	2098808		2224745	181		6342	11596	351
1970	4290459		4313225	112		5104	38308	845
1971	3542921		3600877	99		4871	35787	739
1972	6156529		6091450	85		4619	72430	1319
1973	11162850		10862100	81		4548	137813	2389
1974	9831072		9593015	69		4332	142479	2214
1975	10542082		10270554	93		4763	113356	2156
1976	11817553	10830138	11485983	119	4668	5230	99307	2320
1977	19969104	18356820	19253802	134	5254	5499	149023	3494
1978	17298486	17078890	16708903	119	5046	5230	145365	3385
1979	14436804	13886417	13981934	134	5620	5499	107737	2471
1980	18720165	18713923	18063657	127	5914	5373	147403	3164
1981	20366865		19632839	123		5301	165584	3703
1982	17989434		17367325	114		5140	157802	3379
1983	20820945		20065543	119		5230	174966	3837
1984	13121597		12728640	124		5319	105819	2393
1985	16768889		16204236	144		5678	116451	2854
1986	10971973		10680208	130		5427	84400	1968
1987	13120495		12727589	84		4602	156196	2766
1988	13231368	13231030	12833243	93	5367	4763	142273	2465
1989	8334174	8333994	8166583	96	4924	4817	86814	1693
1990	4523776	4523776	4535558	86	4585	4637	52602	987
1991	5376264	5376223	5347916	85	4683	4619	63250	1148
1992	5061565	5061295	5048031	76	3848	4458	66600	1315
1993	7884001	7868456	7737602	72	4601	4386	109500	1710
1994	6680937	6680785	6591172	99	4382		67484	1525
1995	7002818	7002818	6897900	100	4553		70028	1538
1996	5111423	5111370	5095542	100	3482		51114	1468
1997	5757370	5757060	5711081	100	3975		57574	1448
1998	3980738	3956806	4018084	100	3456		39807	1145
1999	4860883	4855463	4856796	100	2986		48609	1626
2000	5023374	5006982	5011638	100	2713		50234	1846
2001	3329035	3320627	3397059	100	2599		33290	1278
2002	3122050	3113585	3199818	100	2778		31221	1121
2003	2438790	2415194	2548722	100	2288		24388	1056
2004	5411043	5398476	5381057	100	2448		54110	2205
2005	4759545	4752181	4760229	100	2538		47595	1872

Table 5.1 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 5.1 (*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	$N_{a+1,1947} = N_{a,1947}\exp(-Z_{a,1947})$ $N_{8+,1947} = N_{7,1947}\exp(-Z_{7,1947})/[1-\exp(-Z_{8+,1947})]$ $$\varepsilon_y = \sum_{a=0}^{8+} N_{a,y} m_a \gamma_a 0.5$$ $$N_{0,y} = \frac{\varepsilon_y}{\phi_y}\exp\left[h'\left(1-\frac{\varepsilon_y}{R_0\phi_y}\right)\right] + R_y \text{ (Ricker)}$$ $$N_{0,y} = \frac{0.8R_0 h\varepsilon_y}{0.2\phi_y R_0(1-h)+(h-0.2)\varepsilon_y} + R_y \text{ (B-H)}$$ $$N_{a+1,y+1} = N_{a,y}\exp(-Z_{a,y})$$ $$N_{A,y} = N_{A-1,y-1}\exp(-Z_{A-1,y-1}) + N_{A,y-1}\exp(-Z_{A,y-1})$$ 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 5.1 (*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 6.1 Estimates of natural mortality, *M*, at age used in developing the base Ricker run.

	Natural Mortality Rate, M						
Age:	0	1	2	3	4	5	6+
Base Ricker Run*	1.23	0.72	0.60	0.55	0.52	0.51	0.50
Estimated Scalar (new vector)	2.61	1.53	1.27	1.16	1.11	1.08	1.06
Estimated Scalar (old vector)	3.57	0.81	0.47	0.46	0.46	0.46	0.46
Estimated Scalar (ASMFC 2004)	4.31	0.98	0.56	0.55	0.55	0.55	0.55

* Fixed, not estimated.

Table 6.2 Historical performance based on percentiles (median and interquartile range) for output variables, 1955–2005.

Output Variables	Current Year Value (2005)	Percentiles		
		25th	50th	75th
Fishing mortality, F (2+)	0.50	0.83	1.04	1.25
Population Fecundity (billions)	41739	21755	28311	43112
Recruits to Age 0 (billions)	8.8	9.1	13.2	21.5

Table 6.3 Estimated age-specific fishing mortality rates for Atlantic menhaden, 1955-2005. Estimates based only on reduction fishery for 1955-1984, and for both reduction and bait fisheries for 1985-2005.

	Age								
Year	0	1	2	3	4	5	6	7	8
1955	0.02	0.25	1.00	1.26	1.29	1.29	1.29	1.29	1.29
1956	0.03	0.39	1.53	1.94	1.97	1.98	1.98	1.98	1.98
1957	0.03	0.29	1.15	1.45	1.48	1.48	1.48	1.48	1.48
1958	0.02	0.22	0.86	1.09	1.11	1.11	1.11	1.11	1.11
1959	0.02	0.23	0.92	1.16	1.18	1.18	1.18	1.18	1.18
1960	0.01	0.14	0.55	0.70	0.71	0.71	0.71	0.71	0.71
1961	0.02	0.20	0.79	1.00	1.02	1.02	1.02	1.02	1.02
1962	0.03	0.33	1.28	1.61	1.64	1.65	1.65	1.65	1.65
1963	0.04	0.42	1.65	2.09	2.13	2.13	2.13	2.13	2.13
1964	0.04	0.45	1.76	2.23	2.27	2.28	2.28	2.28	2.28
1965	0.05	0.61	2.37	3.00	3.06	3.06	3.06	3.06	3.06
1966	0.05	0.53	2.08	2.64	2.69	2.69	2.69	2.69	2.69
1967	0.03	0.36	1.39	1.76	1.79	1.80	1.80	1.80	1.80
1968	0.04	0.41	1.62	2.05	2.09	2.09	2.09	2.09	2.09
1969	0.02	0.25	0.99	1.25	1.27	1.27	1.27	1.27	1.27
1970	0.03	0.32	1.27	1.61	1.64	1.64	1.64	1.64	1.64
1971	0.02	0.23	0.90	1.13	1.15	1.16	1.16	1.16	1.16
1972	0.03	0.34	1.34	1.69	1.73	1.73	1.73	1.73	1.73
1973	0.03	0.32	1.26	1.59	1.62	1.62	1.62	1.62	1.62
1974	0.03	0.32	1.25	1.59	1.62	1.62	1.62	1.62	1.62
1975	0.03	0.28	1.11	1.41	1.43	1.44	1.44	1.44	1.44
1976	0.03	0.31	1.21	1.52	1.55	1.56	1.56	1.56	1.56
1977	0.02	0.28	1.09	1.38	1.40	1.41	1.41	1.41	1.41
1978	0.03	0.30	1.19	1.51	1.54	1.54	1.54	1.54	1.54
1979	0.03	0.31	1.20	1.52	1.55	1.55	1.55	1.55	1.55
1980	0.03	0.33	1.28	1.62	1.65	1.65	1.65	1.65	1.65
1981	0.03	0.28	1.11	1.41	1.43	1.44	1.44	1.44	1.44
1982	0.03	0.31	1.21	1.53	1.56	1.56	1.56	1.56	1.56
1983	0.03	0.35	1.35	1.71	1.75	1.75	1.75	1.75	1.75
1984	0.03	0.38	1.49	1.89	1.93	1.93	1.93	1.93	1.93
1985	0.02	0.28	1.08	1.66	2.33	2.31	1.72	1.40	1.39
1986	0.02	0.17	0.68	1.15	1.81	1.80	1.20	0.89	0.88
1987	0.02	0.18	0.72	1.20	1.86	1.85	1.25	0.94	0.93
1988	0.02	0.24	0.94	1.48	2.15	2.13	1.53	1.22	1.21
1989	0.03	0.29	1.15	1.74	2.41	2.40	1.80	1.48	1.48
1990	0.02	0.25	0.98	1.53	2.19	2.18	1.58	1.27	1.26
1991	0.03	0.38	1.48	2.16	2.84	2.83	2.23	1.92	1.91
1992	0.02	0.27	1.05	1.62	2.29	2.28	1.68	1.36	1.35
1993	0.02	0.20	0.77	1.27	1.93	1.91	1.32	1.00	0.99
1994	0.01	0.16	0.61	1.06	1.72	1.71	1.11	0.79	0.78
1995	0.02	0.20	0.80	1.29	1.96	1.94	1.34	1.03	1.02
1996	0.01	0.16	0.62	1.08	1.73	1.72	1.12	0.81	0.80
1997	0.02	0.18	0.73	1.20	1.87	1.85	1.25	0.94	0.93
1998	0.02	0.27	1.05	1.62	2.29	2.27	1.67	1.36	1.35
1999	0.02	0.26	1.02	1.57	2.24	2.23	1.63	1.31	1.31
2000	0.02	0.20	0.77	1.26	1.92	1.91	1.31	1.00	0.99
2001	0.02	0.21	0.84	1.35	2.02	2.00	1.40	1.09	1.08
2002	0.02	0.22	0.85	1.37	2.03	2.02	1.42	1.11	1.10
2003	0.01	0.15	0.61	1.06	1.72	1.70	1.11	0.79	0.78
2004	0.01	0.16	0.65	1.10	1.76	1.75	1.15	0.84	0.83
2005	0.01	0.13	0.53	0.96	1.62	1.60	1.00	0.69	0.68

Table 6.4 Estimated numbers of Atlantic menhaden (in billions) at start of fishing year from forward-projecting statistical age-structured model (base Ricker run), 1955–2005.

	Age								
Year	0	1	2	3	4	5	6	7	8
1955	31.12	4.10	2.30	0.53	0.752	0.091	0.0116	0.00067	0.00025
1956	28.93	8.90	1.60	0.51	0.087	0.123	0.0154	0.00221	0.00019
1957	16.87	8.17	3.04	0.21	0.043	0.007	0.0104	0.00146	0.00024
1958	61.69	4.81	3.07	0.58	0.028	0.006	0.0010	0.00162	0.00028
1959	9.25	17.69	1.95	0.78	0.113	0.006	0.0012	0.00022	0.00046
1960	13.42	2.65	7.06	0.47	0.142	0.021	0.0010	0.00024	0.00015
1961	8.69	3.88	1.16	2.44	0.135	0.041	0.0061	0.00035	0.00014
1962	8.22	2.50	1.60	0.32	0.523	0.029	0.0091	0.00152	0.00013
1963	6.59	2.34	0.91	0.27	0.037	0.060	0.0034	0.00120	0.00023
1964	8.41	1.86	0.77	0.11	0.019	0.003	0.0043	0.00028	0.00012
1965	6.58	2.36	0.60	0.08	0.007	0.001	0.0002	0.00031	0.00003
1966	9.31	1.82	0.65	0.03	0.002	0.000	0.0000	0.00001	0.00001
1967	4.94	2.60	0.54	0.05	0.001	0.000	0.0000	0.00000	0.00000
1968	7.83	1.40	0.92	0.08	0.005	0.000	0.0000	0.00000	0.00000
1969	13.21	2.21	0.47	0.11	0.006	0.000	0.0000	0.00000	0.00000
1970	6.48	3.78	0.87	0.10	0.018	0.001	0.0001	0.00000	0.00000
1971	15.60	1.84	1.38	0.15	0.012	0.002	0.0001	0.00001	0.00000
1972	11.03	4.47	0.74	0.34	0.027	0.002	0.0004	0.00003	0.00000
1973	13.13	3.13	1.60	0.12	0.036	0.003	0.0002	0.00005	0.00000
1974	16.29	3.73	1.14	0.27	0.014	0.004	0.0003	0.00003	0.00001
1975	27.55	4.63	1.37	0.20	0.033	0.002	0.0005	0.00005	0.00001
1976	22.63	7.86	1.76	0.27	0.028	0.005	0.0002	0.00008	0.00001
1977	20.48	6.44	2.91	0.32	0.034	0.004	0.0006	0.00003	0.00001
1978	21.40	5.84	2.46	0.59	0.046	0.005	0.0005	0.00010	0.00001
1979	36.48	6.09	2.17	0.45	0.076	0.006	0.0007	0.00008	0.00002
1980	21.52	10.38	2.26	0.39	0.057	0.010	0.0008	0.00009	0.00001
1981	32.38	6.11	3.78	0.38	0.045	0.007	0.0011	0.00010	0.00002
1982	12.25	9.23	2.32	0.75	0.054	0.006	0.0009	0.00018	0.00002
1983	22.32	3.49	3.42	0.42	0.094	0.007	0.0008	0.00014	0.00003
1984	30.79	6.33	1.24	0.53	0.044	0.010	0.0007	0.00010	0.00002
1985	25.32	8.71	2.18	0.17	0.047	0.004	0.0009	0.00007	0.00001
1986	18.44	7.23	3.37	0.46	0.025	0.007	0.0006	0.00015	0.00002
1987	13.80	5.31	3.07	1.03	0.113	0.006	0.0017	0.00016	0.00005
1988	27.27	3.97	2.21	0.88	0.241	0.026	0.0015	0.00046	0.00006
1989	10.50	7.81	1.58	0.52	0.157	0.043	0.0048	0.00031	0.00011
1990	19.04	3.00	2.98	0.31	0.072	0.021	0.0060	0.00079	0.00008
1991	22.48	5.45	1.18	0.68	0.053	0.012	0.0037	0.00117	0.00018
1992	18.24	6.37	1.93	0.17	0.061	0.005	0.0011	0.00041	0.00017
1993	12.64	5.22	2.53	0.44	0.027	0.009	0.0007	0.00022	0.00013
1994	16.90	3.63	2.16	0.71	0.096	0.006	0.0021	0.00019	0.00009
1995	9.35	4.87	1.55	0.69	0.190	0.026	0.0016	0.00063	0.00009
1996	9.04	2.68	1.99	0.41	0.147	0.041	0.0057	0.00039	0.00018
1997	7.91	2.60	1.14	0.62	0.109	0.039	0.0110	0.00165	0.00017
1998	10.29	2.27	1.08	0.32	0.144	0.026	0.0094	0.00287	0.00050
1999	10.12	2.94	0.90	0.24	0.050	0.022	0.0041	0.00179	0.00071
2000	5.53	2.90	1.19	0.22	0.039	0.008	0.0037	0.00087	0.00061
2001	9.32	1.59	1.23	0.35	0.048	0.009	0.0018	0.00102	0.00045
2002	14.85	2.68	0.66	0.33	0.071	0.010	0.0018	0.00045	0.00039
2003	12.72	4.27	1.11	0.18	0.066	0.014	0.0020	0.00045	0.00023
2004	5.44	3.67	1.87	0.38	0.049	0.018	0.0039	0.00065	0.00024
2005	8.81	1.57	1.58	0.60	0.097	0.013	0.0048	0.00121	0.00030

Table 7.1 Summary of benchmarks and terminal year values estimated for base Ricker run and for sensitivity runs.

Benchmarks and terminal year values:	Base Ricker Run	Alternate Bait Landings	Alternate JAI	Alternate PRFC CPUE	Time-Varying Selectivity
Fishing Mortality (*F*):					
F (Ages 2+) 50th (FEC)	0.91	0.91	0.91	0.91	1.04
F (Ages 2+) 75th (FEC)	0.55	0.56	0.55	0.54	0.60
F2005 (current F2+)	0.50	0.50	0.50	0.65	0.45
Population Fecundity (billions):					
50% FECmed	26,350	26,375	26,350	26,488	26,003
MSST [(1-M)*FEC]	13,175	13,187	13,175	13,244	13,002
FEC2005 (current Fec)	41,739	41,786	41,843	33,233	45,461

Figure 2.1 Weighted mean weight at age for Atlantic menhaden.

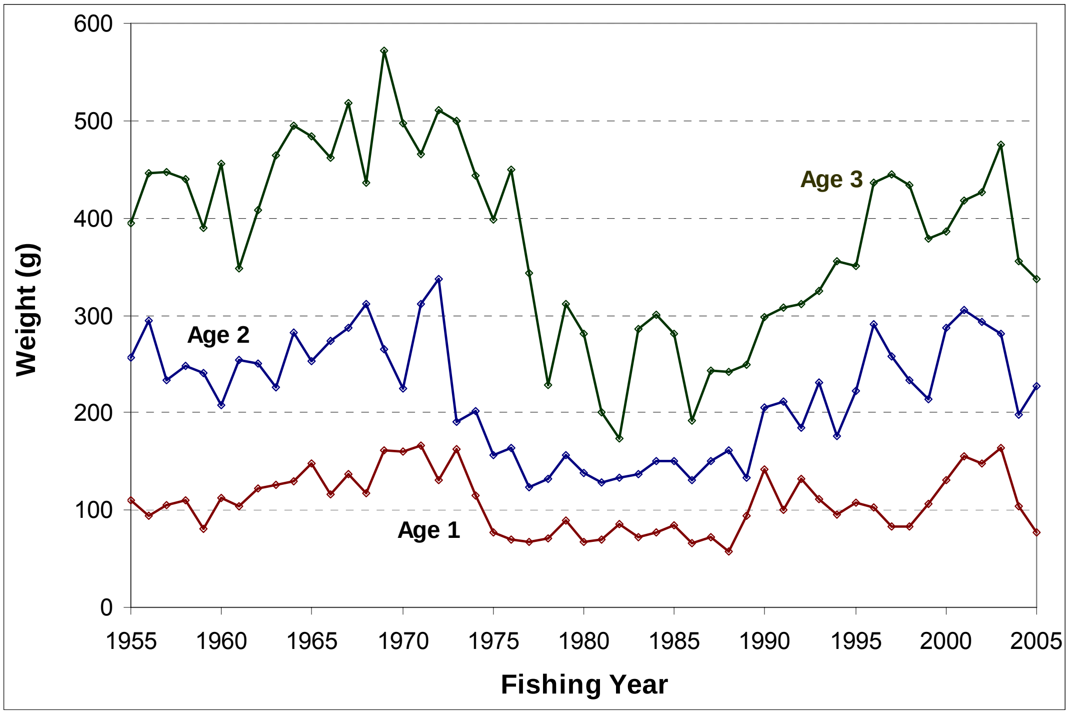


Figure 2.2 Fecundity (no. of maturing or ripe ova) as a function of fork length (mm) for Atlantic menhaden.

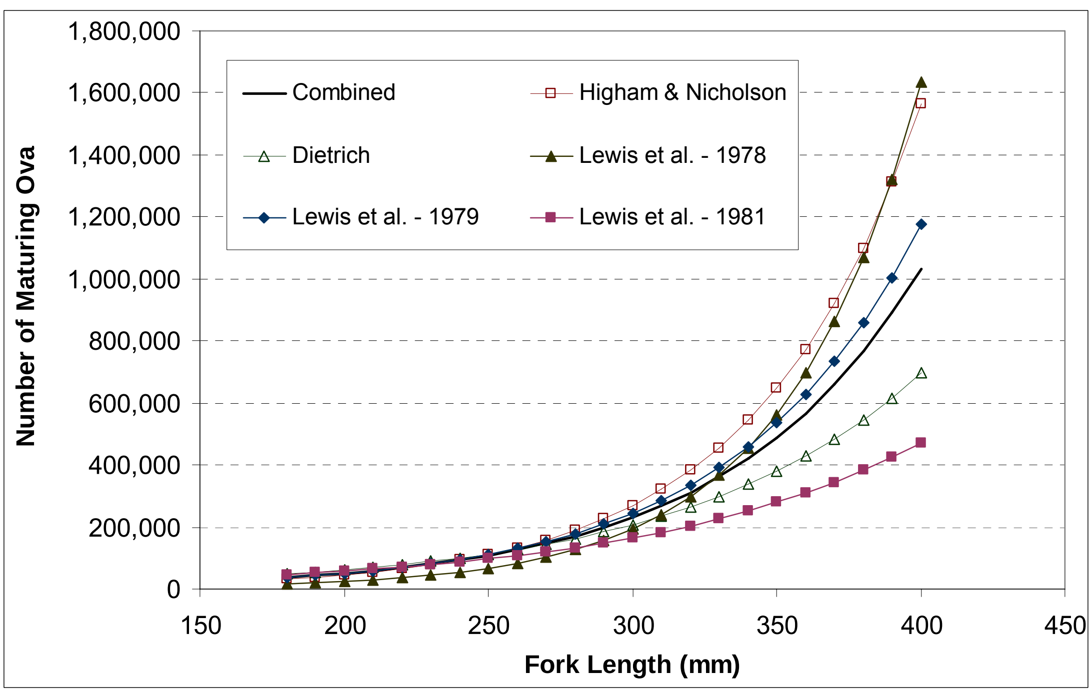


Figure 3.1 Landings from the reduction purse seine fishery (1940–2005) and bait fishery (1985–2005) for Atlantic menhaden.

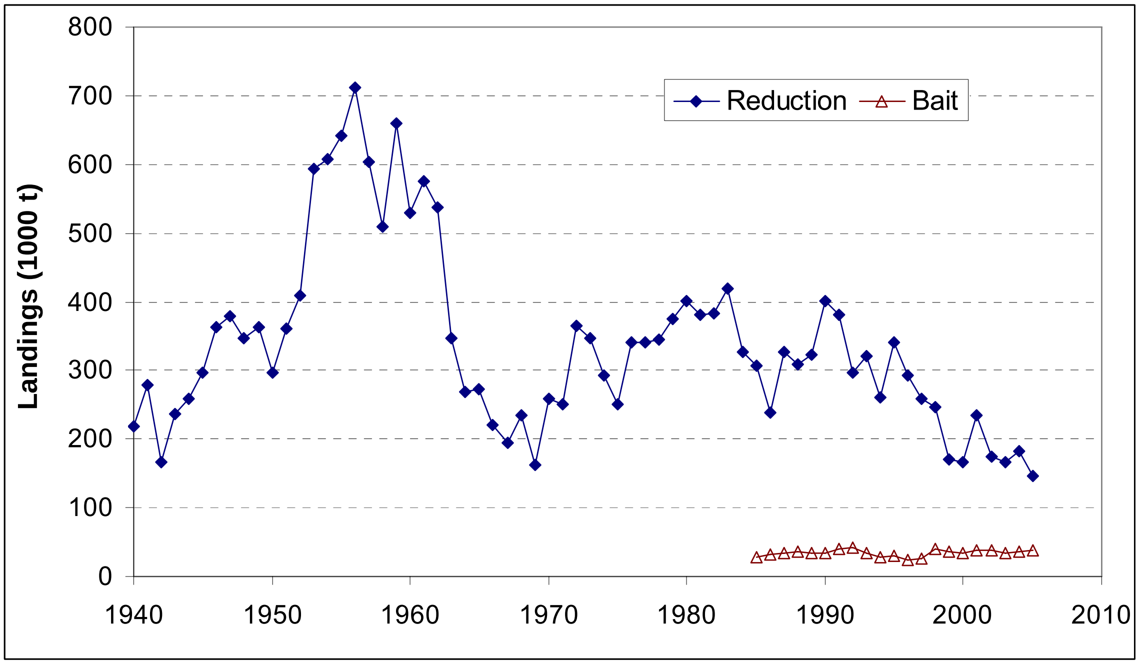


Figure 3.2 Comparison of mean landings by state from the bait fishery for Atlantic menhaden, 1985–2000 and 2001–2005.

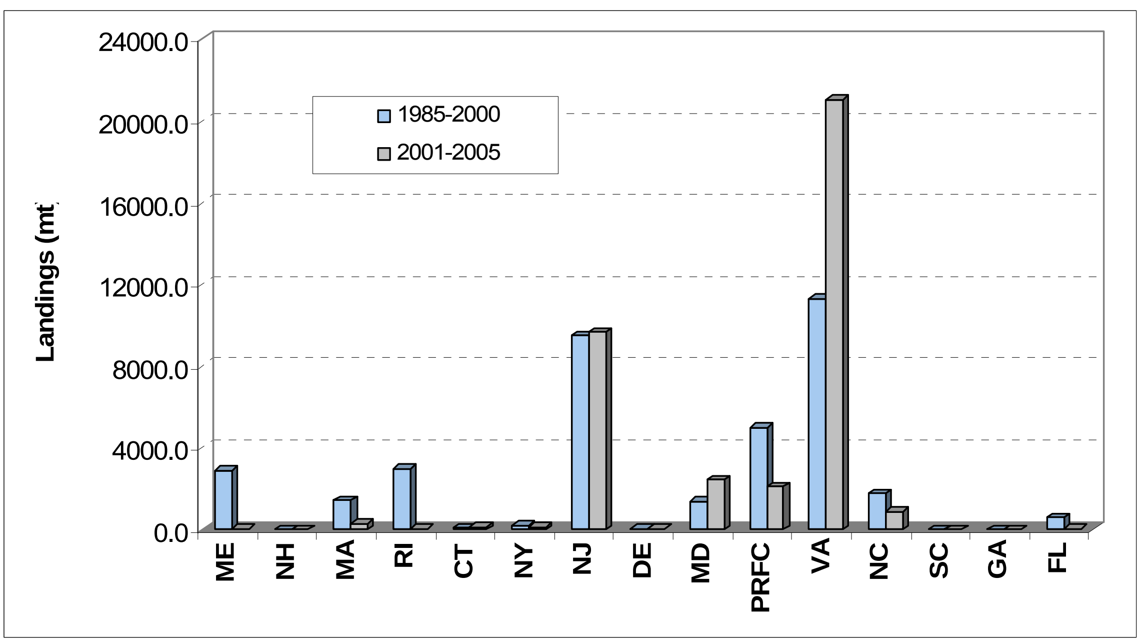


Figure 3.3 Annual landings by region from the bait fishery for Atlantic menhaden, 1985–2005.

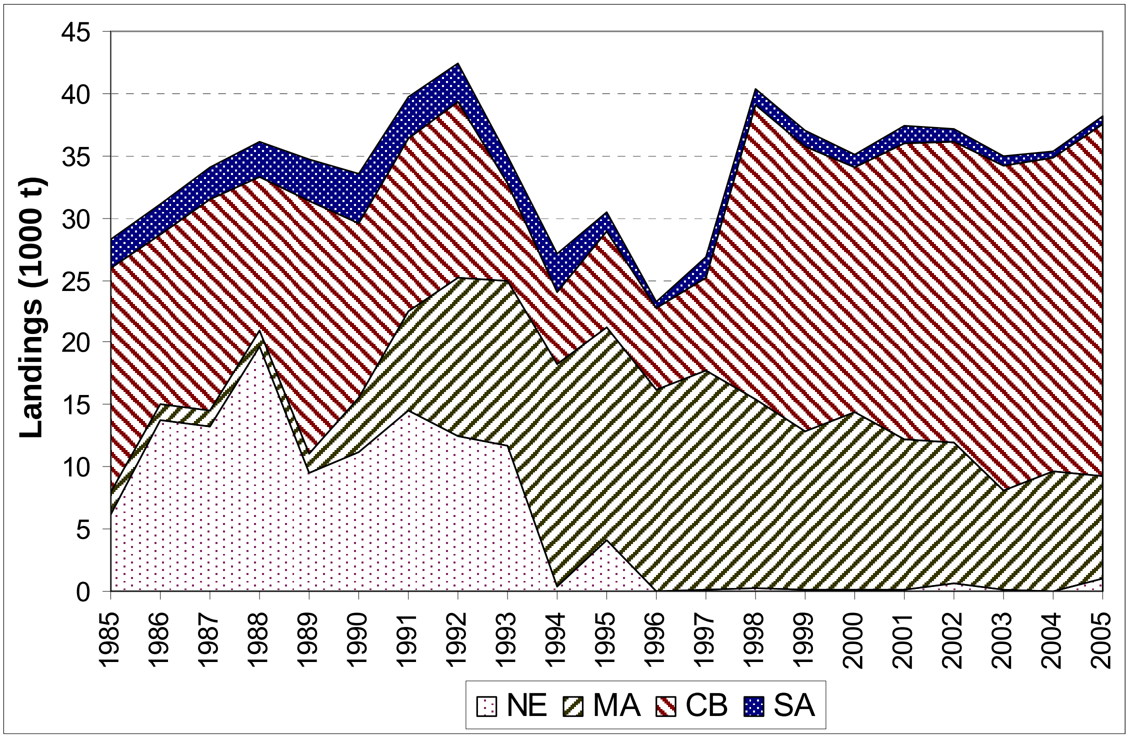


Figure 3.4 Annual coastwide landings (pounds) for all gear types and by purse seine fisheries only from the bait fishery for Atlantic menhaden, 1985–2005.

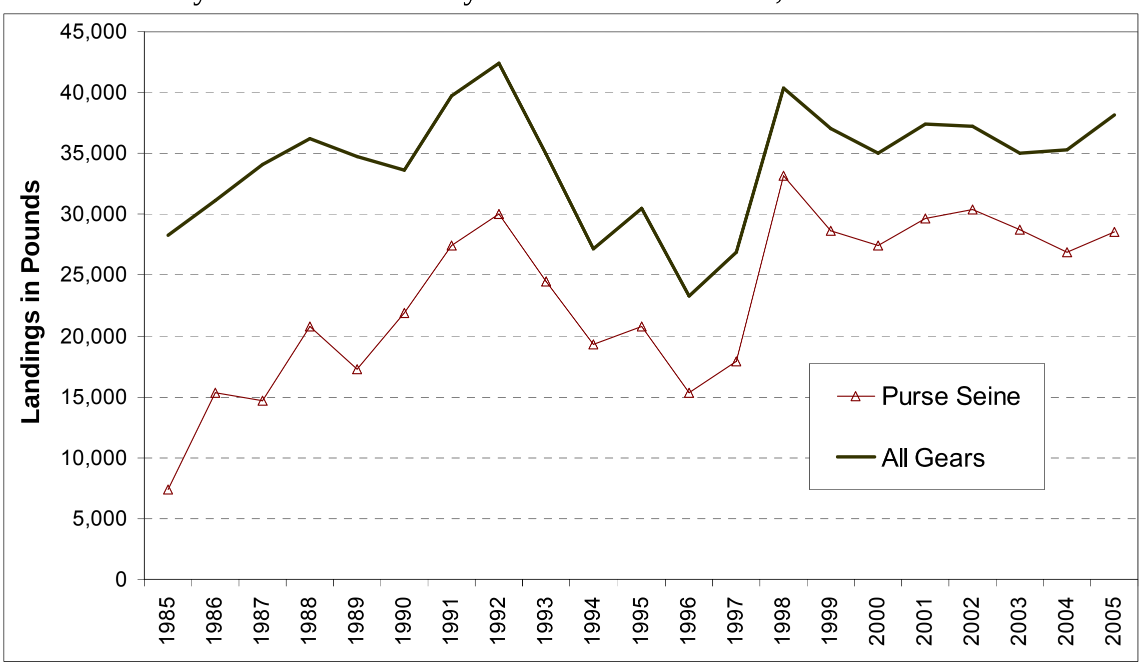


Figure 3.5 Bait landings as reported (base) and with linearly interpolated landings for the Virginia snapper boats for 1993–1997 (alternate).

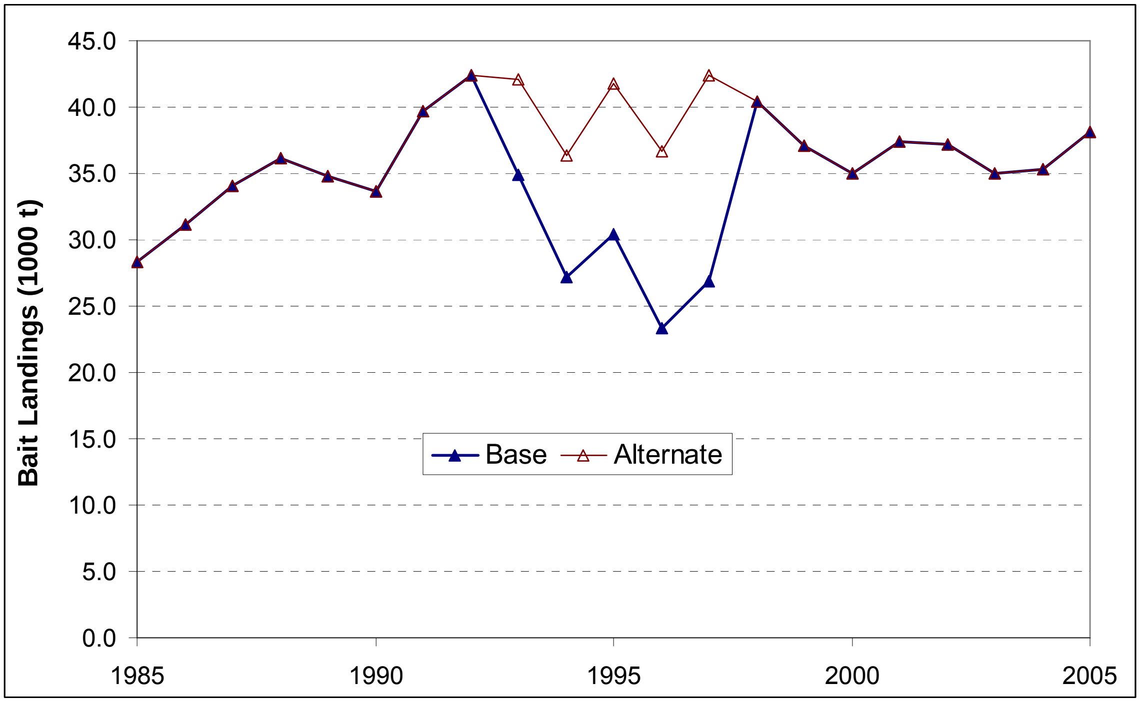


Figure 4.1 Delta-lognormal GLM mean and standard deviation of Atlantic menhaden catch-per-haul from North Carolina alosid seine survey.

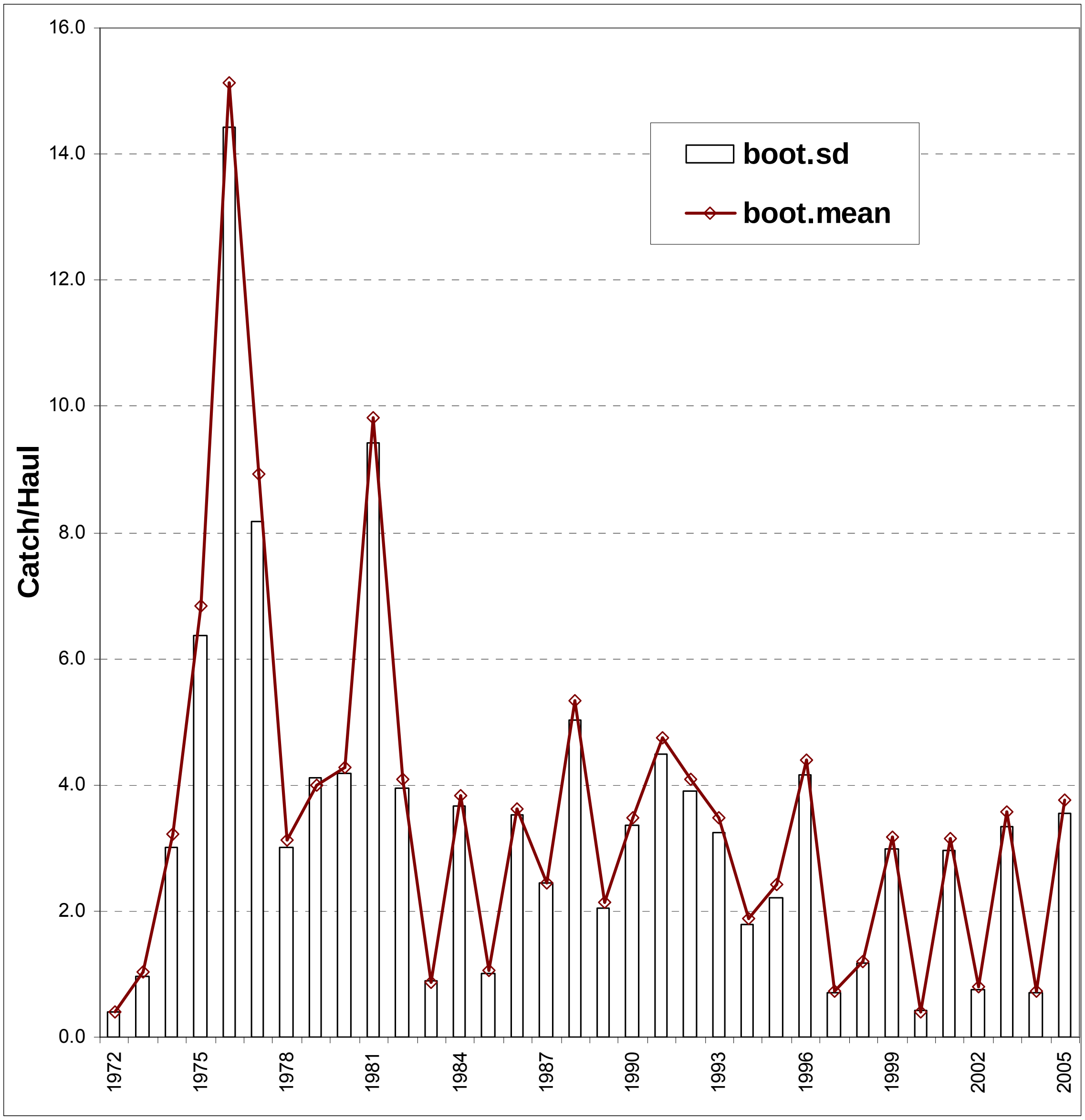


Figure 4.2 Delta-lognormal GLM mean and standard deviation of Atlantic menhaden catch-per-haul from Virginia striped bass seine survey.

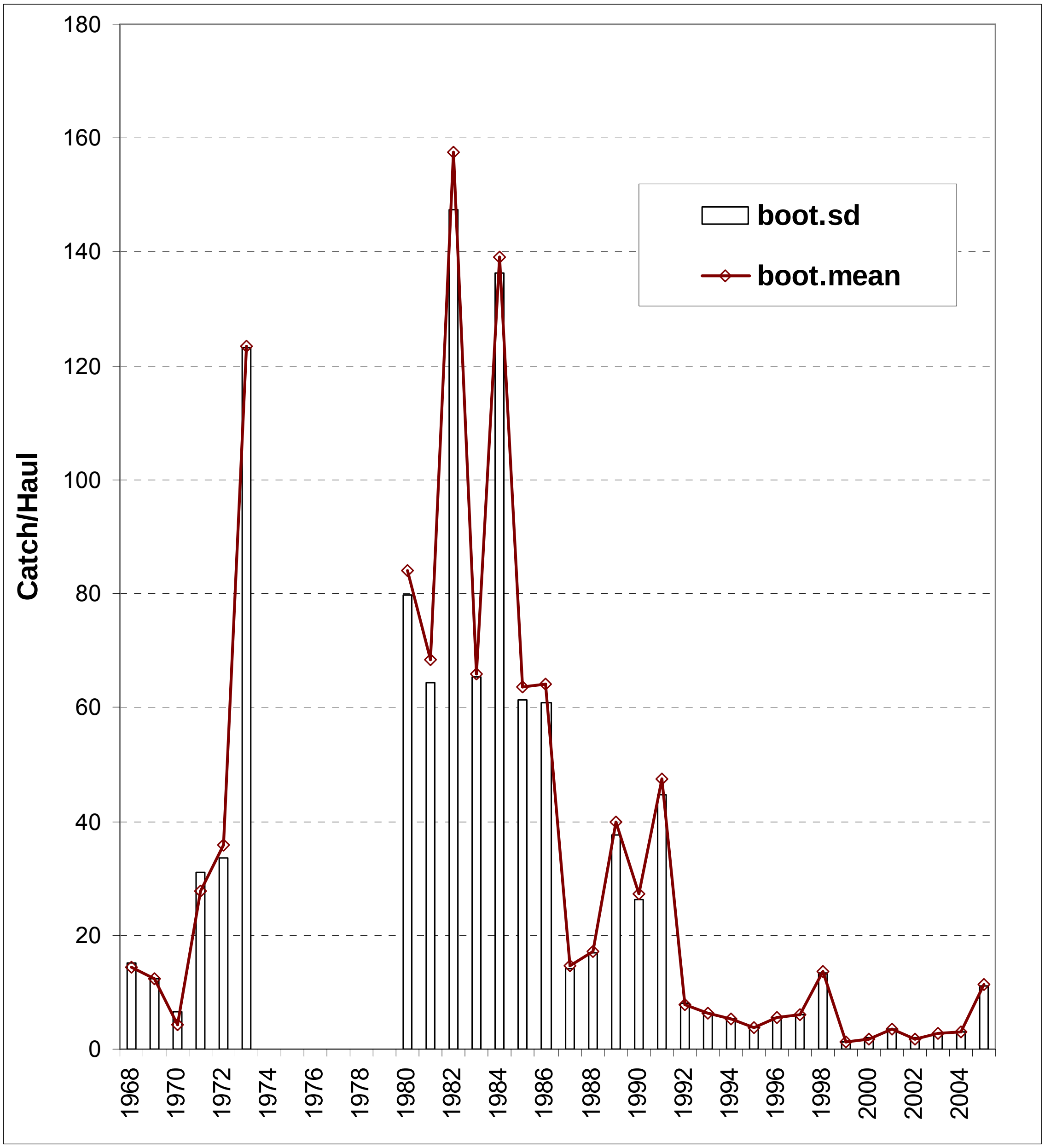


Figure 4.3 Delta-lognormal GLM mean and standard deviation of Atlantic menhaden catch-per-haul from Maryland striped bass seine survey.

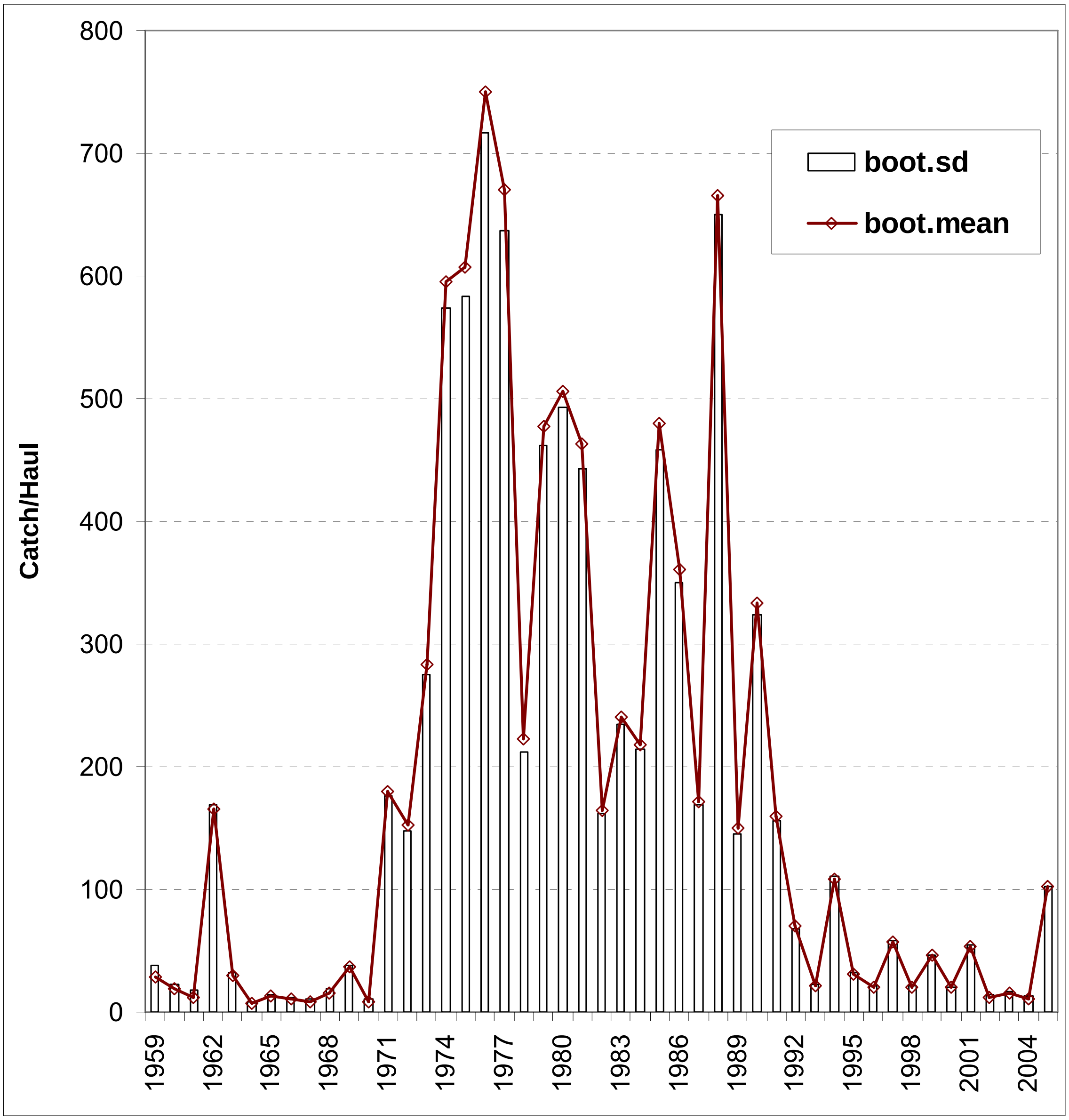


Figure 4.4 Delta-lognormal GLM mean and standard deviation of Atlantic menhaden catch-per-haul from New Jersey seine survey.

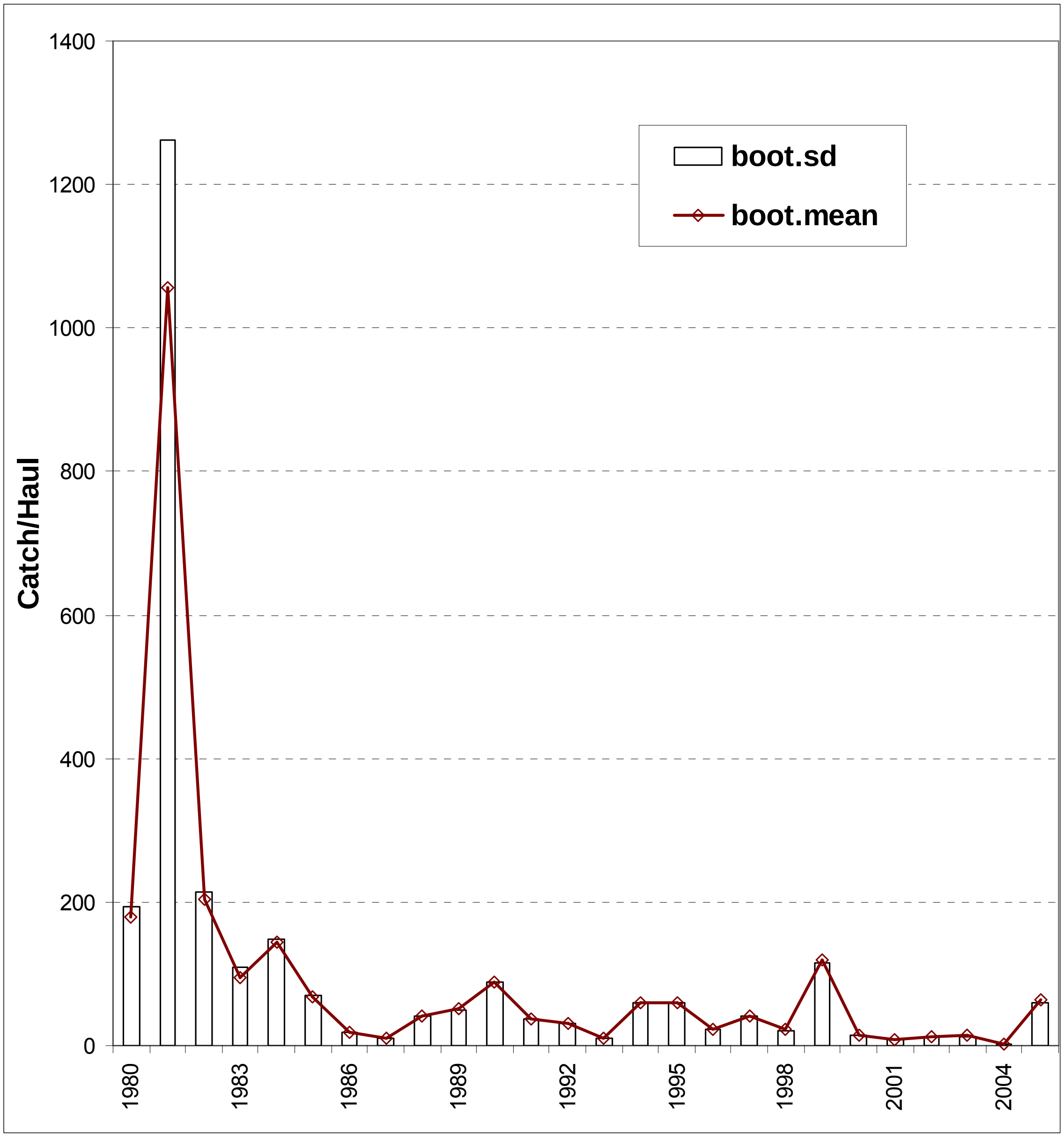


Figure 4.5 Delta-lognormal GLM mean and standard deviation of Atlantic menhaden catch-per-haul from Connecticut River seine survey.

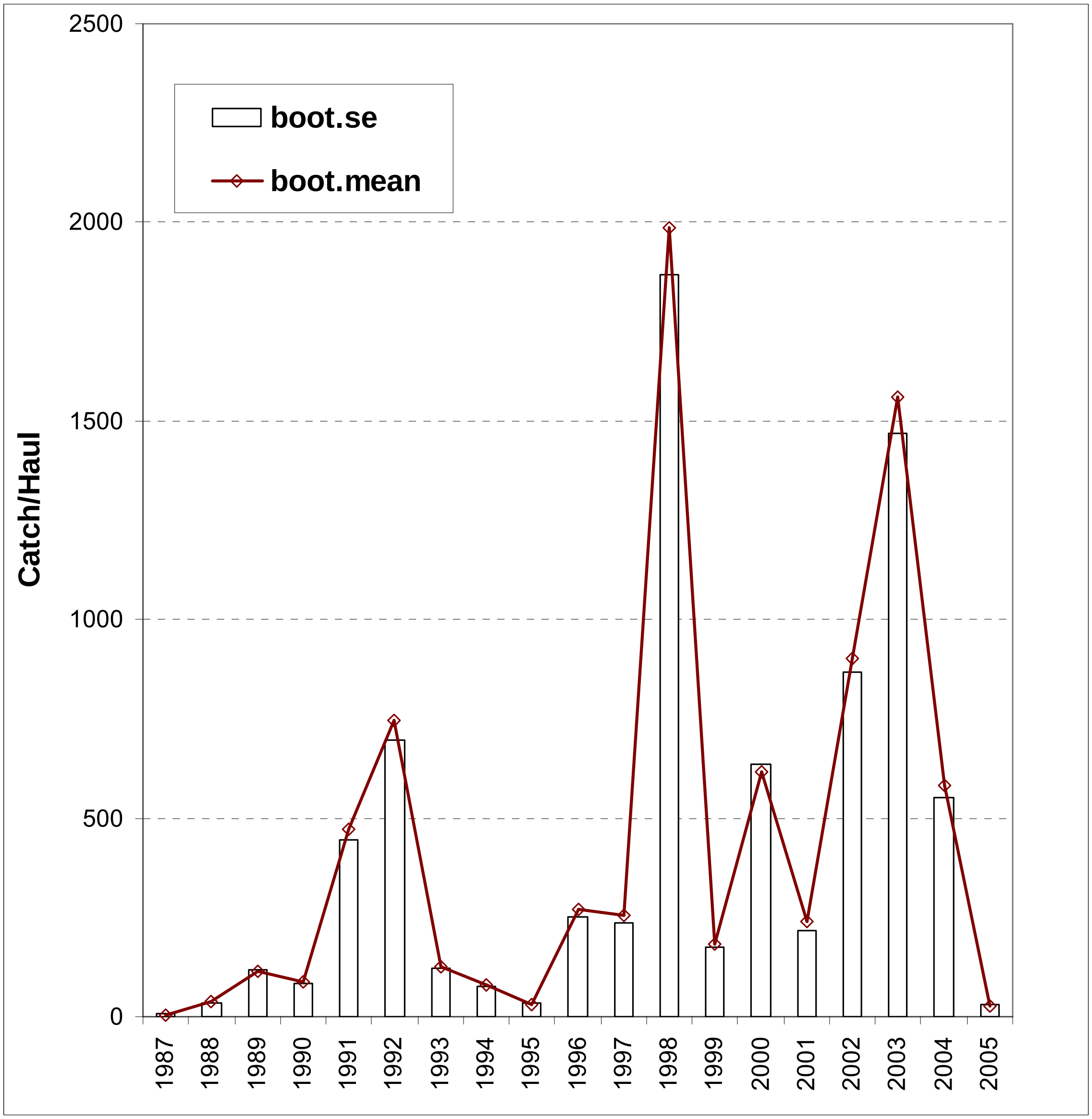


Figure 4.6 Delta-lognormal GLM mean and standard deviation of Atlantic menhaden catch-per-haul from Rhode Island Narragansett Bay seine survey.

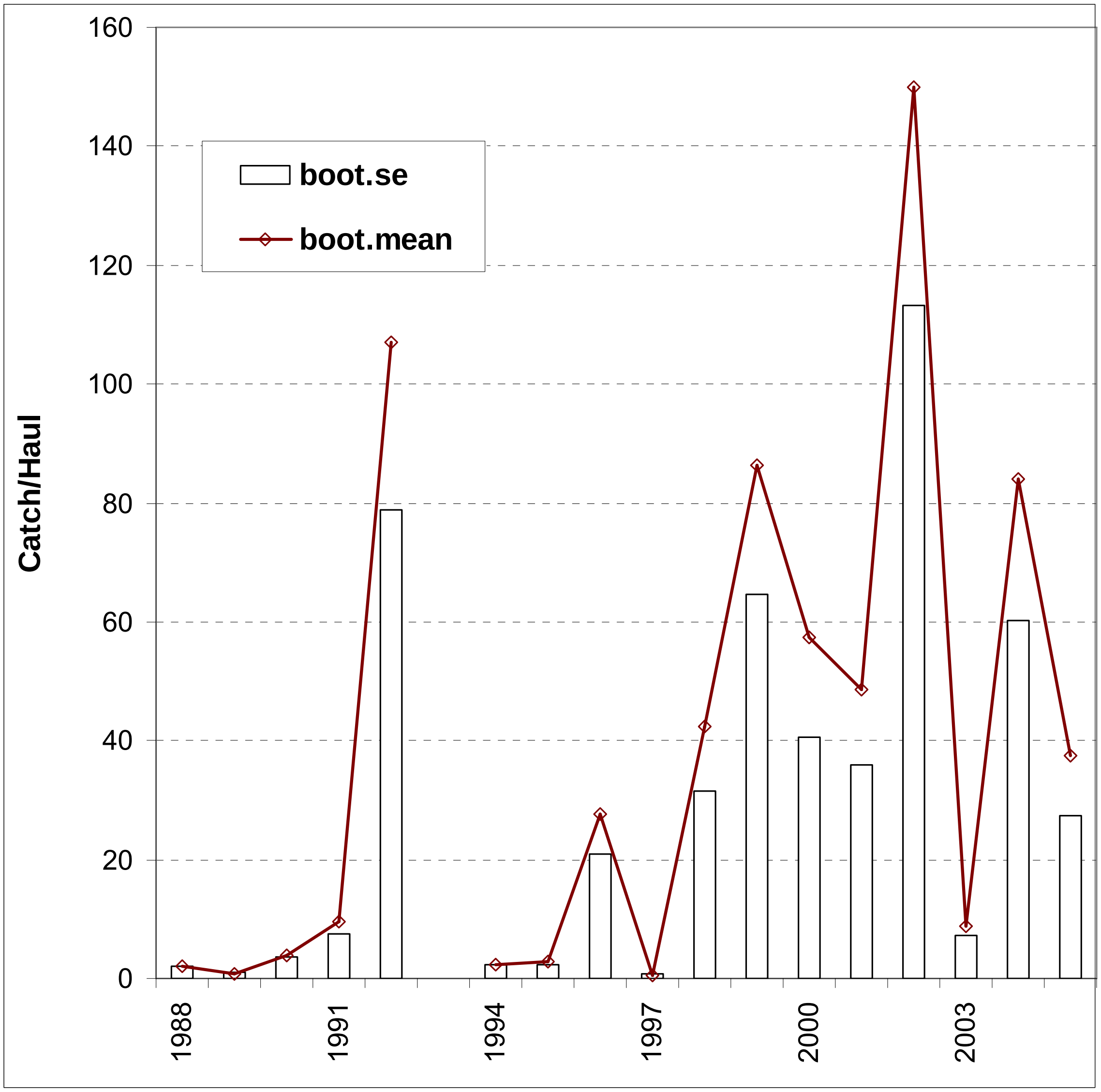


Figure 4.7 Coastwide juvenile Atlantic menhaden abundance indices from state seine surveys (based on % Estuarine Drainage Area adjusted for historic catch-per-tow). Comparison of coastwide JAI for base run without New Jersey seine survey with coastwide JAI for alternate run with New Jersey seine survey.

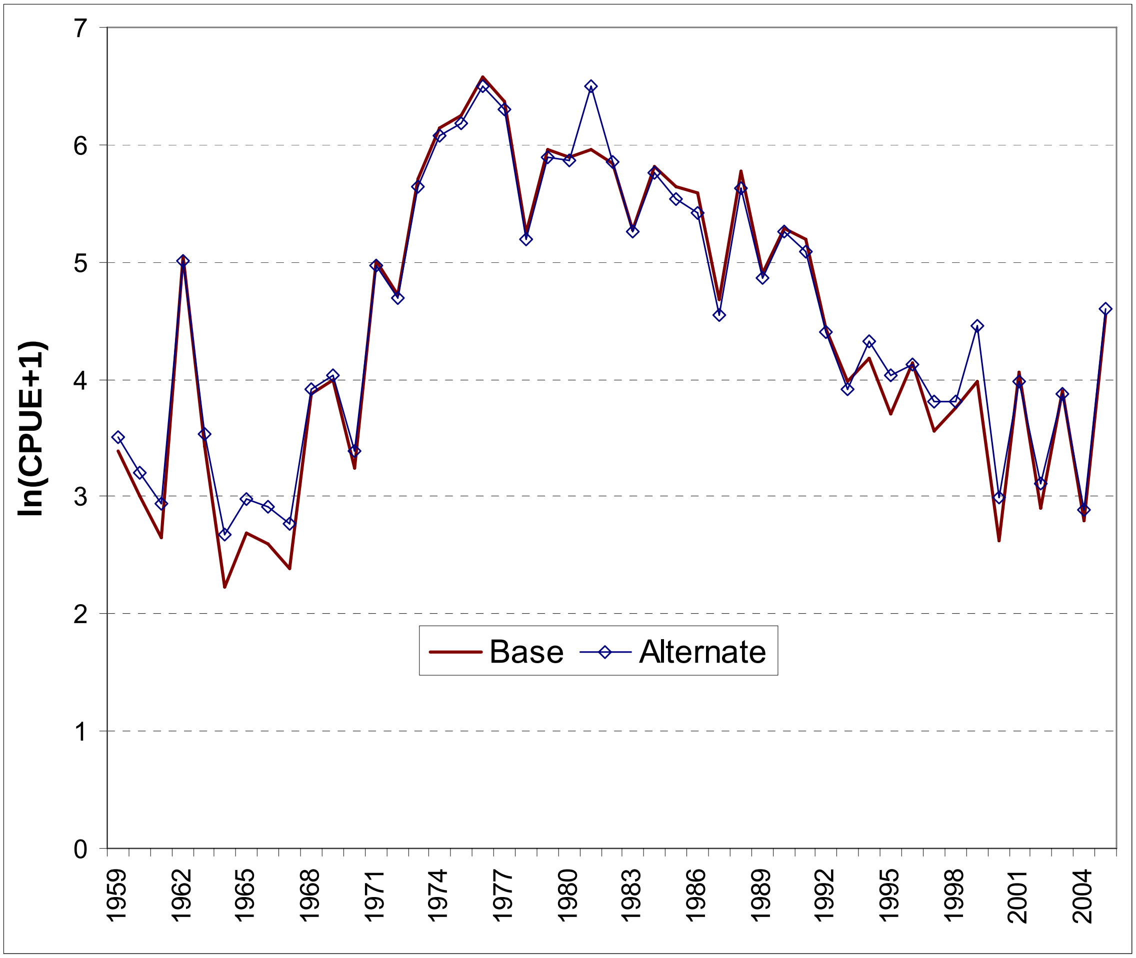


Figure 4.8 Comparison of PRFC Atlantic menhaden abundance index based on published menhaden landings per license (from ASMFC 2004) and poundnet landings per days fished (base run).

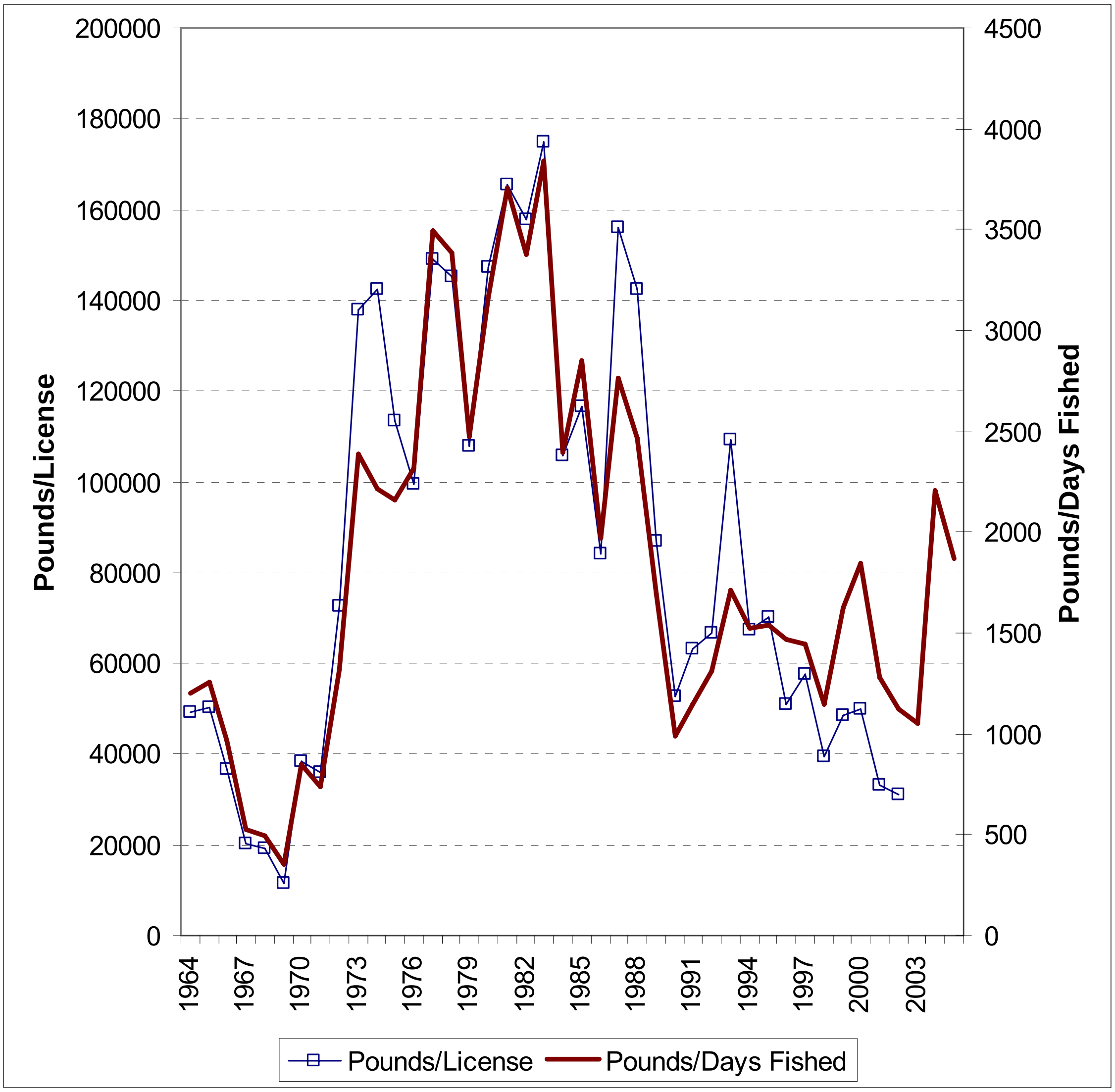


Figure 6.1 Observed and predicted landings of Atlantic menhaden by the reduction fishery (base Ricker model).

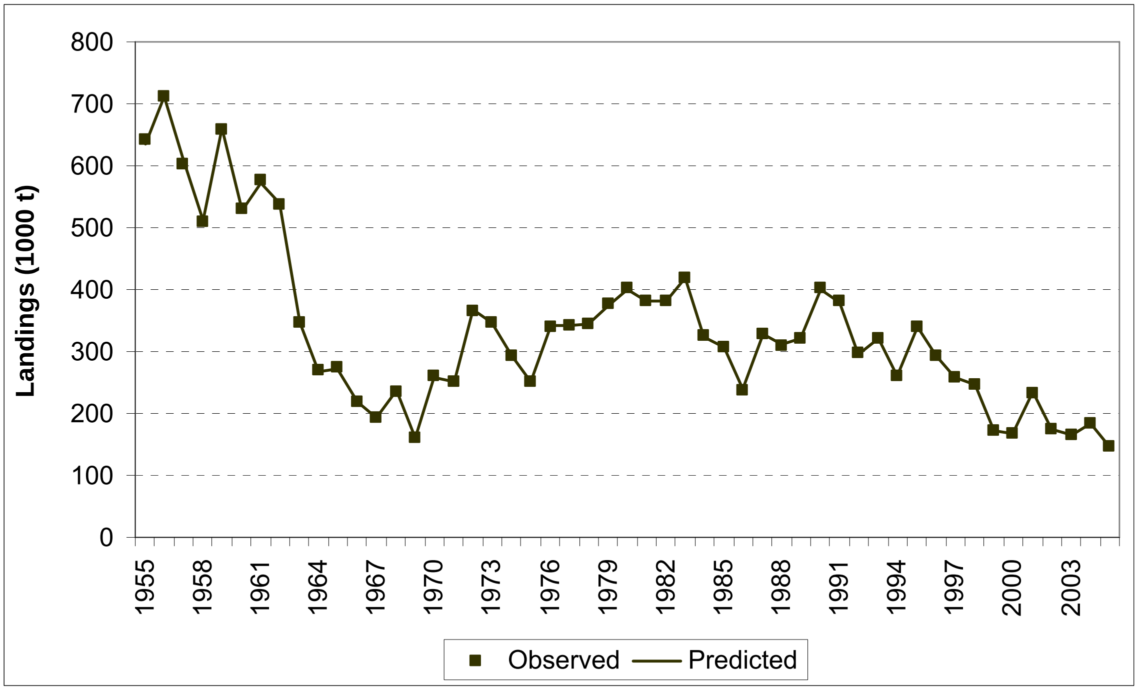


Figure 6.2 Observed and predicted landings of Atlantic menhaden by the bait fishery (base Ricker model).

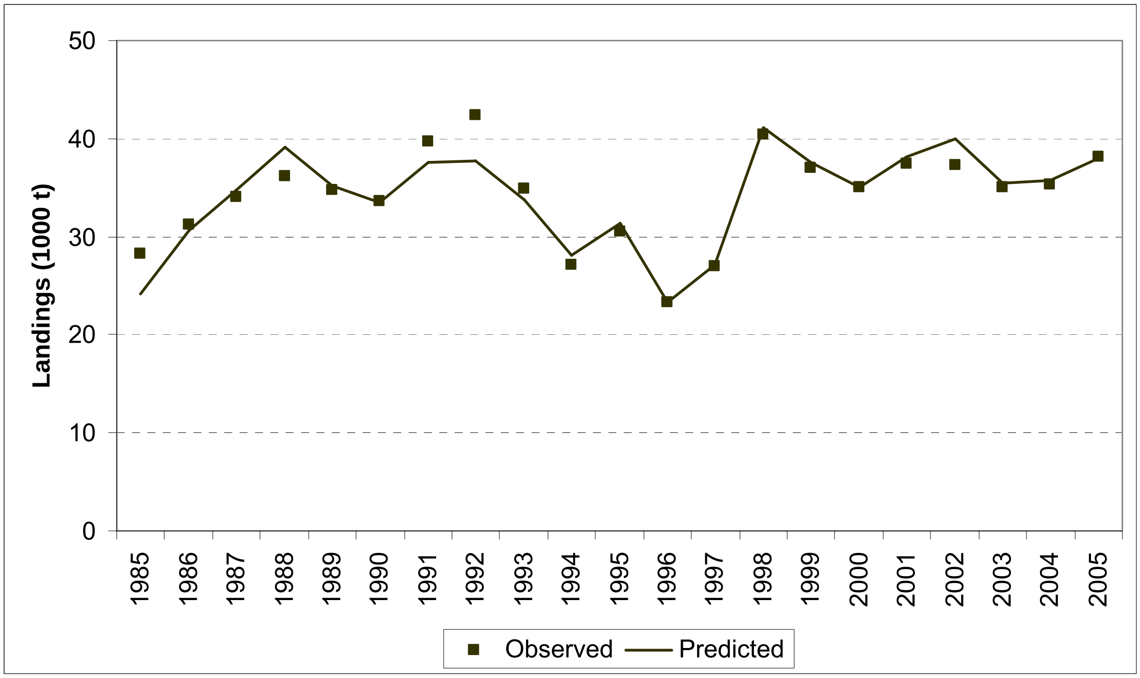


Figure 6.3 Bubble plot for Atlantic menhaden catch-at-age from the reduction fishery (based Ricker model).

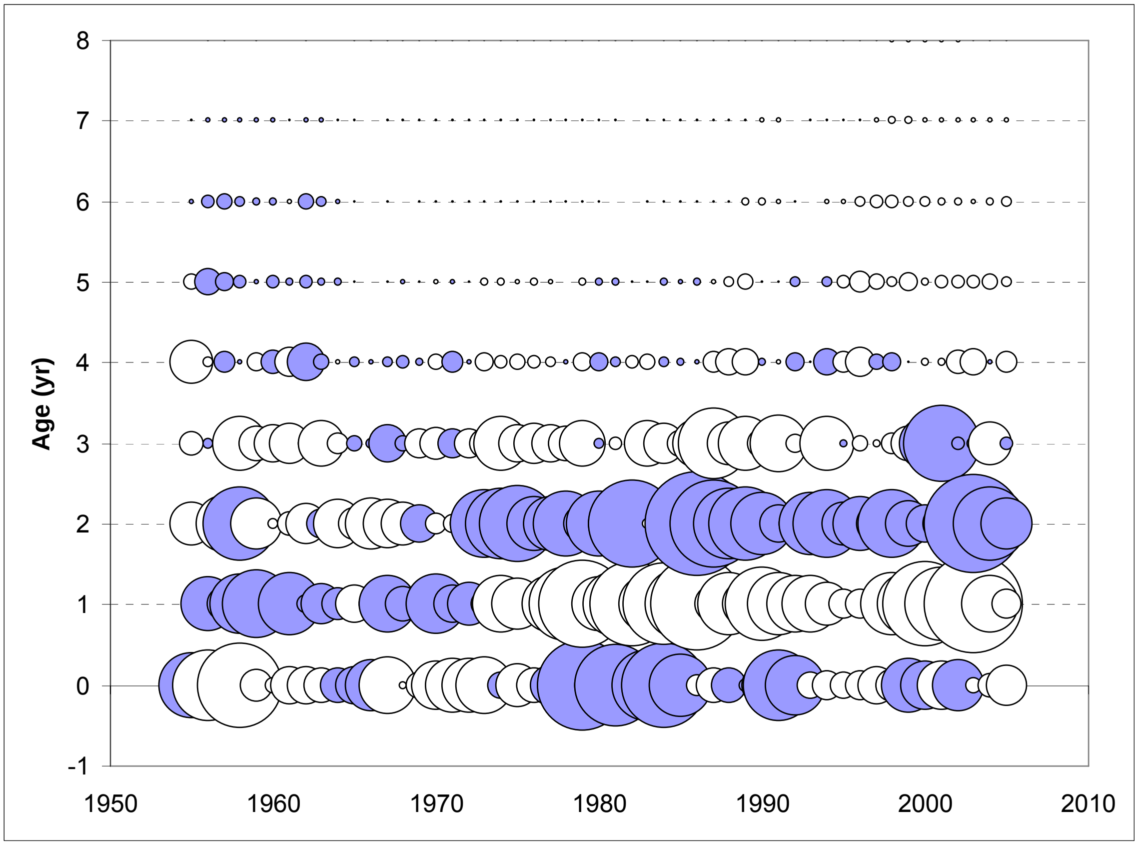


Figure 6.4 Annual observed and predicted proportions at age for Atlantic menhaden from the reduction fishery (based Ricker model).

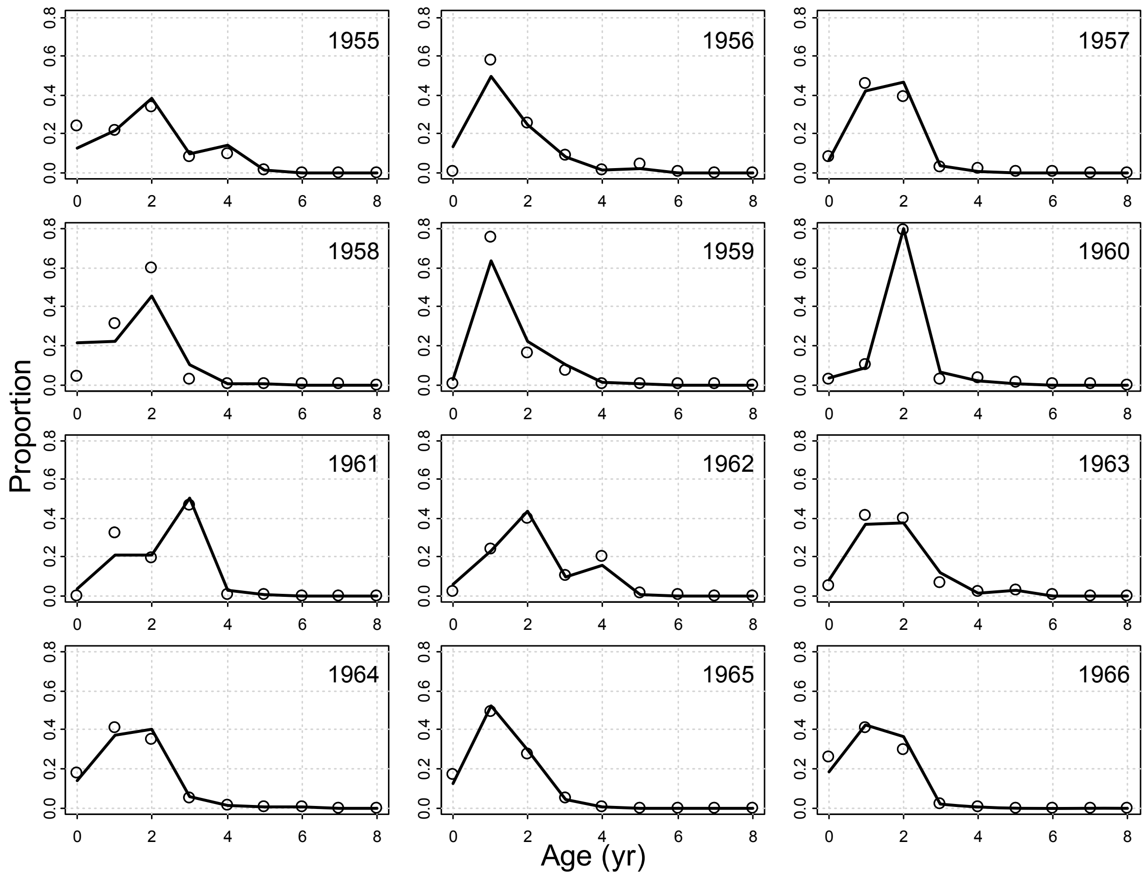


Figure 6.4 (*continued*)

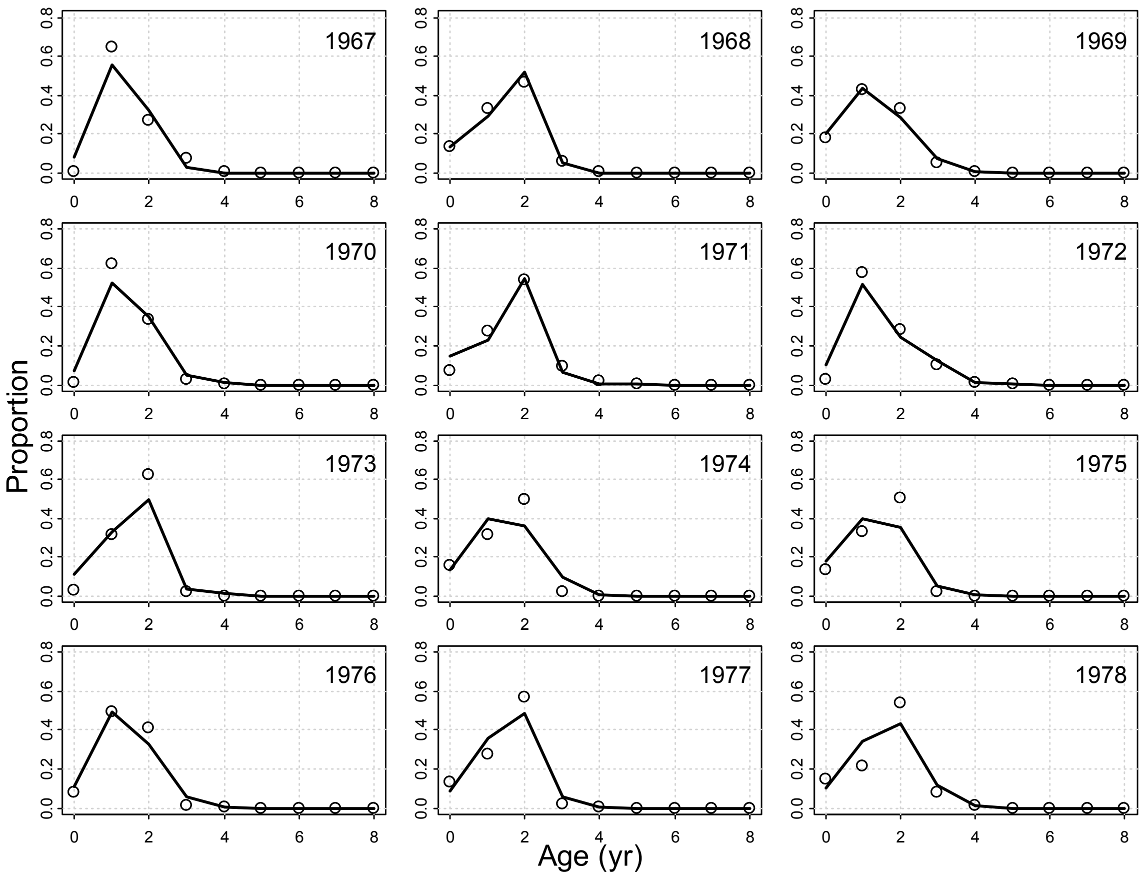


Figure 6.4 (*continued*)

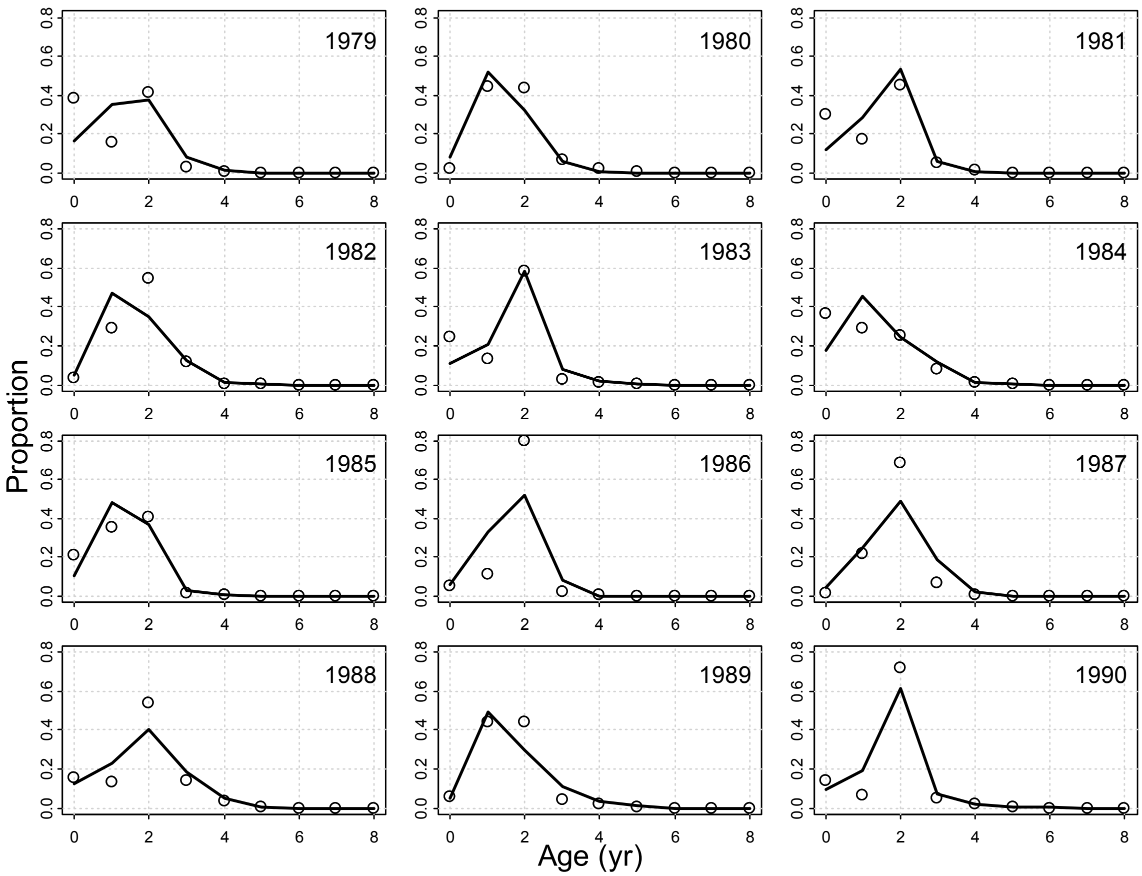


Figure 6.4 (*continued*)

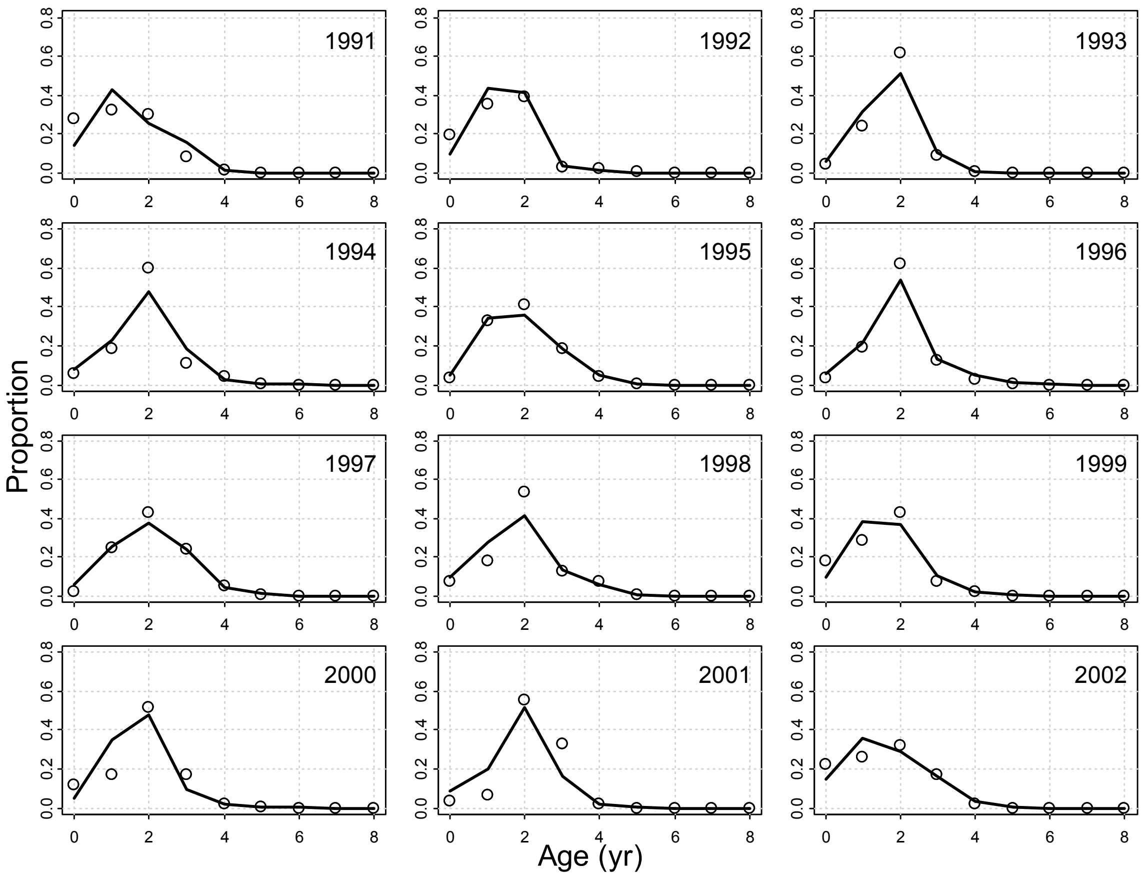


Figure 6.4 (*continued*)

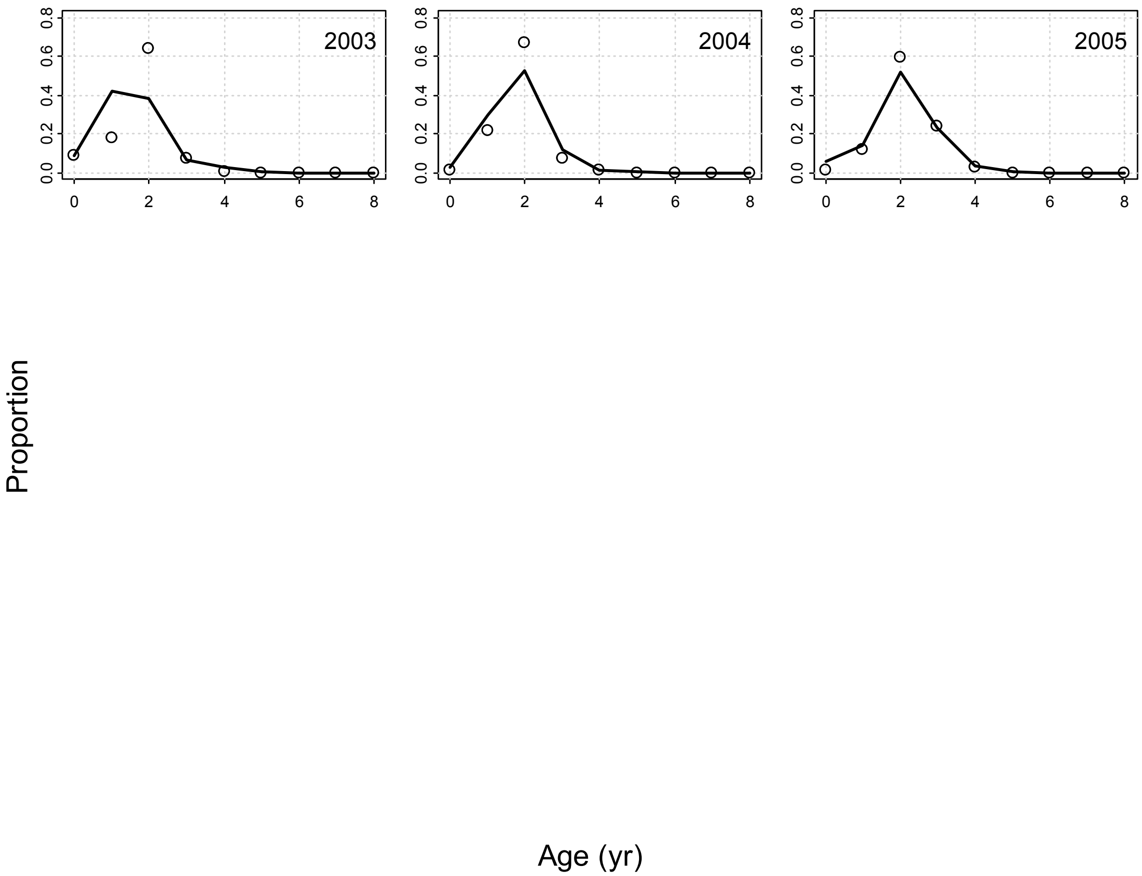


Figure 6.5 Bubble plot for Atlantic menhaden catch-at-age from the bait fishery (based Ricker model).

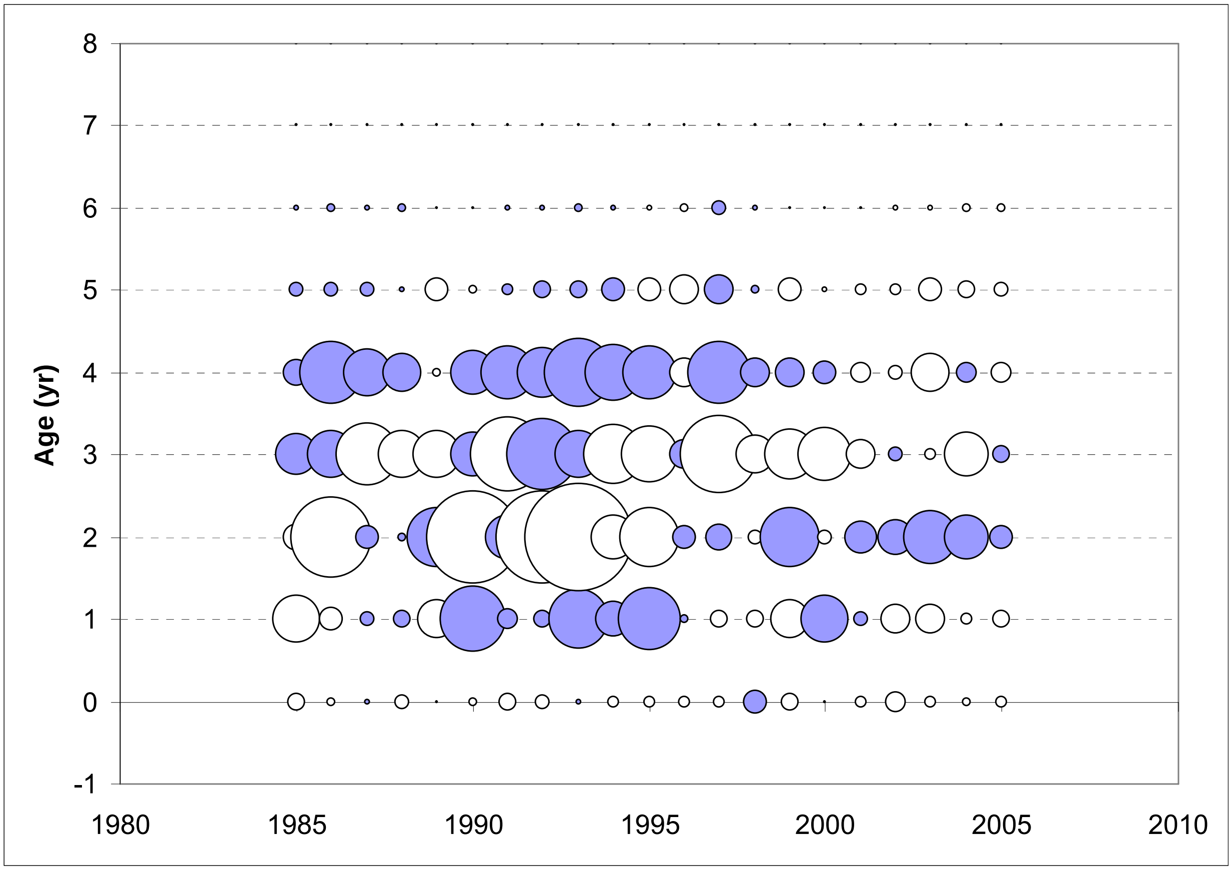


Figure 6.6 Annual observed and predicted proportions at age for Atlantic menhaden from the bait fishery (based Ricker model).

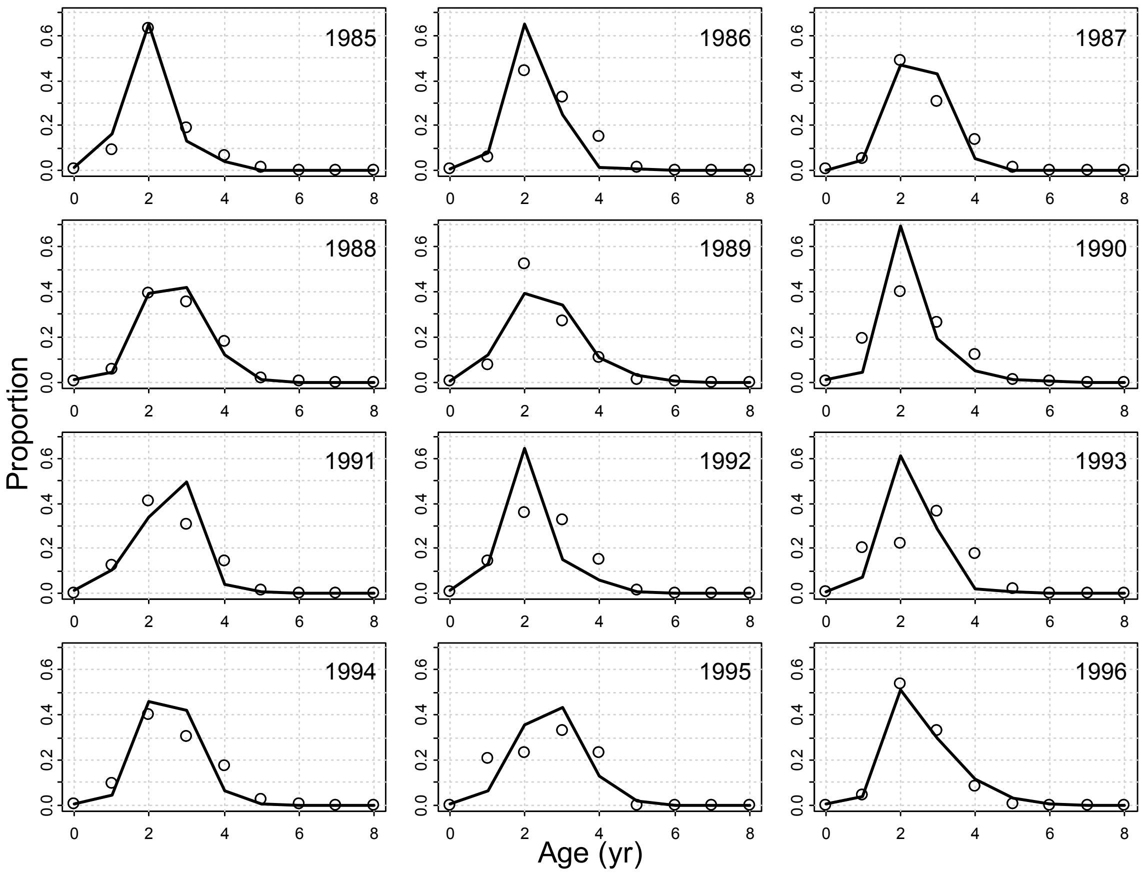


Figure 6.6 (*continued*)

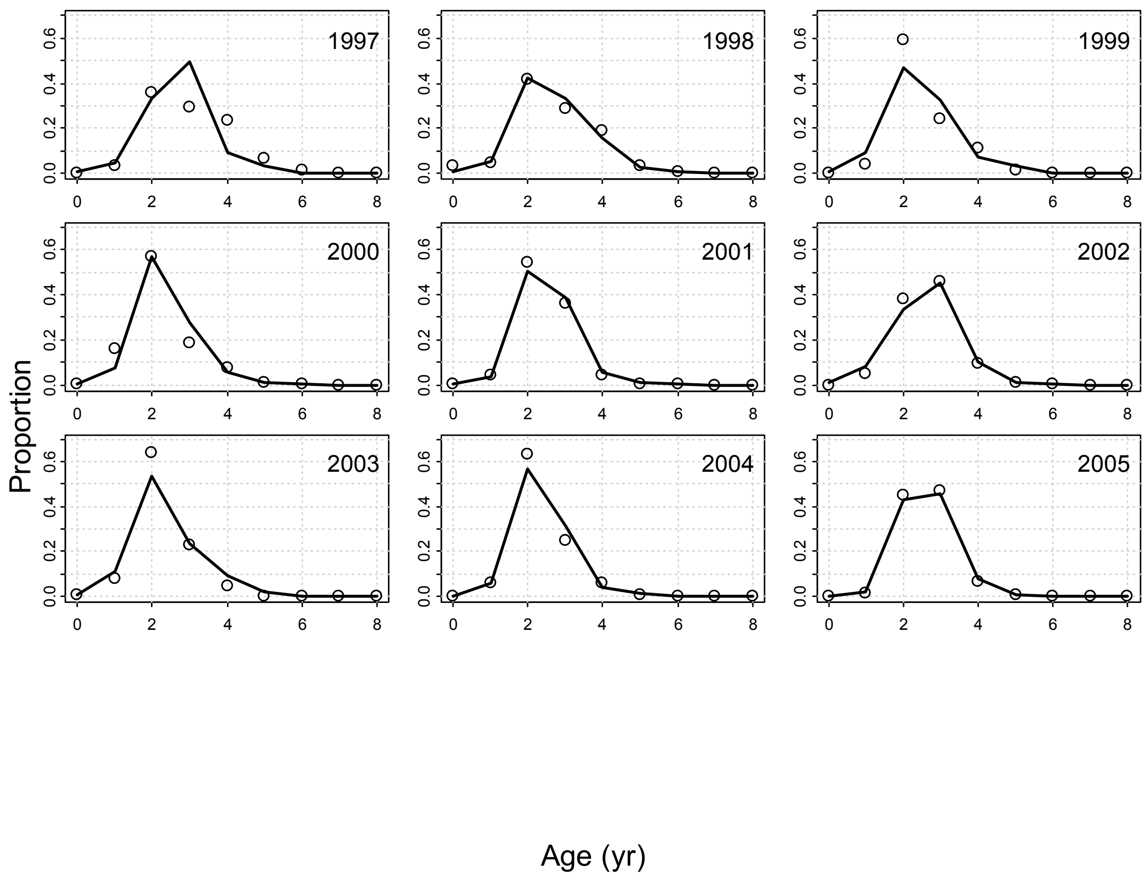


Figure 6.7 Observed and predicted coastwide juvenile abundance indices (logarithm) for Atlantic menhaden (base Ricker model).

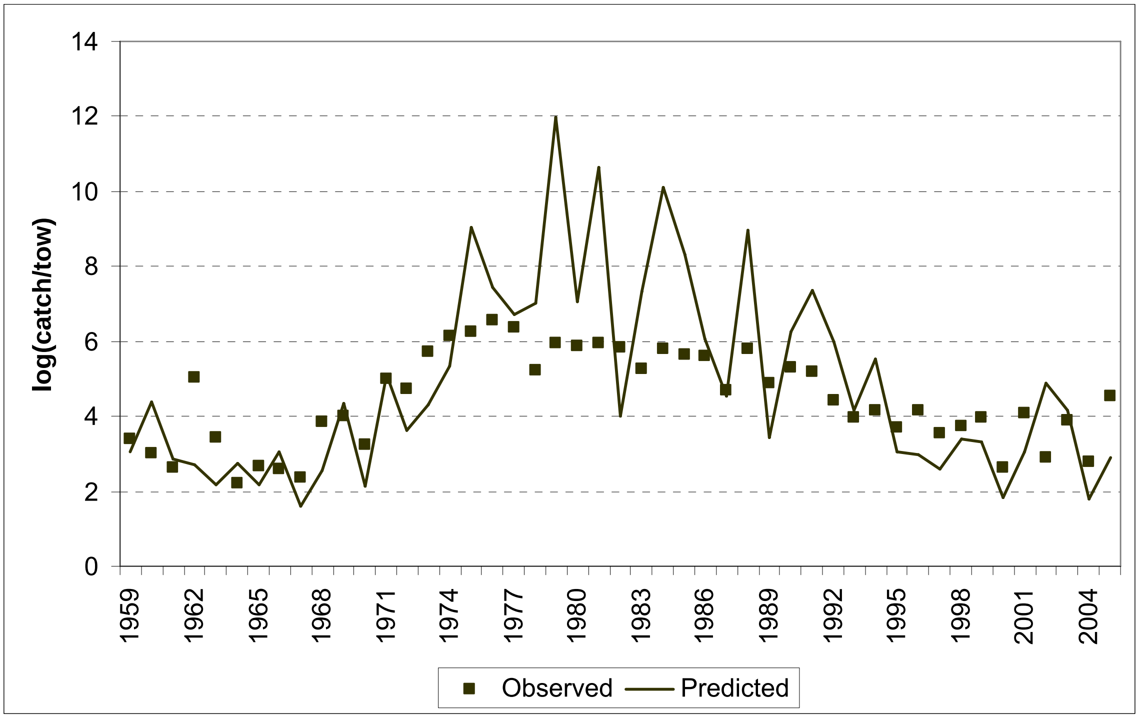


Figure 6.8 Observed and predicted PRFC pound net indices for Atlantic menhaden (base Ricker model).

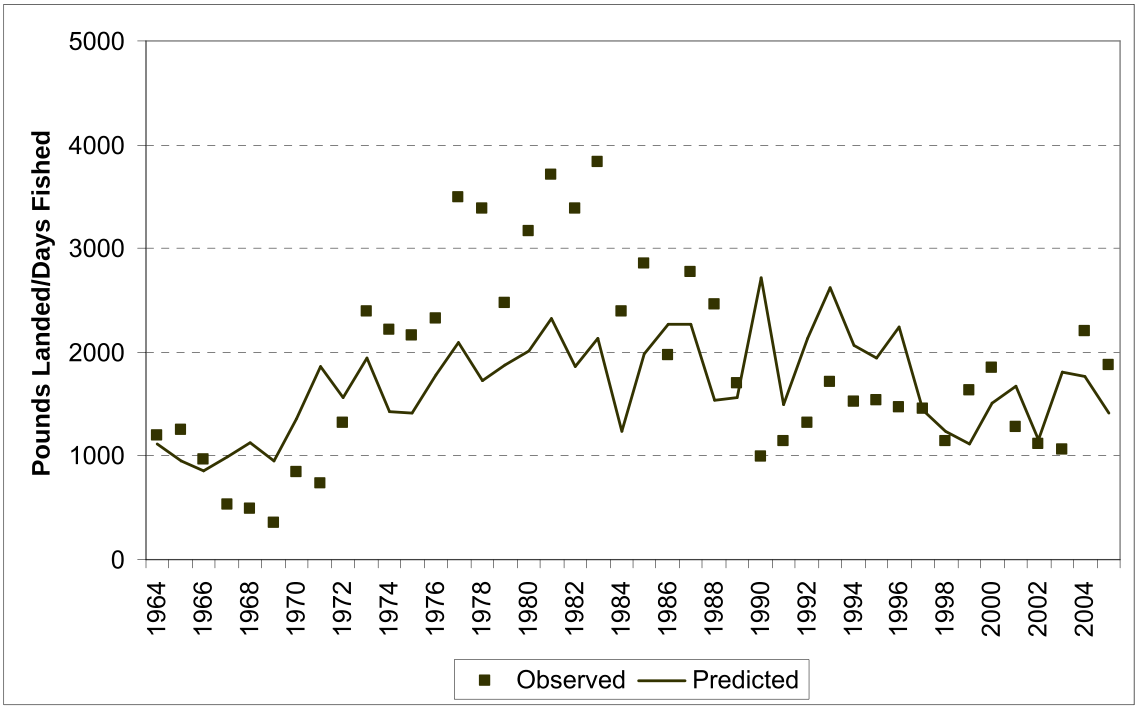


Figure 6.9 Selectivity of reduction and bait Atlantic menhaden fishery estimated in the base Ricker model run.

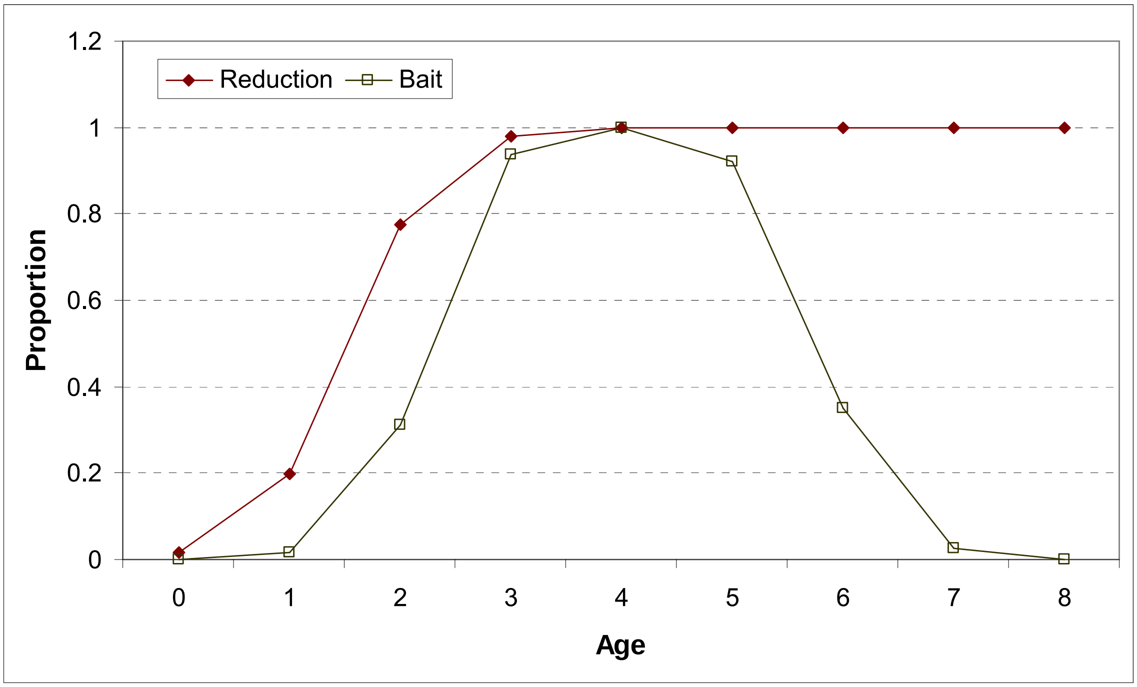


Figure 6.10 Atlantic menhaden fishing mortality rate, F (ages 2+) ± 2 standard errors from the base Ricker model (from Hessian).

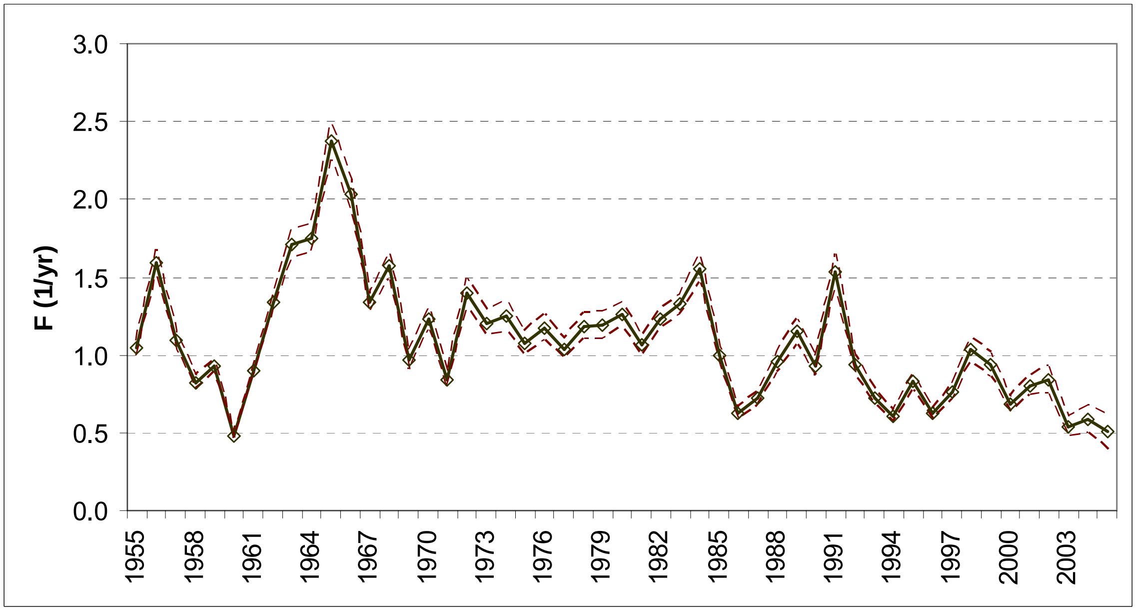


Figure 6.11 Atlantic menhaden population fecundity (# maturing ova) ± 2 standard errors from the base Ricker model (from Hessian).

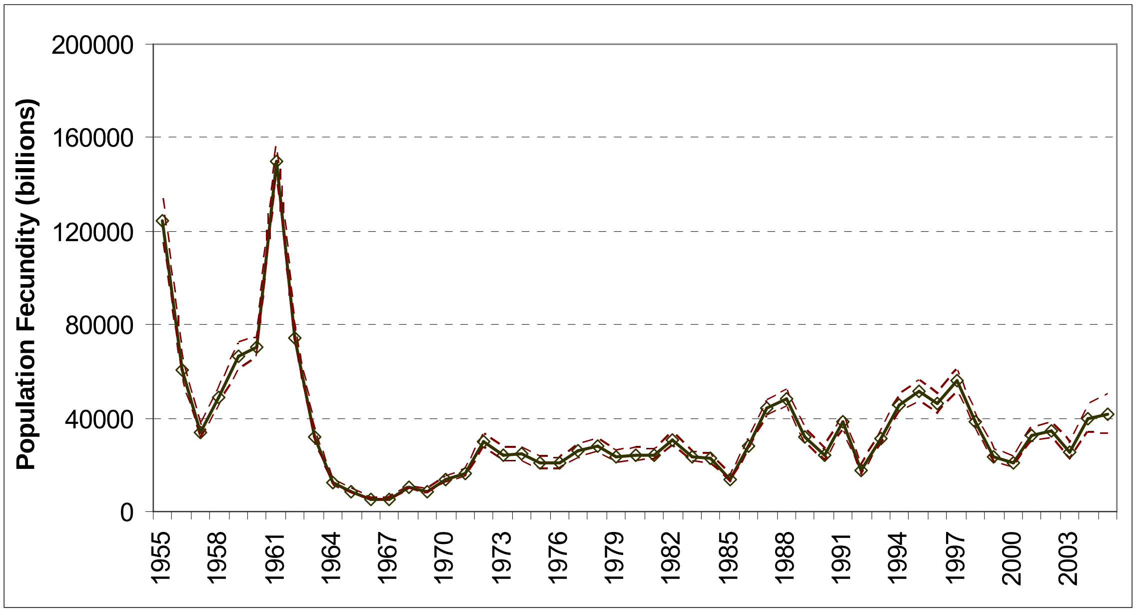


Figure 6.12 Atlantic menhaden recruits to age-0 ± 2 standard errors from the base Ricker model (from Hessian).

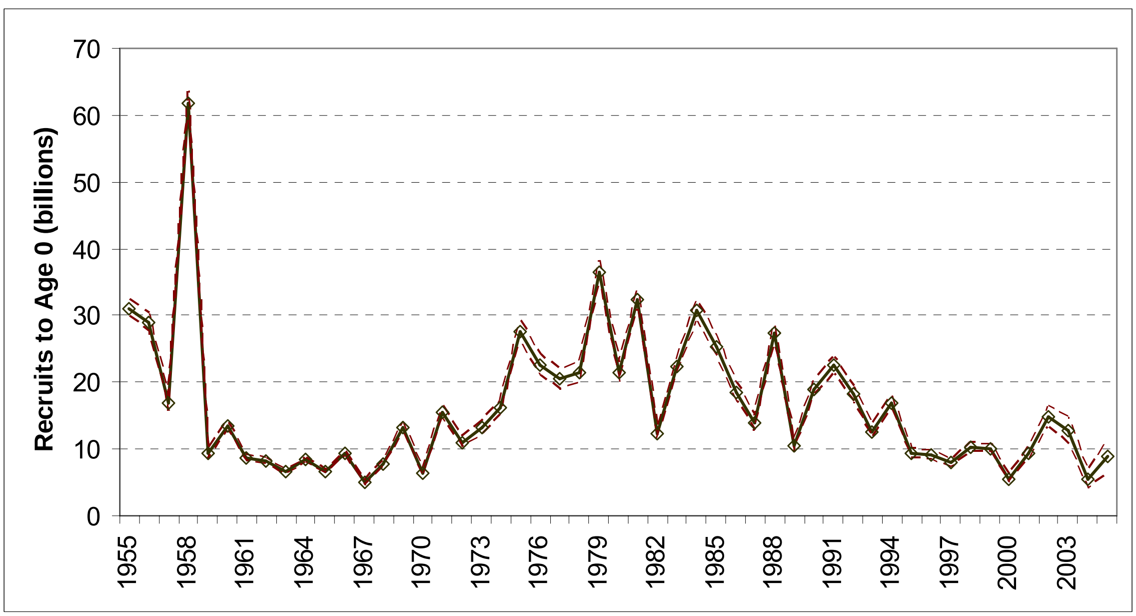


Figure 6.13 Comparison of Atlantic menhaden fishing mortality rate, F (ages 2+) from the update base Ricker model and that from the 2003 Peer Reviewed Assessment (ASMFC 2004a).

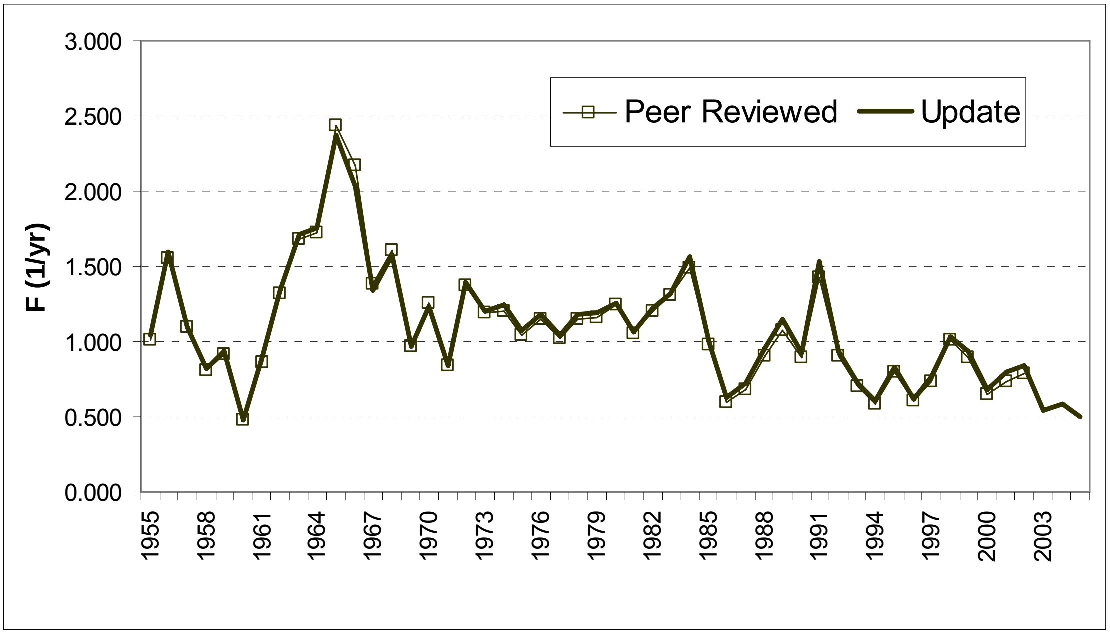


Figure 6.14 Comparison of Atlantic menhaden population fecundity (# maturing ova) from the update base Ricker model and that from the 2003 Peer Reviewed Assessment (ASMFC 2004a).

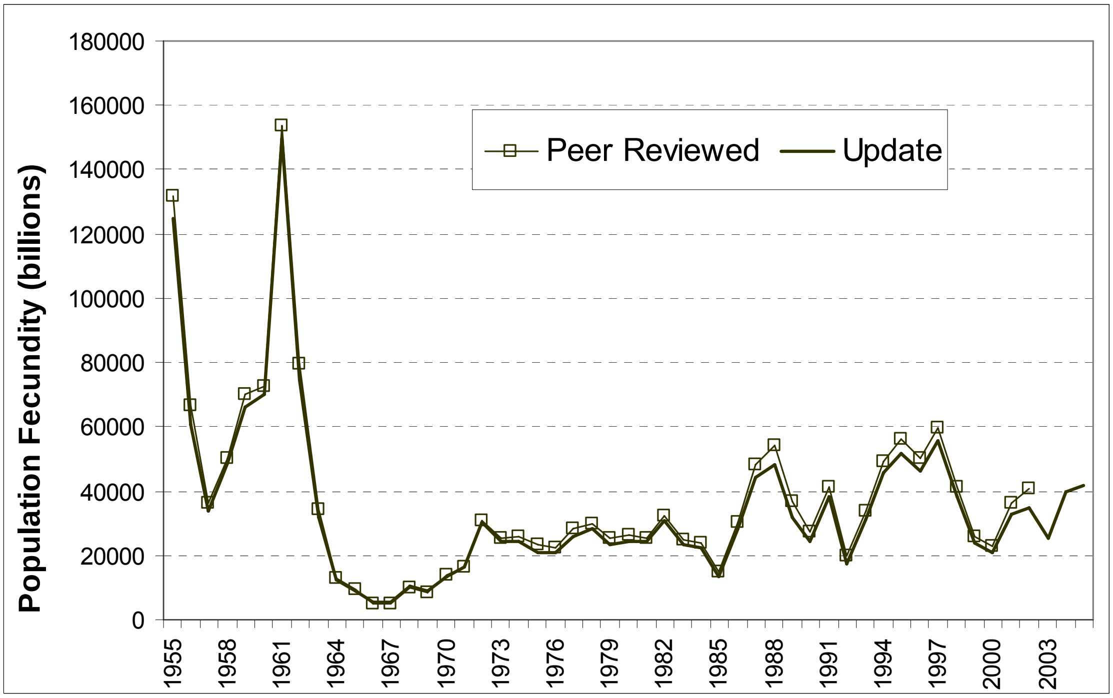


Figure 6.15 Comparison of Atlantic menhaden recruits to age-0 from the update base Ricker model and that from the 2003 Peer Reviewed Assessment (ASMFC 2004a).

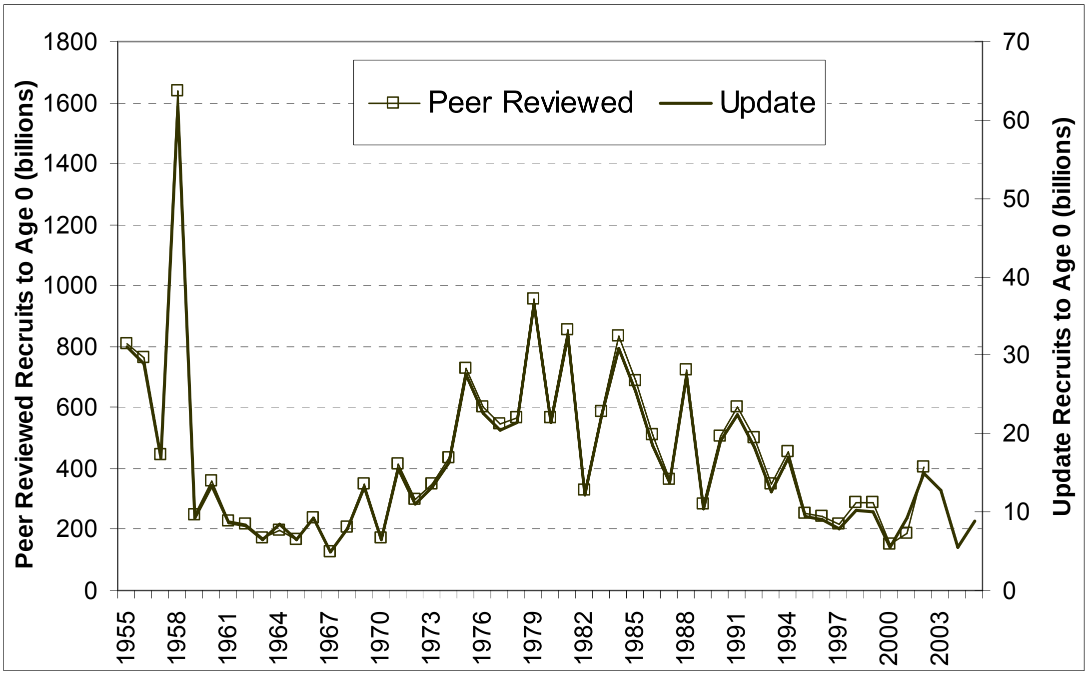


Figure 6.16 Comparison of Atlantic menhaden fishing mortality rate, F (ages 2+) from the base Ricker model and four sensitivity runs (alternate bait landings, coastwide juvenile abundance index, PRFC poundnet CPUE, and varying selectivity).

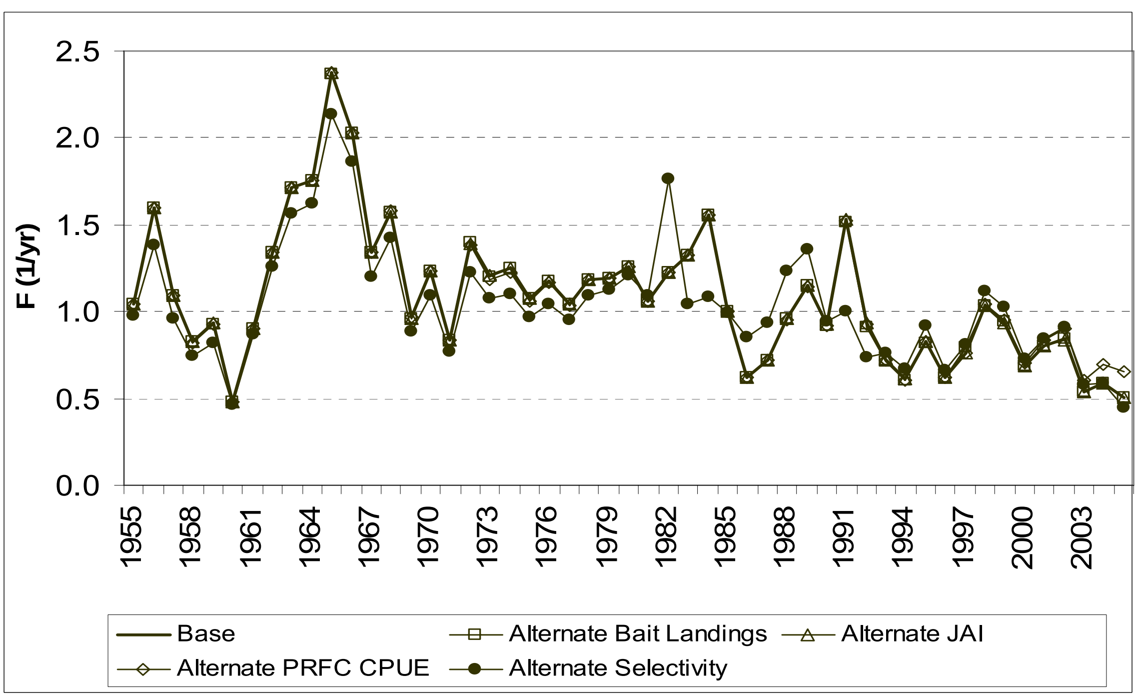


Figure 6.17 Comparison of Atlantic menhaden population fecundity (# maturing ova) from the update base Ricker model and four sensitivity runs (alternate bait landings, coastwide juvenile abundance index, PRFC poundnet CPUE, and varying selectivity).

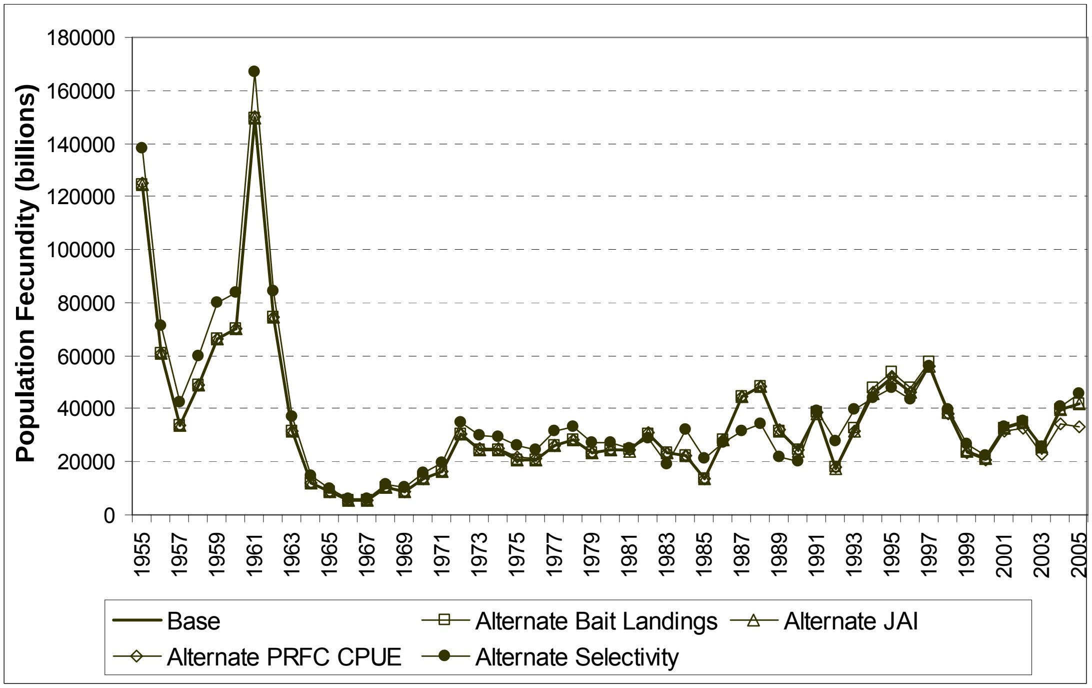


Figure 6.18 Comparison of Atlantic menhaden recruits to age-0 from the update base Ricker model and four sensitivity runs (alternate bait landings, coastwide juvenile abundance index, PRFC poundnet CPUE, and varying selectivity).

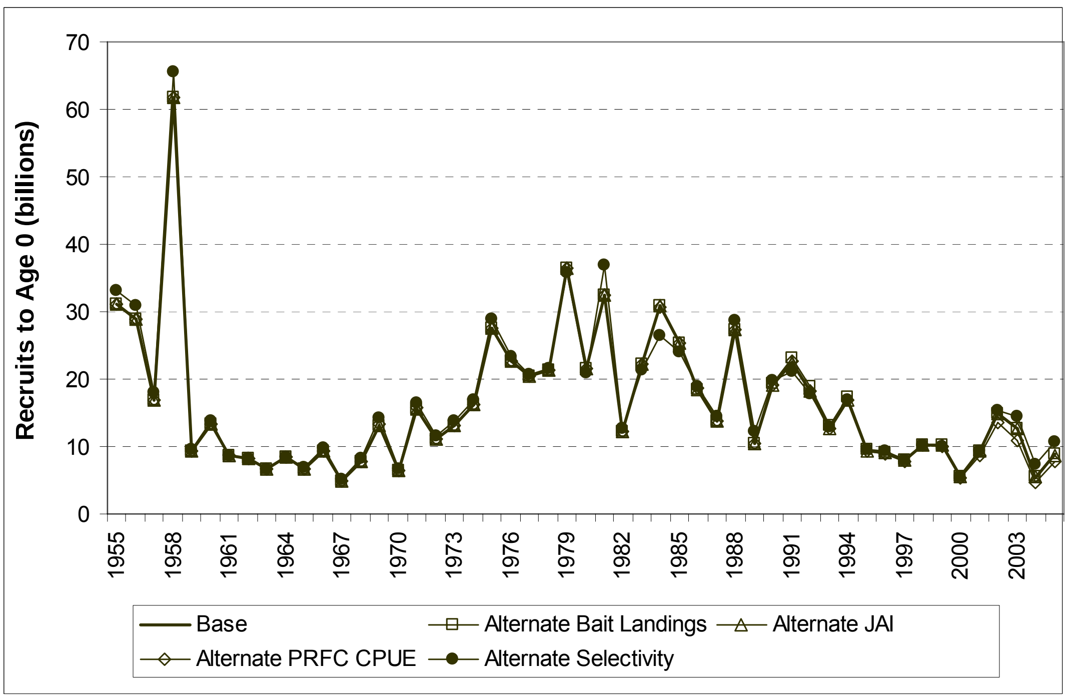


Figure 6.19 Retrospective comparison of Atlantic menhaden fishing mortality rate, F (ages 2+) from the base Ricker model. Terminal year values shown with solid circle.

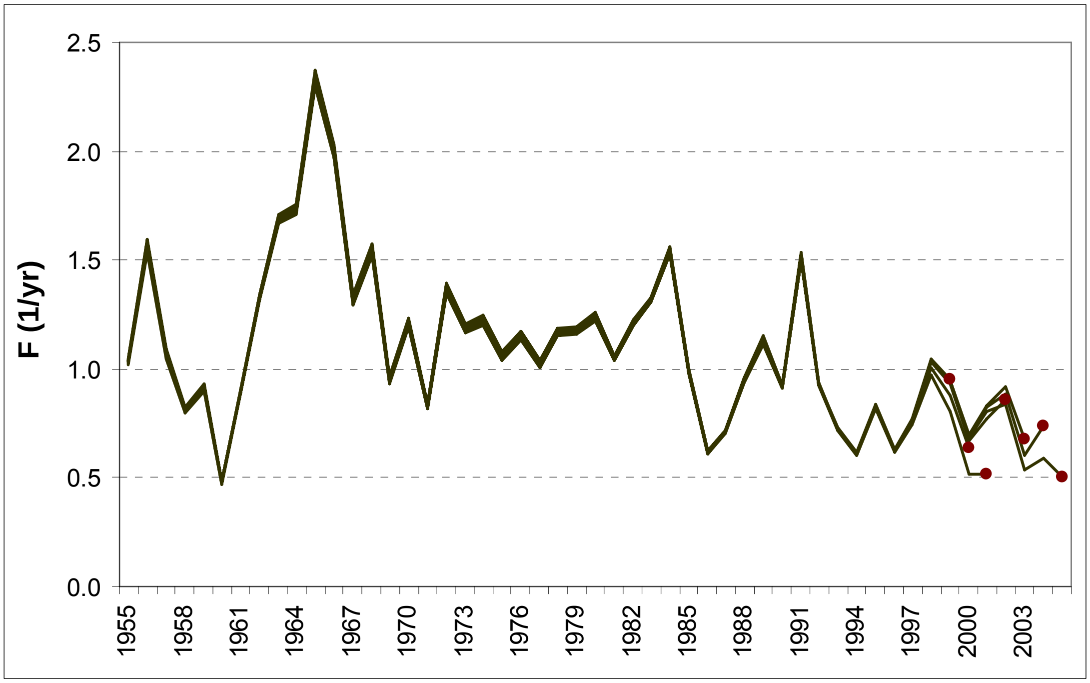


Figure 6.20 Retrospective comparison of Atlantic menhaden population fecundity (# maturing ova) from the base Ricker model. Terminal year values shown with solid circle.

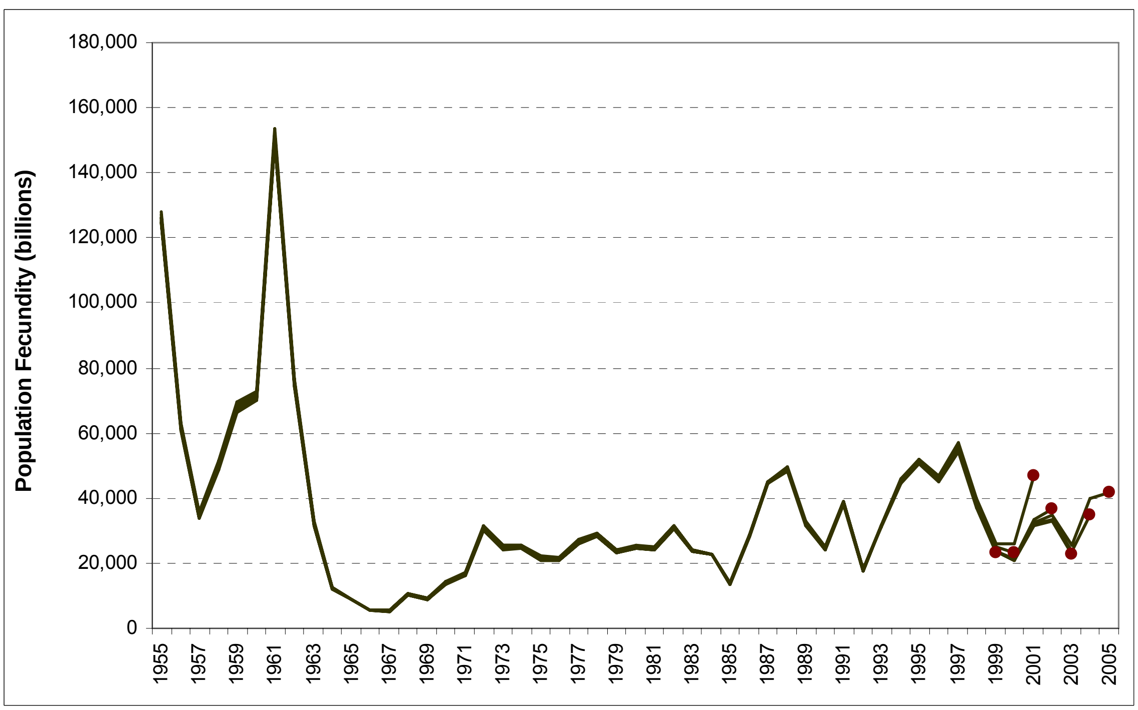


Figure 6.21 Retrospective comparison of Atlantic menhaden recruits to age-0 from the base Ricker model. Terminal year values shown with solid circle.

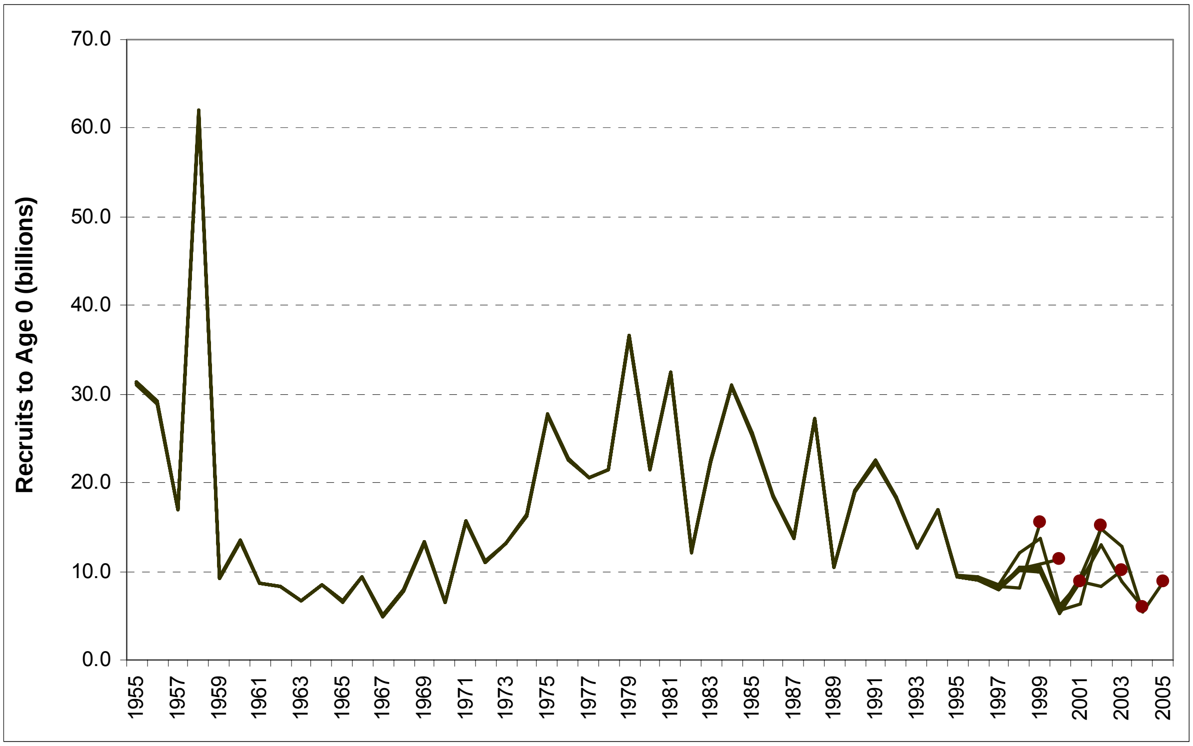


Figure 7.1 Ricker spawner-recruit curve for Atlantic menhaden including replacement line.

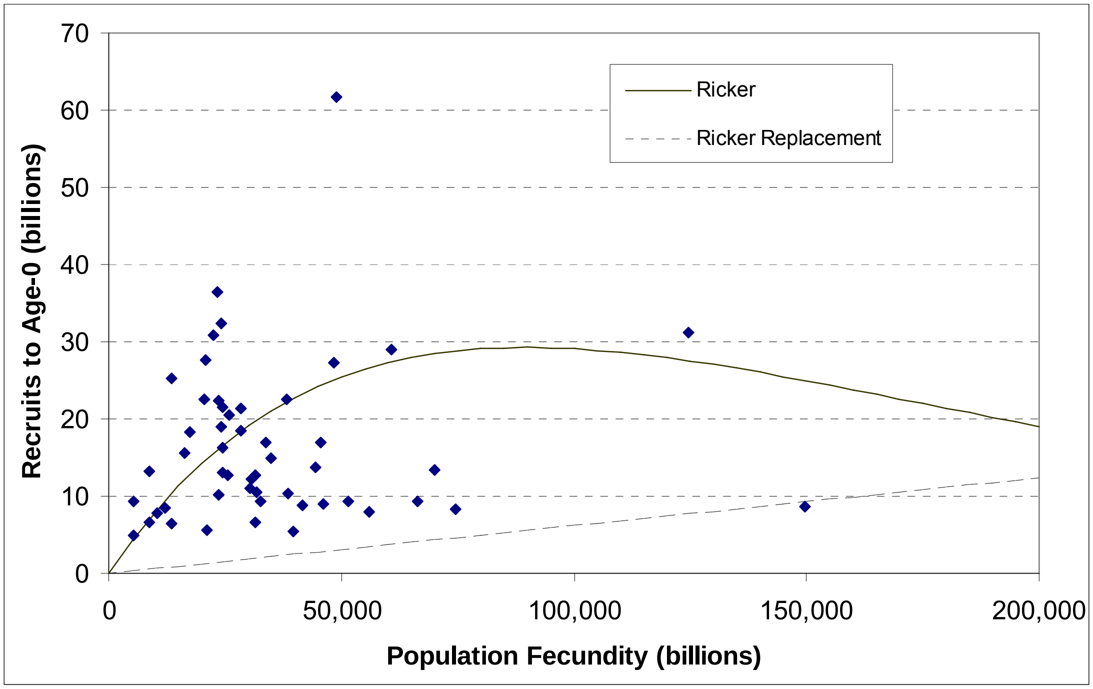


Figure 7.2 Atlantic menhaden fecundity-per-recruit (static FPR) and yield-per-recruit (YPR) from the base Ricker model.

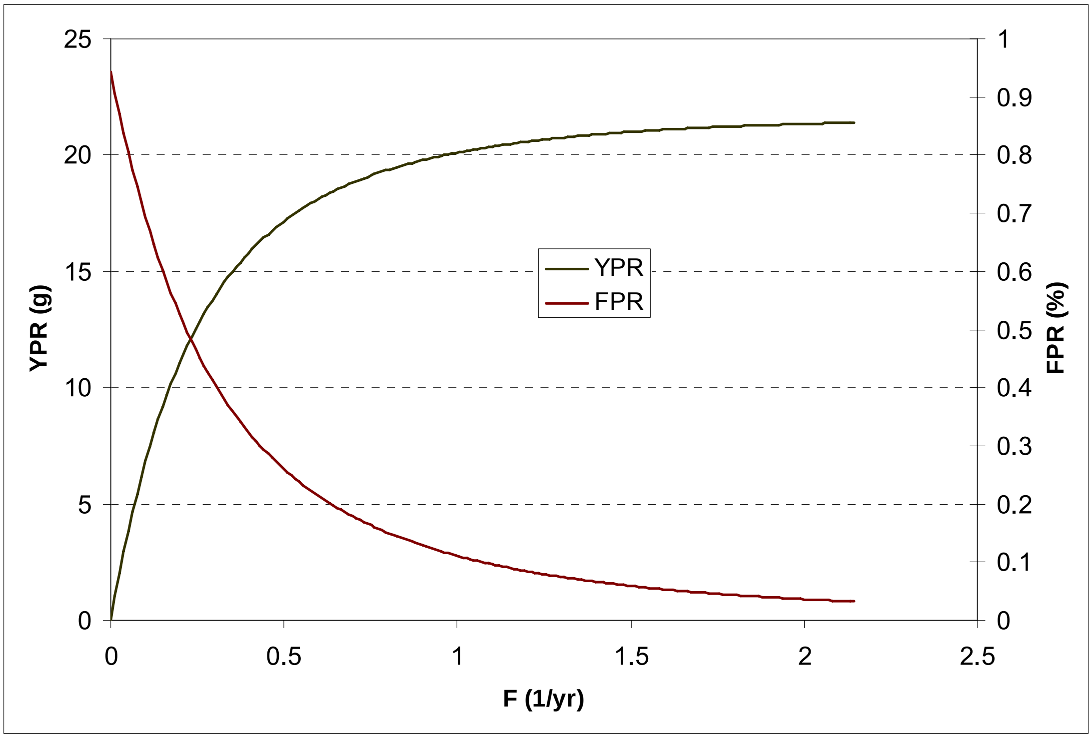


Figure 7.3 Atlantic menhaden spawner-per-recruit (static SPR) for the base Ricker model.

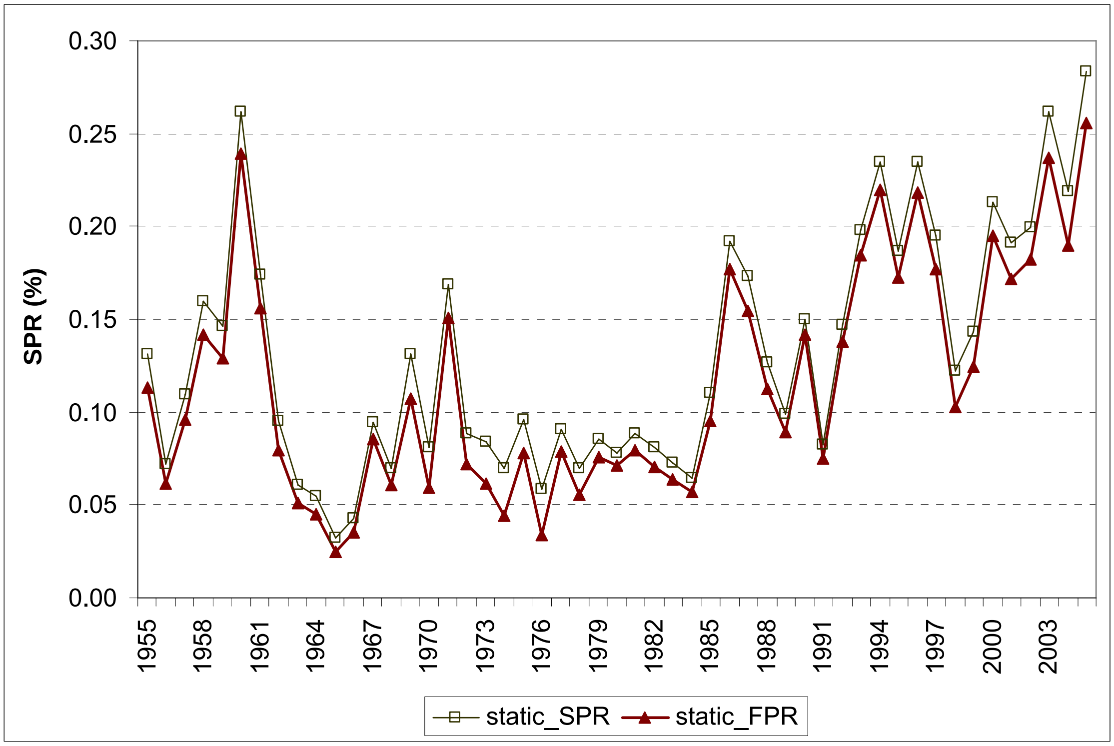


Figure 7.4 Atlantic menhaden population fecundity (# maturing ova) vs recruits to age-0 for the base Ricker model.

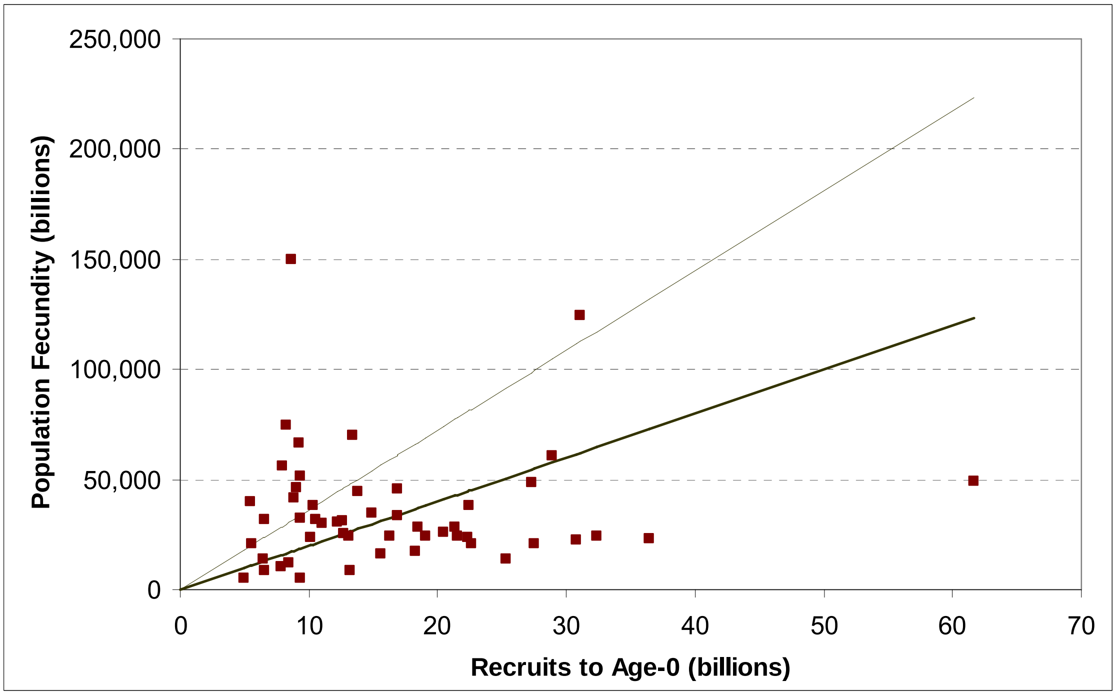


Figure 7.5 Atlantic menhaden fishing mortality rate relative to its annually estimated threshold benchmark (F/F_{rep}) and population fecundity relative to its annually estimated target (FEC/FEC_{target})—these ratios are analogous to F/F_{msy} and SSB/SSB_{msy}.

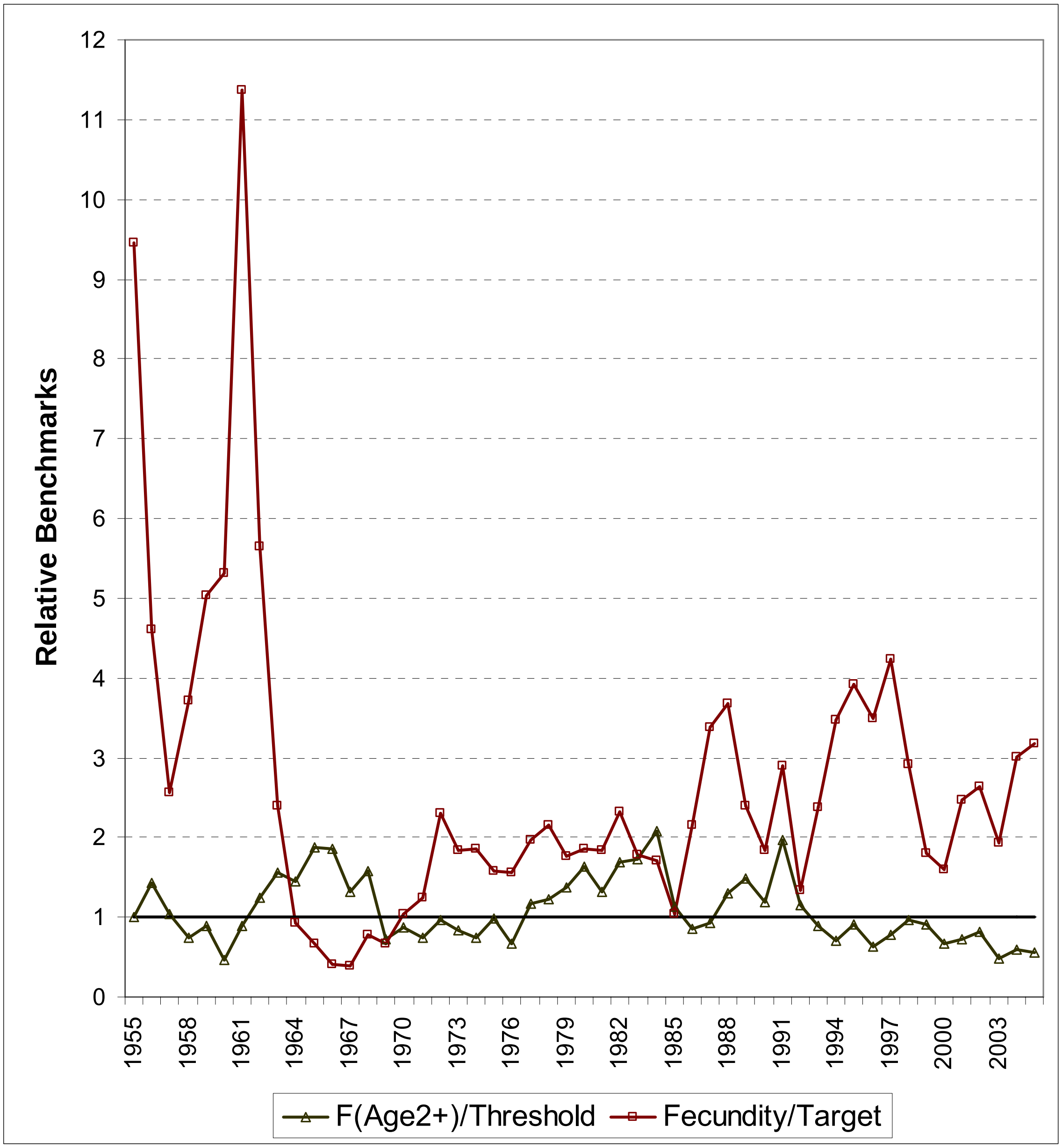


Figure 7.6 Control plot for Atlantic menhaden from the base Ricker model based on the numeric values of the benchmarks in Addendum 1 (ASMFC 2004b). Annual values are presented for 1985–2005 with solid square for initial (1985) and terminal year (2005).

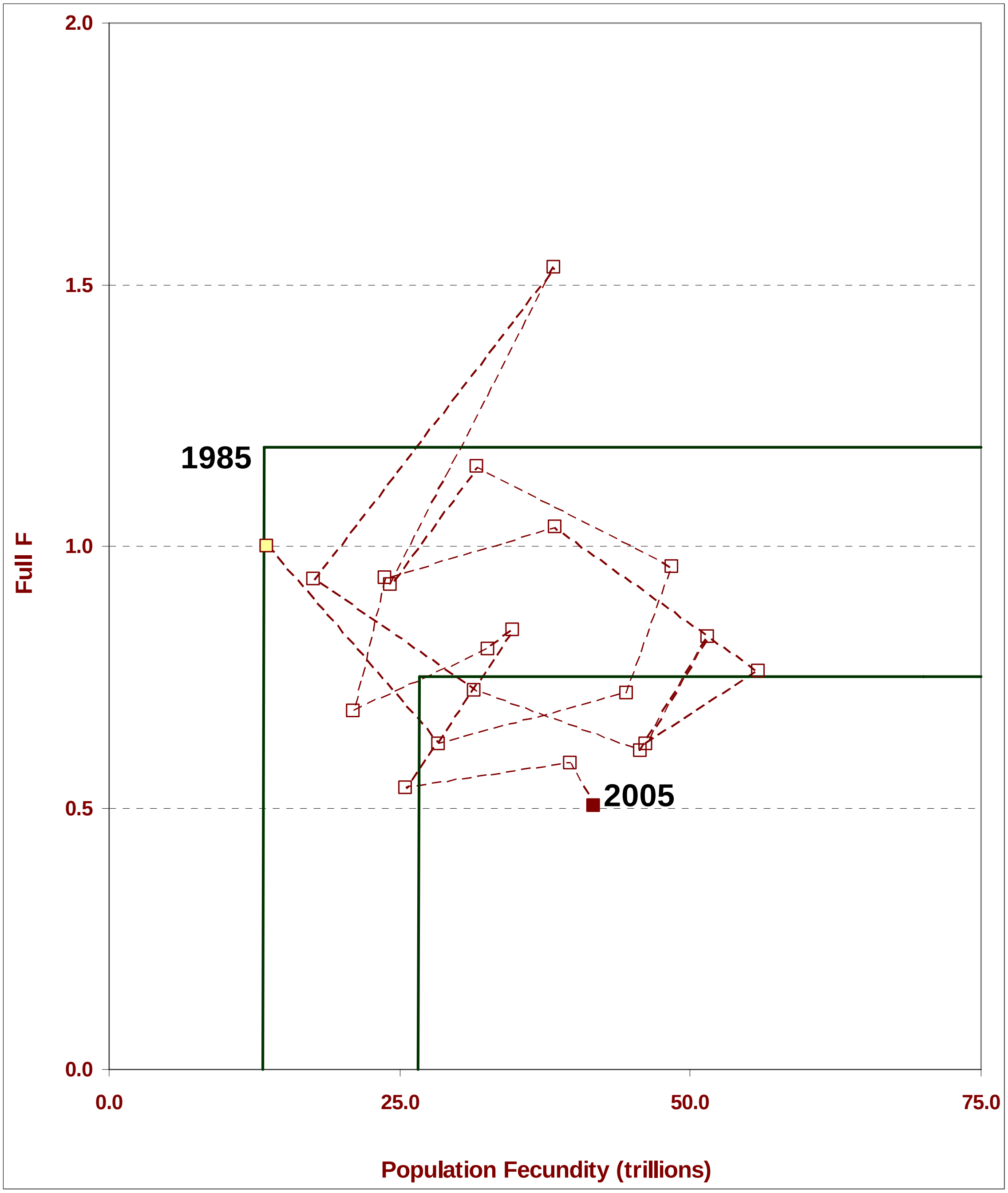
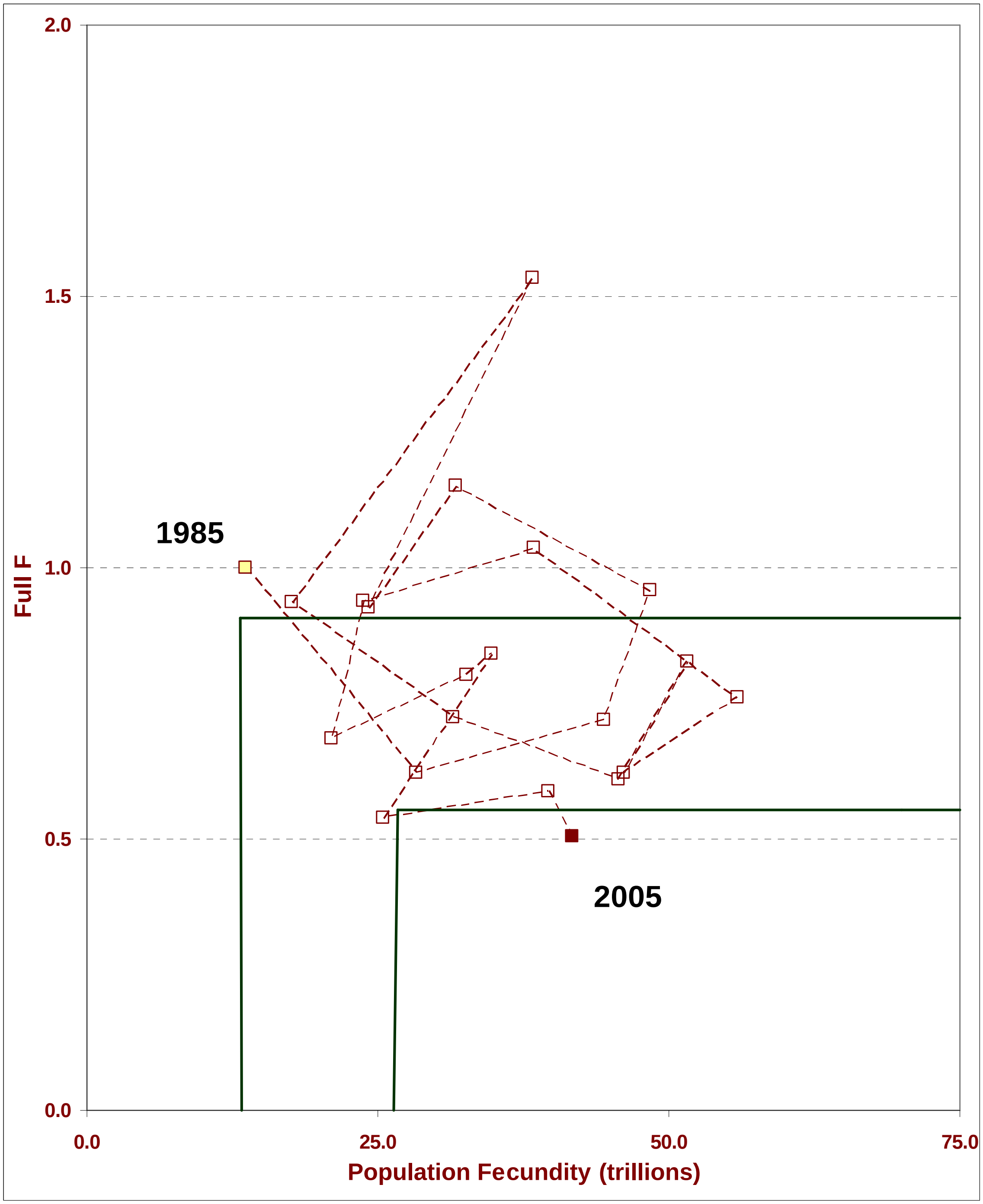


Figure 7.7 Control plot for Atlantic menhaden from the base Ricker model based on estimated values of the benchmarks (terminal year) using the process defined in Addendum 1 (ASMFC 2004b). Annual values are presented for 1985–2005 with solid square for initial (1985) and terminal year (2005).



APPENDICES

Appendix A. List of Participants

Appendix B. Control File for Base Rick Run

Appendix C. Corresponding Input File

Appendix D. ADMB Model Runs Description

APPENDIX A. Atlantic Menhaden Stock Assessment Workshop Participants

Subcommittee Members

Behzad Mahmoudi, Chair (FL)
Matt Cieri (ME)
Brandon Muffley (NJ)
Alexei Sharov (MD)
Erik Williams (NMFS)
Joseph Smith (NMFS)
Douglas Vaughan (NMFS)
Brad Spear, Staff (ASMFC)

Guests:

Jeff Kaelin (Industry representative)
Niels Moore (Industry representative)
Rob Latour (VIMS)
Helen Takade (NC)
Christine Burgess (NC)
Rob Cheshire (NMFS)
Dean Arenholz (NMFS)
Mike Prager (NMFS)

APPENDIX B. Control File for Base Ricker Run

(menhad011.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(0.187647,0.187649,3);
```

```
//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
number var_rec_dev;                    //variance of log recruitment deviations.
                              //Estimated from yrs with unconstrainted S-R(stryR+1 to
endyr)
number BiasCor;                        //Bias correction in equilibrium recruits
number nyrs_Rdev;

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-old.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);

  //compute the number of years R devs are being estimated
  nyrs_Rdev=(endyr-(styrR+1))+1;

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_b
ait_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
  var_rec_dev=norm2(R_log_dev(styrR+1,endyr)-sum(R_log_dev(styrR+1,endyr))
            /nyrs_Rdev)/(nyrs_Rdev-1); //sample variance yrs
  BiasCor=mfexp(var_rec_dev/2.0);   //bias correction

  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_bait(y)));
  }
  if(y<styr)
  {

sel_msy(y)=(sum(C_reduction(y))*sel_reduction(styr)+sum(C_bait(y))*sel_bait(styr))/(s
um(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)))*(BiasCor*4*steep*fpr_msy(1)-
fpr_F0(endyr)*(1-steep));
     R_eq(2)=(R0/((5*steep-1)*fpr_msy(2)))*(BiasCor*4*steep*fpr_msy(2)-
fpr_F0(endyr)*(1-steep));
     R_eq(3)=(R0/((5*steep-1)*fpr_msy(3)))*(BiasCor*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((stee
p*4)/(1-steep)));

//R_eq(2)=(R0/(spr_msy(2)/spr_F0(endyr)))*(1+log(spr_msy(2)/spr_F0(endyr))/log((stee
p*4)/(1-steep)));

//R_eq(3)=(R0/(spr_msy(3)/spr_F0(endyr)))*(1+log(spr_msy(3)/spr_F0(endyr))/log((stee
p*4)/(1-steep)));

R_eq(1)=(R0/(fpr_msy(1)/fpr_F0(endyr)))*(1+log(BiasCor*fpr_msy(1)/fpr_F0(endyr))/l
og((steep*4)/(1-steep)));

R_eq(2)=(R0/(fpr_msy(2)/fpr_F0(endyr)))*(1+log(BiasCor*fpr_msy(2)/fpr_F0(endyr))/l
og((steep*4)/(1-steep)));
```

```
R_eq(3)=(R0/(fpr_msy(3)/fpr_F0(endyr)))*(1+log(BiasCor*fpr_msy(3)/fpr_F0(endyr))/l
og((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),lo
g(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_b
ait));
  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 << "SSB2005/SSBmsy " << SdSSB_msy_end << endl;
  report << "FEC2005/FECmsy " << FECdFEC_msy_end << endl;
  report << "F2005/Fmsy " << FdF_msy_end << endl;
  report << "F_DSV(2005)/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))*(BiasCor*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(BiasCor*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-report-old.cxx"   // ADMB code to write the S-compatible report
```

APPENDIX C. Corresponding Input File

(menhad011.dat)

```
#starting and ending year of the model, respectively
1955
2005

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

#Natural Mortality
1.038  0.606  0.503  0.463  0.441  0.429  0.421  0.421  0.421
#2.343  0.534  0.307  0.3  0.3  0.3  0.3  0.3  0.3  #2003 vector
#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
52.7	144.9	297.4	442.9	561.7	650.8	714.6	758.8	788.9
31.8	90.8	202.2	327.6	448.5	555.0	644.0	715.7	772.0
30.1	91.2	198.3	306.2	398.7	471.6	526.0	565.5	593.6

#weight-at-age for the spawning population (start of year)

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
31.0	79.4	219.8	372.8	506.1	609.8	685.5	738.8	775.3
18.8	48.3	143.3	264.6	389.4	503.9	601.8	681.9	745.6
16.6	47.4	143.0	253.5	354.9	437.6	500.9	547.4	580.8

#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
16346.0159	30690.7328	77468.6610	142516.7381	212892.6042	277274.3028	329956.0231	369992.5524	398967.8430

12473.6959 21782.9767 53106.2432 102593.2382 166887.0963 239086.0061
311830.6529 379455.7323 438678.3517
11341.0430 21089.5481 53759.3573 101801.8286 157389.0960 211879.9633
259533.1183 298064.7037 327591.3481

#CPUE Age0 Index starting and ending years, respectively
1959
2005
#CPUE Age0 values
3.382940524 3.007010276 2.643566402 5.045320533 3.421388203 2.226792039
2.688240181 2.600105148 2.379956271 3.869458374 3.995131755
3.245653473 5.005616597 4.71648952 5.707366287 6.143515958
6.245774157 6.575320596 6.373769984 5.241203598 5.959251152
5.888754912 5.952526091 5.841720839 5.275374369 5.807654502
5.645850996 5.595545096 4.684312318 5.77983146 4.901291853
5.285450794 5.191401576 4.429652404 3.977767449 4.173916646
3.70801666 4.13908117 3.55435657 3.754009024 3.979223313
2.629446157 4.066171494 2.894533617 3.908070573 2.796403555
4.542573177

#CPUE Pound Net Index starting and ending years, respectively
1964
2005
#CPUE Pound Net values
1200.536766 1253.930012 969.1485942 527.3332987 492.1822715 350.7954904
845.0841513 739.3087094 1318.666926 2388.534612 2214.300718
2156.320386 2320.080977 3493.875143 3384.639318 2470.892705
3164.342746 3703.400864 3378.988482 3836.990726 2392.961348
2853.813071 1968.012678 2765.965229 2465.256195 1692.525183
986.646892 1148.029682 1315.305353 1710.162139 1524.597216
1538.066769 1467.940839 1448.316981 1144.909144 1626.076021
1845.551788 1277.655637 1120.800936 1055.591783 2205.259804
1872.411742
#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
2005

#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
167.2 233.7 174.0 166.1 183.4 146.9

```
#Reduction fishery age comp data starting and ending years
1955
2005

#Reduction fishery age comp samples sizes
16136   19875   19698   15324   17960   13513   13189   15793   13033   10443   19550   15670
        15435   26838   15121   8435    8269    6553    6353    5421    7283    6725    7276
        7094    6366    7291    9201    9066    11533   11689   7718    5408    7398    7339
        6997    6828    7690    5610    5318    4708    4606    4218    4125    3808    3620
        3040    3923    3580    3415    4170    3520
# 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
0.0870 0.1826 0.6405 0.0770 0.0112 0.0013 0.0004 0.0000 0.0000
0.0184 0.2188 0.6667 0.0774 0.0178 0.0009 0.0000 0.0000 0.0000
0.0187 0.1216 0.5904 0.2377 0.0288 0.0028 0.0000 0.0000 0.0000

#Starting and ending year of bait fishery
1985
2005

#Bait fishery landings (1000 mt)
28.29578065 31.14656627 34.10955448 36.18720995 34.77440148 33.61007929
39.73585062 42.42757165 34.94348006 27.15080603 30.45883463
23.29435866 26.90788617 40.41874881 37.06617648 35.04611407
37.41385726 37.21761755 34.97758843 35.31883666 38.17096035
#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
2005

#Bait fishery age comp samples sizes
800 420 220 10 30 10 78 70 169 539 362 357
313 636 538 543 962 702 427 354 322

#Bait fishery age comp data
0.0055 0.0888 0.6296 0.1922 0.0681 0.0133 0.0024 0.0000 0.0000
0.0043 0.0603 0.4432 0.3273 0.1492 0.0128 0.0030 0.0000 0.0000
0.0048 0.0536 0.4859 0.3036 0.1373 0.0122 0.0028 0.0000 0.0000
0.0034 0.0530 0.3966 0.3526 0.1763 0.0146 0.0035 0.0000 0.0000
0.0053 0.0756 0.5267 0.2721 0.1073 0.0108 0.0021 0.0000 0.0000
0.0056 0.1937 0.4026 0.2655 0.1189 0.0113 0.0024 0.0000 0.0000
0.0033 0.1216 0.4083 0.3065 0.1435 0.0138 0.0029 0.0000 0.0000
0.0048 0.1433 0.3579 0.3253 0.1499 0.0157 0.0031 0.0000 0.0000
0.0072 0.2003 0.2239 0.3665 0.1796 0.0187 0.0038 0.0000 0.0000
0.0021 0.0925 0.4002 0.3036 0.1746 0.0251 0.0018 0.0000 0.0000
0.0000 0.2052 0.2352 0.3294 0.2294 0.0007 0.0000 0.0000 0.0000
0.0005 0.0425 0.5365 0.3327 0.0846 0.0032 0.0000 0.0000 0.0000
0.0000 0.0344 0.3597 0.2943 0.2336 0.0662 0.0117 0.0000 0.0000
0.0299 0.0450 0.4147 0.2840 0.1898 0.0308 0.0058 0.0000 0.0000
0.0011 0.0410 0.5940 0.2400 0.1078 0.0139 0.0022 0.0000 0.0000
0.0051 0.1579 0.5671 0.1835 0.0747 0.0093 0.0025 0.0000 0.0000
0.0020 0.0454 0.5425 0.3596 0.0433 0.0059 0.0013 0.0000 0.0000
0.0000 0.0501 0.3829 0.4591 0.0978 0.0096 0.0006 0.0000 0.0000
0.0049 0.0807 0.6355 0.2311 0.0460 0.0017 0.0000 0.0000 0.0000
0.0000 0.0568 0.6334 0.2456 0.0600 0.0042 0.0000 0.0000 0.0000
0.0000 0.0120 0.4525 0.4663 0.0644 0.0046 0.0002 0.0000 0.0000

APPENDIX D. ADMB Model Runs Descriptions

<u>Description of 2006 Atlantic menhaden update stock assessment runs</u>:

menhad001 - Ricker base run from 2003 (no changes)

menhad002 - same as menhad001 with updated data through 2005 (from AM_Input_2006.xls) q parameter for pound net CPUE was hitting lower bound

menhad003 - same as menhad002 with reduced lower bound for pound net CPUE q parameter M constant parameter hitting the upper bound

menhad004 - same as menhad003 with raised upper bound for M constant parameter (Original Update base - adult M > 1 found to be unacceptable)

menhad005 - same as menhad004 with old M vector from 2003 assessment (Updated data, old M vector from 2003 assessment)

menhad006 - same as menhad004 with upper bound of M set to 0.55 at oldest ages (estimate hit bound)

menhad007 - (experimental) same as menhad006 with age-year specific parameters for ages 0-3 (assumed to be 1.0 for ages 4+) and all years in the reduction fishery. Interesting to note that M no longer hits the bound.

menhad008 - (experimental) same as menhad004 allow for time-varying a50 parameter (all years with age comps) for reduction fishery

menhad009 - (experimental) same as menhad008 with upper bound on M set to 0.55 at oldest ages

menhad010 - same as menhad006 with time periods of selectivity for reduction fishery, as follows: 1955-1981 (constant logistic), 1982-1993 (logistic with time-varying location parameter), 1994-2005 (constant double logistic)

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menhad011 - same as menhad006 with M set to 0.50 at oldest ages (BASE RUN)

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menhad012 - same as menhad011 with time periods of selectivity for reduction fishery, as follows: 1955-1981 (constant logistic), 1982-1993 (logistic with time-varying location parameter), 1994-2005 (constant double logistic)

menhad013 - same as menhad011 with M set to MSVPA values (i.e. no scalar adjustment)

menhad014 - same as menhad011 with alternate bait landings

menhad015 - same as menhad011 with alternate juvenile abundance index

menhad016 - same as menhad011 without 2005 data (retrospective run)

menhad017 - same as menhad011 without 2004-2005 data (retrospective run)

menhad018 - same as menhad011 without 2003-2005 data (retrospective run)

menhad019 - same as menhad011 without 2002-2005 data (retrospective run)

menhad020 - same as menhad011 without 2001-2005 data (retrospective run)

menhad021 - same as menhad011 without 2000-2005 data (retrospective run)

menhad022 - same as menhad011 with alternate pound net index (old CPUE)