Southeast Data, Assessment, and Review

SEDAR 63

Stock Assessment Report

Gulf Menhaden

December 2018

SEDAR
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Preface

This regional assessment was completed through the SouthEast Data, Assessment, and Review (SEDAR) process and the Gulf States Marine Fisheries Commission (GSMFC). The GSMFC coordinated the Data and Assessment Workshops, while SEDAR coordinated the Review Workshop. This report is the culmination of a year-long effort to gather and analyze available data for Gulf Menhaden from the commercial purse-seine fishery, fishery-independent sampling programs of the Gulf States, and the recreational sector. The Gulf's five marine resource agencies provided experts through the GSMFC's Menhaden Advisory Committee (MAC), which served as the technical committee throughout the assessment process. The GSMFC provided travel and facilitated several conference calls and webinars in preparation for the workshops.

The SEDAR63 draft report was generated and provided to three reviewers from the Center for Independent Experts (CIE) and one outside reviewer representing the GSMFC. The Review Workshop was held in New Orleans, Louisiana on November 6-7, 2018. At the Workshop, the reviewers had opportunities to address any potential concerns they had with the data or model, and query the analysts and agency representatives regarding any additional questions that arose during their reviews. Finally, a Review Workshop Report (Section II) was generated with comments and overall opinions about the data sources, model, and assessment results and projections. Following the Review Workshop Report, the GSMFC began planning a workshop scheduled for early 2019 to begin to define the potential management goals and reference points for the Gulf Menhaden stock and the fishery.

The GSMFC and the MAC wishes to thank the reviewers for their expertise and time that supported the completion of the regional stock assessment for Gulf Menhaden.

SEDAR
Southeast Data, Assessment, and Review

SEDAR 63
Gulf Menhaden

Assessment Report

October 2018

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Executive Summary

Gulf Menhaden, *Brevoortia patronus*, range from the Yucatan Peninsula in Mexico, across the western and northern Gulf of Mexico to Tampa Bay, Florida, but they are most abundant in the central portion of their range from eastern Texas to western Alabama. Gulf Menhaden are estuarine-dependent: adult Gulf Menhaden generally occur in the near-shore waters of the Gulf of Mexico proper, while juveniles spend most of their first year of life in estuarine waters, including brackish and near-freshwater habitats. Spawning peaks in winter and larvae enter the estuaries in the early spring after riding the prevailing currents from the offshore spawning grounds. Genetic evidence suggests a single unit stock of Gulf Menhaden in the northern Gulf of Mexico and tagging studies indicate that the species does not exhibit extensive east-west migrations; generally, older adults tend to occur near the Mississippi River delta and the central Louisiana coast.

The modern Gulf Menhaden fishery began after World War II as the worldwide demand for fish meal and fish oil increased. Annual landings of Gulf Menhaden in the early 1940s were less than about 40,000 mt, but by the early 1960s landings in the Gulf fishery – 437,500 mt in 1963 –exceeded those in the Atlantic Menhaden fishery. During the 1960s and 1970s, the Gulf Menhaden fishery continued to expand and fleet size ranged about 70 to 80 vessels. Landings peaked in 1984 at 982,800 mt. Thereafter through the 1990s, landings, fleet size, and participants in the fishery declined because of corporate consolidation, weak product prices, and weather conditions. Since 2000, the fishery was reasonably stable with four fish factories – at Abbeville, Cameron and Empire, Louisiana and Moss Point, Mississippi – and about forty vessels. Following the closure of the Cameron factory in 2013, the fleet has remained at around 30 vessels at the three remaining plants; Abbeville, Empire, and Moss Point.

The commercial purse-seine reduction fishery for Gulf Menhaden has been extensively sampled by the National Marine Fisheries Service. Fishery-dependent data sources from 1977-2017 that inform this Gulf Menhaden stock assessment include: 1) detailed catch records that enumerate daily vessel landings, 2) port samples that include comprehensive dockside sampling of vessels throughout the fishing season at all menhaden factories for size and age composition of the catch, and 3) daily logbooks that itemize catch and fishing locations for individual purse-seine sets. Landings of Gulf Menhaden for bait are generally less than 2% of total landings for the species. Bait landings and recreational landings of Gulf Menhaden, which are minimal, were combined with landings from the reduction fishery to provide a complete time series (1977-2017) of removals.

The five Gulf States collect a significant amount of fishery-independent data on finfish from their inshore surveys. Although Gulf Menhaden are generally not the target species of these surveys, total Gulf Menhaden numbers and lengths are recorded. Gulf Menhaden data from state surveys form the basis for two indices of relative abundance: 1) a recruitment index from 1996 to 2017 based on the seine survey data from Louisiana, Mississippi, and western Alabama, and 2) an adult abundance index from 1988 to 2017 based on Louisiana gill net survey data.

In this assessment, the Beaufort Assessment Model (BAM, a forward-projecting age-structured model) was used. The base configuration of the BAM incorporated: fishing seasons 1977-2017, ages 0 to 4+, spawning occurring on January 1, age-varying natural mortality scaled to an estimated based on a tagging study, a single time series of landings, commercial age compositions, a recruitment index based on seine data, an adult abundance index based on Louisiana gill net data, length compositions from the gill net survey, a Beverton-Holt stock recruitment curve with a steepness fixed at 0.99, logistic selectivity for the gill net index, and dome-shaped selectivity for the reduction fishery. Uncertainty was explored with BAM using sensitivity runs and Monte Carlo bootstrapping (MCB). Sensitivity runs for BAM investigated differences in the start year of the model, selectivity for the fishery, values of natural mortality, the stock-recruitment curve, weighting, index inclusion, and growth. MCB runs (N = 5,000) included uncertainty in all of the data streams, selectivity, and natural mortality.

The base run fit all of the data streams reasonably well. Highly variable fishing mortalities were noted throughout the time series; highest fishing mortalities occurred in the 1980s and 1990s, with declining fishing mortalities into the 2000s. Nevertheless, Gulf Menhaden are not fully selected until age-2, thus the fishing mortality rate on other ages is much lower. Throughout the time series, the age-1 and -2 fish produced most of the total estimated number of eggs spawned annually. Sensitivity analyses revealed generally small differences from the base run configuration depending upon the assumption tested, and the MCB runs demonstrated the amount of uncertainty around the base run values. None of the results were unexpected.

Currently, the Gulf Menhaden Fishery Management Plan (VanderKooy and Smith 2015) contains the reference points of $F_{30\%}$ and $SSB_{30\%}$ for stock status determination based on spawner-per-recruit. The fishing mortality rate associated with these benchmarks was greater than 10.0 and was thus determined undefined by the assessment panel. Given this, the panel suggested some alternative reference points. For fishing mortality rate, the benchmark of $F=M$ was suggested as a threshold, and for spawning stock biomass as measured in fecundity, the benchmark of $SSB_{25\%\ at\ F=0}$ was suggested as a threshold. Both of these benchmarks have been used in other areas. The fishing mortality rate benchmark represents the fish that would normally die due to natural mortality and can be taken by fishing instead; while, the *SSB* metric represents 25% of the equilibrium fecundity when fishing is not occurring. The *SSB*-based metrics were not paired with the *F*-based metrics because the spread in the associated *SSB* metric was smaller than one standard deviation of the variability in the *SSB* time series. Based on these benchmarks, the stock status of the base run is not overfished and overfishing is not occurring. Moreover, most of the sensitivity runs and the MCB uncertainty analysis runs resulted in a current stock status of not overfished and overfishing not occurring. The assessment panel recommends that managers work to define the goals and objectives for the fishery.

Gulf Menhaden Stock Assessment Terms of Reference
For SEDAR 63 RW

1) Evaluate the data used in the assessment, addressing the following:
    a) Are data decisions made by the Data and Assessment Workshop sound and robust?
    b) Are data uncertainties acknowledged, reported, and within normal or expected levels?
    c) Are data applied properly within the assessment model?
    d) Are input data series reliable and sufficient to support the assessment approach and findings?

2) Evaluate the methods used to assess the stock, taking into account the available data.
    a) Are methods scientifically sound and robust?
    b) Are assessment models configured properly and used consistent with standard practices?
    c) Are the methods appropriate for the available data?

3) Evaluate the assessment findings with respect to the following:
    a) Are abundance, exploitation, and biomass estimates reliable, consistent with input data and population biological characteristics, and useful to support status inferences?
    b) Is the stock overfished? What information helps you reach this conclusion?
    c) Is the stock undergoing overfishing? What information helps you reach this conclusion?
    d) Is there an informative stock recruitment relationship? Is the stock recruitment curve reliable and useful for evaluation of productivity and future stock conditions?
    e) Are the quantitative estimates of the status determination criteria for this stock appropriate for management use? If not, are there other indicators that may be used to inform managers about stock trends and conditions?

4) Consider how uncertainties in the assessment, and their potential consequences, are addressed.
    a) Comment on the degree to which methods used to evaluate uncertainty reflect and capture the significant sources of uncertainty in the population, data sources, and assessment methods
    b) Ensure that the implications of uncertainty in technical conclusions are clearly stated.

5) Consider the research recommendations provided by the Data and Assessment workshop and make any additional recommendations or prioritizations warranted.
    a) Clearly denote research and monitoring that could improve the reliability of, and information provided by, future assessments.
    b) Provide recommendations on possible ways to improve the SEDAR process.

6) Provide guidance on key improvements in data or modeling approaches which should be considered when scheduling the next assessment.

7) Prepare a Peer Review Summary summarizing the Panel's evaluation of the stock assessment and addressing each Term of Reference. Develop a list of tasks to be completed following the workshop. Complete and submit the Peer Review Summary Report in accordance with the project guidelines.

The panel shall ensure that corrected estimates are provided by addenda to the assessment report in the event corrections are made in the assessment, alternative model configurations are recommended, or additional analyses are prepared as a result of review panel findings regarding the TORs above.

1.0 Introduction

1.1 Species Composition of the Fishery

The commercial fishery in the U.S. Gulf of Mexico catches three species of menhaden:

Gulf Menhaden:	*Brevoortia patronus*
Yellowfin Menhaden:	*Brevoortia smithi*
Finescale Menhaden:	*Brevoortia gunteri*

Gulf Menhaden comprise over 99% of the catch in the commercial purse-seine fishery (Ahrenholz 1981) with a minor aggregation of the other menhaden species and other clupeids.

Guillory and Hutton (1982) reviewed previous studies, which characterized bycatch in the reduction fishery, and in a number of those studies, additional clupeid species occurred with differing regularity. While Dunham (1975) noted that Atlantic Thread Herring (*Opisthonema oglinum*) was encountered 2.33% by weight, Guillory and Hutton (1982) found Threadfin Shad (*Dorosoma petenense*) occurred in the catch at 13.2% (by numbers), while Skipjack Herring (*Alosa chrysochloris*), Gizzard Shad (*D. cepedianum*) and Scaled Sardine (*Harengula pensacolae*) each accounted for a mere 0.1% by number or weight. Similarly, Condrey (1994) found that Atlantic Thread Herring made up less than 1% of the catch in the two years he sampled directly from the reduction fleet.

1.2 Brief Overview and History of Fisheries

For those interested in the history and evolution of the Gulf Menhaden fishery, unfortunately, a volume equivalent to that which Goode (1887) compiled for the Atlantic Menhaden (*B. tyranus*) fishery is unavailable. However, a considerable effort was undertaken in the revision to the Gulf Menhaden Fishery Management Plan (VanderKooy and Smith 2015) to interview participants in the fishery and build the history for the Gulf reduction fishery. In addition, several other sources provided glimpses of the Gulf Menhaden fishery from its beginning in the mid-twentieth century.

Frye (1978) delved into the genealogy of menhaden factory ownership for the Gulf fishery. He recounts that numerous corporate families active in the Atlantic Menhaden fishery moved some or all of their operations to the northern Gulf of Mexico just before and after World War II. Simmons and Breuer (1964) make brief reference to the establishment of menhaden fishing operations in Texas in 1951. Kutkuhn (1965) was among the first to recognize that the surging landings in the Gulf Menhaden fishery during 1958-1961 were primarily due to the “vastly improved efficiency of the fishing fleet rather than to greater abundance or availability of the resource.” Fishing fleet innovations included spotter aircraft, nylon seines, fish pumps, power blocks, refrigerated fish holds, and larger carrier vessels. Henry (1969) noted that the Gulf Menhaden fishery “started much later than that for the Atlantic species.” He reported that the annual catch of Gulf Menhaden in the early 1940s was less than about 40,000 mt, but that the fishery had grown steadily and in 1963, for the first time in history, the Gulf Menhaden catch of about 445,000 mt exceeded that of the Atlantic fishery. Henry (1969) also pointed out that although the Atlantic Menhaden fleet tended to make one-day trips to the fishing grounds, the Gulf Menhaden fleet generally made multiple-day trips, thus the need for refrigerated fish holds. Additionally, he categorized Gulf Menhaden landings by state, noting that in 1966,

> "70% of the menhaden catch from the Gulf of Mexico was landed in Louisiana, 24% in Mississippi, 5% in Texas, and 1% in Florida".

Perhaps, Nicholson (1978) best summarized the evolution of the Gulf Menhaden fishery. He canvassed confidential company records and statistical digests for landings in the Gulf Menhaden fishery from the first half of the 1900s. Nicholson (1978) reported that although a menhaden fishery had existed along the U.S. Gulf coast since the late 1800s, records of catches, the location and years of operation of plants, and the numbers of vessels prior to 1946 were fragmentary at best. Historically, up to 14 menhaden processing plants existed in the northern Gulf of Mexico, ranging from Apalachicola, Florida, to Sabine Pass, Texas. One plant was known to have operated in Texas from around the turn of the century until at least 1923; another near Port St. Joe and Apalachicola, Florida, from about 1918 to 1961; and another near Pascagoula, Mississippi, from the 1930s until 1959.

Nicholson (1978) claimed that the modern Gulf Menhaden fishery began after World War II as the worldwide demand for fish meal and fish oil increased. The first plant in Louisiana opened around 1946; shortly thereafter, additional plants opened in Mississippi, Louisiana, and Texas. As older plants were closed, larger and more efficient plants replaced them. During the 1950s to the early 1970s, the number of menhaden plants fluctuated between 9 and 13 (Nicholson 1978). Between the mid-1970s to the early 1980s, the number of processing plants in the Gulf was stable at 11 (Smith 1991). Two periods of corporate consolidation followed. In 1985 the number of plants fell to seven and then increased during 1989-1990 to nine. The number of plants declined to seven in 1991, to six in 1992, then to five between 1996 and 1999. After the 1997 fishing season, the menhaden company at Morgan City, Louisiana, was acquired by one of its competitors, who closed the facility after 1999. That left only four factories (owned by two companies, i.e., Omega Protein, Inc. [OPI] and Daybrook Fisheries, Inc. [DFI]) operational throughout 2000 to 2011, one each at Moss Point, Mississippi [OPI], and Empire [DFI], Abbeville [OPI], and Cameron [OPI], Louisiana. OPI closed its Cameron plan in 2014 leaving three plant in operation in the Gulf of Mexico. In 2016, Oceana (South Africa) purchased the land-based operations of DFI while the vessels were operated by Westbank LLC and in late 2017, Cooke Inc. (New Brunswick, Canada) purchased OPI on both the Gulf and Atlantic and the vessels were operated by Alpha VesselCo Holdings, Inc. The complete history of the companies and factories in the region can be found in Section 4.1 through 4.2.

In 1945, only about ten menhaden vessels were reported operating in the Gulf of Mexico (Nicholson 1978). After World War II, the fleet grew rapidly and reached 81 vessels by 1956. During the 1960s and 1970s, fleet size fluctuated and ranged from 65 vessels in 1973 to 92 vessels in 1966 (Nicholson 1978, Smith 1991). Fleet size peaked at 82 vessels in 1982, followed by two major downsizings. The first occurred in 1985 when the fleet was reduced from 81 to 73 vessels (Smith 1991); the second occurred in 1991 when the fleet was reduced from 75 to 58 vessels (Vaughan et al. 1996). Between 1995 and 1999, fleet size was about 50-55 vessels. Through the past decade, the number of Gulf Menhaden vessels gradually declined from 47 in 2000 to 41 in 2006. The fleet continued to be reduced through 2013 when 35 vessels fished annually. Since the closure of the Cameron, Louisiana factory, the fleet has remained at around 30 vessels [see Section 4.1 for more detailed information on the modern reduction fishery (post WWII)].

1.3 Geographic Distribution and Management Unit

Geographic Distribution: Gulf Menhaden range from the Yucatan Peninsula in Mexico, across the western and northern Gulf of Mexico to Tampa Bay, Florida (Figure 1.1). Finescale Menhaden occur from Mississippi Sound southwestward to the Gulf of Campeche in Mexico. Yellowfin Menhaden range from Chandeleur Sound, Louisiana, southeastward to the Caloosahatchee River, Florida (and presumably around the Florida peninsula), to Cape Lookout, North Carolina (Hildebrand 1948, Suttkus 1956 and 1958, Christmas and Gunter 1960, Gunter and Christmas 1960, Reintjes and June 1961, Reintjes 1964, Turner 1969 and 1970). The Yellowfin Menhaden was reported from Grand Bahamas Island and became the first authenticated record of a North American species from beyond the Continental Shelf (Levi 1973).

Management Unit: Gulf Menhaden dominate the reduction fishery in the Gulf with other menhaden species representing less than 1% of the annual catch (Ahrenholz 1981). Considering that *B. patronus* is the only significant species in the fishery and is biologically considered to be a unit stock in the Gulf, the management unit is defined as the total population of *B. patronus* in the U.S. Gulf of Mexico.

Genetic evidence: Genetic evidence suggests a single unit stock of Gulf Menhaden in the northern Gulf of Mexico (see Section 3.1 for genetics details). From samples taken in the western Gulf, a single population of Gulf Menhaden has been identified using mtDNA (Anderson 2007). Anderson and McDonald (2007) noted that Gulf and Finescale Menhaden may hybridize occasionally. East of the Mobile River, Anderson and Karel (2007) indicate that there is considerable hybridization between Gulf and Yellowfin Menhaden. Gulf Menhaden genes have been found in the southeastern Atlantic in populations of *B. tyrannus*, while *B. tyrannus* genes have not been found in the Gulf of Mexico populations of the other three menhaden species.

Biogeographical break: The hybridization zone east of the Mobile River is further supported in additional literature. An overlapping region usually defines the geographical separation between two closely related species. The northern Gulf of Mexico is no exception, with general separation occurring at the Mississippi River or to the east at Mobile Bay. It is postulated, that the glacial melting within these two watersheds provided a fresh water barrier extending out into the Gulf of Mexico (Hoese and Moore 1998, McEachran and Fechhelm 1998). Increased winter and spring river flows coming out of Mobile Bay provided a boundary that determined species composition due to sediment type and nutrient load. Additionally, the Loop Current moving north and then easterly along the Florida panhandle adds to a boundary that explains species distributions (Hoese and Moore 1998). Brackish water collections of *Brevoortia* in the bays of Alabama to the Florida line have yielded only *B. patronus*, with no mention of *B. smithi* (Boschung et al 2004, Mettee et al. 1996). The distribution of *B. patronus* is reported as rare east of Pensacola, FL and that of *B. smithi* being limited to the west by the Chandeleur Sound (Hoese and Moore 1998, McEachran and Fechhelm 1998, Walls 1975). Providing an equidistant division of the overlapping region (Fort Morgan, Alabama, 88°W) based on a biogeographical break, provides an equal probability of including and excluding each species.

1.4 Regulatory History and Data Monitoring

The Gulf Menhaden reduction fishery is one of the largest fisheries by volume in the United States and has been successfully managed under a regional Fishery Management Plan since 1978. The fishery continues to be classified by the National Marine Fisheries Service (NMFS) as ‘not overfished’ with ‘no overfishing occurring’, and a population that is sustainable based on the most recent stock assessment

(GDAR02 - Schueller 2016). Through the partnerships, which have been developed among NMFS Beaufort Laboratory, the state marine agencies, the menhaden industry, and the Gulf States Marine Fisheries Commission (GSMFC), the Gulf Menhaden fishery-dependent data set is one of the most detailed and data-rich of the fisheries currently operating in the Gulf of Mexico.

The NMFS personnel have had access to the catch at each of the plants for biostatistical and stock assessment purposes since 1964, and the menhaden companies report daily vessel unloads to the NMFS on a daily or weekly basis throughout the fishing season. Additionally, vessel captains complete daily logs of each vessel's activities called Captain's Daily Fishing Reports (CDFRs). They include an at-sea catch estimate, fishing location, set duration, and weather conditions for each and every set; compliance is 100% and they are provided to NMFS on a weekly or bi-weekly basis throughout the fishing season. The NMFS continues to publish monthly menhaden landings in the form of a status memo, which is available on the NOAA's Fishery Market News (https://www.st.nmfs.noaa.gov/Assets/commercial/market-news/doc77.pdf).

1.4.1 Fishing Season

The five Gulf states have common regulations for season duration, which traditionally lasted 26 weeks from April through mid-October. In 1993, the fishing season was extended two additional weeks to approximately 28 weeks creating the current season, which starts on the third Monday in April and runs through November 1 each year. In 1989, Louisiana established a specially permitted bait season for menhaden, which extended the season until the Louisiana Department of Wildlife and Fisheries (LDWF) determines that the bait quota of 3,000 metric tons has been met or December 1. If the November bait quota is not met, then the bait season re-opens on March 15 for the remaining quota. LDWF monitors any bait season activity through daily trip-tickets.

1.4.2 Quotas

As the Gulf Menhaden fishery generally operates in state waters, the respective state marine agencies are responsible for regulating and monitoring the Gulf Menhaden fishing activities in their waters and provide management for the fishery directly.

In the state waters off Escambia and Santa Rosa counties along the Florida Panhandle (inside the COLREGS, the line that divides inland waterways and coastal waterways), a quota of 1.0 million pounds (454 mt) is in place for commercial harvest of menhaden by all gears combined. The quota applies to the inside waters of Escambia and Santa Rosa counties only, not any offshore fishery. Purse seines are not allowed to harvest menhaden anywhere else in the state within the COLREGS other than off these two counties. The purse seines within the COLREGS must be less than 500 sq foot. The closing date for the inside waters is based upon

> "[t]he total commercial harvest of menhaden in Escambia and Santa Rosa Counties during a particular commercial fishing season shall consist of those menhaden commercially harvested by all forms of gear from all waters of these counties and waters of the federal Exclusive Economic Zone (EEZ) contiguous to such waters, based on projections from official statistics collected and maintained by the Florida Department of Environmental Protection pursuant to Florida's Marine Fisheries Information System."

Purse-seine gear used by the extant reduction fishery precludes reduction vessels from operating in Florida state waters, however they would be free to operate offshore of the COLREGS. The Florida quota is designed to control landings by a Gulf Menhaden bait fishery inside the COLREGS in those two particular counties of Florida.

The extended bait season in Louisiana is managed for a 3,000 mt quota. The bait season is intended solely for harvest of menhaden for bait after the reduction fishing season ends on November 1. The extended bait season runs from November to December 1 or until the 3,000 mt quota is reached. Additionally, an early bait season may begin on March 15, prior to the opening of the regular menhaden season, and that harvest is also included in that quota. LDWF monitors any bait season activity through trip-tickets which can be checked daily if necessary.

Currently, Texas is the only state with a quota or 'cap' on the reduction removals of Gulf Menhaden from state waters. In March 2008, the Texas Parks and Wildlife Commission approved changes to the statewide hunting and fishing regulations that included establishing a Total Allowable Catch (TAC) on menhaden catches in the Texas Territorial Sea, the waters off Texas out to nine nautical miles. The TAC is 31.5 million pounds (14,288 mt) per year, which was set at the approximate five-year average of Texas catches during 2002-2006 (with penalties for overages). This regulation was heralded as precautionary management, capping removals at recent levels with an eye toward minimizing bycatch.

1.4.3 Fishing Area Closures

Each state has its own designation of closed or restricted areas to purse-seine fishing for Gulf Menhaden. In 1995, Florida banned all gill and entangling nets, and any nets greater than 500 square feet in state waters; thus, purse-seine reduction vessels were virtually excluded from state waters. In the decade prior to the Florida Net Ban, the purse-seine fishery for reduction rarely operated in Florida waters. Minor removals were made along the western Panhandle by vessels from the port of Moss Point, Mississippi.

In Alabama, reduction fishing is restricted to Mississippi Sound and the Gulf of Mexico west of roughly Point aux Pines, Bayou La Batre, and Isle aux Herbes (Coffee Island). There is also no purse fishing allowed within a radius of one mile from the western point of Dauphin Island.

Mississippi prohibits purse-seine fishing within one mile of the shoreline of Hancock and Harrison counties and the adjacent barrier islands. Jackson County has no restrictions relative to the shoreline other than around the barrier islands. Commercial fishing (including purse seining for menhaden) is prohibited north of the CSX bridge in the Pascagoula River system.

In Louisiana, the harvest of menhaden is restricted to waters seaward of the inside-outside line described in R.S. 56:495, including waters in the federal EEZ and in Chandeleur and Breton sounds. All other inside waters and passes are permanently closed to menhaden fishing. Waters on the south side of Grand Isle from Caminada Pass to Barataria Pass in Jefferson Parish, from the southeast side of Caminada Bridge to the northwest side of Barataria Pass at Fort Livingston, extending from the beach side of Grand Isle to 500 ft beyond the shoreline into the Gulf of Mexico, are designated closed zones. These waters are closed to the taking of fish with saltwater netting, trawls, and seines from May 1 to September 15.

In Texas, menhaden may not be fished in any bay, river, or pass within 0.5 mile from shore in Gulf waters or within one mile of any jetty or pass. The menhaden industry has had a “gentleman’s” agreement with TPWD not to fish within 1 mile of Gulf beaches, and has agreed to leave Texas waters if significant quantities of game fish are documented by TPWD to be in the vicinity.

1.4.5 Bycatch

Individual states regulate incidental bycatch in the menhaden fisheries. In Alabama, menhaden purse-seine boats may not possess more than 5% by number of species (excluding game fish) other than menhaden, herrings, and anchovies.

In Mississippi, it is unlawful for any boat or vessel carrying or using a purse seine to have any quantity of red drum on board in Mississippi territorial waters. It is unlawful for any person, firm, or corporation using a purse seine or having a purse seine aboard a boat or vessel within Mississippi territorial waters to catch in excess of 5% by weight in any single set of the net or to possess in excess of 10% by weight of the total catch of any of the following species: Spotted Seatrout (*Cynoscion nebulosus*), Bluefish (*Pomatomus saltatrix*), Spanish Mackerel (*Scomberomorus maculatus*), King Mackerel (*Scomberomorus cavalla*), Dolphinfish (*Coryphaena hippurus*), Pompano (*Trachinotus carolinus*), Cobia (*Rachycentron canadum*), or Jack Crevalle (*Caranx hippos*).

In Louisiana waters, anyone legally taking menhaden shall not have in their possession more than 5% by weight, of any species of fish other than menhaden and herring-like species.

In Texas, purse seines used in taking menhaden may not be used to harvest any other edible products for sale, barter, or exchange. Purse-seine catches may not contain more than 5% by volume of other edible products.

1.5 Assessment History

Quantitative analyses of Gulf Menhaden began in the early 1970s, as the time series of detailed data developed (accurate reduction landings have been recorded since 1948, and detailed biostatistical sampling began in 1964). The first quantitative analysis was that based on a Schaefer-type surplus production model using CPUE and effort data (Chapoton 1972). Schaaf (1975) updated this analysis and provided some cautionary comments on applying this model in a developing fishery. A further update of this analysis can be found in the original management plan for this stock (Christmas and Etzold 1977). Ahrenholz (1981) developed estimates of rates of exploitation, population movements, and recruitment into the fishery from returns of tagged juveniles and adults. An important result from this study that has been used in subsequent assessments was the estimate for natural mortality (M = 1.1) based on tagged adults.

Two formal stock assessments were completed during the 1980s. First, Nelson and Ahrenholz (1986) included data through 1978, and the second, Vaughan (1987) included data through 1985. These assessments used an untuned virtual population analysis (VPA) approach based on the cohort-linked method described by Murphy (1965) to estimate age- and year-specific fishing mortality and population numbers from the catch-at-age matrix computed from the reduction fishery landings and biostatistical samples. Yield-per-recruit analyses, spawner-recruit relationships, and surplus production models were then developed from the VPA output. Results of these two assessments appeared in revisions to the Fisheries Management Plan (Christmas et al. 1983 and 1988). Stock assessment results were also summarized in the special menhaden issue of Marine Fisheries Review (Vaughan and Merriner 1991).

Two formal stock assessments were conducted during the 1990s (Vaughan et al. 1996, Vaughan et al. 2000) and results incorporated into further revisions to the Gulf Menhaden Fisheries Management Plan (Leard et al. 1995, VanderKooy and Smith 2002). Vaughan et al. (1996) included fisheries data through 1992. In addition to applying the VPA approach of Murphy (1965), they also applied the separable VPA approach of Doubleday (1976). The separable VPA was fit to the full catch-at-age matrix (1964-1992) and discrete fits to two separate time periods (1964-1975, 1976-1992). Vaughan et al. (2000) continued these methods, applying the method of Murphy (1965) to the early time period (1964-1975) and updating the separable VPA to the later time period (1976-1997). As in the 1980s, results from the VPAs were used in developing, yield-per-recruit analyses, spawner-recruit relationships, and surplus production models. Vaughan et al. (2000) also began investigating the utility of recruitment indices from Louisiana (trawl survey) and Texas (bag seine). They also updated the relationship between menhaden recruitment and Mississippi River flow reported by Govoni (1997).

As noted above, assessment methods used the “untuned” VPA method of Murphy (1965) and later separable VPA (SVPA) of Doubleday (1976) as the primary assessment methodology through 2000. The next completed assessment of the status of the Gulf Menhaden stock was Vaughan et al. (2007). As before, data included abundance indices, recorded landings, and samples of annual size and age compositions from the landings through 2004. Several important improvements were made for this assessment. First, age-varying natural mortality was implemented based on the approach of Boudreau and Dickie (1989). Natural mortality was related inversely to the weight at age of Gulf Menhaden and scaled to M estimated by Ahrenholz (1981) for adult menhaden. More importantly, a flexible forward-projecting statistical model similar to that currently used for Atlantic Menhaden (ASMFC 2004, ASMFC 2010) was applied to these data. Finally, given this added flexibility, a recruitment index that was developed from fishery-independent seine and trawl data from three states was incorporated into the model structure. A base assessment model run was developed and sensitivity model runs were made to evaluate performance of the assessment model. The forward-projecting statistical modeling approach was found to be more useful in characterizing the temporal trends and status of the Gulf Menhaden stock, than the previously used VPA approaches. The status of the stock was based on the terminal year (2004) estimates relative to their corresponding limits (or threshold), and these benchmarks corresponded to the approach used by ASMFC for Atlantic Menhaden (ASMFC 2004). Benchmarks were estimated based on the results of the updated base run, and the terminal year estimate of fishing mortality rate (F_{2+}) was estimated to be 75% of its limit (and 116% of its target). Correspondingly, the terminal year estimate of population fecundity (*FEC*) was estimated at 93% of its spawning stock biomass target or SSB_{target} (and 186% of its limit). Hence, the stock was not considered to be overfished, nor was overfishing occurring.

The most recent benchmark stock assessment completed for Gulf Menhaden had a terminal year of 2011 and was part of SEDAR32A (SEDAR 2013a). That benchmark assessment was updated in 2017 with a terminal year of 2015 (Schueller 2016). Both the benchmark and update assessments considered the stock to be not overfished and overfishing not occurring using spawner per recruit (SPR) based benchmarks of $F_{30\%}$ and $SSB_{30\%}$ (measured as fecundity). These benchmarks were new for the SEDAR

32A assessment and were used as *MSY* proxies because *MSY* was not estimable. The fishing mortality rate value from the benchmark assessment that specified the threshold was at 9.73. The benchmark assessment included state seine survey data for a juvenile abundance index and the Louisiana gill net data for the adult abundance index. With the addition of these state surveys, length data were also available with the surveys catching the largest menhaden during the entire time series. Because of these length data and the growth data, it was determined that the fishery exhibited dome-shaped selectivity.

1.6 Biological Reference Points and Control Measures

In the 2015 revision to the regional management plan for the menhaden fishery in the Gulf of Mexico (VanderKooy and Smith 2015), recommendations were made related to adoption of reference points. Since the benchmark assessment for Gulf Menhaden (SEDAR 2013a) did not produce reliable estimates of maximum sustainable yield (*MSY*), levels of effort in reference to the *MSY* proxy (fecundity (SSB)) were selected as reference points by the MAC and approved by the GSMFC. Estimates of equilibrium landings associated with a reference target ($F_{35\%}$) and limit ($F_{30\%}$) levels were calculated at 663,583 mt and 680,765 mt, respectively. These harvest levels were designated as accountability measures to ensure the fishery remains viable. In the event that two consecutive fishing years produce harvests exceeding the target $F_{35\%}$, a stock assessment update will be requested. If harvest surpasses the limit $F_{30\%}$ in a single year, a stock assessment update will be requested. Finally, it was recommended that a benchmark stock assessment should be conducted every five years in conjunction with a management plan revision and that forecasts of year class strength utilizing the state agencies' fishery-independent data should be provided to the GSMFC's Menhaden Advisory Committee prior to the fishing season to help track fluctuations in population abundance and year class strength.

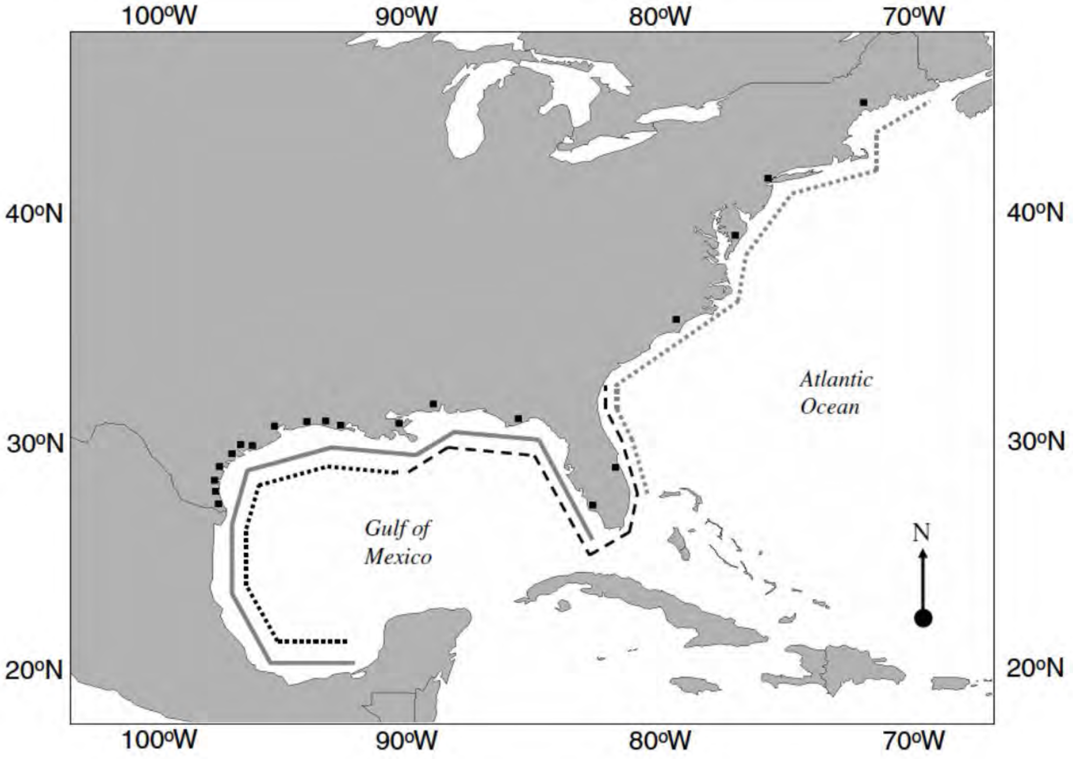


Figure 1.1 Geographic range of the four menhaden species: Gulf Menhaden (*Brevoortia patronus*) - smooth gray line, Gulf; Atlantic Menhaden (*B. tyrannus*) - dotted gray line, Atlantic; Finescale Menhaden (*B. gunteri*) - dotted black line, western Gulf; and Yellowfin Menhaden (*B. smithi*) - dashed black line, eastern Gulf. Sample sites are indicated by black boxes (*from* Anderson 2007).

2.0 Habitat Description

2.1 General Conditions

Gulf Menhaden range throughout the Gulf of Mexico from the Yucatan Peninsula to Tampa Bay, Florida; however, they are most abundant in the north-central Gulf (Christmas et al. 1982). Gulf Menhaden are found in a wide range of salinities, from offshore to freshwater, since their life cycle includes offshore spawning, mostly during winter, with recruitment to and maturation in coastal rivers, bays, bayous, and other nearshore habitats. Upon maturation, the fish return to offshore waters to complete the life cycle.

While juveniles and adults are typically found in open water with non-vegetated bottoms, larvae and early juveniles are often found associated with estuarine marsh edges where adequate forage and protection from predators can be found (Reintjes 1970). Upon entering estuaries, post-larvae occupy quiet, low salinity waters to bottom depths of 2m (Fore and Baxter 1972b). After transformation, most juvenile menhaden remain in nearshore estuaries until they are approximately 100 mm FL (Lassuy 1983). Lewis and Roithmayr (1981) reported that some maturing juveniles emigrate with adults to offshore waters during the spawning season.

2.2 Physical Habitat

Gulf Menhaden are found throughout the northern Gulf of Mexico and utilize a number of brackish and freshwater habitats. Larvae arrive in the upper estuaries in the early spring after riding the prevailing currents from the offshore spawning grounds (June and Chamberlin 1959, Christmas et al. 1982, Minello and Webb 1997).

Christmas et al. (1982) used numerous variables (temperature, salinity, dissolved oxygen, marsh habitat, substrate, and water color) to evaluate certain Gulf Coast estuaries as nursery habitat for larval and juvenile Gulf Menhaden. They found that these factors directly influenced the availability of food and the survival of all stages, and that optimum habitat included estuaries with extensive marsh (>1,000 acres), mud substrate, and brown or green water color.

Minello and Webb (1997) demonstrated the importance of *Spartina alterniflora* saltmarsh to several species including the Gulf Menhaden. The authors compared the use of natural and created marsh by various estuarine organisms. Their results indicate that Gulf Menhaden dominated the fish samples in spring and were associated primarily with open water, non-vegetated bottom and, to a lesser degree, with marsh edge salinities of 9.3-9.8ppt. They occurred in the same habitat in fall, but in much smaller numbers. A stepwise multiple regression indicated that depth and salinity are the critical environmental variables in predicting Gulf Menhaden density. Likewise, Akin et al. (2003) conducted seasonal and spatial surveys of fish and macro-crustaceans around Mud Island Marsh in Matagorda Bay, Texas, and determined that Gulf Menhaden were the most abundant in the upper reaches of the bay where there were higher abundances of detritus from Widgeon Grass (*Ruppia maritima*), which dominated the marsh.

2.3 Salinity

Offshore spawning necessitates that Gulf Menhaden eggs and larvae be euryhaline. Gulf Menhaden eggs and larvae have been collected in waters with salinities ranging from 6-36 ppt (Fore 1970, Christmas and Waller 1975); 88% of the eggs were collected from waters over 25 ppt. Collections of eggs and larvae were made throughout the Gulf of Mexico at the peak of spawning from waters ranging in salinity from 20.7-36.6 ppt (Table 2.1; Christmas et al. 1982). As the larvae move inshore, they require low salinity waters to complete metamorphosis from the larval body form to the deeper–bodied juvenile/adult form. June and Chamberlin (1959) observed that arrival in estuaries may be essential to the survival of larvae and their metamorphosis to juveniles based on food availability and lower salinities. Combs (1969) found that gonadogenesis occurred only in menhaden larvae that arrived in euryhaline, littoral habitats.

The value of low salinity marsh habitat to juvenile Gulf Menhaden is well known, but not well documented. Only a few studies have looked at the dependence of nektonic menhaden on low salinity marshes as nursery habitat. Gunter and Shell (1958) reported that young menhaden enter upper marshes with salinities around 0.9 ppt at Grand Lake, part of the Mermentau River Basin, Louisiana. Copeland and Bechtel (1974) investigated the environmental parameters associated with several commercial and recreational species and reported juvenile Gulf Menhaden were most frequently collected in primary rivers and secondary streams at salinities ranging from 0-15 ppt. The authors point out that these low salinity waters supported the greatest numbers of juvenile menhaden (Copeland and Bechtel 1974). Likewise, Chambers (1980) found a similar relationship among young Gulf Menhaden and both freshwater and low salinity, brackish areas in the upper Barataria Basin of Louisiana.

Tolan and Nelson (2009) determined that after examining a number of abiotic factors in three tidal streams in the Matagorda Bay estuary, Texas, salinity was the driving factor in determining fish assemblages. Juvenile and sub-adult Gulf Menhaden were the most abundant species in all three tidal creeks over the course of their study and community responses were based on the prevailing salinity regime more than dissolved oxygen.

Observations by Haley et al. (2010) found larval and juvenile menhaden up to 79 river miles upstream on the Alabama River, near the Claiborne Lock and Dam. Although the authors did not record station salinities, the drought situation that occurred during their sampling season may have pushed the salt wedge, and consequently associated ichthyoplankton, farther upriver than during 'normal' years.

2.4 Temperature

Gulf Menhaden occupy a wide range of habitats; therefore, temperature may be more critical to egg development than to juveniles and adults, although Gulf Menhaden are occasionally victims of large fish kills related to freeze events (Hildebrand and Gunter 1951, McEachron et al. 1994).

Turner (1969) collected eggs and larvae from stations off northern Florida at surface water temperatures ranging from 11.0°C (February) to 18°C (March). In southern Florida, samples were taken from 16°C (January) to 23°C (March), and in Mississippi Sound, temperatures ranged from 10°C (January) to 15°C (December).

Larval and juvenile menhaden have been collected in Gulf estuaries at temperatures ranging from 5-25°C (Table 2.1; Christmas and Waller 1973, Perret et al. 1971, Swingle 1971). Reintjes and Pacheco (1966) cited references indicating that larval menhaden may suffer mass mortalities when water temperatures are below 3°C for several days or fall rapidly to 4.5°C. Likewise, juvenile and adult menhaden suffer cold kills during periods of freezing winter conditions, especially in narrow or shallow tidal areas.

McEachron et al. (1994) documented one such cold kill in Texas. In December 1983, the entire Texas coast suffered a freeze that was one of the most severe in recorded history. Water temperatures dropped about 15°C in about 10 days to near 0.0°C and remained between 0.0-5.0°C for about seven days. Two more cold-kill events occurred in February and December 1989 which resulted in additional widespread fish kills. Coastwide, about 980,000 Gulf Menhaden died in 1983 and around 600,000 died in the two freezes of 1989. Gulf Menhaden that succumbed to the cold ranged in size from 80-130 mm TL.

Cold kills of Gulf Menhaden are uncommon in the central northern Gulf. Overstreet (1974) suggests that:

> "Lack of proper acclimation probably determines why mass mortalities occur more frequently in Texas and Florida than in Mississippi. Fishes in Mississippi, living in water normally cooler than in Texas, are necessarily acclimated to lower temperatures. Consequently, a sudden drop to near-freezing levels would affect those fishes less."

Tolan and Nelson (2009) surveyed ichthyoplankton in Nueces Bay, Texas, which tends to be more saline than most Gulf estuaries due in part to the impoundment of the river by the Lake Corpus Christi Reservoir, resulting in greatly reduced flow rates. He hypothesized that large freshwater inflow events early in the year may prevent larvae from entering the uppermost reaches of the Bay's lower salinity waters. His results indicate that the transforming juvenile menhaden were able to navigate the higher flows and enter the nursery areas up-bay. This was likely a response to increased food availability as primary production increased in the low salinity upper reaches.

2.5 Dissolved Oxygen (DO)

Large fish kills occur in summer as well, often resulting from plankton blooms and low dissolved oxygen (DO) or hypoxic conditions. Mass fish mortalities, which include Gulf Menhaden, attributed to low DO concentrations have occurred in most Gulf estuaries (Crance 1971, Christmas 1973, Etzold and Christmas 1979). Recent fish kills of juvenile Gulf Menhaden in Gulf Coast estuaries that have been noted in the popular press include mortalities at Choupique Bayou, Louisiana (August 2011), Bay Chaland, Bay Joe Wise, and Bayou Robinson in Plaquemines Parish, Louisiana (September 2010), and Weeks Bay, Alabama (July 2010).

Postlarvae and juveniles are frequently killed by anoxic conditions in backwaters (e.g., dead-end canals) during summer. Hypoxic and anoxic conditions may also occur in more open estuarine areas as a result of phytoplankton blooms. In Louisiana, west of the Mississippi River delta, low DOs in nearshore Gulf waters may serve to concentrate schools of Gulf Menhaden closer to shore as they avoid hypoxic areas known as the 'dead zone' (Langseth et al. 2014). The 'dead zone' results from increased levels of nutrient influx from freshwater sources coupled with high summer water temperatures, strong salinity-based stratification, and periods of reduced mixing (Justić et al. 1993). Most life history stages of Gulf Menhaden, from eggs to adults, occur inshore (i.e., inshore of the 10 fathom curve) of areas where historically the hypoxic zone 'sets up' by midsummer. Gulf Menhaden appear to be only moderately susceptible to low DOs and probably move out of hypoxic areas, resulting in displacement rather than mortality (Smith 2000, Langseth et al. 2014).

2.6 Habitat Elasticity

O’Connell et al. (2004) examined the fish assemblages that occurred in the Lake Pontchartrain estuary from roughly 1950-2000 using museum specimens and collections. Over the 50 years of records, they found that although the estuary had deteriorated substantially in environmental quality, Gulf Menhaden did not change in their frequency or position within the estuary while a number of other species had. Overall the assemblage shifted from a croaker-dominated complex to an anchovy-dominated complex, suggesting that Gulf Menhaden are very elastic in their ability to handle changing environmental conditions, both short and long-term (O’Connell et al. 2004).

Table 2.1 Optimum temperature and salinity conditions for the egg and larval stages based on the habitat suitability indices (HSI) for Gulf Menhaden (Christmas et al. 1982).

Life History Stage	Salinity (ppt)	Temperature (°C)
eggs/yolk-sac larvae (marine)	25-36*	14-22*
feeding larvae (marine)	15-30*	15-25*
feeding larvae/juveniles (estuarine)	5-13*	5-20*

*lowest mean monthly winter value

3.0 Life History

3.1 Stock Definition

3.1.1 Genetics

Appropriate management of a stock must consider aspects of stock delineation and the potential that the unit stock may be comprised of multiple genetically distinct populations. The presence of sub-stock complexes influences the jurisdictional and logistical aspects of management and has implications to the formulation of the stock assessment model that may or may not include sub-stock structure. The detection of sub-stocks is generally detected using genetic tools.

Anderson (2006) described genetic stock structure of Gulf Menhaden using extensive sampling across the range of the fishery and found little evidence of genetic structure that indicates the presence of multiple stocks. He demonstrated in that paper that Gulf Menhaden stock structure is best described by an isolation-by-distance model, where genetic structure is a function of the upper limits on dispersal of individuals within a stock. In this conceptual framework, genetic distance among samples increases linearly with geographic distance. While the spatial sampling was adequate, the study was limited in scope by a small genetic sample. In particular, five DNA microsatellites were assayed, with one of the five being removed due to stability/reliability issues identified prior to analysis. A mitochondrial DNA (mtDNA) locus was also assayed to test repeatability of the pattern found in the microsatellite data set, and a similar pattern (single stock) was indeed found. However, resolution of the issue of stock structure could be achieved with more extensive genetic sampling.

In subsequent work, Anderson (2007) identified the presence of a single population of Gulf Menhaden in Texas waters using mtDNA. Anderson and McDonald (2007) noted that the sympatric species, Gulf and Finescale Menhaden, may hybridize occasionally, although there is little evidence of introgression. Anderson and Karel (2007) reported that unidirectional gene flow and hybridization has occurred in the eastern Gulf of Mexico between Gulf and Atlantic Menhaden with ‘Gulf’ genes flowing into the Florida Atlantic coast; ‘Atlantic’ genes have not been found in the Gulf of Mexico population.

Along Florida’s Panhandle, Turner (1969) found extensive hybridization and introgression between Gulf and Yellowfin Menhaden. Hybridization is so common that the FWC now only identifies menhaden to the genus level in their fishery-independent sampling (R. McMichael, personal communication). Anderson (2006) reported that from Charlotte Harbor, Florida, 1 in 30 individuals was a Gulf and Yellowfin Menhaden hybrid.

In summary, Anderson (2006) noted that:

> “There appears to be no organized structure of Gulf Menhaden populations which would indicate distinctive genetic ‘stocks’ delineated by geographic boundaries. Gulf Menhaden sampled from southern Texas to southern Florida are not significantly different, and variation across the entire northern Gulf of Mexico exhibits only a modest degree of genetic isolation by distance. It appears that the very large and semi-migratory spawning aggregates of Gulf Menhaden contributed to Gulf-wide genetic variation which exhibits only a limited geographic component.”

Lynch et al. (2010) suggested that the genetic divergence observed between Atlantic and Gulf Menhaden was consistent with populations of the same species, bringing into question the validity of two species. Further, the work by Lynch et al. (2010) indicates that there are not distinctive populations of Gulf Menhaden that exist on local scales.

Anderson (2016) provided an overview of genetic investigation to the Gulf States Marine Fisheries Commission's Menhaden Advisory Committee. Anderson compared samples collected in 2015 with similar samples from 2002 to 2003. He found no genetic differences spatially or temporally. His results suggest the existence of a single genetic stock and the presence of diversity within the population "as high as any other species he's worked with". In addition, he did not report hybridization in the Western Gulf, although evidence of hybridization was detected in the East around the Florida panhandle between Perdido and Cedar Key. Anderson reported that genetic variability is greatest in areas around the center of distribution of the species (between Galveston Bay and the Mississippi River). To date, Anderson's results suggest that Gulf Menhaden genetic variability follows the pattern that would be expected in an unexploited stock: there is no evidence that a genetic bottleneck exists. Anderson attempted to measure the effective population size for Gulf Menhaden and concluded that it was relatively large.

3.1.2 Migration and Movement

Gulf Menhaden are a coastal pelagic species that inhabit estuarine, shallow-water habitats in the summer (age-0 young-of-year fish may overwinter in estuaries; Turner and Johnson 1973, Deegan 1985) and the majority of juveniles and adults inhabit offshore throughout summer and fall. The extent of the offshore range is unknown. Suttkus (1956) reported that migration of age-0 menhaden from Lake Pontchartrain, Louisiana, appeared to occur in August or September. Copeland (1965) found that the greatest migration of advanced juveniles from estuaries at Port Aransas, Texas, occurred from November through May. Roithmayr and Waller (1963) reported catches of adult Gulf Menhaden from December to February in the northern Gulf from 4 to 48 fathoms both east and west of the Mississippi River Delta. Roithmayr and Waller (1963) concluded that at least some fish do not move far offshore, but winter on the inner and middle continental shelf area just off the Mississippi River delta. Christmas and Gunter (1960) reported capturing Gulf Menhaden in mid-water trawls at depths ranging from 40 to 55 fathoms, although in very low numbers. Likewise, some menhaden have been reported in the SEAMAP bottom trawl sampling throughout the northern Gulf of Mexico, but in very low numbers and infrequently (see Section 5.4).

Gulf Menhaden do not exhibit extensive east and west movement, and generally, older adults are believed to occur near the center of the population's range (around the Mississippi River delta). Ahrenholz (1981) tagged 38,445 Gulf Menhaden from 1970 to 1972 using ferromagnetic tags from southeast Texas to the Florida Panhandle. Juveniles were tagged in estuaries during late summer or early fall just before emigration and adults were obtained, tagged, and released from the commercial fishing grounds during late spring. Tags were subsequently recovered later in the year on magnets in the reduction factories during processing of the catch. Because reduction vessels at that time tended to fish more intensively in the area near their home ports, most tags recovered at a specific port were assumed to have been from fish caught in the waters closest to that port. As a result, Ahrenholz (1981) concluded that fish first entered the fishery primarily in the same geographic area in which they resided in the early spring. As fish age, there appeared to be a slight tendency of fish from eastern and western fishing grounds to move toward the Mississippi River delta. Fish tagged in the two most western areas (southeast Texas and Galveston) were captured in greater numbers their second year after release at the two more central ports in Louisiana (Morgan City and Dulac, Louisiana).

Likewise, Pristas et al. (1976) tagged approximately 76,000 adult Gulf Menhaden from 1969 to 1971 using internal metallic tags, which were also recovered on magnets at the various reduction plants. Adult fish were tagged and released from commercial purse boats operating on the menhaden fishing grounds. They noted very little east/west movement of adults as many of the returns were from plants near the release sites. Second-year returns showed the same pattern with little east/west mixing. Most of the adult fish that had moved offshore to over-winter returned to the areas where they had been released the previous season.

3.2 Age Determination

In 1964, the National Marine Fisheries Service (NMFS) Beaufort Laboratory (formerly the U.S. Bureau of Commercial Fisheries) began monitoring the Gulf Menhaden purse-seine fishery to understand the size and age composition of the catch (Nicholson 1978). From the outset, program managers realized using sagittal otoliths to age Gulf Menhaden was impractical because 1) sagittal otoliths were small and fragile, and 2) large amounts of time and effort would be required to extract, process, and read whole or sectioned sagittae. Moreover, large numbers of ageing parts (> ca. 10,000) would be required to adequately characterize the fishery with annual landings of several hundred thousand metric tons. Therefore, scales were selected for Gulf Menhaden ageing.

Chapoton (1967) determined that scale development on Gulf Menhaden began on larval specimens at ca. 21 mm FL and was complete in specimens > ca. 27 mm FL. Gulf Menhaden scales are generally thin and translucent (Figure 3.1). Unlike most herrings, the posterior margin of Gulf Menhaden scales is pectinate or serrated. The anterior field is embedded in the integument. The entire scale is sculptured with fine circuli, which are roughly semi-circular and parallel the anterior and lateral margins. The largest and most symmetrical (nearly rectangular) scales occur in a median lateral band above the lateral line and below the dorsal fin. Scale samples for ageing are removed from this area.

A scale patch is removed with a blunt-edged scalpel and placed in a small vial of water. The patch is removed from the vial, blotted dry, and rubbed between the thumb and forefinger to remove residual integument. Individual scales are then mounted between two glass microscope slides. Ten individual scales (two rows of five) are placed on the first slide with pectinations pointing down, and then covered with the second slide. Slides are fastened together with short lengths of transparent tape. The cover slide is labeled with a unique port and specimen number combination.

3.2.1 Scale Reading

Gulf Menhaden scales, which are mounted between microscope slides, are viewed on an Eberbach macro-projector at 48x magnification. Circuli on Gulf Menhaden scales are defined as compressions or interruptions of uniformly spaced circuli in the anterior field of the scale, which are continuous through the lateral fields. Under transmitted light, age rings form narrow, continuous, dark bands roughly parallel to the lateral and anterior margins of the scale. A focus is arbitrarily chosen near the center of the posterior field at the base of the circuli. Straight-line measurements are made from the focus to successive scale rings and the scale edge (Figure 3.1).

Nicholson and Schaaf (1978) found that ageing Gulf Menhaden with scales was problematic; citing that only about 50% of the fish examined during 1971-1973 could be aged by scale annuli. They determined that many fish had well-defined scale circluli, but others had no circuli or circuli that were oddly spaced. Their criteria for scale ageing were based on appearance of the scales, number and spacing of the rings, and fish fork length at time of capture. Although admitting some subjectivity, they determined that fish with one or two scale circuli displayed true annuli. For fish with oddly-spaced circuli, it was possible to separate out age classes by circuli location. Finally, for fish with no discernible circuli, they believed age could be estimated by examining the length frequency distribution.

In an attempt to increase the probability of encountering legible scales with true annular rings, Menhaden Program personnel at the Beaufort Laboratory in the early 1990s instructed port agents to mount ten scales for ageing per specimen versus the previous directions to mount six scales. Percent legibility increased; for example in fishing year (2003), 86% (6,780 of 7,839) of Gulf Menhaden scale samples had legible annular circuli (compared to ca. 50% by Nicholson and Schaaf [1978]; see above). Age assignments based on circuli spacing and/or length frequencies were only required for 14% of the samples.

Scale annuli form in winter, and by convention the birth date for Gulf Menhaden is January 1. Gulf Menhaden spawn between October and April, with peak activity from December through March (Turner 1969, Fore and Baxter 1972a, Brown-Peterson et al. 2017). Because the purse-seine fishery operates April through October, advancing or “bumping” age estimates because of calendar date (and unformed circuli) is not an issue relative to the fishing season.

3.2.2 Ageing Error Matrix

Historically, data for the ageing error analyses had come from two unpublished studies conducted at the NMFS Beaufort Laboratory. The first was a scale-to-otolith comparison by Smith and Levi (1990), and the second was a scale-to-scale comparison by Smith and Hall (2009). The comparison between scale and otolith readings was completed by two separate readers, one for the scales and one for the otoliths (n = 228). The comparison between scale readings was completed by one reader who read all of the scales from the 2005 fishing season, then re-read 54.9% of the scales from that same fishing season (n = 3,405). However, further work has been completed, was used for this stock assessment, and is described below.

Two separate ageing error matrices have been created for this assessment (and explored in sensitivity analyses). The first is based on the analysis of a subset of random (with respect to age and length) scales from the early 1970s to the present. Ethel Hall (NOAA Fisheries) had been ageing Gulf Menhaden since 1969. NOAA staff was able to pull representative scale samples from the sample storage building and get Hall to re-estimate ages from 12 previous fishing years – three years each from the 1970s, 1980s, 1990s, and 2000s. The intent was to detect if there was the presence of directional change “drift” of mean age at length estimates or other error issues. The scales were read with knowledge of the length and date of capture of the specimen. The matrix she developed was extensive (in terms of the lengths and ages of specimens re-analyzed) and included a large number of samples (n ≈ 6,000).

In a subsequent analysis, Meyers and Price (unpublished data) constructed an ageing error matrix based on the comparisons done by two readers, using different ageing structures, and incorporating blind reading (with respect to fish length). The analysis of the investigation of the scale comparison is reported in this work. Gulf Menhaden from four states (Texas, Louisiana, Mississippi, and Alabama) were collected from fishery independent gill net sampling from the spring to the summer. Meyers and Price (unpublished data) received fish from the states' natural resource management agencies and then processed the scales under the current ageing protocol. Otoliths (whole and sectioned) were processed using standard otolith extraction and mounting techniques. This work was part of a larger effort by Leaf and Schueller to collect information on age composition from the fishery-independent state survey - a need identified by the CIE reviewers in the last benchmark assessment. Currently, the gill net survey from Louisiana provides information about the length composition of the stock and no information about age determination are available from this or any other Gulf State. Meyers and Price (unpublished data) selected a target of *n* = 5 fish in strata of fish length ("small", "medium", and "large") for each of the four Gulf states that contributed specimens. Reader agreement for n = 42 scales was 64.4%, for n = 80 mounted and polished otoliths was 62.5%, and for whole otoliths (n = 59) it was 61.7%. Scales had the longest processing time, mostly during the microscopy portion of age determination.

Accounting for error in age estimation is an important consideration for stock assessment (Punt et al. 2008). Thus, to account for any error associated with the age estimation process for Gulf Menhaden and to get contemporary precision estimates, an ageing error analysis was completed using a program called "Agemat" developed by André Punt. Agemat uses age estimation data from multiple readers to 1) estimate the coefficient of variation and standard deviation associated with age estimates and 2) to provide an ageing error matrix. This program has been used to create ageing error matrices for other SEDAR assessments (ASMFC 2010, SEDAR 2010a, SEDAR 2013a, SEDAR 2015).

Agemat requires some model specifications, such as the minimum and maximum age of the species, a reference age, and the type of standard deviation to be estimated, in addition to inputting the ageing data and number of readers in the appropriate format. The minimum age used for this analysis was age-0, and the maximum age used was age-4. The reference age was age-2. The standard deviation was estimated using an asymptotic function. The maximum allowable standard deviation was input as 5; however, the standard deviation for neither comparison came near that bound. All specifications were the same for both comparisons analyzed.

For the first scale-to-scale comparison [10 years between 1977 and 2010, (n=5,275 scales)], the standard deviation was an increasing, asymptotic curve, which started at a low of 0.18 at age-0 and increased to a maximum of 0.38 for fish age-4. The coefficient of variation was a curve, which increased from 0.18 at age-0 and age-1, and then decreased to 0.09 at age-4. The ageing error matrix is provided in Table 3.1.

Similarly, for the second scale-to-scale comparison [A. Myers and K. Price, (n=78)], the standard deviation was an increasing, asymptotic curve, which started at a low of 0.38 at age-0 and increased to maximum of 4.99 for fish age-4. The coefficient of variation was a curve, which decreased from 0.38 at age-0 to 0.13 at age-3, and then increased to 1.24 at age-4. The ageing error matrix is provided in Table 3.2.

These comparisons indicate different levels of ageing error and the divergence is likely due to differences in sample sizes among the two comparisons as well as experience of the readers at the time of the comparison. For the first set of scales, the reader read over 5,000 samples and had been reading menhaden scales since 1969. For the second set of scales, the sample size is much smaller and was read by two different readers that each have less than five years of experience reading menhaden scales. In addition, the second ageing error matrix was produced from reads of scales which did not use the standard method for reading. Specifically, the agers did not have information on the size of the sample.

3.2.3 Longevity, Maximum Size, and Contemporary Age Composition

Gulf Menhaden as old as age-6 occur in the annual NMFS biostatistical data bases (from port samples); however, these specimens are rare and only 14 age-6 individuals have been sampled (in 1981 [2], 1982 [2], 1987 [1], 1990 [1], 1992 [7], 1993 [1] from over 545,000 fish processed from 1964 to 2017. Gulf Menhaden older than age-4 are uncommon in the landings, including 98 age-5 Gulf Menhaden and the 14 age-6 Gulf Menhaden already mentioned. As noted elsewhere, most Gulf Menhaden landed in the reduction fishery were either age-1 or age-2, representing 45% and 49%, respectively.

Maximum fork length (FL) of Gulf Menhaden as recorded in the NMFS biostatistical data bases is about 308 mm FL (n=544,879); maximum weight of Gulf Menhaden from the same data bases is about 571 grams (n=544,879). Because of the size of this data base, more realistic values for maximum size might be based on 99th percentiles; e.g., 212 mm for fork length and 201 grams for weight. Fork length frequencies by age for 2017 port samples of Gulf Menhaden are shown in Figure 3.2.

3.3 Length Conversions and Growth

The Gulf states use standard and total length measurements for their surveys, while NMFS uses fork lengths in their biostatistical database. To rectify this data mismatch, each Gulf state collected and measured lengths [fork length (FL), standard length (SL), and total length (TL)] for several hundred fish in late March and early April 2011 (Schueller et al. 2012). The sampled fish included both juveniles and adults and a broad range of sizes and geographic locations.

For the length-length conversions, Texas provided data from the 1970s for which both SL and TL were measured (n = 9,158). A recent study funded by Omega Protein (Brown-Peterson 2010) was also included where both FL and SL were measured (n = 195). In 2011, for the last benchmark assessment for Gulf Menhaden (SEDAR 2013a), a Gulf-wide study was conducted to provide length-length conversions for TL, SL, and FL, which each of the five Gulf states records in their fishery-independent sampling programs. A total of 9,158 historic samples (Classen et al. 1988) were contrasted to 927 additional samples collected by the TPWD, LDWF, MDMR, and AMRD in the spring and summer of 2011 (Schueller et al. 2012). Sample sizes by state are summarized in Table 3.2. Separate regressions were conducted relating FL with SL and with TL for direct use in developing length compositions (Table 3.3).

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

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

using the Marquardt algorithm for the nonlinear minimization (PROC NLIN in SAS). Overall and annual parameters for these regressions are summarized with sample sizes (number of fish measured) in Table 3.4. Annual parameters are based on cohort-based data, meaning growth curves were estimated for each cohort of recruitment moving through the population.

The annual, bias corrected cohort values of L_∞ are also shown in Figure 3.3. Because little change in L_∞ has occurred over time given the confidence interval plotted, the DW decided to use the overall parameters of the growth function as estimated with the commercial reduction fishery data with a bias correction to represent the growth for the fishery portion of the stock assessment model (Schueller et al. 2014). Bias corrections were applied to the fishery dependent data for determining the growth curve because some of the smaller and larger lengths of Gulf Menhaden are not being captured by the fishery. Specifically, the gill net survey in LA capture larger fish than have ever been captured in the fishery. Thus, the estimation of the L_∞ parameter is biased lower due to missing data on the upper end of the distribution. The bias correction method has been used in other stock assessments with similar growth data availability (SEDAR 2015). The assessment panel used the bias corrected, cohort based growth curve estimates for 1997-2017 as the parameter estimates in the stock assessment. These values were chosen because the years most closely matched the years over which the index spans.

Overall and annual regressions of weight (W in g) on fork length (FL in mm) were conducted based on the natural logarithm transformation:

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

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

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

Annual estimates for parameters *a* and *b*, along with sample size and root MSE, are summarized in Table 3.4. 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. Given the small difference in growth as estimated on the annual time step, the overall weight-length relationship was used in the stock assessment model. This decision is consistent with using an overall von Bertalanffy growth curve and was supported by the assessment panelists.

Former assessments used the annual von Bertalanffy growth fits and annual weight-length relationships to construct matrices of weight at ages-0 to -4+, representing the average size-at-age 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 the current assessment, we selected an overall von Bertalanffy growth curve and an overall weight-length relationship to estimate time-invariant weights-at-age for the fishery in the middle of the year and time–invariant weights-at-age for spawning stock biomass at the beginning of the year (Table 3.5).

3.4 Reproduction

Spawning Times and Locations: In general, Gulf Menhaden life history is typical of the cycle followed by most estuarine-dependent species in the Gulf of Mexico. Spawning occurs offshore, and young move into estuarine nursery areas where they spend the early part of their lives (Reid 1955). Maturing adults return to offshore waters to spawn completing the cycle.

Peak spawning periods for Gulf Menhaden fluctuate from year to year probably in response to varying environmental conditions (Suttkus 1956). Lewis and Roithmayr (1981) agreed with several earlier researchers (Suttkus and Sundararaj 1961, Combs 1969, Turner 1969, Fore 1970, Christmas and Waller 1975) that spawning in Gulf Menhaden generally begins in October and ends about March with a peak between December and February. Combs (1969) and Lewis and Roithmayr (1981) reported that Gulf Menhaden were multiple, intermittent spawners with ova being released in batches or fractions over a protracted spawning season. More recent work by Brown-Peterson et al. (2017) examined the histology of the female fish and found that Gulf Menhaden are asynchronous batch spawners, potentially spawning every seven days over a roughly five month spawning season (October – March), which means a single female may spawn up to 25 times in a single season.

Actual spawning sites have not been delineated, but data indicate that Gulf Menhaden spawn offshore. Turner (1969) presented indirect evidence of spawning areas in the eastern Gulf from collections of menhaden eggs and larvae off Florida. He observed that eggs were collected within the five-fathom curve and suggested that spawning takes place nearshore in Florida waters. Combs (1969) did not delineate the geographical areas of Gulf Menhaden spawning, but he provided evidence that spawning occurs only in high-salinity waters.

Based on the distribution of eggs, Fore (1970) indicated that spawning of Gulf Menhaden occurs mainly over the continental shelf between Sabine Pass, Texas, and Alabama. Greatest concentrations were found in waters between the 4-40 fathom (ca. 8-70 m) contours off Texas and Louisiana and near the Mississippi Delta. Sogard et al. (1987) found high densities of larvae near the Mississippi River supporting the conclusions of Fore (1970) and Christmas and Waller (1975) that spawning is concentrated near the mouth of the Mississippi River. Shaw et al. (1985) found highest egg densities between the 10-m and 23-m isobaths and at temperatures of 15-18°C and salinities of 30-36 ppt, respectively. Christmas and Waller (1975) found highest egg densities at temperatures >15°C and salinities >25 ppt.

Maturity Schedule: Lewis and Rothmayr (1981) concluded “that Gulf Menhaden spawn for the first time at age-1, after they have completed two seasons of growth, and then continue to spawn each year thereafter.” Brown-Peterson et al. (2017) indicated that the length at maturity for Gulf Menhaden (L_{50}) is between 125 and 150 mm FL, which indicates that age-1 individuals are mature and spawning. Given these updated data, the assessment panel used the most updated maturity curve whereby age-1 individuals were mature 80% of the time and fish age-2 and older had 100% maturity. The maturity schedule shown in Table 3.5 (age-0 immature, age-1 80% mature, and full maturity for age-2 and older) will be used for this stock assessment

Fecundity: Fecundity is calculated based on the total number of ova produced by individual fish over an entire season and is the product of batch fecundity, fish weight, and spawning frequency. Brown-Peterson (2017) reports that Gulf Menhaden have relative batch fecundity of 107.8 eggs/g fish. This estimate is consistent with the observation that the number of eggs spawned by a mature female usually increases with the size of the fish. Previous estimates include those by Suttkus and Sundararaj (1961) who examined ovaries of female Gulf Menhaden at age-1, -2, and -3 and reported that the mean numbers of eggs per fish per age group were 21,960, 68,655, and 122,062, respectively. Lewis and Roithmayr (1981) examined spawning age and egg number per cohort to determine the reproductive potential of Gulf Menhaden and provide an annual length-specific relationship for Gulf Menhaden fecundity:

$$E = 0.0000516\ L^{3.8775}$$

where L is the length of the individual and was used for the more recent stock assessments.

However, new research from Brown-Peterson et al. (2017) found that Gulf Menhaden have indeterminate fecundity. Their total fecundity estimate suggests egg production in Gulf Menhaden is about ten times greater than the value used in the last benchmark assessment (SEDAR 2013a). Annual mean fecundity for age-1 fish is 164,106 eggs, for age-2 fish 404,404 eggs, age-3 fish 744,264, and age-4 fish 1,149,697 eggs.

3.5 Natural Mortality

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

This section summarizes decisions made by the assessment panel. Several life history based approaches were explored for developing estimates of *M*, as well as tagging estimates of *M*. Often *M* is related to the parameters from the von Bertalanffy growth equation (K, L_∞), or as an inverse function of size-at-age, so consideration of growth of Gulf Menhaden is relevant to this section.

3.5.1 Life-History Based Approaches

Age-Constant M Approaches: Several methods are available to determine an age-constant *M* based on life history characteristics, notably maximum age (t_{max}) and von Bertalanffy growth parameters (K, L_∞). Methods using average water temperature were discussed, but selecting a representative temperature over such a large area was not feasible or realistic. Thus, methods based on water temperature were excluded from further consideration.

The maximum age used in calculations was age-4. The “rule of thumb” method has a long history in fisheries science, but its source has been difficult to identify. Hewitt and Hoenig (2005), recently compared the “rule of thumb” approach to that of Hoenig (1983) and noted that the Hoenig (1983) method provides an estimate of *M* only when fishing mortality can be assumed small ($F \sim 0$).

Methods used to determine a constant natural mortality rate over age and time:

Alverson and Carney (1975)	$M = 3K/(\exp(0.38 * t_{max} * K)-1)$
Hoenig (1983; $F \sim 0$)	$M = \exp(1.46 - 1.01 * \ln(t_{max}))$
Jensen (1996)	$M = 1.5 * K$
"Rule of thumb" (Hewitt and Hoenig 2005)	$M = 3/ t_{max}$

Assessment panelists, in previous assessment efforts and during this assessment, agreed that a constant value for natural mortality over ages for Gulf Menhaden was inappropriate because younger age classes are more susceptible as a prey source and likely had higher natural mortality rates.

Age-Varying M Approaches: Several approaches have been developed to provide age-varying, yet time-invariant estimates of *M* (Peterson and Wroblewski 1984, Boudreau and Dickie 1989, Lorenzen 1996, Charnov et al. 2013). All use an inverse relationship between size and natural mortality (*M*). To apply these methods, weight-at-age was calculated for the middle of the calendar year (July 1). Because the middle of the fishing year is approximately July 1, or 6 months into the calendar year, the fraction 1⁄2 a year (6 months), was added to each age in the overall von Bertalanffy growth equation to calculate corresponding length on July 1, then converted to weight using the overall corresponding weight-length relationship.

The method of Peterson and Wroblewski (1984) has been used to describe natural mortality for young-of-year Atlantic menhaden (Heimbuch et al. 2007) and uses a dry weight as its independent variable. The method of Boudreau and Dickie (1989) has been applied in several assessments, notably for Gulf Menhaden in Vaughan et al. (2007). However, the method of Lorenzen (1996) has gained favor in recent years, especially in the SEDAR arena and has been used for both Atlantic and Gulf Menhaden recently (e.g., SEDAR 2006, SEDAR 2008a, SEDAR 2008b, SEDAR 2009, SEDAR 2010a, SEDAR 2013a (Gulf Menhaden), SEDAR 2015 (Atlantic menhaden)).

Assessment panelists discussed all age-varying approaches, but the Lorenzen method was recognized as the favored approach due to the direct use of wet weight and its use in past SEDAR and menhaden assessments. The shape of the Lorenzen curve was very similar to the curves estimated using Peterson and Wroblewski and Boudreau and Dickie.

3.5.2 Estimates Based on Tagging

The only field estimate of natural mortality known for Gulf Menhaden was based on tagging data (Ahrenholz 1981). Adult fish were tagged with internal ferro-magnetic tags from 1969 to 1971 (Ahrenholz 1981); later tags were recovered on magnets at commercial reduction plants and adjusted for tag loss. Estimates of *M* varied between 0.69 and 1.61 for the western, central, and eastern Gulf of Mexico after adjusting for a 20% tag loss rate and had a mean M of 1.10. Ahrenholz (1981) estimated natural mortality, M = 1.05, for Gulf Menhaden using tagging data from 1969-1971 for the entire area with upper and lower confidence intervals of 1.09 and 1.01, respectively.

The assessment panelists decided that the estimates of natural mortality from the comprehensive tagging study completed by Ahrenholz (1981) likely gave an indication of the scale of natural mortality for Gulf Menhaden in the Gulf of Mexico. These values constitute the best available data for natural mortality of Gulf Menhaden. Thus, age varying natural mortality rates, in the form of the Lorenzen curve, were scaled to *M* estimated from the tagging study. The Lorenzen was scaled to the mean *M* of 1.10 estimated from the tagging data across the entire Gulf of Mexico, and this estimate was suggested for the base run (Table 3.6). The vector was scaled to a value of 1.10 at age-2 because age-2 represents the adult age class most likely represented in the tagging study. Each of the scaled vectors was scaled using age-2 as the anchor age. The uncertainty surrounding natural mortality was 0.69-1.61 and was based on the range of *M* estimated for areas of the Gulf of Mexico for 1969 and 1971. These values were suggested as potential sensitivity runs (Table 3.6).

3.5.3 Estimates from Multi-Species Models (e.g., MSVPA-X, EwE)

Beginning in 2003, age-varying estimates of *M* from the MSVPA-X have been favored in Atlantic menhaden stock assessments due to the ability of MSVPA to explicitly account for predation effects through the incorporation of diet data (ASMFC 2004). However, this approach has since been abandoned due to problems with scaling (SEDAR 2015). The MSVPA approach was discussed for Gulf Menhaden; however, a MSVPA-X for the northern Gulf of Mexico is not available, nor are estimates of age- and year-varying *M* for Gulf Menhaden. The estimates from the Atlantic menhaden MSVPA-X were deemed inappropriate for Gulf Menhaden use because of the difference between longevity of the two species and the difference in ecosystems between the Gulf of Mexico and Atlantic Ocean.

The group also discussed using *M* estimates obtained from predator-prey interactions modeled in the Ecopath with Ecosim framework (EwE). However, pre-existing EwE models do not currently distinguish between the life stages of Gulf Menhaden (e.g., Walters et al. 2008, Robinson et al. 2015, Geers et al. 2016, Sagarese et al. 2017). Furthermore, these EwE models are deterministic and so largely ignore the substantial uncertainty in Gulf Menhaden's relative contribution to predator diet (Sagarese et al. 2016). While work is currently underway to build a Gulf Menhaden EwE model that resolves these issues, it was not ready for consideration by the time of the assessment.

3.6 Environmental Factors

Environmental factors that affect recruitment are generally viewed as density independent. These factors include physical processes, for example transport mechanisms, water temperature, dissolved oxygen, freshwater inflow, and nutrient loadings. Biological factors, such as amount of food and competition for food, or predation by higher trophic levels, which control survival and growth of young-of-the-year menhaden prior to recruitment to the fishery, can be either density independent or density dependent. Environmental factors can also affect the fishing process itself. We provide a brief description of two additional topics in this section: 1) a recurring hypoxic zone that forms along the northern Gulf of Mexico and 2) the British Petroleum (BP) Deep Water Horizon (DWH) disaster in 2010. Environmental factors influence population dynamics; however, these factors are often difficult to quantify and therefore, were not included in the current stock assessment. Those factors that could be quantified were not included in the assessment analyses because they were low priority when compared to other uncertainties surrounding the assessment.

3.6.1 Physical Processes

Nelson et al. (1977) developed a Ricker spawner-recruit model relating coastwide spawning stock of

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

Stone (1976) conducted a series of stepwise regressions of Gulf Menhaden catch and effort related to a wide range of environmental data (air temperature, water temperature, rainfall, tides, and wind speed and direction). Not unexpectedly, several significant correlations were found including minimum and mean air temperature, maximum water temperature, and wind direction at several locations, resulting in an R^2 value of 0.86. Subsequently, Guillory et al. (1983) refined much of this work to forecast Gulf Menhaden harvest in Louisiana. Currently, the state of Louisiana no longer provides these forecasts.

Other Environmental Factors: Govoni (1997) demonstrated an association between the discharge of the Mississippi and Atchafalaya Rivers and Gulf Menhaden recruitment. In particular, he found an inverse association between Mississippi River discharge (Figure 3.4) and estimates of half-year old recruits, using recruitment data from Vaughan et al. (1996). Vaughan et al. (2000) updated this relationship with regression analysis. Vaughan et al. (2007) revisited this relationship with additional years of data through 2004. They found that the inverse relationship still held. In addition, they reframed this relationship to produce a 1-yr ahead prediction model for forecasting recruitment to age-1 from Mississippi River flow for consideration in fishery management. Finally, they revisited the stock assessment model of Vaughan et al. (2007), and they demonstrated improved model performance when information on annual river flow was incorporated. More recently, Sanchez-Rubio and Perry (2015) found that cold, wet conditions were associated with larger recruitment events. These findings are in contrast with previous findings. Thus, evidence for river discharge as an environmental driver is inconclusive.

El Niño [also referred to as El Niño Southern Oscillation (ENSO)] is a change in the eastern Pacific’s atmospheric system, which contributes to major changes in global weather (Figure 3.5). El Niño is characterized by a dwindling or sometimes reversal of equatorial trade winds causing unusually warm ocean temperatures along and on both sides of the equator in the central and eastern Pacific. The change in ocean temperature affects global atmosphere and causes unusual weather patterns around the world. In the southeastern United States, winter droughts are sometimes followed by summer floods. These conditions may have an impact on freshwater inflow patterns into the Gulf of Mexico and could ultimately affect menhaden distribution, recruitment success, and can influence oil yield from the reduction fishery. In many parts of the world, fish migration has been attributed to El Niño (Arntz and Tarazona 1990, Bakun and Broad 2003).

The effects of La Niña are nearly opposite that of El Niño and is characterized by a warmer than average winter in the southeast United States. This provides favorable conditions for a strong hurricane season. Likewise, these abnormal conditions may influence fish migration and occurrence in the Gulf of Mexico (Lewis et al. 2011).

Historically, the Gulf Menhaden fishing season frequently reflects the tropical activities during a particular year (Figure 3.6). For example, in years of minimal tropical activity, fishing effort and landings generally increased. The opposite was true in years of high tropical activity. Landings were low in 1998 due to the high number of storms that entered the Gulf and reduced the number of fishable days. In 2005, the high frequency of storms and the direct impacts to the fleet and fishery from hurricanes Katrina and Rita virtually eliminated fishing after August. Effort remained low as the reduction plants were put back on-line and the vessels, in some cases, were returned to the water. Other factors such as visibility for spotter planes can affect the ability of the fleet to fish and the 'dead zone' (Section 3.6.3) can move fish into areas inaccessible to the fleet. It should be noted that many of these environmental parameters and events described in this section are probably related with each other, possibly mediated through such processes as El Niño and La Niña events.

3.6.2 Biological Processes

Predation is a process that potentially plays a major role in controlling menhaden dynamics. These fish serve as prey for animals that span a range of trophic levels that include chaetognaths, ctenophores and jellyfish, squid, piscivorous birds, marine mammals, scombrids, serranids, flatfish, drum, and even cannibalistic adult menhaden (Ahrenholz 1991, Thronson and Quigg 2008). Any of these predators may exert substantial mortality on the menhaden population, pressures that may be consistent, vary between areas (e.g., different bays), or over time (e.g., seasonally). The food and nutrition of menhaden may also have influence on population dynamics, depending on the amounts and types of available prey. Menhaden depend on planktonic prey throughout their life-cycle, feeding on large phytoplankton as young larvae (Stoecker and Govoni 1984) and varying amounts of phytoplankton, zooplankton, and detritus as juveniles and adults (Peck 1893, Ahrenholz 1991, Lewis and Peters 1994, Thronson and Quigg 2008). The relative availability of any one of these prey items to inshore menhaden, where young-of-the-year and age-1 menhaden are concentrated, may therefore influence recruitment success. Simulation modeling of Atlantic menhaden in the Chesapeake (Brandt and Mason 2003) suggests that growth rate may be positively and linearly related to the availability of plankton biomass. Prey biomass can also influence mortality if conditions are such to limit their availability to menhaden (i.e., starvation). Furthermore, in Fourleague Bay, LA, seasonal peaks in the plankton production of inshore marshes and open bay estuaries have coincided with observed migrational patterns of juvenile Gulf Menhaden (Deegan 1990), suggesting a potential linkage between plankton distributions and that of Gulf Menhaden, a relationship already noted in Atlantic Menhaden (Friedland et al. 1989). If fishing effort or sampling is also spatially heterogeneous, plankton production may also need to be considered in standardizing catch rates (i.e., catchability effect). Note that many of the biological processes described above may also be correlated with some of the physical processes described in the previous section, complicating attempts to discern the actual driver(s) of menhaden dynamics. Given the uncertainty in whether predation influences the Gulf Menhaden population, but also how, such relationships were not considered further in this assessment.

3.6.3 Hypoxic Zone

Extensive areas of low DO (<2 ppm) occur in offshore waters along the Louisiana and Texas coasts during summer (Rabalais et al. 1999; Figure 3.7). Increased levels of nutrient influx from freshwater sources coupled with high summer water temperatures, strong salinity-based stratification, and periods of reduced mixing appear to contribute to what is now referred to in the popular press as the ‘dead zone’ (Justic et al. 1993). Most life history stages of Gulf Menhaden, from eggs to adults, occur inshore of areas where historically the hypoxic zone ‘sets- up’ during mid-summer. Gulf Menhaden, although susceptible to low DO conditions, probably move out of hypoxic areas, resulting in displacement, rather than mortality. After analyzing menhaden logbook data, Smith (2000) suggested that during some years exceptionally low catches of Gulf Menhaden off the central Louisiana coast may have been a result of hypoxic waters impinging upon near shore waters in mid-summer. He further speculated that the hypoxic zone might force Gulf Menhaden into narrower corridors of more normoxic waters near shore where they could be more vulnerable to the fishery. This was further investigated by Langseth et al. (2014), who showed that indeed the fishery is moving west and offshore when hypoxia events were large. Changes in hypoxia have impacts on the catchability of the fishery, which was explored in Langseth et al. (2016). Specifically, allowing for time varying catchability in the fishery accounted for hypoxia effects on catchability and reduced bias in the stock assessment. However, the assessment as configured here does not estimate catchability for the fishery nor does it use a fishery dependent index of abundance.

3.6.4 BP Deep Water Horizon Oil Spill in 2010

The 2010 Gulf Menhaden fishing season opened on Monday, April 19th, 2010. The BP DWH oil rig exploded and sank on Tuesday, April 20th, 2010 (Figure 3.8). Beginning about two weeks after the DWH disaster, the Gulf Menhaden fishery experienced unprecedented closures of long-established fishing grounds because of the subsequent oil spill. Over the course of the next three months, the fishery was gradually restricted to fish in a narrow corridor of state territorial sea (0-3 miles from the shore line), west of about Morgan City, Louisiana. In mid-summer landings were down 30-40% from landings in previous years. By August many of the restricted areas had re-opened to commercial fishing, and the Gulf Menhaden fleet returned to fish traditional areas.

The effects of the risk of port closures and the restriction of fishing efforts had a large impact in the short term, with landings reaching their nadir in July of 8,340 mt, the lowest monthly total on record in the NMFS Beaufort data base. This resulted in the annual landings through July being 41% below the previous 5-year average and 39% below 2009 values for the equivalent time (Table 3.7). State-restricted fishing areas were re-opened in phases and the EEZ west of the Mississippi River re-opened in September. October landings were above average for the month, narrowing the seasonal landings to within 17% of the 2009 season and 15% of the previous 5-year average.

Table 3.1 Ageing error matrix from a scale to scale comparison of ages done by Hall over four decades.

	0	1	2	3	4+
0	0.994	0.006	0.000	0.000	0.000
1	0.006	0.987	0.117	0.008	0.001
2	0.000	0.006	0.765	0.202	0.030
3	0.000	0.000	0.117	0.580	0.235
4+	0.000	0.000	0.000	0.210	0.734

Table 3.2 Ageing error matrix from a scale to scale comparison of ages done by Myers and Price as blind reads.

	0	1	2	3	4+
0	0.905	0.095	0.000	0.000	0.242
1	0.095	0.811	0.095	0.000	0.067
2	0.000	0.095	0.810	0.114	0.074
3	0.000	0.000	0.095	0.772	0.078
4+	0.000	0.000	0.000	0.114	0.540

Table 3.3 Results of length-length regressions from historical and recently collected data for Gulf Menhaden (Schueller et al. 2012).

Source	Relationship	Years	Gears	FL (mm)	SL (mm)	TL (mm)	N	R^2	Intercept	Slope
Alabama	TL = f(SL)	2011	Gill net, Trawl, BPL	-	21-201	25-258	90	0.9994	-3.270	1.299
Louisiana	TL = f(SL)	2011	Gill net, Trawl, Seine	-	23-192	27-247	409	0.9962	-1.389	1.298
Mississippi	TL = f(SL)	2011	Gill net, Trawl, BPL	-	19-246	23-296	235	0.9983	1.049	1.237
Texas	TL = f(SL)	1975-1978 & 2011	Gill net, push net, bag seine, trawl, rotenone & fish trap	-	18-315	23-390	9,158	0.9903	2.993	1.261
Overall	**TL = f(SL)**	**2010-2011**		**-**	**18-315**	**23-390**	**9,892**	**0.9927**	**1.739**	**1.267**
Alabama	FL = f(SL)	2011	Gill net, Trawl, BPL	23-222	21-201	-	90	0.9996	-0.956	1.109
Louisiana	FL = f(SL)	2011	Gill net, Trawl, Seine	26-206	23-192	-	409	0.9964	0.378	1.088
Mississippi	FL = f(SL)	2011	Gill net, Trawl, BPL	21.5-255	19-246	-	235	0.9984	3.547	1.046
Omega Protein	FL = f(SL)	2010	Purse Seine	115-201	103-184	-	195	0.9657	1.768	1.107
Texas	FL = f(SL)	2011	Seine, Trawl				191	0.9987	1.814	1.045
Overall	**FL = f(SL)**	**2010-2011**		**21.5-255**	**19-246**	**-**	**1,120**	**0.9968**	**0.110**	**1.094**
Alabama	FL = f(TL)	2011	Gill net, Trawl, BPL	23-222	-	25-258	90	0.9996	1.869	0.854
Louisiana	FL = f(TL)	2011	Gill net, Trawl, Seine	26-206	-	27-247	410	0.9974	1.571	0.838
Mississippi	FL = f(TL)	2011	Gill net, Trawl, BPL	21.5-255	-	23-296	236	0.9990	2.710	0.846
Texas	FL = f(TL)	2011	Seine, Trawl				191	0.9986	1.506	0.840
Overall	**FL = f(TL)**	**2010-2011**		**21.5-255**	**-**	**23-297**	**927**	**0.9987**	**1.191**	**0.850**

Table 3.4 Overall (1977-2017), time blocked (1977-1996; 1997-2017), and annually estimated parameters obtained from annual weight-length relationships and cohort based length at age regressions from biological sampling of Gulf Menhaden, 1964-2017. Blank values indicate non-convergence. The overall and time blocked estimates are bias corrected values for the von Bertalanffy parameter estimates.

Year	Weight-Length				Von Bertalanffy Curve			
	n	a	b	RMSE	n	L_∞	K	t_0
1964	12,375	-12.695	3.365	0.0095	14,932	383.3	0.140	-2.004
1965	15,672	-12.481	3.329	0.0081	11,242	462.6	0.121	-1.723
1966	12,704	-11.592	3.157	0.0070	17,541	299.7	0.251	-1.277
1967	14,400	-11.270	3.085	0.0083	13,113	238.3	0.520	-0.466
1968	15,830	-11.668	3.167	0.0076	15,750	236.9	0.439	-0.772
1969	15,043	-11.374	3.107	0.0087	9,110	450.9	0.114	-2.181
1970	10,530	-11.959	3.224	0.0056	8,416	255.4	0.432	-0.627
1971	7,847	-12.192	3.269	0.0080	9,919	612.1	0.085	-1.836
1972	9,974	-11.756	3.180	0.0080	8,897	243.5	0.595	-0.370
1973	8,953	-11.663	3.181	0.0078	11,655	275.1	0.363	-0.941
1974	10,084	-10.793	2.995	0.0097	8,089	236.7	0.628	-0.235
1975	9,527	-11.562	3.144	0.0078	13,853	244.6	0.387	-1.106
1976	13,531	-10.791	2.988	0.0077	16,927	260.4	0.332	-0.998
1977	14,909	-11.382	3.098	0.0060	13,230	237.6	0.489	-0.625
1978	12,982	-12.052	3.239	0.0058	12,001	233.1	0.464	-0.910
1979	11,617	-12.238	3.268	0.0053	6,516	245.6	0.381	-0.907
1980	9,947	-13.045	3.427	0.0229	11,635	225.8	0.645	-0.079
1981	10,404	-11.682	3.166	0.0100	13,123	226.8	0.602	-0.284
1982	10,677	-12.669	3.361	0.0110	12,074	231.2	0.535	-0.479
1983	14,836	-12.256	3.280	0.0082	14,976	222.8	0.583	-0.336
1984	15,954	-11.906	3.215	0.0072	20,644	239.0	0.348	-1.280
1985	13,226	-11.531	3.131	0.0075	13,072	242.2	0.416	-0.526
1986	16,494	-11.782	3.194	0.0061	13,136	243.5	0.363	-0.980
1987	16,457	-11.707	3.173	0.0056	12,380	243.5	0.403	-0.685
1988	12,402	-11.363	3.110	0.0113	14,643	224.2	0.629	-0.156
1989	13,950	-11.819	3.202	0.0072	12,726	241.5	0.422	-0.722
1990	11,499	-11.707	3.184	0.0117	11,661	243.3	0.374	-1.297
1991	11,636	-12.178	3.274	0.0082	13,698	238.2	0.433	-0.887
1992	15,230	-10.408	2.932	0.0095	16,057	226.7	0.571	-0.490
1993	15,346	-11.308	3.111	0.0116	17,768	233.5	0.424	-1.090
1994	16,784	-10.976	3.030	0.0072	12,700	234.6	0.414	-1.149
1995	14,272	-12.036	3.248	0.0077	9,100	230.4	0.500	-0.670
1996	13,052	-12.576	3.339	0.0177	11,451	248.7	0.329	-1.397
1997	10,633	-11.640	3.162	0.0058	8,079	224.1	0.586	-0.473
1998	10,033	-10.969	3.034	0.0053	10,558	237.3	0.391	-1.351
1999	11,773	-11.701	3.177	0.0057	7,837	221.0	0.675	-0.236
2000	9,587	-10.027	2.833	0.0118	5,161	217.7	0.493	-1.393
2001	7,350	-10.896	3.027	0.0085	6,722	230.8	0.330	-1.947
2002	6,610	-11.339	3.097	0.0054	5,340	213.1	0.603	-0.449
2003	9,238	-11.142	3.056	0.0048	7,800	225.2	0.429	-1.007
2004	7,654	-11.850	3.204	0.0055	4,693	259.5	0.247	-2.045
2005	7,202	-11.042	3.046	0.0087	4,138	233.4	0.329	-1.788
2006	5,762	-11.359	3.105	0.0061	5,932	226.0	0.483	-0.817

Table 3.4 Con’t

Year	Weight-Length				Von Bertalanffy Curve			
	n	a	b	RMSE	n	L_∞	K	t_0
2007	5,150	-11.782	3.192	0.0056	6,295	215.4	0.580	-0.776
2008	5,876	-12.256	3.284	0.0057	2,446	219.9	0.480	-1.231
2009	7,418	-10.871	3.007	0.0064	4,953	217.4	0.585	-0.537
2010	4,529	-11.065	3.048	0.0067	10,007	217.5	0.486	-0.861
2011	8,305	-11.912	3.205	0.0056	6,902	226.2	0.402	-1.165
2012	8,833	-11.041	3.026	0.0051	5,559	209.6	0.687	-0.376
2013	6,925	-4.135	1.711	0.0283				
2014	7,244	-10.954	3.029	0.0055	7,535	224.0	0.430	-1.071
2015	9,650	-11.496	3.126	0.0088	4,696	197.3	0.776	-0.593
2016	6,805	-11.450	3.130	0.0081				
2017	6,309	-9.671	2.767	0.0159				
Overall	434,603	-11.55	3.14	0.104	405,898	280.2	0.227	-1.966
1977-1996	271,696	-11.87	3.21	0.103	262,591	239.3	0.400	-1.005
1997-2017	162,907	-11.01	3.04	0.104	122,687	236.2	0.331	-1.744

Table 3.5 Estimated fork lengths and weights for Gulf Menhaden calculated for the start of the year (January 1) and middle of the fishing year based on the overall, bias corrected von Bertalanffy and weight-length equations for the years 1977-2017, as well as, female maturity at age *from* Brown-Peterson et al. (2017), and fecundity at age *from* Brown-Peterson et al. (2017).

Year	FL (mm) start	Weight (g) start	FL (mm) middle	Weight (g) middle	Maturity (%)	Fecundity (ova)
0	-	-	121.1	35.9	0	0
1	137.4	53.4	161.9	89.3	80	164,106
2	166.5	97.5	186.9	140.4	100	404,404
3	189.6	146.7	202.3	179.9	100	744,264
4+	208.0	196.4	211.7	207.6	100	1,149,697

Table 3.6 Lorenzen age-specific estimates of M scaled to the mean, upper, and lower range of estimates of M from the tagging study throughout the Gulf of Mexico by Ahrenholz (1981) and as determined by the assessment panelists. The assessment panelists suggested the vector scaled to the mean as the M for the base run, and the vectors scaled to the lower and upper values as sensitivity analyses runs.

Age	Scaled to mean value	Scaled to lower value	Scaled to upper value
0	1.67	1.05	2.44
1	1.26	0.79	1.85
2	1.10	0.69	1.61
3	1.02	0.64	1.49
4+	0.98	0.61	1.43

Table 3.7 Cumulative monthly purse-seine landings of Gulf Menhaden for reduction in 2010 (year of the BP DWH disaster), and percent change, as compared to 2009 and the previous five-year average.

Total landings through	Cumulative 2010 (*mt*)	Cumulative 2009 (*mt*)	Cumulative previous 5-yr mean (*mt*)	Change from 2009	Change from previous 5-yr mean
Apr	20,790	9,775	21,998	+113%	-5%
May	84,587	86,553	90,009	-2%	-6%
Jun	154,242	179,151	185,827	-14%	-17%
Jul	162,472	264,759	274,026	-39%	-41%
Aug	236,465	347,495	360,969	-32%	-35%
Sep	290,880	431,060	417,079	-33%	-30%
Oct	379,727	457,457	446,982	-17%	-15%

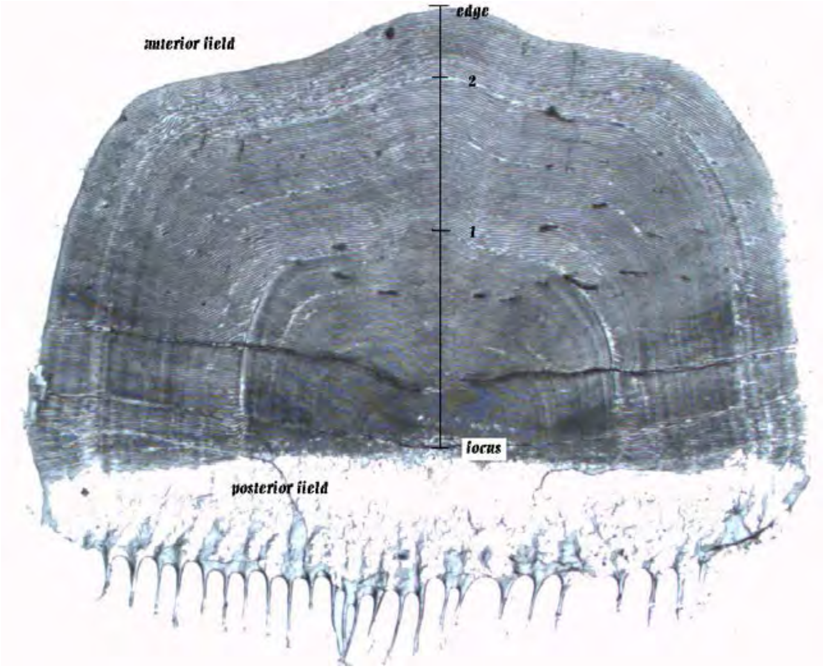


Figure 3.1 Scale sample from age-2 Gulf Menhaden.

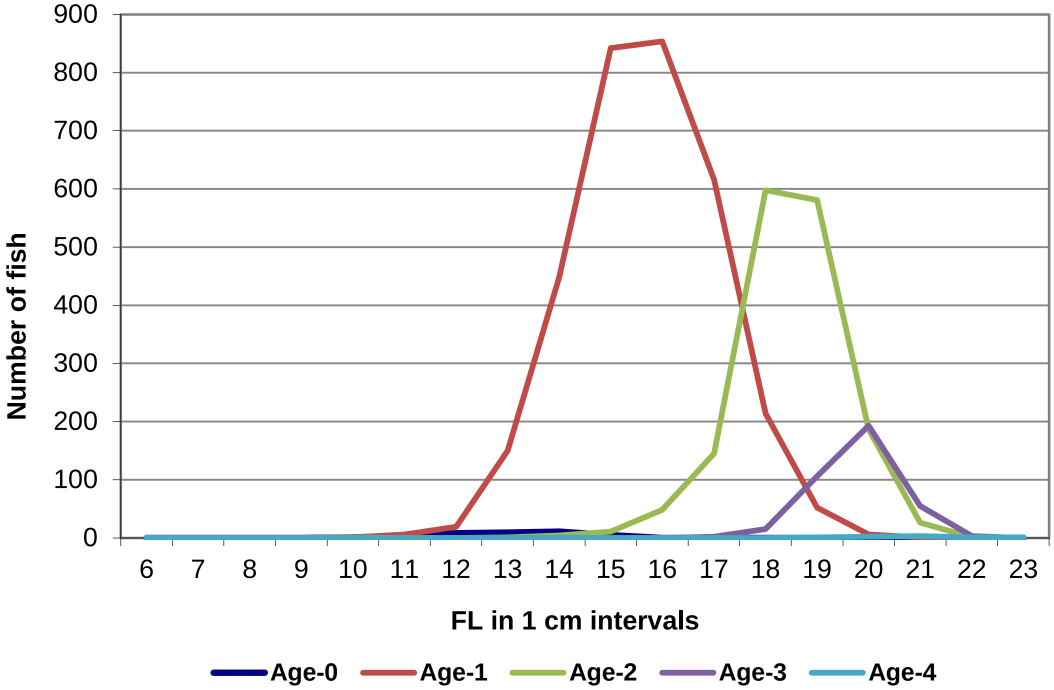


Figure 3.2 Fork length (cm) frequencies by age of Gulf Menhaden in the 2017 port samples.

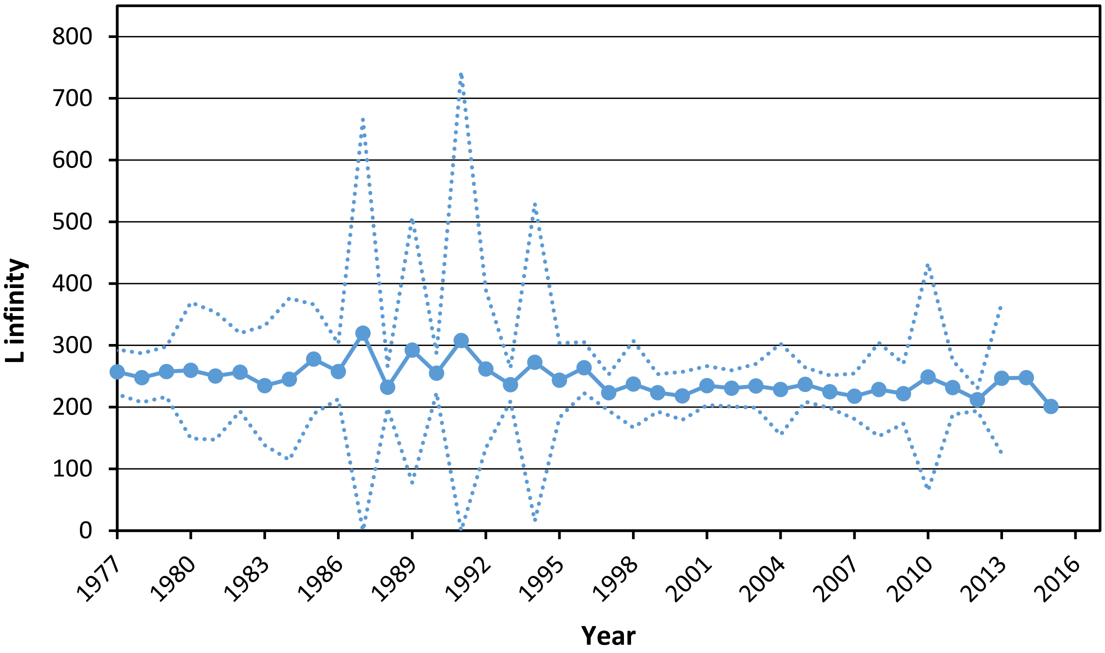


Figure 3.3 The annual values of L_∞ based on bias corrected, cohort based fits of the von Bertalanffy growth curve for 1977-2017. The dashed line is one standard deviation away from the mean value.

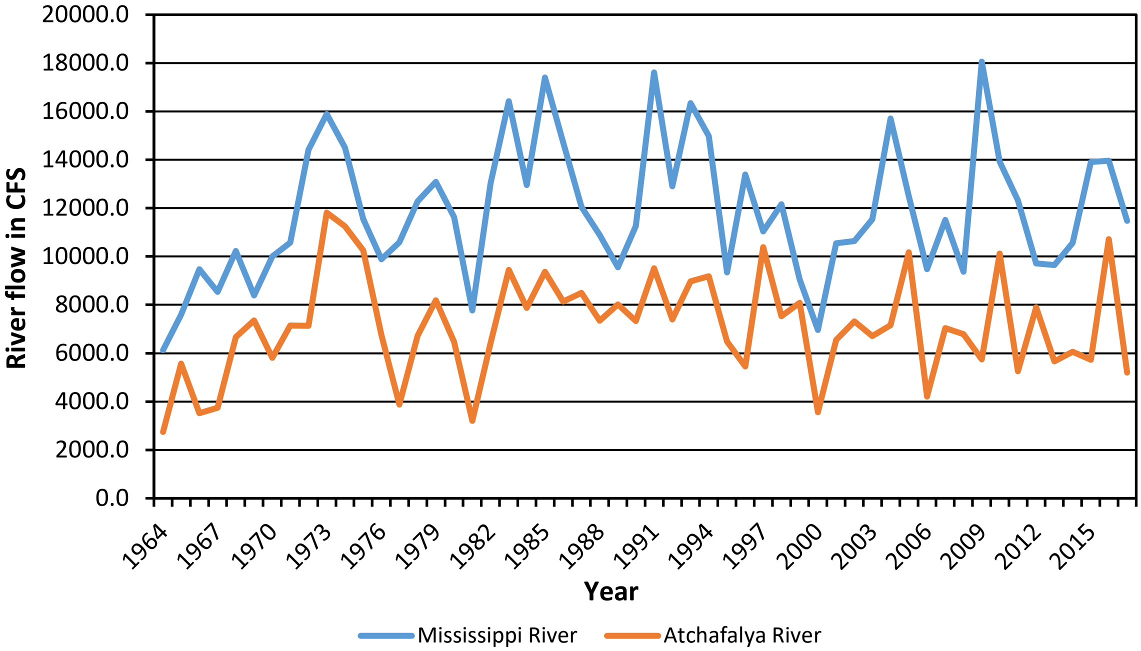


Figure 3.4 Winter (Nov-Mar) Mississippi River flow measured at two US Corps of Engineers gauges (Simmesport, Louisiana, on the Atchafalaya River and Tarbert Landings, Mississippi, on the Mississippi River) for 1963 to 2017.

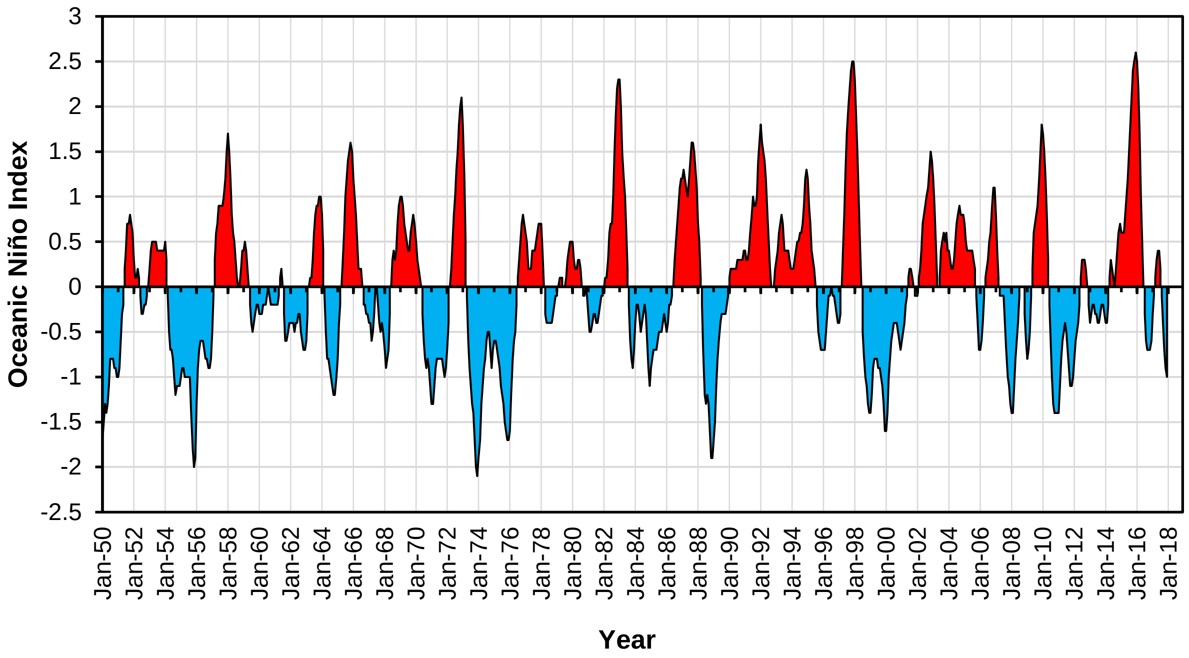


Figure 3.5 Warm (red) and cold (blue) episodes based on a threshold of +/- 0.5°C for the Oceanic Niño Index (ONI) from 1950-2017 [each month is 3 month (center month noted) running mean of ERSST.v3b SST anomalies in the Niño 3.4 region (5°N-5°S, 120°-170°W)], based on centered 30-year base periods updated every 5 years.

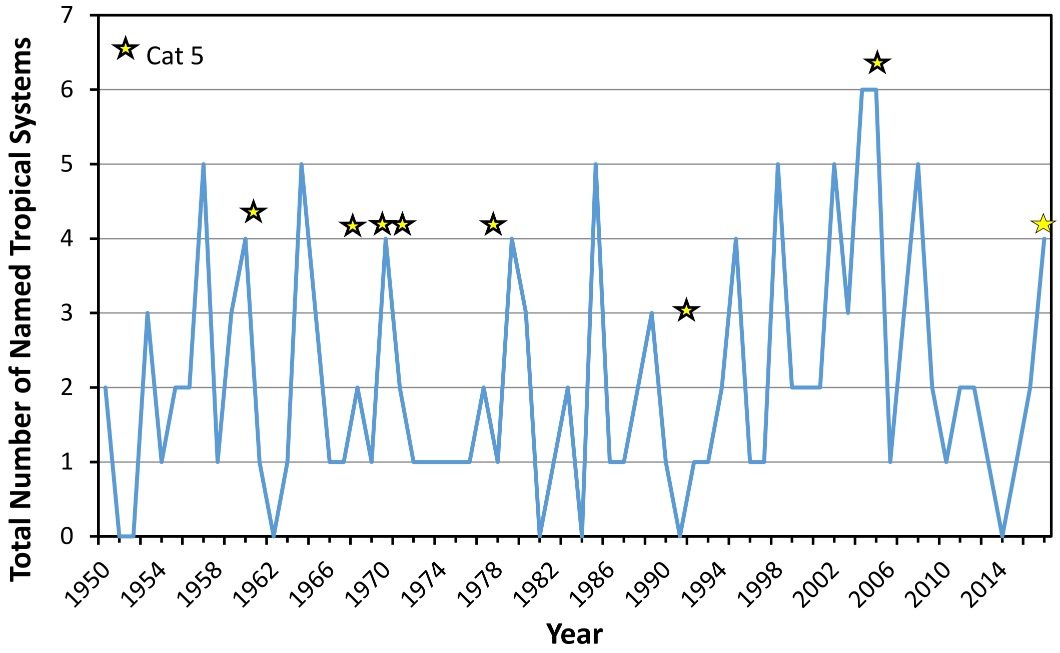


Figure 3.6 Number of tropical storms and hurricanes in the northern Gulf of Mexico, 1950-2017.

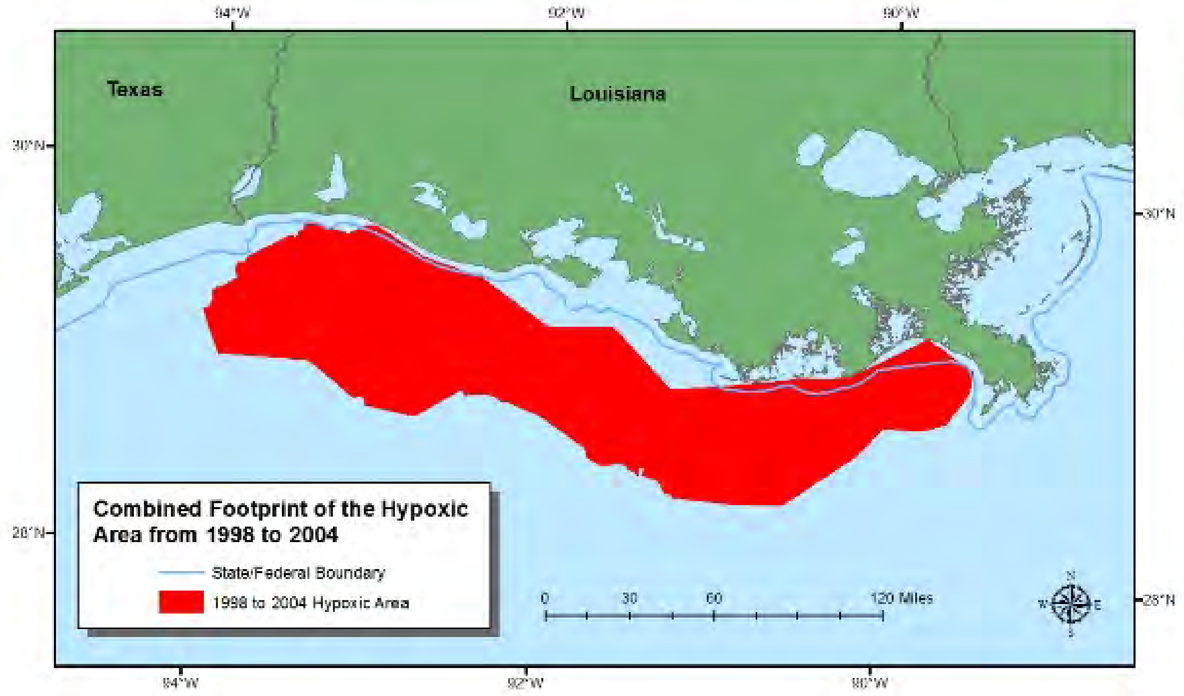


Figure 3.7 Map of the Gulf of Mexico showing the combined footprint of the Hypoxic Area or 'Dead Zone' for the period 1998-2004.

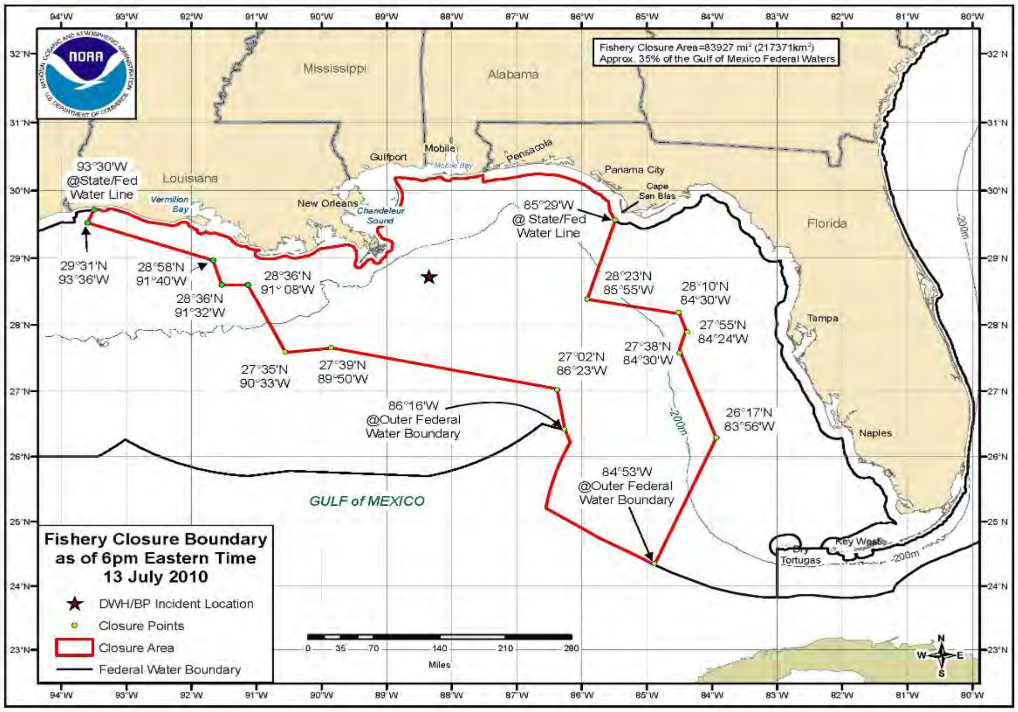


Figure 3.8 Map of the Gulf of Mexico showing the site of the BP Deepwater Horizon (DWF) Oil Spill and fishery closure boundary on 13 July 2010 (Source: NOAA/SERO).

4.0 Fishery-Dependent Data Sources

Commercial menhaden landings for the bait and reduction fisheries tend to be limited to the northern Gulf because the central part of the range of Gulf Menhaden is predominantly east and west of the Mississippi River. The majority of commercial purse-seine fishing activities occur off Louisiana (92.9%) with smaller contributions from Mississippi 6.7%, and with Texas and Alabama both contributing <1% (based on 2013-2017 averages).

4.1 Development of Historical Commercial Landings, 1873-1947

Landings of Gulf Menhaden for reduction purposes prior to about 1948 are limited and occur intermittently in a series of historical publications to be described in the next two subsections.

4.1.1 Commercial Catch Statistics from Historical Reports, 1880-2000

Data from various annual reports (Fishery Industries of the United States, 1920-1939; Fishery Statistics of the United States, 1939-1977; and Fisheries of the United States, 1966-2007) are summarized for 1880-2000 (NOAA various years). Other than 2,000 pounds of Gulf Menhaden reported in 1902, positive landings appear in the records in about 1918; they are not identified by gear or use, but are assumed to be for reduction and for other commercial gears/uses (e.g., bait). Intermittent landings from the west coast of Florida were reported from 1918-1948, after which consistent annual landings were shown through 2000. Alabama only reported consistent values starting in the 1980s. Landings from the other Gulf States were inconsistent until 1948. This generally agrees with our understanding of the historical development of the fishery in the Gulf of Mexico. Because of the gaps in these data, we used a process of linear interpolation to ‘smooth’ data between 1918 and 1948.

4.1.2 Menhaden Fishery, 1873-1964

During a previous Atlantic Menhaden assessment (ASMFC 2010), we discovered a report titled Menhaden Fishery, 1873-1964. This report, which can be found in USFWS (1966), contains summary statistics for the menhaden fishery (both coasts combined) from 1873-1964. Atlantic Menhaden landings were extended back to 1873 during SEDAR 20 (ASMFC 2010). We also used these data to extend Gulf Menhaden landings back as well. The average proportion of Gulf to total menhaden for 1918-1940 was calculated at 2.46% when data were more robust (1918 onward). This proportion was applied to the total menhaden landings from 1873-1917 to separate landings between the two coasts (ASMFC 2010). These landings are shown in Figure 4.1, along with subsequent landings developed for 1948-2017. The important point taken from these reconstructed data is that overall commercial Gulf Menhaden landings were generally small prior to World War II (averaging about 5 mt for 1873-1939). Landings rose during WWII to about 133 mt estimated for 1947. As described in the next section, detailed landings from the reduction fishery became available in 1948.

4.2 Commercial Reduction Fishery (1948-2011)

4.2.1 Overview of Fishery

The commercial fishery for Gulf Menhaden consists primarily of a directed purse-seine fishery for *B. patronus* for reduction purposes and is almost exclusively a single species fishery for Gulf Menhaden. Small and relatively insignificant amounts of other menhaden species, i.e., Yellowfin Menhaden or Finescale Menhaden, may be incidentally harvested as these species may overlap with *B. patronus* at the extreme east and west ranges of the Gulf Menhaden fishery (Ahrenholz 1991).

Official commercial landings of Gulf Menhaden from the reduction purse-seine fleet have been maintained by the Beaufort Laboratory of the National Marine Fisheries Service (NMFS). When the Menhaden Program began at the Beaufort Laboratory in the early 1950s, staff visited menhaden plants along the Gulf of Mexico coast, obtaining detailed fishery landings for the reduction fishery consistently back to 1948. Subsequently, detailed dockside landings from the reduction fishery have been maintained on computer files by calendar year. These landings are considered the best available data for purposes of stock assessments.

The reduction fishery for Gulf Menhaden is a daytime fishery, which employs purse-seine gear to encircle schools of menhaden. Two purse boats (approximately 40 ft long), each holding one-half of the seine, are deployed from a large carrier vessel (approximately 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 directing the purse boat crews to set 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 4-5 sets per fishing day and median catch size per set is about 17-22 mt (Smith et al. 2002). At the end of the fishing trip, which is often a multi-day trip, the catch is pumped at dockside into the fish factory. Then, the catch is reduced into the three main processed products of the menhaden industry - fish meal, fish oil, and fish solubles.

Prior to World War II, most menhaden was dried and sold as ‘fish scrap’ for fertilizer. By the early 1950s, the demand for fish meal as an ingredient in poultry feeds increased as the ‘fryer’ chicken industry expanded. During the latter half of the twentieth century, menhaden meal also became an integral component in swine and ruminant feeds. By the 1990s, menhaden meal was milled in greater quantities into aquaculture feeds. Previously, 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 utilized by the pharmaceutical, processed-food, and aquaculture industries of the U.S.

Location and activity of the reduction plants are summarized in Table 4.1 for 1964-2017. The number of plants operating between 1964 and 1985 ranged between 10 and 14. After that, plants consolidated and reduced to four factories on the U.S. Gulf coast from 2000-2013. After 2013, another plant closed, leaving three factories, two owned by Omega Protein, Inc. (at Moss Point, Mississippi, and Abbeville, Louisiana) and one owned by Daybrook Fisheries, Inc. (at Empire, Louisiana). Through the past decade, the number of Gulf Menhaden vessels gradually declined from 47 in 2000 to 41 in 2006. Since 2013, the fleet has been reasonably stable fielding 30 to 35 vessels.

Fishery-dependent data for the Gulf Menhaden reduction fishery are maintained at the NMFS Beaufort Laboratory in three large data sets. Commercial catch and effort data (Table 4.2) for the reduction fishery are available from 1948 through 2017. Contemporary landings data are supplied to the Beaufort Laboratory by the menhaden industry on a daily or weekly basis; catches are enumerated as daily vessel unloads. The biostatistical data, or port samples, for length and weight at-age are available from 1964 through 2017, and represent one of the longest and most complete time series of fishery data sets in the nation. The Captains Daily Fishing Reports, or CDFRs (daily logbooks), itemize purse-seine set locations and estimated catch, and vessel compliance is 100%. Annual CDFR data sets for the Gulf Menhaden fleet are available from 1983 to 2017.

4.2.2 Data Collection Methods

Biological sampling for the menhaden purse-seine fishery is based on a two-stage cluster design and is conducted over the range of the fishery, both temporally and geographically (Chester 1984). 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 (g), and have scales removed for ageing. Nicholson and Schaaf (1978) performed detailed examinations of Gulf Menhaden scales and determined that rings on the scales were reliable age marks (Section 3.3). The number of fish sampled in the second cluster was reduced during the early 1970s from 20 fish to 10 fish to increase sampling of the first cluster (number of purse-seine sets).

The original premise of the Gulf Menhaden port sampling routines remained relatively unchanged for over thirty years; namely, sampling is based on a two-stage design (above) and port agents, who were employed by the NMFS, collected and processed the fish samples. Prior to about 1995, NMFS agents were hired as temporary Federal workers on an intermittent basis, that is, they (mostly undergraduate or graduate students) were employed during the fishing season to collect and process Gulf Menhaden from about May through October. In about 1994, the Federal government eliminated most temporary positions, and the NMFS was no longer able to hire seasonal port agents.

Beginning in about 1995, the solution to acquiring Gulf Menhaden port samples without temporary Federal hires was two-faceted. First, dockside personnel at each fish factory in Louisiana were identified and asked to acquire a target number of fish samples each week of the fishing season; factory personnel are paid a nominal fee per sample. Samples are labeled with date, vessel, and catch location, then frozen in a chest freezer. Second, between about 1995 and 2003 GSMFC wrote "independent contracts" to temporary employees who retrieved frozen samples at the fish factories, then processed the fish samples for size and age composition, mailing data and scale samples to the NMFS Beaufort Laboratory. Beginning in 2004, the LDWF has processed the fish samples from Empire, Abbeville, and Cameron. Port samples from Moss Point, Mississippi, beginning about 1995 were acquired and processed by an employee of the NMFS Pascagoula Laboratory. In recent years, the task of processing the samples from reduction plants has been performed by independent contractors hired through GSMFC and overseen by the NMFS Beaufort Laboratory.

4.2.3 Reduction Fishery Landings

Nicholson (1978) suggested that the "modern" Gulf Menhaden fishery began just after World War II; he documented that 102,900 mt of Gulf Menhaden were landed in 1948 at ports in Florida, Mississippi, Louisiana, and Texas. He noted that landings were incomplete for 1946 and 1947 (Table 4.3). Chapoton (1970 and 1972) reviewed the history and status of the fishery from 1946 to 1970. He cited a general trend toward greater landings over the 25-year period. This upward trend in landings continued during the 1980s culminating with six consecutive years of landings over 800,000 mt (1982 through 1987) and record landings of 982,800 mt in 1984 (Smith et al. 1987, Smith 1991). The historical pattern in landings and corresponding nominal fishing effort (discussed later) are shown in Figure 4.2.

Consolidation within the menhaden industry (plant closures and fewer vessels), weak product prices, and weather were the major contributing factors to declining landings during the 1990s; annual landings during the decade averaged 552,000 mt per year and ranged from 421,400 mt in 1992 (Hurricane Andrew) to 761,600 mt in 1994. During 2000 to 2009, landings averaged 489,580 mt annually, a decline of ~11% from the average of the previous decade. With the exception of 2010 when landings were down slightly following BP's Deep Water Horizon (DWH) Disaster, landings since 2010 have consistently been higher at an average of around 493,000 mt (Table 4.4).

Tropical weather systems in the northern Gulf have played a major role in depressing landings in recent years (Figure 3.10). In 2004 (468,700 mt), the Gulf Menhaden fleet lost considerable fishing time because of Hurricanes Charley and Ivan. In 2005 (433,800 mt), Hurricanes Katrina and Rita severely damaged all four menhaden plants and a number of vessels, shortening the fishing season for most of the factories. In 2008 (425,400 mt), Hurricane Ike delivered significant damage to the two plants in western Louisiana. Moreover, in 2010 (379,700 mt), the DWH Disaster forced major closures to traditional menhaden fishing grounds (Figure 3.12).

Since 1964, the menhaden fishery in the northern Gulf of Mexico has reported Gulf Menhaden landings for reduction during the fishing year directly to the Beaufort Laboratory. Daily vessel unloads are provided in thousands of standard fish (1,000 standard fish = 670 lbs), which are converted to kilograms. Between 2015 and 2017 the reduction fleet (ca. 33 vessels) unloaded an average of 2,080 times during each fishing year; the average unload per vessel was 238 mt.

4.2.4 Age and Size Composition

Detailed sampling of the reduction fishery permits conversion of landings in biomass to numbers-at-age. For each port/week with landings, biostatistical sampling provides an estimate of mean weight and the age distribution of fish caught. Hence, dividing landings for that port/week caught by the mean weight of fish allows the numbers of fish landed to be estimated (Table 4.4). The age proportion then allows numbers-at-age to be estimated. Developing the catch matrix at the port/week caught-level of stratification provides for considerably greater precision than is typical for most assessments.

About 6,300 Gulf Menhaden from the reduction fishery have been processed annually for size and age composition over recent fishing seasons, 2003-2017 (Table 4.4). In comparing menhaden sampling intensity to the old rule-of-thumb criteria once used by the NOAA 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. Because of these high numbers of fish sampled, and the two-stage sampling procedure, we also provide the number of sets sampled by the port samplers (Table 4.4). Number of sets, was favored over number of fish, to indicate sample sizes in the recent Atlantic Menhaden stock assessment (ASMFC 2010) and in the most recent Gulf Menhaden assessments (Vaughan et al. 2007, SEDAR 2013a).

Over the 54-year period that the NMFS has collected fishery-dependent data from the Gulf Menhaden fishery (1964-2017), age-2 fish have been increasingly represented in the catch-at-age matrices (Figure 4.3; Table 4.5). The percentage of age-2 Gulf Menhaden peaked in 2009, representing 73% of the total numbers-at-age in the catch-at-age matrix, but has declined in subsequent years. Reasons for the variation in the age structure of the landings are not well understood. Surely, recruitment success of juveniles into estuarine areas, which are believed to be largely driven by environmental factors, plays a major role. Additionally, decreased fishing pressure over time is another plausible explanation. However, several additional hypotheses have been proposed (at the GMAC meeting in Orange Beach, Alabama, in March 2010) such as: 1) contraction of the fishery over time from the extremes of the species' range (Texas and Florida, where smaller and younger fish are more abundant) towards the center of the species' range (Louisiana and Mississippi); 2) re-distribution over time of age-1 fish toward more 'inside' waters (where they become unavailable to the fishery) due to marsh habitat loss across the Gulf (this is somewhat supported by data from systematic gill net surveys in Louisiana and Texas); and, 3) a 'corralling-effect' that hypoxic waters of the northern Gulf may have on the distribution of Gulf Menhaden (Smith 2000).

4.2.4.1 Run Boats

Since 2000, one Gulf Menhaden plant has employed carry vessels or 'run boats' to transport some of the catch from the fishing grounds to the factory. Run boats are former menhaden steamers that are not involved with deploying purse seines. Rather, they rendezvous with regular steamers on the fishing grounds, pump fish from the fish holds of the steamers into their own fish hold, then transport accumulated catches back to the fish factory. Run boats have been used almost exclusively at Moss Point (briefly used at Cameron in 2000). For most years, about two run boats have been utilized each fishing season since 2000 and on average they have operated during 23 weeks of the 28-week fishing season.

It should be reiterated that the use of run boats is not pervasive throughout the fishery. On the contrary, run boats (usually about two per year) are only used at the Moss Point fish factory. We examined the port sampling databases for the past decade to determine number of run-boat sampling events and to compare samples for size and age from run boats to those of samples from regular fishing steamers (Table 4.6).

For all but one of the six years when port samples from run boats were acquired, they represented less than 1% of all samples obtained for the menhaden fishery; 2 of 836 (0.2%) in 2002, 6 of 1066 (0.6%) in 2003, 2 of 657 (0.3%) in 2007, 2 of 919 in 2012 (0.2%), and 7 of 966 in 2015 (0.7%). Greatest number of samples from run boats occurred in 2011: 23 of 835 (2.8%). For years with samples from run boats, we compared weekly size and age composition of the run boat samples to the regular steamer samples (Table 4.6); for most weekly comparisons, size and age differences varied only slightly. Hence, we conclude that run boat samples are minimally represented in the Gulf Menhaden port sampling data base and that their effect on the size and age composition of the catch is negligible. However, beginning in 2012, we have instructed port agents to avoid sampling run boats.

4.2.5 Nominal Reduction Fishing Effort

4.2.5.1 Background on Units of Observed Fishing Effort in the Menhaden Purse-Seine Fisheries.

Often, menhaden vessels unload their catches daily, although trips of 2-3 days are common. The menhaden plant records, while showing the date and amount of fish unloaded per vessel, do not list number of days fished, or days when the catch was zero. Logbooks were placed on Atlantic Menhaden vessels during the late 1950s and early 1960s to try and collect better information on 'fishing' and 'non-fishing' days at sea (Roithmayr 1963), but compliance was incomplete (Nicholson 1971). Similar attempts to maintain logbooks on Gulf Menhaden vessels (1964-1969) also met with mixed results (Nicholson 1978). Thus, through about the 1970s there was no satisfactory way to acquire a complete at-sea history of each menhaden vessel.

Considering that menhaden vessels generally operate continuously over the course of a fishing season and fish every day that weather permits, Nicholson (1971) argued that the vessel-week (one vessel fishing at least one day of a given week) was a satisfactory unit of nominal fishing effort for the Atlantic Menhaden purse-seine fishery. Thus, a vessel unloading a catch at least one time during a given week was assigned one vessel-week of effort. Vessel-weeks for all vessels in the Atlantic fleet were calculated across all months of operation, and then summed for an estimate of annual nominal or observed fishing effort for the fishery. For the Gulf Menhaden fishery, Chapoton (1972) noted that fishing efficiency is more directly related to size of the vessel and its fish hold capacity. Thus, the vessel-ton-week (VTW - one vessel fishing at least one day of a given week multiplied by its net tonnage) is used as a measure of nominal fishing effort for the Gulf Menhaden fishery, as it better accounts for efficiencies among different-sized vessels (Figure 4.2). Similar to Atlantic Menhaden, the correlation between landings and nominal fishing effort (VTW) for the Gulf Menhaden fishery is statistically significant ($r^2 = 0.76$ for 1955-2017). The regression of landings on nominal effort is presented with observed values in Figure 4.5.

As a rule, estimates of nominal fishing effort have only been used by the Menhaden Program at the NMFS Beaufort Laboratory for forecasting annual catches for the Gulf and Atlantic Menhaden fisheries. In a general predictive sense, the amount of nominal fishing effort expended is a good indicator of the amount of fish that may be removed from the stock in a given year. Save for production models such as ASPIC and SRA (see SEDAR 2011a), estimates of nominal fishing effort have not been used in menhaden statistical catch-at-age models for reasons outlined below.

4.2.5.2 CPUEs for the Fishery

In a general sense for many fisheries, catch-per-unit-effort (CPUE) is used as an index of abundance, where a proportional change in CPUE is expected to represent the same proportional change in stock size. However, for purse-seine fisheries it has been demonstrated that CPUE and nominal or observed fishing effort are poor measures of population abundance (Clark and Mangel 1979), which is especially true for those fisheries that utilize spotter aircraft. Thus, we have been wary of using fishery-dependent CPUE as a measure of population abundance for the menhaden fisheries. Specifically, there is concern about hyperstability in the CPUE measure because the effectiveness of spotter pilots and the schooling nature of menhaden strongly suggest that catch level could be maintained relatively constant in the presence of declining population abundance. For reference purposes, CPUE in total landings divided by vessel-ton-weeks (VTW) for the Gulf Menhaden fishery for 1948-2017, are shown in Figure 4.6.

That said, while attempting to develop indices of abundance for the previous assessment, staff were intrigued with the relationships between two exploratory CPUE indices - numbers of age-1s and age-2s caught by the fishery and observed fishing effort of the Gulf Menhaden fleet (in terms of number of purse-seine sets; Table 4.7) – when compared to fishery-independent indices developed for the assessment, namely, the juvenile seine index and the adult gill net index. The exploratory indices were calculated by dividing annual numbers of age-1s and age-2s from the catch-at-age matrices by the annual number of purse-seine sets made by the fishery from the CDFR data bases. CDFR data are incomplete for years 1994-95 and 2005; effort for these years was estimated by averaging adjacent years where the data sets were complete. The resulting CPUEs were scaled to their respective means. The age-1 index was assumed to be a signal of incoming recruitment to the fishery; it was lagged one year and was plotted with the juvenile fishery-independent seine survey data. The correlation between the age-1 fishery-dependent index and the seine index was 0.42. The age-2 index was assumed to be a signal of adult abundance in the fishery; it was plotted with the adult fishery-independent gill net data. The correlation between the age-2 fishery-dependent index and the gill net index was 0.68. Although both indices seem closely correlated with their fishery-independent analogs, the fishery-dependent indices were ultimately deemed inappropriate for use in the assessment because of concerns related to fishery hyperstability as noted above.

4.2.5.3 Alternate Measures of Nominal Fishing Effort in the Gulf Menhaden Fishery

In fall 2007, the GSMFC's Menhaden Advisory Committee (MAC) requested that the NMFS Beaufort Laboratory explore alternate units of nominal fishing effort for the Gulf Menhaden fishery that might replace the traditional effort unit, the VTW, for predicting annual menhaden forecasts. Since annual CDFR data sets are available electronically for most years with 100% compliance beginning in 1983 (except 1992, 1993, and 2005), we explored two potential alternate units of nominal fishing effort: 1) total number of purse-seine sets, and 2) total number of fishing days when at least one purse-seine set was made (Table 4.8). Some conclusions of this exercise were that:

1) total number of sets and number of days with >=1 purse-seine set were closely correlated with the traditional unit of observed effort, VTWs, and

2) VTWs were adequate for current use in NMFS landings forecast models.

During the Data Workshop portion of SEDAR20 for Atlantic Menhaden (ASMFC 2010), catch per trip was investigated as an alternate unit of CPUE for the Atlantic Menhaden purse-seine fishery. Therefore, we explored the use of catch per fishing trip as a unit of CPUE for the Gulf fishery. Catch-per-trip was calculated simply as the total annual landings of Gulf Menhaden for reduction divided by the number of times Gulf Menhaden vessels unloaded during the fishing season (unload events for 1983 and 1984 are incomplete). Surprisingly, catch-per-trip for the Gulf fleet has risen steadily from the mid-1980s to present (Table 4.9). Reasons for this increase potentially include: 1) longer trip duration, affording increased chances of encountering fish schools; 2) newer vessels with larger hold capacities; 3) improved efficiencies within the fleet, notably use of stern ramps or similar devices by most vessels to launch and retrieve the purse boats, reducing time between sets allowing for more sets to be made each day; and 4) reduced numbers of vessels and plants over time has reduced fishing pressure and therefore increased the ability to catch fish (NMFS Beaufort Lab unpublished data).

These three measures of nominal fishing effort were scaled to the terminal year (2017) for comparison purposes in Figure 4.5. Similarly, CPUE based on these three measures of nominal fishing effort are compared in Figure 4.6. From about 1980 onwards, trends were similar for all three measures. However for the period from 1964 to about 1980, there were differences found between VTW and trips as measures of fishing effort. Changes in fleet characteristics since about the 1980s may explain this divergence. Beginning in the 1970s and early 1980s, newer vessels with larger fish holds and greater net tonnages joined the fleet (net tonnage is a calculation of the volume of cargo space within a ship). Vessels with larger fish hold capacities presumably can stay on the fishing grounds longer and necessarily make fewer trips in a given fishing year. Table 4.10 illustrates this trend toward greater mean vessel net tonnage in the Gulf Menhaden fleet over the past forty years, showing an increase of about 100 net tons since 1970.

4.2.6 Commercial Reduction Catch-At-Age

Methodology for estimating catch in numbers at age from the fishery has been used consistently with time (Nelson and Ahrenholz 1986, Vaughan 1987, Vaughan et al. 1996, Vaughan et al. 2000, Vaughan et al. 2007, SEDAR 2013a). Catch in numbers at age are developed by week and port based on the detailed port sampling and weekly catch records. For much of the time period, age-2 fish have been making up an increasing percentage of the catch (Figure 4.3). The percentage of age-2 fish increased from 20% or less in the early portions of the time period until 2009, when 73% of the landings were age-2 fish. In the years since, the proportion of age-2 and age-1 fish in the landings have alternated in holding the majority, but the last three years have seen a relative increase in age-1s since 2009.

4.2.7 Potential Biases, Uncertainty, and Measures of Precision

4.2.7.1 Catch-Measuring Conventions and Devices Used by the Fishery

When the menhaden program began in the early 1950s at the NMFS Beaufort Lab, staff visited all menhaden plants along the Gulf coast to obtain detailed information back to 1948. These landings and those subsequently collected are thought to be quite accurate. A study (Kutkuhn 1966) was conducted to determine the quantity of fish passing through a given plant based on the number of dumps of the fish hopper. The results suggest that these are accurate to about 3.7% coefficient of variation. It was noted that greater uncertainty was associated with fish spoilage (more likely in the earlier years with unrefrigerated fish holds on vessels).

The menhaden industry self-reports landings in 1,000s of standard fish. This convention dates to the early days of the fishery on the Atlantic coast when 1,000 standard fish were taken to weigh 670 pounds and the volume of a standardized hopper used at reduction plants to offload landings held 1,000 standard fish. The question of consistency among measuring devices for landings at menhaden factories on the Atlantic and Gulf coasts no doubt concerned staff during the early stages of the Menhaden Program at the NMFS Beaufort Laboratory. Kutkuhn (1966) noted that the traditional unit of measurement for landings in the menhaden fishery is the ‘quarter-box’ dump [or hopper], which volumetrically, by the menhaden industry’s definition, measures 22,000 cubic inches, and traditionally recognized to hold 667 lbs. Kutkuhn empirically showed that

> “the factor 0.667 - or 0.67, whichever is more convenient - should now be affirmed as the official standard for converting to weight all landings of menhaden measured volumetrically in ‘quarter-box’ dumps and reported by the industry in terms of thousands-fish units (i.e., 1,000 ‘standard’ fish weigh on the average, 667 pounds or one-third short ton).”

Furthermore, a coefficient of variation about his results of 3.7% suggested a high degree of accuracy for the landings. Kutkuhn also recognized that some extant fish plants at the time used continuous weighing machines to measure landings. Such devices were calibrated to tally one thousand standard fish with each passage of 755 lbs; the difference (88 lbs from the 667 lb value above) was "attributed to additional water, dirt, and slime that adhere to the fish as they are pumped from the vessel." June and Reintjes (1976), in describing the evolution and methods of the menhaden fishery, reaffirmed that each segment of the rotating hopper device used to measure landings holds volumetrically 22,000 cubic inches, "representing a unit measure of 1,000 'standard' fish." They also noted that regardless of the weighing equipment employed, this "unit of measure [1,000 standard fish] is used throughout the industry to express the quantity of catch." Based on the information above, the conversion factor of 0.670 (1,000 standard fish = 670 lbs) was adopted by the NMFS Beaufort Lab's Menhaden Program.

To address any contemporary concerns about the consistency of hopper dimensions and weigh-out devices, plant managers at the four extant Gulf Menhaden factories were queried about the dimensions and operation of their fish weigh-out machines. It was learned that two factories, at Moss Point and Empire, still use rotating hopper devices, or 'quarter-box' dumps, to measure their landings. On the other hand, the other two factories, at Abbeville and Cameron, used continuous weigh-out conveyors, or belts, to measure their fish unloads.

Prior to the start of the 2012 fishing season, the plant engineer at the Moss Point factory measured the internal volume of the fish hopper at the Mississippi facility. He provided: 1) photographs of the hopper's dimensions and 2) the subsequent calculations for the hopper's volume. The hopper at Moss Point measured 21,935.6 in^3, remarkably close to the convention of 22,000 in^3 per 1,000 standard fish.

Plant personnel at the Empire fish factory had no available drawings of their fish measuring devices. However, they did report that their fish hoppers are 1.5 times larger than the traditional menhaden fish dump, and as such, they measure approximately 33,264 in^3 in volume (33,264 in^3 / 22,000 in^3 = 1.5).

The fish factories at Abbeville and formerly at Cameron use continuous belt scales to measure their Gulf Menhaden landings. The scales and systems at both plants are virtually identical. The fish are pumped from the vessels and discharged onto a conveyor belt with an in-line belt scale and integrator. The scale measures the mass of fish and an optical speed sensor measures the belt velocity; weight and speed data are integrated into an instantaneous mass flow value. Belt scales are calibrated at the start of the fishing season. Adjustments (proprietary information) to weigh-outs are made for excess water and slime in the fish stream. Dry weight of fish is determined to be 667 lbs.

In summary, the fish measuring convention for landings in the menhaden industry has been exceptionally consistent over the course of the fishery's long history. The basic unit-of-measure remains the fish hopper, or dump, which holds 1,000 'standard' fish, or one-third of a short ton. Vessel crews, and to some extent spotter pilots, are paid based on each measure of 22,000 in^3 of fish unloaded. For convenience, the NMFS has used the conversion factor of 670 lbs/1,000 'standard' fish measure reported by the industry. Reduction landings of menhaden since the 1940s are believed to be both accurate and precise compared to most other U.S. fisheries. Assessment panelists agreed to use a CV of 0.04 for the Gulf Menhaden landings over time.

4.2.7.2 Catch-at-Age Matrices

Development of catch matrices depended on three data sources, including the landings, sampling for weight, and age determination. The landings are thought to be both accurate and precise, and the hopper measurements have been reevaluated recently. The sampling for size and age has been conducted weekly by port since 1964 (Smith 1995). The catch matrix was built from samples by port, week, and area fished as noted above. There are two main uncertainties associated with ageing of the port samples. The first concern is precision and accuracy of ageing over time. The second concern is the implicit assumption that the samples taken from the top of the hold represent the catch throughout the hold on a week by port basis.

Precision and accuracy of ageing over time: During the early decades of the Menhaden Program at the NMFS Beaufort Laboratory, scales from individual menhaden specimens were read multiple times by several readers. Disagreements on age estimates were decided by an additional reading. By the early 1970s, probably because of budget constraints, only a single reader was retained on staff to age menhaden scales. This NMFS employee, Mrs. Ethel A. Hall, read menhaden scales from 1969 to her retirement in 2015.

There has been some concern (SEDAR 2011a) that the menhaden scale reader at the Beaufort Laboratory read scales over several decades and that there "may be some drift in her readings" over time (from younger to older age assignments). We resolved to check the consistency of her age readings throughout the whole time series. To address this issue, archived Gulf Menhaden scale samples were retrieved from storage at the Beaufort facility and E.A. Hall re-read sub-samples of scales that she had read from previous decades. Scales from three years for each of four decades were randomly chosen. Years selected were 1972, 1974, and 1978; 1981, 1984, and 1988; 1992, 1995, and 1999; 2002, 2005, and 2010. Within each year, 600-650 scale samples were chosen (Thompson 2002) representing three or four fishing ports. Our scale reader was instructed to re-age the scales under original conditions, that is, she had access to specimen collection date, port of landing, fork length, and weight. Only annual ages were re-recorded with no measurements made to successive annuli.

The general condition of the archived scales samples was quite remarkable, considering their age, number of times they were moved and re-packaged, and conditions under which they were stored. However, scales from two (1972 and 1992) of the twelve years were deemed in poor to fair condition, as mold and/or debris had occluded some of the scales and the two microscope slides between which the scales are sandwiched. A total of 6,631 scales were re-read and assigned ages. Across all years, agreement between original and second readings was 82% (annual ranges: 70-90%). Least agreement occurred in 1972 (71%) and 1992 (70%), years when scales were obscured by contaminants. Across all years but within age classes, agreement for age-1s was 80% (range: 66-100%), for age-2s was 85% (range: 72-94%), and for age-3s was 76% (range: 50-90%, but with generally low N's for all years).

If an 'ageing drift' had occurred, then considerable disagreement in the paired age readings would have been likely during analysis years in the 1970s and 1980s. On the contrary, age agreements across most years and age classes were somewhat invariate, save for 1972 and 1992 as noted above.

To compare the initial reading with the re-read, confidence intervals for a proportion were calculated to see if they overlapped for the ages and years resampled. Additionally, simultaneous multinomial confidence intervals were calculated for each year to determine if there was a significant difference in the proportions at age for the re-reads as compared to the original reading of the scales. Based on the multinomial confidence intervals, which are the more appropriate statistical test, the years 1972, 1974, 1988, and 1992 had significantly different age proportions (Figure 4.7).

Based on these analyses, no apparent ageing drift has been occurring over time. If ageing drift had been occurring over time, we would have seen systematic differences between the initial age read and the re-read; however, that was not the case. As discussed in Section 3.2.2, the assessment panelists did exclude age composition data from the earliest years.

Representative sampling of the catch: There has been additional concern (SEDAR 2011a) about the potential bias associated with sampling only the last purse-seine set of the trip. Are there sampling biases and are they toward larger/older fish or smaller/younger fish? Are the samples from the last set of the day on a port-week basis representative of what is contained throughout the hold on a port-week basis? To address these issues, ideally one would place agents onboard menhaden vessels to serially sample purse-seine sets for size and age composition during assigned fishing trips throughout the fishing season. Unfortunately, our sampling resources are limited. Alternately, we devised a plan to sample vessels at dockside and to acquire fish samples from throughout the fish hold during the vessel unloading operation, not just the top of the fish hold. Fish factory dockside workers at each menhaden plant were asked to sample several vessels seasonally in 2012 as the vessels were unloading their catches. For each vessel, a sample was acquired (as per regular sampling protocols; see Section 4.2.2) from the top of the fish hold, with three additional samples taken periodically during the pumpout process and from the fish stream at the hopper or catch-measuring device (see Section 4.2.7.1), i.e., start, middle and end of the unloading process. Samples from the fish stream were not necessarily assumed to represent identifiable purse-seine sets of the fishing trip, rather, they were assumed to be mixed fish from many sets of the given trip.

Sampling efforts varied by port and season. A total of 31 pumpout events were sampled with four replicates each (top of the hold and start, middle and end of the pumpout); overall, 1,240 fish were sampled for size and age composition. At Moss Point, three pumpout events were sampled (one in August and two in October); at Empire 11 pumpout events were sampled (one in May, one each in August and September, and eight in October); at Abbeville, 13 pumpout events were sampled (three each in June, August, and September, and four in October); at Cameron, four pumpout events were sampled (one in August and three in October).

These pumpout data were explored a number of ways, but because sample sizes were small statistical analyses were limited and generalizations about the data could not be provided. First, the samples were looked at overall across all pumpout dates and ports. No difference was apparent between the traditional sample and the samples from throughout the hold (Figure 4.8). Second, samples examined within the month of August, but across all ports. The samples in August were collected from August 6-10, so within a shortened period of time. The traditional sample did not collect any age-4 individuals, collected more age two individuals, and fewer age-1 and age-3 individuals (Figure 4.9); however, the samples sizes were inadequate to make any generalized statement about the adequacy of sampling from the top of the fish hold, as traditionally done. Third, samples were examined within the month of October, but across all ports. The samples in October were collected from October 8-30. The traditional sample did not collect any age-4 individuals, but did collect similar proportions of the other age classes

(Figure 4.10). Samples sizes were larger than in August, but were still small and inadequate to make any generalized statement about the adequacy of sampling from the top of the fish hold, as traditionally done. Lastly, samples were examined within a port for the month of October. The samples in October were from Moss Point (n = 2), Empire (n = 4), Abbeville (n = 8), and Cameron (n = 3) with samples sizes being the number of boats sampled at each port. For Moss Point, the end position was different from the traditional sample (Figure 4.11A); for Empire, the traditional sample captured age-0 but no age-4 individuals (Figure 4.11B); for Abbeville, the traditional sample captured age-0 and age-3 (Figure 4.11C); and for Cameron, the traditional sample didn't capture any age-0 individuals (Figure 4.11D). The traditional sample was different at individual ports, but samples sizes were still small and inadequate to make any generalized statement about the adequacy of sampling from the top of the fish hold, as traditionally done. Although there doesn't seem to be any concern at the moment, the assessment panelists would like this explored further and have included this in their research recommendations. A research effort has been funded to examine this further, samples have been collected and are being processed to complete this research effort.

4.3 Commercial Bait Fishery (1950-2017)

The bait fishery for menhaden has historically accounted for only a minute portion of the total landings of Gulf Menhaden. Until the mid-1980s, the bait purse-seine fishery for Gulf Menhaden occurred almost exclusively in Florida. Louisiana and Alabama began landing menhaden for bait in 1984, and Louisiana's landings increased substantially through the mid to late 1980s. Through the 1990s, two companies in Morgan City and Cameron, Louisiana, were responsible for a majority of the Gulf Menhaden landings for bait in the central northern Gulf. Bait landings of Gulf Menhaden have declined substantially since the early to mid-2000s but some landings still occur in Louisiana. Minimal bait landings of menhaden come from Florida and Alabama but in very low quantity and don't exclusively include Gulf Menhaden.

4.3.1 Bait Fishery Overview

Although little published information exists on menhaden bait fisheries (Smith and O'Bier 2011), the majority of Gulf Menhaden harvested for bait in the northern Gulf of Mexico probably are used as bait in the blue crab trap fishery and the crawfish fishery. Some bait is sold fresh at dockside; however, most is probably frozen and trucked throughout the Gulf region.

Menhaden are also used commercially by long-line and hook and line fishermen as bait and chum for Red Snapper, Grouper, and other reef fishes. In the recreational fishery, menhaden are used for bait and chum by sport fishermen and the charter boat industry.

Historically, Florida and Louisiana have been the main participants in the Gulf Menhaden bait fisheries. During the peak years, Florida bait landings were concentrated in Tampa Bay and off the Panhandle region. Closure of Tampa Bay to purse-seine fishing by about 1991-1992 and the Net Limitation Amendment to the Florida Constitution in 1995 (prohibiting purse-seine gear in state waters) no doubt contributed to the decline in landings that followed. Since 1995, Alabama has begun to provide a larger component of the bait landings to meet the bait demands of other commercial and recreational fisheries primarily using gillnets. In Florida and Alabama, harvesting gears for menhaden include cast nets, gill nets, and some modified purse type gear, which are smaller than the traditional gear still used by the reduction fleet. In Louisiana and Mississippi, bait may be commercially harvested using any legal gear including traditional purse nets.

The majority of bait still originates from Louisiana. In the 1990s, two bait companies began using former reduction fishery steamers to harvest Gulf Menhaden near Morgan City and Cameron. The operation in Cameron was closed in 2000. The company in Morgan City closed in 2007; consequently, Gulf Menhaden landings for bait in Louisiana declined sharply until 2013. A startup bait company with a single boat began operating in 2013 and continues to fish in Louisiana waters today.

4.3.2 Bait Landings

Gulf Menhaden commercial bait landings are available by gear through the NMFS Office of Science and Technology, Fisheries Statistics Division's Commercial Landings website (1950-2017), particularly for 1950-1961 prior to availability of data from the NOAA Accumulated Landings System (NOAA ALS) for 1962-2017. The NOAA ALS data were provided by NOAA Southeast Fisheries Science Center staff in Miami, Florida, in June of 2018. During SEDAR 2013a, two Florida gear codes (100 - ENCIRCLINLING NETS (PURSE) and 125 - PURSE SEINES, MENHADEN) from the ALS database were censored as those landings were thought to be part of the reduction landings. However, during the 2015 revision to the Gulf Menhaden FMP (VanderKooy and Smith 2015), it was discovered that there was a long history of menhaden along the Florida Panhandle being landed as bait using these gears (100 and 125) and others (145 – PURSE SEINES, OTHER), which also includes the new bait participants in Louisiana. During the Gulf Menhaden Update Assessment GDAR02 (Schueller 2016), the assessment panelists agreed to keep codes 100 and 125 as bait landings and not censor them as they had during SEDAR 2013a. However, the majority of the landings are confidential due to the few participants in the fishery and must be summarized across all gears and states. In addition, NOAA does not break out the bait landings by species and so represent a mix of the three species that occur in the Northern Gulf and their hybrids, although Gulf Menhaden are the dominant species in the bait fishery.

Purse-seine fisheries for Gulf Menhaden for bait were active off the west coast of Florida and Louisiana during the 1980s through about 2000, but landings for bait were minor compared to the reduction fishery. A mixed-species aggregate by-catch of Gulf Menhaden mostly from gill nets and haul seines also exists in several states, but total bait landings are minor compared to the reduction fishery.

Purse-seine landings were the dominant gear for bait landings. Gill nets and haul seines also were important gears for landing Gulf Menhaden for bait with the remaining bait landings caught by a variety of gears. An annual plot of the bait landings lumped for all three species Gulf-wide by percent contribution from various gears demonstrates a period between 1986 and 2007 when purse seines dominated the bait landings (Figure 4.12). Peaks in the other gears also occurred during the 1980s and 1990s. Bait landings were very small prior to 1980 and more recently. The total landings cannot be broken out further than by general gear across all states due to confidentiality. Bait and recreational landings are compared with reduction landings in Figure 4.13.

The assessment panelists recommended using average bait landings for 1950-1959 (9 mt) for 1948-1949. For the recent period 2010-2017, bait landings averaged about 2,600 mt or 0.5% of the average of 493,000 mt for the reduction fishery (Table 4.11). However, bait landings did range between 1% and 2% of the coastwide landings between 1987 and 1999.

4.3.3 Commercial Bait Catch-At-Age

The small amount of bait landings was combined with reduction landings to produce a single landings stream for 1948-2017 and a single catch at age matrix for use in stock assessment models for 1964-2017 (Table 4.11) for both the base run (1977-2017) and sensitivity runs (which included start years of both 1964 and 1948).

4.3.4 Potential Biases, Uncertainty, and Measures of Precision

Uncertainty associated with bait landings is likely to be substantial, but no formal means is available for estimating either bias or precision. We suspect that these estimates are more likely to be underestimates, but the degree to which this might be true is unknown.

4.4 Recreational Fishery (1981-2017)

A small amount of Gulf Menhaden harvest can be attributed to the recreational fishery, predominantly by cast net. Comparable data for Atlantic Menhaden were considered in the recent assessment on that species (ASMFC 2010). To examine the potential recreational landings, the Marine Recreational Information Program (MRIP), its predecessor, the Marine Recreational Fisheries Statistical Survey (MRFSS), and the ongoing Texas Parks and Wildlife Department (TPWD) Creel Survey were queried. The level of catch from the TPWCS was too small to provide estimates. However, the MRIP/MRFSS provided the information that follows.

4.4.1 Data Collection Methods

Data from the MRIP/MRFSS were downloaded from the NMFS Office of Science and Technology, Fisheries Statistics Division’s Recreational Landings website using the Custom Query option (NOAA unpublished data). See MRIP/MRFSS online for discussion of methods. Insufficient biological samples were available to develop a catch at age matrix. See below for a discussion of the treatment of recreational landings.

4.4.2 Recreational Landings and Discards

Estimated recreational catches are reported as number of fish harvested (Types A and B1), released alive (Type B2), and total caught (Types A+B1+B2). The fundamental cell structure for estimating recreational catches is by state [Florida - Texas], mode of fishing [beach/bank, man-made, shore, private/rental, charter], fishing area [inland, ocean (<=3mi), ocean (>3mi)], and wave [six 2-month periods]. To determine total removals, an estimate of release mortality to apply to the B2-caught fish was required. The assessment panelists suggested using a value of 100% mortality. Based on this value, the total number of fish dying due to recreational fishing would then be given by A+B1+B2. To provide estimates of harvest (Type A+B1) in weight, the catch records were retained at the basic cell level for which both harvest in numbers and harvest in weights were available. These landings were then pooled and the ratio was used to obtain an average weight. For lack of data, we make the assumption that the size (mean weight) of the B2-caught fish is similar to that of the A+B1 fish and combine them in calculating our harvest in weight. Thus, the average weight (121 g) was applied by region to total harvest (A+B1+B2) in numbers to obtain harvest in weight. Recreational landings for 1981-2017 are summarized in Table 4.2. Similar to filling in missing values for landings to the reduction fishery, average values were obtained from 1981-1990 and were used to fill in recreational landings for the years 1948-1980.

To put these removals into perspective, for 2010-2017, reduction landings have averaged 493,000 mt, bait landings have average about 2,635 mt, and recreational landings have averaged about 412 mt. In general, the recreational landings represent about 0.08% of the reduction landings and about 15.6% of the bait landings.

4.4.3 Recreational Catch-at-Age

The combined landings by bait and recreational fisheries are compared with those by the reduction fishery in Figure 4.13. This small amount of recreational catches was combined with reduction and bait landings to produce a single catch at age matrix for use in stock assessment models (Table 4.12). Specifically, the total landings in weight based on all three fisheries were divided by the reduction landings to calculate an annual expansion factor. This expansion factor was multiplied by the catch at age matrix in Table 4.4.

4.4.4 Potential Biases, Uncertainty, and Measures of Precision

Uncertainty associated with recreational landings is substantial, but probably no worse than for bait. The MRIP/MRFSS provides estimates of PSE (proportional standard error) as a measure of precision. These values (not reported here) ranged between 22% and 99%, and averaged 42%.

4.5 Discards and Bycatch

Shrimp bycatch estimates for Gulf of Mexico Gulf Menhaden were generated using an approach modified from Nichols (2004a, 2004b) in the SEDAR 7 Gulf of Mexico Red Snapper assessment (SEDAR 2004a), and applied by Linton (2012) in the SEDAR 31 Gulf of Mexico Red Snapper assessment (SEDAR 2013d; Figure 4.14). The primary data on CPUE in the shrimp fishery came from a series of shrimp observer programs beginning in 1981 that extend to the current shrimp observer program. Additional CPUE data were obtained from the SEAMAP groundfish survey (Figure 4.15). Point estimates and associated standard errors of shrimp effort were generated by the NMFS Galveston Lab using their SN-pooled model (Nance 2004). Most CPUE data were reported in fish per net-hour. As shrimp effort data were reported in vessel-days, data from the Vessel Operating Units File were needed to estimate the average number of nets per vessel for the shrimp fishery to convert total shrimp effort to net-hours. A detailed description of data and methods used to produce shrimp bycatch estimates can be found in Linton (2012). Gulf Menhaden bycatch was estimated using the total effort for a given year (E), total bycatch for a given year (B), and the proportion of effort that caught Gulf Menhaden as bycatch (P) such that:

$$\text{Bycatch} = E \cdot B \cdot P.$$

Shrimp effort was used as an index of shrimp fishing mortality in addition to its use in the estimation of shrimp bycatch. Shrimp effort for depths greater than 10 fm was chosen to provide an index of shrimp fishing mortality, because effort from these depths is thought to best represent the fishing pressure experienced by Gulf Menhaden in the shrimp fishery (Figure 4.16). The values in these figures are relatively low and highly uncertain, therefore the data workshop panelists agreed that they would not be considered for the assessment.

Discarding of Gulf Menhaden from the shrimp trawl fishery prosecuted across the northern Gulf of Mexico has been shown to occur. However, data regarding the magnitude of the discards is unavailable.

4.5.1 Potential Biases, Uncertainty, and Measures of Precision

Uncertainty in the discard estimates from the shrimp trawl fishery are probably large, but generally unknown. Potential biases exist, but are also unknown due to lack of data.

Table 4.1 Years of activity for individual menhaden reduction plants along the U.S. Gulf of Mexico coast, 1964-2017.

Year	Plant																	Total Plants
	54	55	56	57	58	59	60	61	62	63	64	65	68	69	70	71	72	
1964	●	●	●	●	●	●	●		●	●	●	●						11
1965	●	●	●	●	●		●		●	●		●	●	●	●			12
1966	●	●	●	●	●		●	●	●	●	●	●	●	●				13
1967	●	●	●	●	●		●		●	●	●	●	●	●		●		13
1968	●	●	●	●	●		●	●	●	●	●	●	●	●		●		14
1969	●	●	●	●	●			●	●	●	●	●	●	●		●		13
1970	●	●	●	●	●		●		●	●	●	●	●	●		●		13
1971	●	●	●	●	●		●		●	●	●	●	●	●		●		13
1972	●	●	●	●	●				●	●	●		●	●		●		11
1973		●	●	●	●				●	●	●		●	●		●		10
1974		●	●	●	●				●	●	●		●	●		●		10
1975	●	●	●	●	●				●	●	●		●	●		●		11
1976	●	●	●	●	●				●	●	●		●	●		●		11
1977	●	●	●	●	●				●	●	●		●	●		●		11
1978	●	●	●	●	●				●	●	●		●	●		●		11
1979	●	●	●	●	●				●	●	●		●	●		●		11
1980	●	●	●	●	●				●	●	●		●	●		●		11
1981	●	●	●	●	●				●	●	●		●	●		●		11
1982	●	●	●	●	●				●	●	●		●	●		●		11
1983	●	●	●	●	●				●	●	●		●	●		●		11
1984	●	●	●	●	●				●	●	●		●	●		●		11
1985		●	●	●							●		●	●		●		7
1986		●	●	●	●						●		●	●		●		8
1987		●	●	●	●						●		●	●		●		8
1988		●	●	●	●						●		●	●		●		8
1989		●	●	●	●						●		●	●		●	●	9
1990		●	●	●	●						●		●	●		●	●	9
1991			●	●	●								●	●		●	●	7
1992			●		●								●	●		●	●	6
1993			●		●								●	●		●	●	6
1994			●		●								●	●		●	●	6
1995			●		●								●	●		●	●	6
1996			●		●								●			●	●	5
1997			●		●								●			●	●	5
1998			●		●								●			●	●	5
1999			●		●								●			●	●	5
2000			●		●								●			●		4
2001			●		●								●			●		4
2002			●		●								●			●		4
2003			●		●								●			●		4
2004			●		●								●			●		4
2005			●		●								●			●		4

Table 4.1 (*cont.*)

Year	Plant																	Total Plants
	54	55	56	57	58	59	60	61	62	63	64	65	68	69	70	71	72	
2006			●		●								●			●		4
2007			●		●								●			●		4
2008			●		●								●			●		4
2009			●		●								●			●		4
2010			●		●								●			●		4
2011			●		●								●			●		4
2012			●		●								●			●		4
2013			●		●								●			●		4
2014			●		●								●					3
2015			●		●								●					3
2016			●		●								●					3
2017			●		●								●					3

Plant	Name	Location
54	Fish Meal Company	Moss Point, MS
55	Standard Product Company	Moss Point, MS
56	Haynie Products Company, currently Omega Protein, Inc.	Moss Point, MS
57	Empire Menhaden Company	Empire, LA
58	Quinn Menhaden Fisheries, currently Daybrook Fisheries, Inc.	Empire, LA
59	Fish Meal & Oil Company (Bennett)	Dulac, LA
60	Quinn Menhaden Fisheries	Dulac, LA
61	Smith Meal Company	Apalachicola, FL
62	Fish Meal Company	Morgan City, LA
63	Gulf Menhaden Company	Cameron, LA
64	Louisiana Menhaden Company	Cameron, LA
65	Texas Menhaden Company	Sabine Pass, TX
68	Seacoast Products, currently Omega Protein, Inc.	Intracoastal City, LA
69	Terrebonne Menhaden Company	Dulac, LA
70	Florida Reduction Plant	Dulac, LA
71	Omega Protein, Inc.	Cameron, LA
72	Gulf Protein	Morgan City, LA

Table 4.2 Gulf Menhaden landings and effort (vessel-ton-weeks, VTW) from the reduction purse-seine fishery, 1948-2017; landings from the bait fisheries, 1950-2017; landings estimated from the recreational fishery (MRFSS/MRIP), 1981-2017, and combined landings for all fisheries. Recreational landings represent removals of A+B1+B2 by weight. Average values used for shaded areas: subsequent 10-yr average for early years.

Year	Reduction Landings (1000 mt)	Reduction Effort (vtw)	Bait Landings (1000 mt)	Recreational Catches (1000 mt)	Combined Total Landings (1000 mt)
1948	74.6	40.7	0.009	0.199	74.81
1949	107.4	66.2	0.009	0.199	107.61
1950	147.2	82.2	0.000	0.199	147.40
1951	154.8	94.2	0.003	0.199	155.00
1952	227.1	113.3	0.004	0.199	227.30
1953	195.7	104.7	0.001	0.199	195.90
1954	181.2	113.0	0.001	0.199	181.40
1955	213.3	122.9	0.011	0.199	213.51
1956	244.0	155.1	0.014	0.199	244.21
1957	159.3	155.2	0.003	0.199	159.50
1958	196.2	202.8	0.040	0.199	196.44
1959	325.9	205.8	0.009	0.199	326.11
1960	376.8	211.7	0.005	0.199	377.00
1961	455.9	241.6	0.011	0.199	456.11
1962	479.0	289.0	0.009	0.199	479.21
1963	437.5	277.3	0.020	0.199	437.72
1964	407.8	272.9	0.038	0.199	408.04
1965	461.2	335.6	0.196	0.199	461.59
1966	357.6	381.3	0.254	0.199	358.05
1967	316.1	404.7	0.058	0.199	316.36
1968	371.9	382.8	0.207	0.199	372.31
1969	521.5	411.0	0.137	0.199	521.84
1970	545.9	400.0	0.280	0.199	546.38
1971	728.5	472.9	0.366	0.199	729.06
1972	501.9	447.5	0.292	0.199	502.39
1973	486.4	426.2	0.446	0.199	487.04
1974	587.4	485.5	0.319	0.199	587.92
1975	542.6	538.0	0.211	0.199	543.01
1976	561.2	575.8	0.328	0.199	561.73
1977	447.1	532.7	0.298	0.199	447.60
1978	820.0	574.3	0.404	0.199	820.60
1979	777.9	533.9	1.727	0.199	779.83
1980	701.3	627.6	0.999	0.199	702.50
1981	552.6	623.0	1.073	0.036	553.71
1982	853.9	653.8	1.577	0.051	855.53
1983	923.5	655.8	1.739	0.023	925.26
1984	982.8	645.9	2.317	0.005	985.12
1985	881.1	560.6	2.870	0.424	884.39
1986	822.1	606.5	1.675	0.244	824.02

Table 4.2 Con't

Year	Reduction Landings (1000 mt)	Reduction Effort (vtw)	Bait Landings (1000 mt)	Recreational Catches (1000 mt)	Combined Total Landings (1000 mt)
1987	894.2	604.2	11.660	0.197	906.06
1988	623.7	594.1	10.287	0.462	634.45
1989	569.6	555.3	12.201	0.416	582.22
1990	528.3	563.1	10.210	0.128	538.64
1991	544.3	472.3	5.325	0.048	549.67
1992	421.4	408.0	7.902	0.130	429.43
1993	539.2	455.2	9.308	0.161	548.67
1994	761.6	472.0	9.987	0.179	771.77
1995	463.9	417.0	8.068	0.053	472.02
1996	479.4	451.7	12.270	0.077	491.75
1997	611.2	430.2	11.927	0.019	623.15
1998	486.2	409.3	7.403	0.045	493.65
1999	684.3	414.5	8.137	0.049	692.49
2000	579.3	417.6	0.793	0.196	580.29
2001	521.3	400.6	0.760	0.045	522.11
2002	574.5	386.7	0.467	0.102	575.07
2003	517.1	363.2	0.487	0.112	517.70
2004	468.7	390.5	0.417	0.122	469.24
2005	433.8	326.0	0.261	0.069	434.13
2006	464.4	367.2	0.174	0.079	464.65
2007	453.8	369.2	0.251	0.042	454.09
2008	425.4	355.8	0.139	0.027	425.57
2009	457.5	377.8	0.134	0.052	457.69
2010	379.7	320.3	0.069	0.157	379.93
2011	613.3	367.2	0.156	0.370	613.83
2012	578.4	332.7	0.319	1.121	579.84
2013	497.5	332.5	0.955	0.304	498.76
2014	391.8	310	8.130	0.688	400.72
2015	535.7	294.2	4.295	0.318	540.31
2016	485.8	307.7	5.354	0.226	491.48
2017	460.7	301.3	1.694	0.061	462.46

Table 4.3 Purse seine catch of Gulf Menhaden, in thousands of metric tons, by State, 1945-1973 (Table 3 *from* Nicholson 1978); NA = Records not available.

Year	Florida	Mississippi	Louisiana	Texas	Total
1945	3.2	26.0	0.0	0.0	29.2
1946	NA	NA	8.9	0.0	NA
1947	NA	10.1	24.0	0.0	NA
1948	15.4	34.8	40.0	12.7	102.9
1949	11.2	30.1	75.2	19.0	135.5
1950	0.6	31.1	94.3	21.2	147.2
1951	1.5	43.4	96.7	13.2	154.8
1952	4.8	70.7	129.2	24.0	228.7
1953	2.0	22.1	142.1	30.3	196.5
1954	0.0	36.0	121.8	23.4	181.2
1955	0.9	56.0	135.1	23.0	215.0
1956	0.0	70.3	144.6	29.9	244.8
1957	0.0	59.3	74.5	26.1	159.9
1958	4.6	56.1	109.5	31.3	201.5
1959	8.2	79.7	191.5	55.9	335.3
1960	2.8	99.1	213.2	65.6	380.7
1961	1.9	136.7	260.2	60.7	459.5
1962	0.0	119.5	314.1	47.1	480.7
1963	0.0	113.6	288.4	35.8	437.8
1964	0.0	107.8	271.4	30.2	409.4
1965	0.0	126.4	308.6	28.1	463.1
1966	3.1	86.4	252.0	17.6	359.1
1967	0.0	75.5	231.4	10.4	317.3
1968	0.3	67.8	282.2	23.2	373.5
1969	0.0	102.2	388.3	33.2	523.7
1970	0.0	93.4	435.2	19.5	548.1
1971	0.0	138.8	560.9	28.5	728.2
1972	0.0	80.8	420.9	0.0	501.7
1973	0.0	80.4	405.7	0.0	486.1

Table 4.4 Sample size as number of fish (N Fish) and number of sets (N Sets), landings in numbers and biomass of fish, and mean weight of fish landed from the Gulf Menhaden reduction fishery, 1964-2017.

Year	Sample Size (N Fish)	Sample Size (N Sets)	Landings		Mean Weight (g)
			(millions)	(1000 mt)	
1964	12,260	625	4,949.61	407.8	82.4
1965	15,185	790	6,232.41	461.2	74
1966	12,429	640	4,244.05	357.6	84.3
1967	14,065	721	4,640.74	316.1	68.1
1968	15,273	795	4,579.55	371.9	81.2
1969	14,764	759	7,413.81	521.5	70.3
1970	10,402	527	5,646.10	545.9	96.7
1971	7,654	393	7,924.12	728.5	91.9
1972	9,886	998	4,892.95	501.9	102.6
1973	8,953	896	4,290.77	486.4	113.4
1974	10,086	1,009	5,378.89	587.4	109.2
1975	9,527	953	4,510.51	542.6	120.3
1976	13,389	1,355	6,169.25	561.2	91
1977	14,897	1,492	6,107.66	447.1	73.2
1978	12,944	1,300	9,587.37	820	85.5
1979	11,121	1,163	7,922.39	777.9	98.2
1980	9,883	1,014	7,220.39	701.3	97.1
1981	10,273	1,042	7,539.08	552.6	73.3
1982	10,341	1,076	9,014.50	853.9	94.7
1983	14,523	1,485	8,902.67	923.5	103.7
1984	15,936	1,599	11,119.14	982.8	88.4
1985	13,225	1,324	11,451.55	881.1	76.9
1986	16,494	1,652	9,369.73	822.1	87.7
1987	16,458	1,647	11,115.25	894.2	80.4
1988	12,402	1,240	8,088.53	623.7	77.1
1989	13,950	1,392	7,241.50	569.6	78.7
1990	11,456	1,152	5,824.35	528.3	90.7
1991	11,378	1,164	4,803.74	544.3	113.3
1992	14,214	1,524	3,916.22	421.4	107.6
1993	14,576	1,537	5,241.47	539.2	102.9
1994	16,062	1,680	7,316.97	761.6	104.1
1995	13,489	1,470	3,896.31	463.9	119.1
1996	12,115	1,506	4,566.80	479.4	105
1997	9,923	1,124	5,950.04	611.2	102.7
1998	9,043	1,073	4,598.36	486.2	105.7
1999	10,641	1,183	6,198.27	684.3	110.4
2000	8,383	969	5,607.89	579.3	103.3
2001	6,222	740	3,951.25	521.3	131.9
2002	5,597	836	4,999.81	574.5	114.9
2003	7,839	1,066	5,274.69	517.1	98
2004	6,644	942	5,001.29	468.7	93.7
2005	6,206	899	4,398.26	433.8	98.6

Table 4.4 Con’t

Year	Sample Size	Sample Size	Landings		Mean Weight (g)
	(N Fish)	(N Sets)	(millions)	(1000 mt)	
2006	4,698	594	4,895.06	464.4	94.9
2007	3,989	657	4,750.05	453.8	95.5
2008	4,663	594	3,608.25	425.4	117.9
2009	6,193	748	3,603.26	457.5	127
2010	3,678	461	3,891.65	379.7	97.6
2011	7,254	835	7,208.81	613.3	85.1
2012	8,244	949	6,783.03	578.4	85.3
2013	5,804	693	4,538.96	497.5	109.6
2014	6,088	726	3,511.84	391.8	111.6
2015	8,747	966	6,166.49	535.7	86.9
2016	5,879	697	4,618.59	485.8	105.2
2017	5,233	631	5,418.04	460.7	85.0

Table 4.5 Estimated reduction landings of Gulf Menhaden in numbers by age (in millions) from 1964-2017.

Year	Age-0	Age-1	Age-2	Age-3	Age-4+	Total
1964	2.76	3,329.28	1,495.15	118.07	4.35	4,949.61
1965	43.43	5,031.39	1,076.63	80.27	0.70	6,232.41
1966	30.45	3,314.42	865.16	33.76	0.26	4,244.05
1967	22.44	4,267.65	337.66	13.00	0.00	4,640.74
1968	65.06	3,475.23	1,001.30	37.45	0.50	4,579.55
1969	20.80	6,075.00	1,286.34	31.66	0.00	7,413.81
1970	50.19	3,279.85	2,279.98	36.08	0.00	5,646.10
1971	21.59	5,761.13	1,955.45	181.84	4.12	7,924.12
1972	19.11	3,047.74	1,733.53	88.54	4.03	4,892.95
1973	49.90	3,033.00	1,106.98	99.62	1.27	4,290.77
1974	1.41	3,846.75	1,471.65	59.08	0.00	5,378.89
1975	108.77	2,440.51	1,499.21	461.83	0.19	4,510.51
1976	0.00	4,591.39	1,373.94	203.92	0.00	6,169.25
1977	0.00	4,659.95	1,331.72	110.37	5.63	6,107.66
1978	0.00	6,787.44	2,742.01	52.67	5.24	9,587.37
1979	0.00	4,701.22	2,877.16	337.20	6.81	7,922.39
1980	65.86	3,409.41	3,261.11	436.15	47.86	7,220.39
1981	0.00	5,750.53	1,424.94	329.40	34.22	7,539.08
1982	0.00	5,146.74	3,301.96	503.54	62.26	9,014.50
1983	0.00	4,685.73	3,809.23	382.61	25.10	8,902.67
1984	0.00	7,749.55	2,881.49	438.36	49.75	11,119.14
1985	0.00	8,682.70	2,498.62	233.71	36.52	11,451.55
1986	0.00	4,275.99	4,892.04	174.92	26.78	9,369.73
1987	0.00	6,699.48	3,975.56	427.77	12.45	11,115.25
1988	0.00	5,337.69	2,581.40	151.47	17.97	8,088.53
1989	0.00	5,550.44	1,622.02	66.98	2.06	7,241.50
1990	0.00	3,889.22	1,785.01	136.21	13.91	5,824.35
1991	0.00	2,217.51	2,339.91	215.62	30.70	4,803.74
1992	0.00	2,187.28	1,505.75	197.12	26.07	3,916.22
1993	4.81	3,492.05	1,532.49	193.48	18.64	5,241.47
1994	0.00	3,627.60	3,195.61	441.16	52.61	7,316.97
1995	0.00	1,369.16	2,423.43	99.65	4.07	3,896.31
1996	0.61	1,784.16	2,513.17	251.08	17.78	4,566.80
1997	0.00	3,235.59	2,398.83	276.10	39.52	5,950.04
1998	0.00	1,804.82	2,587.12	189.66	16.76	4,598.36
1999	0.00	3,368.77	2,392.99	416.85	19.66	6,198.27
2000	0.00	2,029.80	3,164.53	347.67	65.89	5,607.89
2001	0.00	987.61	2,653.34	290.52	19.78	3,951.25
2002	0.00	1,585.63	2,863.10	533.96	17.12	4,999.81
2003	0.00	1,910.07	3,011.72	339.55	13.35	5,274.69
2004	0.00	2,799.37	1,764.03	400.32	37.57	5,001.29
2005	82.00	1,731.94	2,380.94	188.97	14.40	4,398.26
2006	0.00	2,246.46	2,301.27	317.77	29.57	4,895.06
2007	0.00	2,199.69	2,421.38	111.75	17.23	4,750.05

Table 4.5 Con't

Year	Age-0	Age-1	Age-2	Age-3	Age-4+	Total
2008	0.00	960.56	2,465.66	160.32	21.71	3,608.25
2009	0.00	455.00	2,633.36	466.61	48.30	3,603.26
2010	0.00	2,057.65	1,572.35	238.80	22.85	3,891.65
2011	49.11	4,553.35	2,287.46	266.98	51.92	7,208.81
2012	18.46	2,091.71	4,459.01	205.81	8.04	6,783.03
2013	10.23	1,113.59	3,297.83	114.62	2.68	4,538.96
2014	19.86	907.81	2,093.32	469.36	21.49	3,511.84
2015	0.00	3,767.46	2,147.01	237.96	29.25	6,166.49
2016	28.62	2,380.90	1,898.35	286.22	24.49	4,618.59
2017	56.88	3,566.57	1,482.97	303.68	7.94	5,418.04

Table 4.6 Weeks at Omega Protein fish factory in Moss Point, MS, where port samples were collected from run boats; size and age compositions are compared to samples from regular fishing steamers for the same week in 2002, 2003, 2007, 2011, 2012, and 2015. No samples were acquired from run boats in years not listed (samples from 2005 lost due to Hurricane Katrina).

2015

Week ending date: 5/16/2015

Run Boats

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1	2	13%	148	61
2	14	88%	179	117
3		0%		
total	16			

Steamers

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1	59	21%	146	64
2	208	73%	175	110
3	19	7%	195	143
total	286			

Week ending date: 5/23/2015

Run Boats

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1	1	14%	161	81
2	6	67%	179	117
3		0		
total	7			

Steamers

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1	108	42%	144	61
2	179	70%	177	112
3	29	11%	150	87
total	316			

Week ending date: 6/26/2015

Run Boats

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1	4	24%	158	76
2	13	144%	178	113
3		0		
total	17			

Steamers

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1	178	69%	150	66
2	156	61%	180	118
3	14	5%	197	153
total	348			

Week ending date: 7/10/2015

Run Boats

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1	14	82%	149	56
2	6	67%	178	102
3		0		
total	20			

Steamers

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1	299	116%	149	63
2	143	56%	181	120
3	34	13%	199	158
total	476			

Week ending date: 8/28/2015

Run Boats

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1	10	59%	148	61
2		0%		
3		0		
total	10			

Steamers

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1	273	106%	153	70
2	103	40%	180	117
3	6	2%	196	156
total	382			

2012

Week ending date: 10/5/2012

Run Boats

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1	9	90	152	63
2	1	10	161	77
3	0	0		
total	10			

Steamers

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1	71	25%	151	64
2	212	75%	173	98
3	1	0%	199	157
total	284			

Week ending date: 10/19/2012

Run Boats

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1		0		
2	9	100%	172	100
3		0		
total	9			

Steamers

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1	58	23%	146	60
2	152	59%	180	116
3	47	18%	200	158
total	257			

2011

Week ending date: 6/4/2011

Run Boats

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1	21	35	139	52
2	34	57	182	120
3	5	8	196	145
total	60			

Steamers

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1	73	36	145	60
2	123	61	179	117
3	7	3	200	160
total	203			

Week ending date: 6/11/2011

Run Boats

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1	41	31	152	67
2	90	67	180	111
3	3	2	202	151
total	134			

Steamers

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1	48	39	151	66
2	73	59	179	113
3	3	2	200	149
total	124			

2007

Week ending date: 5/19/2007

Run Boats

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1				
2	9	90	172	108
3	1	10	195	148
total	10			

Steamers

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1	9	20	157	77
2	36	78	175	113
3	1	2	194	154
total	46			

Week ending date: 7/07/2007

Run Boats

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1	1	13	154	63
2	7	87	176	107
3				
total	8			

Steamers

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1	18	16	154	71
2	87	79	177	113
3	5	5	194	145
	110			

2003

Week ending date: 5/24/2003

Run Boats

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1	4	14	160	75
2	24	86	174	103
3				
total	28			

Steamers

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1	2	22	149	67
2	7	78	171	96
3				
total	9			

Week ending date: 8/02/2003

Run Boats

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1	1	11	152	59
2	8	89	175	103
3				
total	9			

Steamers

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1	4	11	164	85
2	33	89	179	117
3				
total	37			

Week ending date: 8/30/2003

Run Boats

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1	6	35	165	84
2	9	53	182	117
3	2	12	194	132
total	17			

Steamers

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1	2	8	165	88
2	24	92	184	126
3				
total	28			

2002

Week ending date: 7/06/2002

Run Boats

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1	3	30	166	92
2	6	60	189	139
3	1	10	209	162
total	10			

Steamers

Age	N at age	% age comp	Mean FL (mm)	Mean wgt (g)
1	25	48	162	84
2	24	46	182	121
3	3	6	200	172
total	52			

Table 4.7 Standardized fishery-dependent indices of age-1 and age-2 Gulf Menhaden (from the catch-at-age matrix) divided by fishery effort (number of purse-seine sets per year) for 1983–2017.

Year	Age-1 index	Age-2 index
1983	0.12	0.10
1984	0.18	0.07
1985	0.35	0.10
1986	0.14	0.16
1987	0.19	0.11
1988	0.19	0.09
1989	0.21	0.06
1990	0.14	0.06
1991	0.09	0.09
1992	0.11	0.06
1993	0.11	0.06
1994	0.14	0.12
1995	0.06	0.11
1996	0.08	0.11
1997	0.14	0.10
1998	0.08	0.12
1999	0.14	0.10
2000	0.09	0.13
2001	0.05	0.13
2002	0.07	0.13
2003	0.08	0.13
2004	0.12	0.08
2005	0.11	0.11
2006	0.10	0.11
2007	0.11	0.12
2008	0.06	0.16
2009	0.02	0.14
2010	0.14	0.11
2011	0.23	0.12
2012	0.10	0.22
2013	0.06	0.17
2014	0.05	0.11
2015	0.23	0.13
2016	0.14	0.11
2017	0.23	0.09

Table 4.8 Nominal fishing effort information for the Gulf Menhaden fishery from CDFRs, 1983-2017. ***Note:*** *CDFR data sets for 1992, 1993, and 2005 are incomplete.*

Year	Gulf Menhaden landings (1000 mt)	CDFR data				Catch (mt)/set
		Total no. of sets	No. of vessel-days w/ 1 or more sets	Total no. of possible vessel-days	Percent days fished (at least one set made)	
1983	923.5	37,587	7,764	10,412	0.75	24.6
1984	982.8	42,040	7,821	10,023	0.78	23.4
1985	881.1	25,145	4,987	6,921	0.72	35.0
1986	822.1	33,860	6,634	9,027	0.73	24.3
1987	894.2	34,898	7,026	8,779	0.80	25.6
1988	623.7	28,262	6,115	8,430	0.73	22.1
1989	569.6	26,427	6,174	8,621	0.72	21.6
1990	528.3	28,163	6,711	8,829	0.76	18.8
1991	544.3	26,648	5,624	7,372	0.76	20.4
1992	421.4	-	-	-	-	
1993	539.2	-	-	-	-	
1994	761.6	26,234	5,272	6,975	0.76	29.0
1995	463.9	21,264	4,662	6,824	0.68	21.8
1996	479.4	22,777	4,870	6,718	0.72	21.0
1997	611.2	23,378	4,707	6,623	0.71	26.1
1998	486.2	21,317	4,153	6,552	0.63	22.8
1999	684.3	24,704	4,617	6,058	0.76	27.7
2000	579.3	23,733	4,077	5,592	0.73	24.4
2001	521.3	21,223	4,043	5,788	0.70	24.6
2002	574.5	22,579	4,056	5,655	0.72	25.4
2003	517.1	22,825	3,940	5,391	0.73	22.7
2004	468.7	22,839	3,973	5,557	0.71	20.5
2005	433.8	-	-	-	-	
2006	464.4	21,913	3,772	5,193	0.73	21.2
2007	453.8	19,428	3,570	5,396	0.66	23.4
2008	425.4	15,532	3,112	5,409	0.58	27.4
2009	457.5	18,260	3,752	5,579	0.67	25.1
2010	379.7	14,604	2,868	5,384	0.53	26.0
2011	613.3	19,644	3,513	5,082	0.69	31.2
2012	578.4	20,271	2,730	3,267	0.84	28.5
2013	497.5	19,124	3,393	4,740	0.72	26.0
2014	391.9	18,386	2,480	4,289	0.58	21.3
2015	535.7	16,470	2,737	4,210	0.65	32.5
2016	484.8	16,802	2,941	3,896	0.75	28.9
2017	460.7	15,641	2,440	3,586	0.68	29.5

Table 4.9 Number of fishing trips, catch per trips, and standard error of mean catch per trip by the Gulf Menhaden reduction fleet, 1964-2017. Note that trip information is incomplete (*) for 1983 and 1984.

Year	All Data		
	N	Catch/Trip (mt)	SE (mt)
1964	4,692	87.3	1.186
1965	4,235	109.4	2.508
1966	3,617	99.3	1.617
1967	3,221	98.6	1.521
1968	3,176	117.6	1.736
1969	3,638	144	1.84
1970	3,769	145.5	1.854
1971	4,453	163.6	1.755
1972	3,659	137.2	1.609
1973	3,437	141.5	1.654
1974	3,943	149	1.676
1975	3,987	136.1	1.515
1976	4,066	138	1.576
1977	3,724	120.1	1.417
1978	4,474	183.3	1.727
1979	4,078	190.8	1.88
1980	4,186	167.5	1.717
1981	3,811	145	1.566
1982	4,695	181.9	1.712
1983	1,218*	151	3.28
1984	2,128*	190.6	2.487
1985	3,343	263.6	2.139
1986	4,028	204.1	1.793
1987	4,427	202	1.694
1988	3,629	171.9	1.757
1989	3,618	157.4	1.743
1990	3,557	148.5	1.657
1991	2,977	182.8	2.06
1992	2,468	170.8	1.955
1993	2,928	184.2	1.952
1994	3,238	235.2	2.137
1995	2,587	179.3	2.135
1996	2,693	178	2.09
1997	2,831	215.9	2.222
1998	2,447	198.7	2.307
1999	2,811	243.4	2.339
2000	2,600	222.8	2.622
2001	2,434	214.2	2.613
2002	2,552	225.1	2.533
2003	2,370	218.2	2.666
2004	2,371	197.7	2.499
2005	2,083	208.3	2.675
2006	2,088	222.4	2.807

Table 4.9 Con’t

Year	All Data		
	N	Catch/Trip (mt)	SE (mt)
2008	1,896	224.4	3.041
2009	2,280	200.6	2.579
2010	1,755	216.4	3.223
2011	2,457	249.6	2.667
2012	2,366	244.5	2.67
2013	2,224	223.7	2.66
2014	1,857	211.0	2.82
2015	2,094	255.8	2.77
2016	2,509	193.6	2.55
2017	1,879	246.4	3.43

Table 4.10 Mean net tonnage (metric) of the Gulf Menhaden purse-seine fleet by selected fishing years since 1970.

Fishing Year	Mean net tonnage	No. of vessels in calculation	Range of net tonnages
1970	248	72	80-386
1980	315	79	139-453
1990	317	75	147-447
2000	338	43	197-453
2010	361	32	293-453
2017	354	34	213-453

Table 4.11 Gulf Menhaden bait landings (mt) by gear from NOAA Fisheries OST and NOAA ALS data bases, 1950-2017.

Year	Gear				Total Bait
	Purse	Gill	Haul	Other	
1950	0.0	0.0	0.0	0.0	0.0
1951	0.0	0.0	2.9	0.0	2.9
1952	0.0	0.0	3.7	0.0	3.7
1953	0.0	0.0	1.2	0.0	1.2
1954	0.0	0.0	1.1	0.0	1.1
1955	0.0	1.5	9.3	0.0	10.8
1956	0.0	11.2	2.0	1.1	14.4
1957	0.0	2.9	0.5	0.0	3.4
1958	0.0	31.0	9.0	0.0	40.1
1959	0.0	3.7	5.5	0.0	9.2
1960	0.0	2.9	2.4	0.0	5.4
1961	0.0	4.3	5.7	1.5	11.4
1962	0.0	8.9	0.0	0.0	8.9
1963	0.0	0.5	0.0	19.6	20.2
1964	0.0	33.8	0.5	3.9	38.1
1965	0.0	140.3	44.8	10.8	195.9
1966	0.0	190.0	51.4	12.8	254.1
1967	2.3	38.6	13.5	3.4	57.7
1968	41.8	129.3	34.4	1.7	207.2
1969	0.0	83.1	52.4	1.8	137.3
1970	0.5	231.5	42.2	5.6	279.8
1971	2.3	255.6	92.8	15.2	365.9
1972	39.2	97.2	153.4	2.3	292.2
1973	125.4	66.3	253.0	1.1	445.9
1974	54.5	124.6	138.4	1.1	318.6
1975	45.9	48.9	113.0	3.6	211.5
1976	102.2	52.1	173.1	0.1	327.5
1977	98.0	30.1	169.1	0.4	297.6
1978	134.2	32.0	236.9	0.5	403.6
1979	838.7	37.0	849.4	1.7	1,726.8
1980	502.9	22.9	472.8	0.1	998.7
1981	544.6	21.4	507.0	0.0	1,073.0
1982	797.6	40.0	739.1	0.0	1,576.7
1983	883.4	36.3	819.5	0.0	1,739.2
1984	1,167.3	72.7	1,077.3	0.0	2,317.4
1985	1,447.5	359.3	1,063.0	0.2	2,870.0
1986	251.3	1,353.5	70.5	0.1	1,675.4
1987	8,567.7	2,931.3	155.9	5.6	11,660.5
1988	8,485.8	1,594.9	205.5	1.0	10,287.2
1989	11,226.7	894.3	79.6	0.2	12,200.8
1990	9,996.4	178.7	2.0	32.5	10,209.6
1991	4,958.6	91.6	272.4	2.4	5,325.0
1992	6,503.1	1,295.0	57.0	47.3	7,902.4

Table 4.11 Con't

Year	Gear				Total Bait
	Purse	Gill	Haul	Other	
1993	6,470.1	836.8	46.6	1,954.4	9,308.0
1994	7,320.8	670.3	0.1	1,995.8	9,987.1
1995	5,828.3	1,276.1	0.0	963.7	8,068.0
1996	10,758.4	1,500.2	0.0	11.5	12,270.1
1997	10,349.4	1,559.0	9.6	8.7	11,926.8
1998	6,505.3	892.0	0.0	5.4	7,402.8
1999	7,210.4	914.7	0.1	11.5	8,136.5
2000	0.0	744.8	0.3	48.0	793.1
2001	1.2	698.9	0.1	59.9	760.1
2002	0.0	439.3	0.2	27.7	467.2
2003	0.0	460.6	0.5	25.6	486.6
2004	0.0	370.8	0.9	45.8	417.5
2005	12.8	214.8	2.9	30.4	260.9
2006	4.7	158.3	0.6	10.1	173.7
2007	1.4	210.8	5.2	33.7	251.0
2008	0.0	119.8	0.1	19.6	139.4
2009	1.0	85.4	2.2	45.5	134.1
2010	0.1	33.6	0.0	34.9	68.7
2011	9.6	140.2	9.5	111.9	271.2
2012	0.0	183.2	1.2	135.0	319.4
2013	632.3	177.1	4.1	141.1	954.7
2014	7723.5	297.7	0.2	109.0	8130.4
2015	3923.3	295.3	12.7	63.5	4294.9
2016	4830.0	330.6	2.5	190.7	5353.9
2017	1167.2	486.6	11.8	28.3	1694.0

Table 4.12 Gulf Menhaden catch in numbers (in millions) at age from the reduction, bait and recreational fisheries combined, 1964-2017.

Year	Age-0	Age-1	Age-2	Age-3	Age-4+	Total
1964	2.80	3,331.20	1,496.00	118.10	4.4	4,952.48
1965	43.50	5,035.70	1,077.50	80.30	0.7	6,237.74
1966	30.50	3,318.60	866.30	33.80	0.3	4,249.42
1967	22.50	4,271.10	337.90	13.00	0.0	4,644.51
1968	65.10	3,479.00	1,002.40	37.50	0.5	4,584.54
1969	20.80	6,078.90	1,287.20	31.70	0.0	7,418.58
1970	50.20	3,282.70	2,282.00	36.10	0.0	5,651.05
1971	21.60	5,765.60	1,957.00	182.00	4.1	7,930.26
1972	19.10	3,050.70	1,735.20	88.60	4.0	4,897.73
1973	50.00	3,037.00	1,108.40	99.70	1.3	4,296.46
1974	1.40	3,850.10	1,472.90	59.10	0.0	5,383.63
1975	108.90	2,442.40	1,500.30	462.20	0.2	4,513.92
1976	0.00	4,595.70	1,375.20	204.10	0.0	6,175.03
1977	0.00	4,665.10	1,333.20	110.50	5.6	6,114.44
1978	0.00	6,792.40	2,744.00	52.70	5.2	9,594.41
1979	0.00	4,712.90	2,884.30	338.00	6.8	7,942.00
1980	66.00	3,415.20	3,266.70	436.90	47.9	7,232.72
1981	0.00	5,762.10	1,427.80	330.10	34.3	7,554.22
1982	0.00	5,156.60	3,308.30	504.50	62.4	9,031.68
1983	0.00	4,694.70	3,816.50	383.30	25.1	8,919.65
1984	0.00	7,767.90	2,888.30	439.40	49.9	11,145.41
1985	0.00	8,715.20	2,508.00	234.60	36.7	11,494.37
1986	0.00	4,286.00	4,903.50	175.30	27.1	9,391.61
1987	0.00	6,788.30	4,028.30	433.40	12.7	11,262.64
1988	0.00	5,429.70	2,625.90	154.10	18.4	8,227.93
1989	0.00	5,673.40	1,658.00	68.50	2.1	7,401.91
1990	0.00	3,965.30	1,819.90	138.90	14.2	5,938.32
1991	0.00	2,239.40	2,363.00	217.70	31.2	4,851.16
1992	0.00	2,229.00	1,534.40	200.90	26.8	3,990.88
1993	4.90	3,553.40	1,559.40	196.90	19.1	5,333.52
1994	0.00	3,676.00	3,238.30	447.00	53.5	7,414.64
1995	0.00	1,393.10	2,465.90	101.40	4.1	3,964.52
1996	0.60	1,830.10	2,577.90	257.50	18.2	4,684.42
1997	0.00	3,298.80	2,445.70	281.50	40.3	6,066.33
1998	0.00	1,832.50	2,626.70	192.60	17.1	4,668.80
1999	0.00	3,409.10	2,421.60	421.80	19.9	6,272.41
2000	0.00	2,033.30	3,169.90	348.30	67.2	5,617.47
2001	0.00	989.10	2,657.40	291.00	20.1	3,957.36
2002	0.00	1,587.20	2,865.90	534.50	17.4	5,004.77
2003	0.00	1,912.30	3,015.20	339.90	13.5	5,280.80
2004	0.00	2,802.60	1,766.10	400.80	38.0	5,007.04
2005	82.10	1,733.30	2,382.80	189.10	14.5	4,401.60
2006	0.00	2,247.70	2,302.50	317.90	29.8	4,897.72
2007	0.00	2,201.10	2,422.90	111.80	17.4	4,753.12

Table 4.12 Con’t

Year	Age-0	Age-1	Age-2	Age-3	Age-4+	Total
2008	0.00	960.90	2,466.60	160.40	21.7	3,609.66
2009	0.00	455.20	2,634.40	466.80	48.3	3,604.73
2010	0.00	2,058.90	1,573.30	238.90	22.9	3,893.96
2011	49.20	4,557.30	2,289.40	267.20	52.0	7,214.99
2012	18.50	2091.70	4459.0	197.80	8.1	6,775.01
2013	10.20	1113.60	3297.80	114.60	2.7	4,538.96
2014	19.90	907.80	2093.30	469.40	22.0	3,511.84
2015	0.0	3894.40	1927.60	384.60	29.5	6,235.89
2016	28.60	2380.90	1898.30	286.20	24.8	4,618.59
2017	56.60	3558.0	1488.30	304.20	8.0	5,415.03

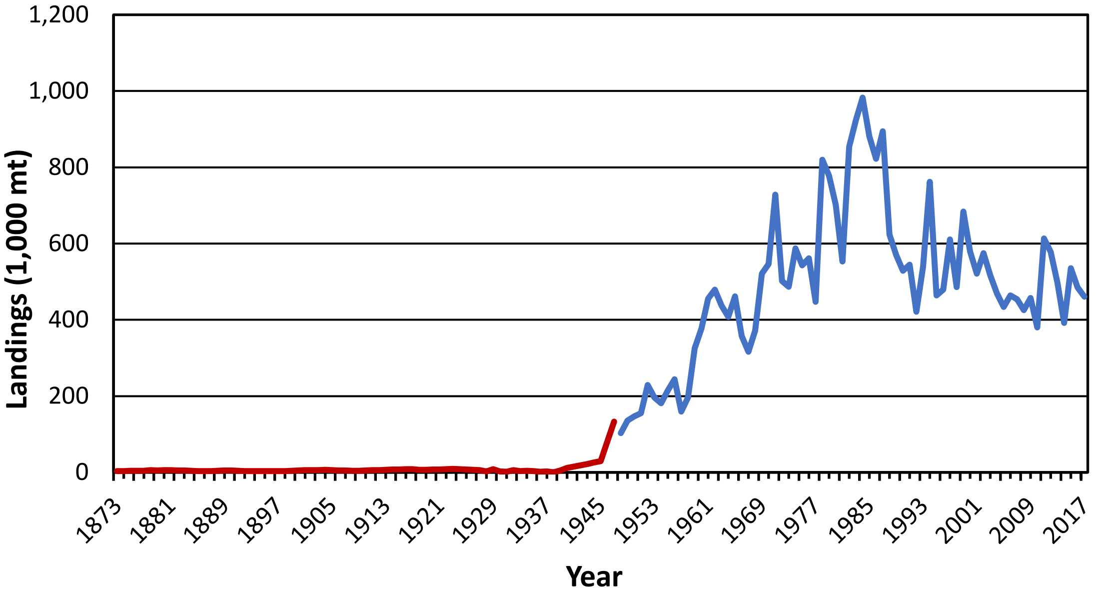


Figure 4.1 Total Gulf Menhaden landings along the Gulf of Mexico coast of the U.S., 1873-2017. Reconstructed landings were developed from historical reports for 1873-1947. Reduction landings maintained at NMFS Beaufort are combined with bait and recreational landings for 1948-2017.

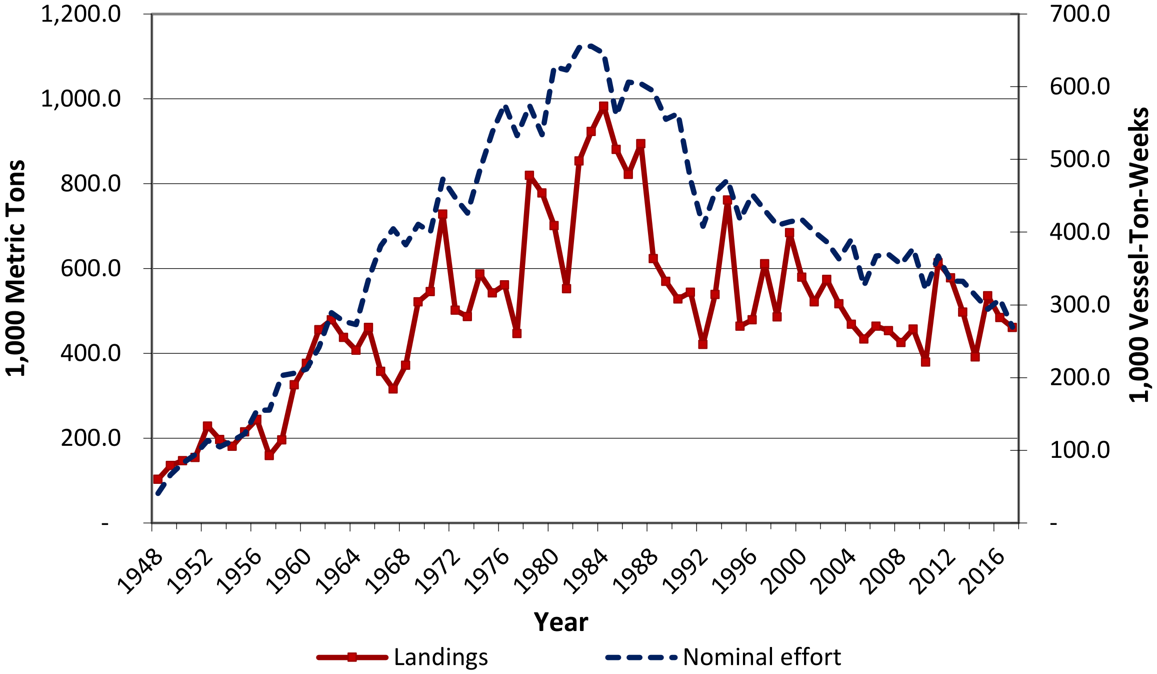


Figure 4.2 Annual values of Gulf Menhaden reduction landings (1000 mt) and nominal effort (vessel-ton-week), 1948-2017.

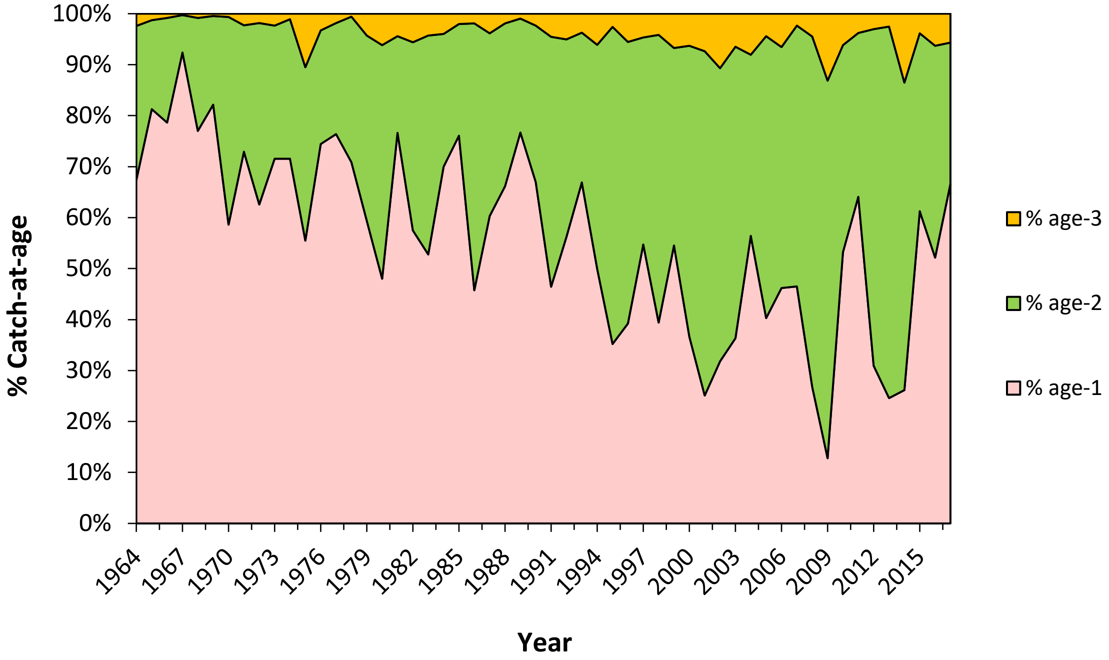


Figure 4.3 Percent age-1, age-2, and age-3 Gulf Menhaden in the catch-at-age matrix, 1964-2017.

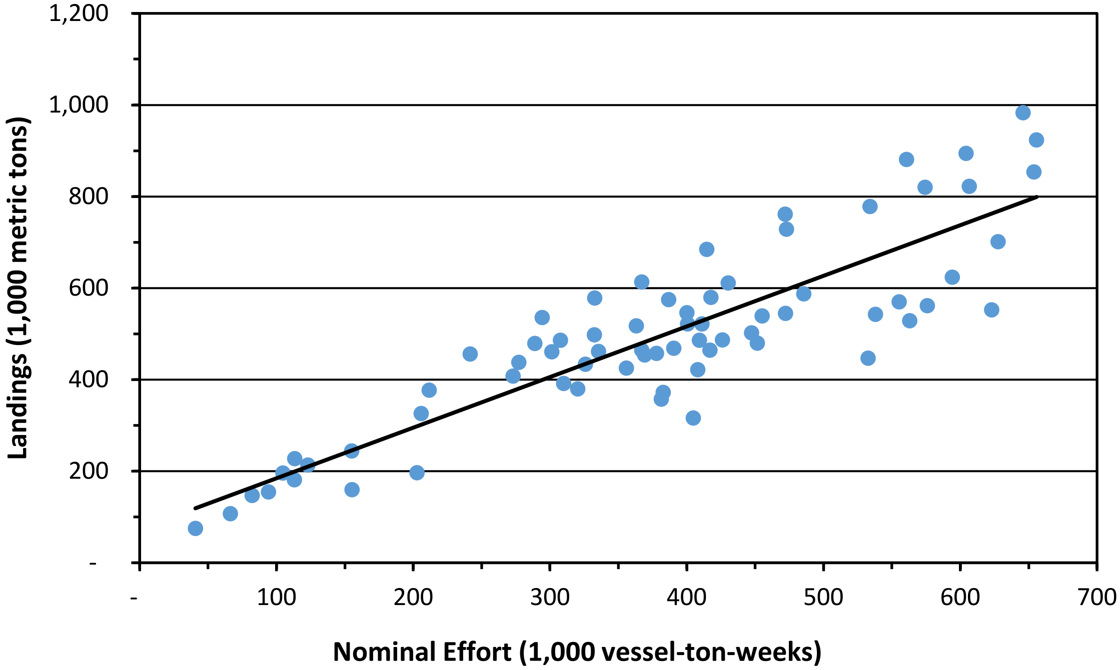


Figure 4.4 Relationship between Gulf Menhaden reduction landings (1000 mt) and nominal fishing effort (vessel-ton-week), 1948-2017. The linear regression of landings on effort explains 76% (r^2) of the annual variability in landings.

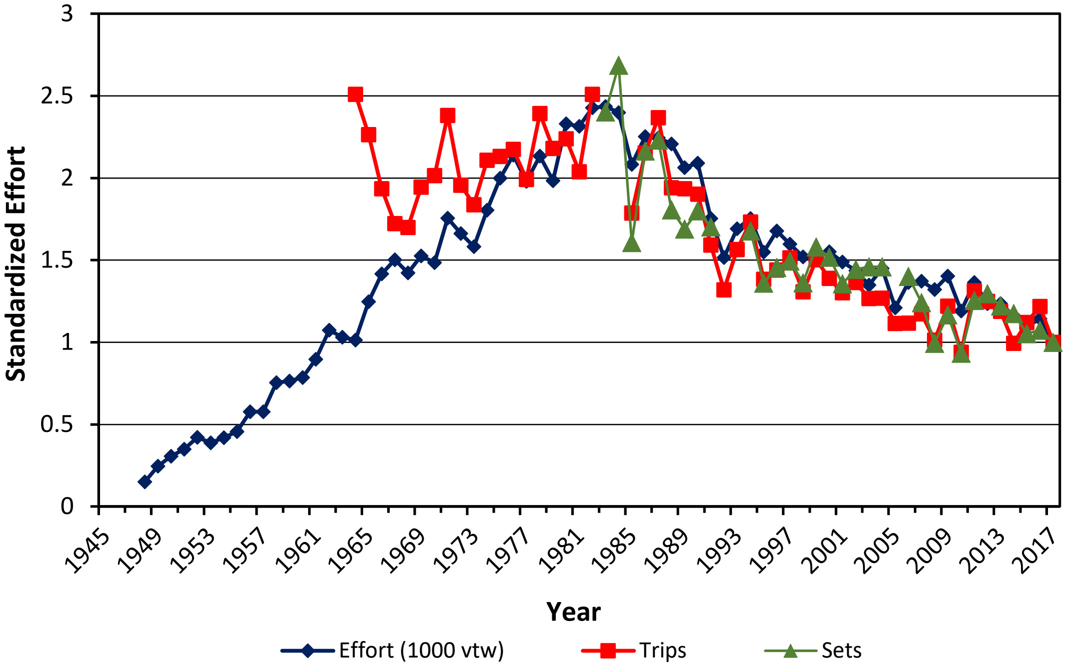


Figure 4.5 Comparison of nominal fishing effort for Gulf Menhaden reduction fleet. Effort compared includes: (1) vessel-ton-week, 1948-2017, (2) trips, 1964-2017, and (3) purse-seine sets, 1983-2017. All effort estimates are standardized by dividing by the respective value in 2017 to put them on a common scale. Years with incomplete data (sets in 1992, 1993, and 2005 and trips in 1983-1984) are left blank.

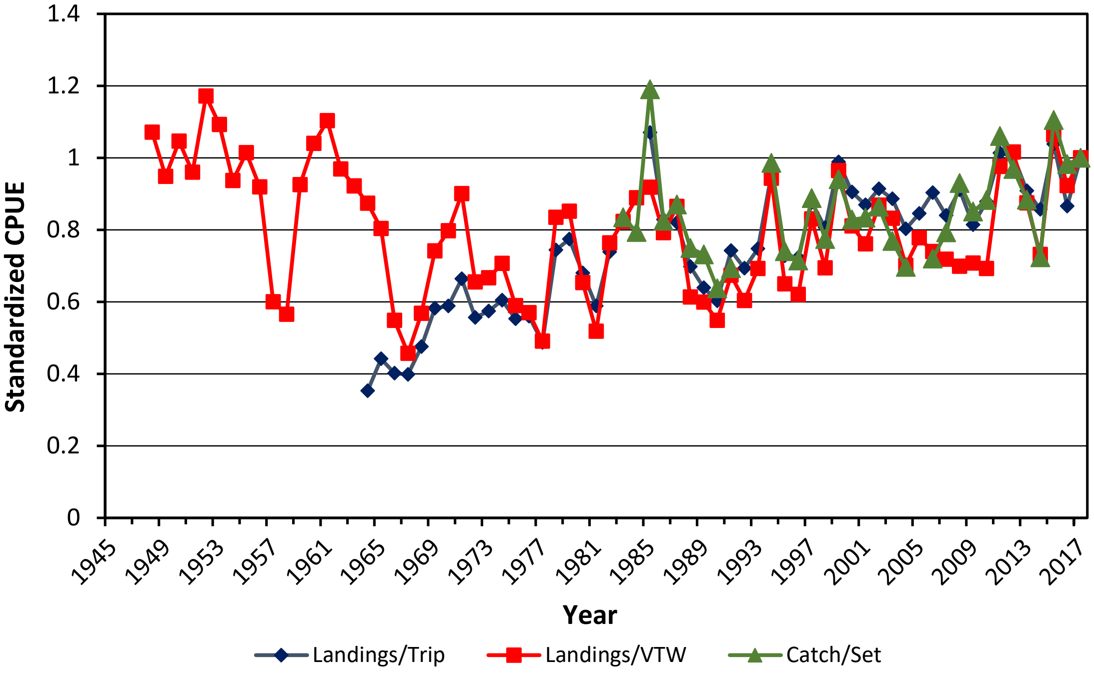


Figure 4.6 Comparison of calculated CPUE across different measures of fishing effort 1948-2017, including landings per vessel-ton-week (C/VTW), landings per trip (C/Trip) and catch per set.

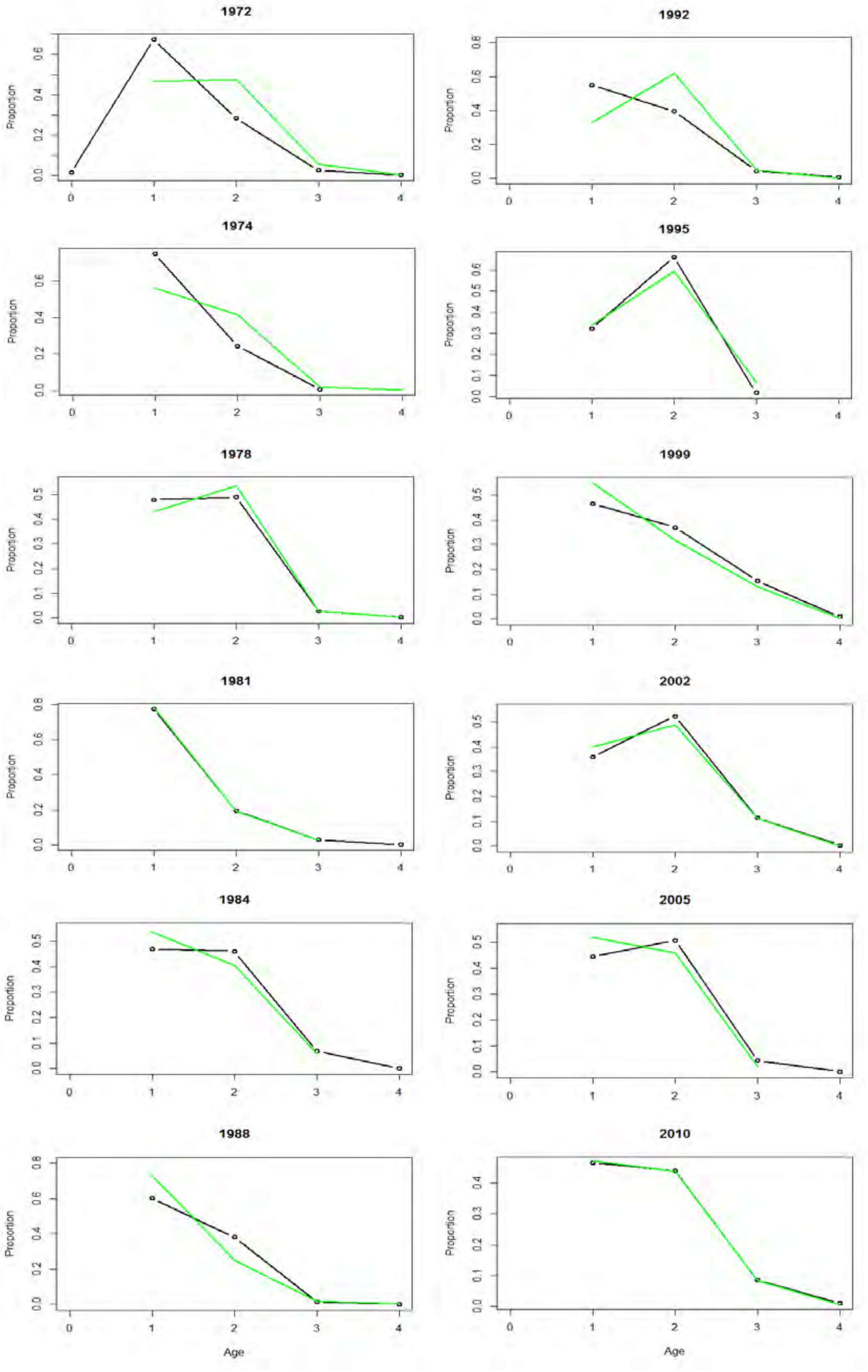


Figure 4.7 Plots of the proportion at age by year for the initial age reading done in the specified year (black) and for the re-read of the scale completed in 2012 (green).

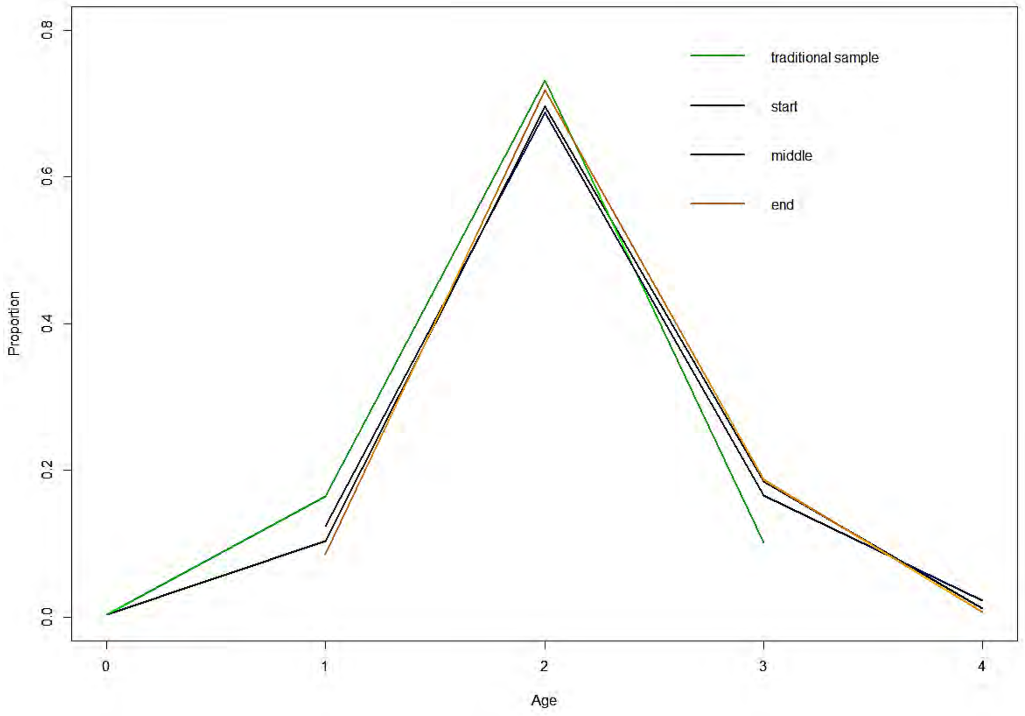


Figure 4.8 Age proportions across all pumpouts at all ports from all samples collected in 2012 for the traditional sample taken from the top of the hold and from samples from throughout the hold.

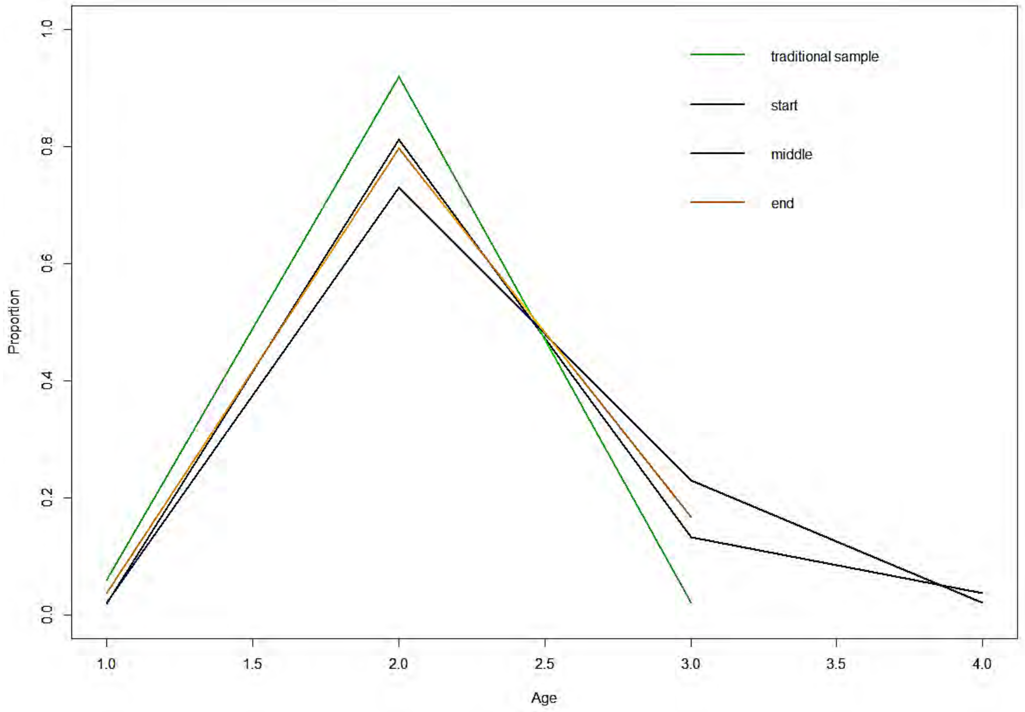


Figure 4.9 Age proportions across pumpouts during August 6-10 across all ports from samples collected in 2012 with the traditional sample taken from the top of the hold and the other samples taken from throughout the hold.

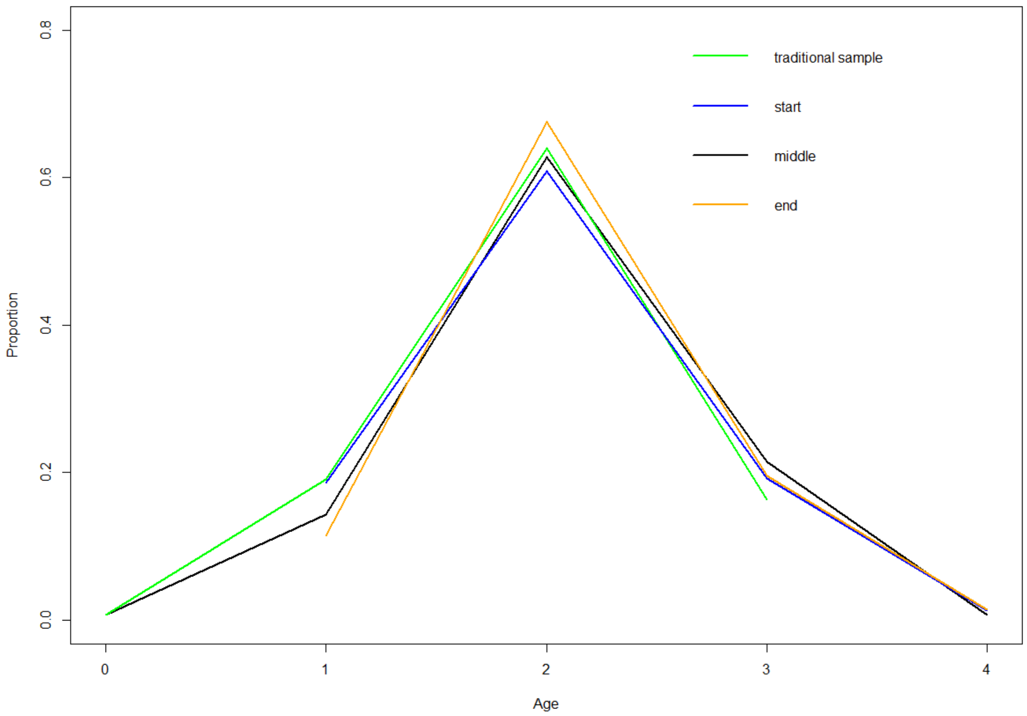


Figure 4.10 Age proportions across pumpouts during October 8-30 across all ports from samples collected in 2012 with the traditional sample taken from the top of the hold and the other samples taken from throughout the hold.

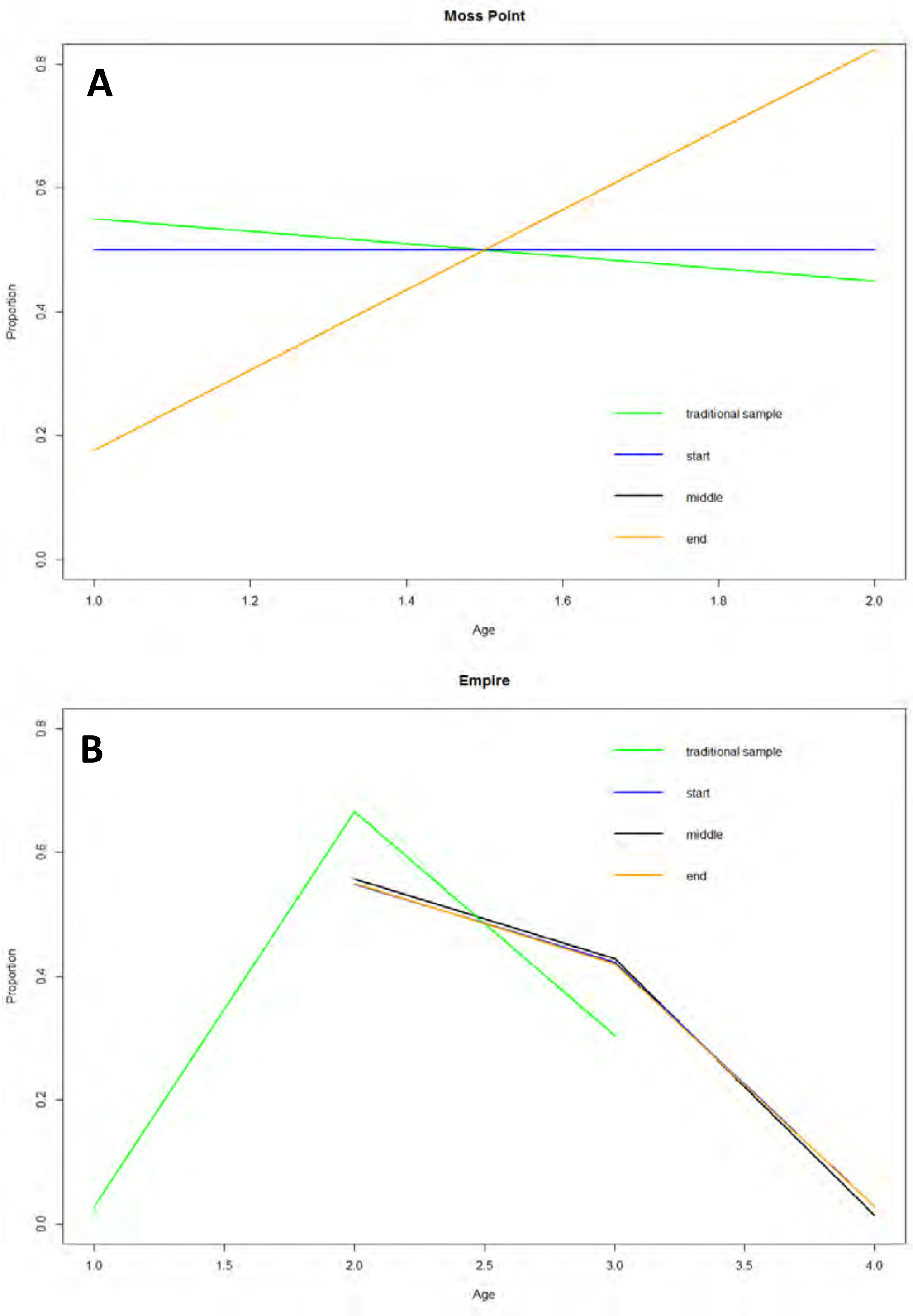


Figure 4.11 Age proportions across pumpouts during October 8-30 for each port from samples collected in 2012 with the traditional sample taken from the top of the hold and the other samples taken from throughout the hold; Moss Point, MS (panel A) and Empire, LA (panel B).

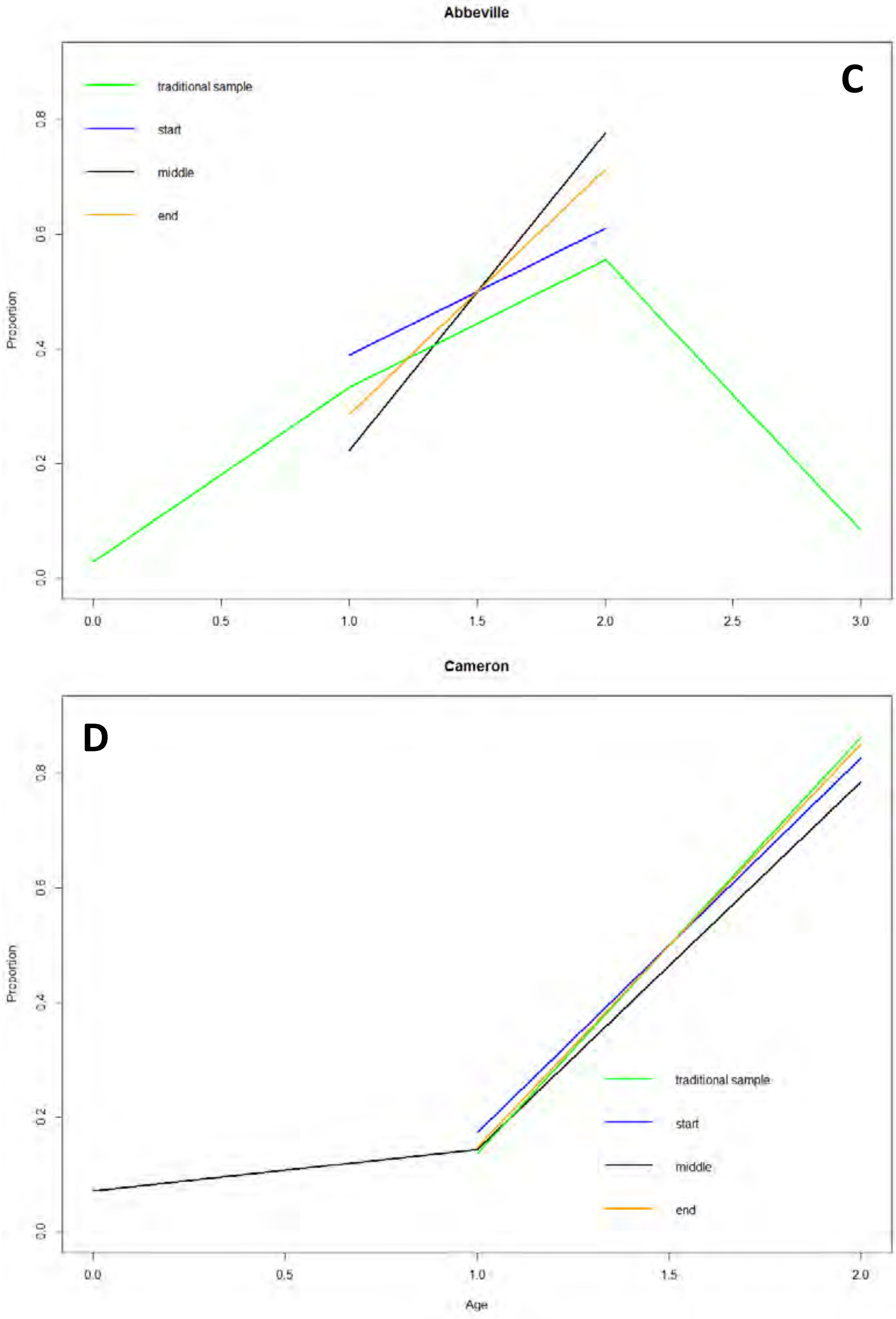


Figure 4.11 Con't - Abbeville, LA (panel C) and Cameron, LA (panel D).

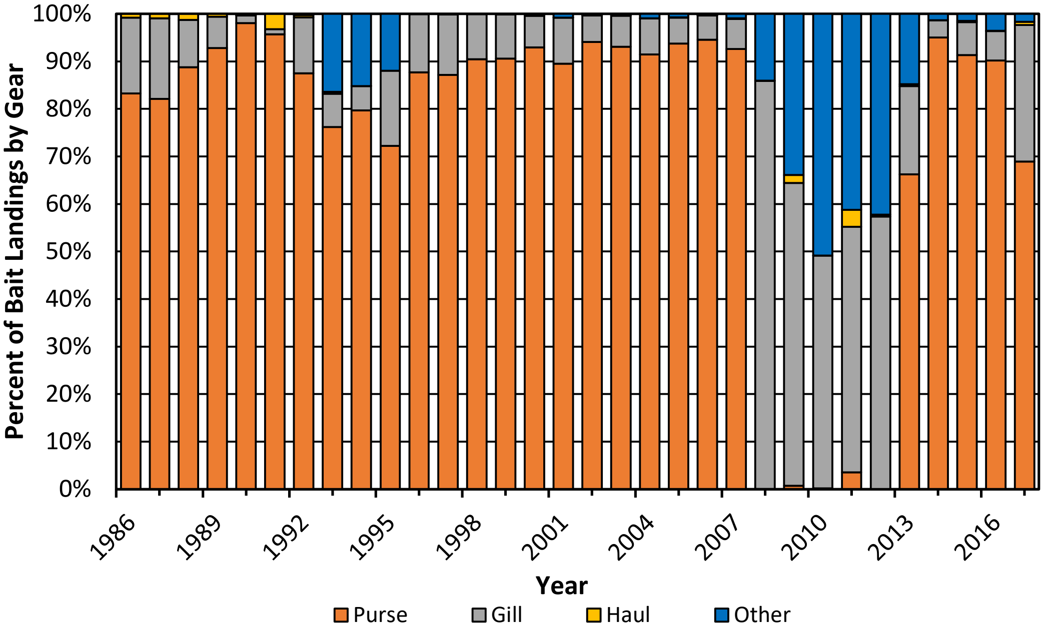


Figure 4.12 Percentage of bait landings by primary gear for all Gulf Menhaden (three species) in the Gulf of Mexico obtained from the NOAA Fisheries Commercial Landings database (ALS), 1986-2017.

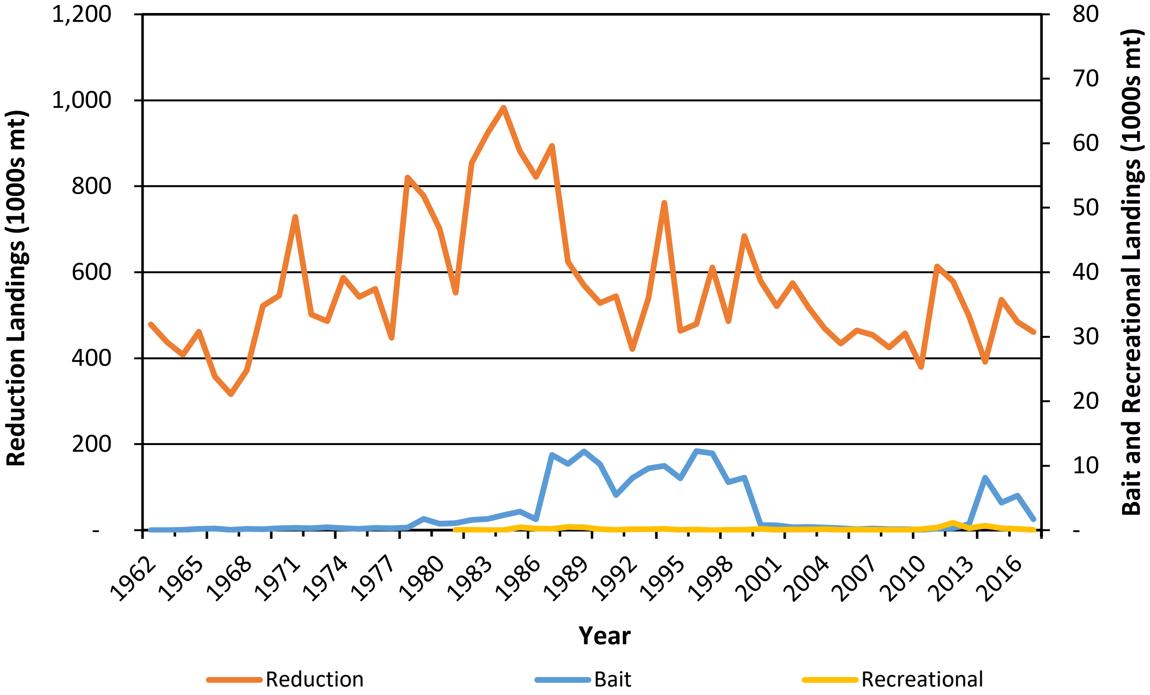


Figure 4.13 A comparison of Gulf Menhaden reduction purse-seine landings obtained maintained by NOAA Fisheries at Beaufort, NC, for 1962-2017 to bait landings for all species of menhaden obtained from the NOAA Fisheries Commercial Landings database (ALS), and recreationally landed Gulf Menhaden from the NOAA MRIP survey from 1981-2017. Bait and recreational landings are scaled on the right axis.

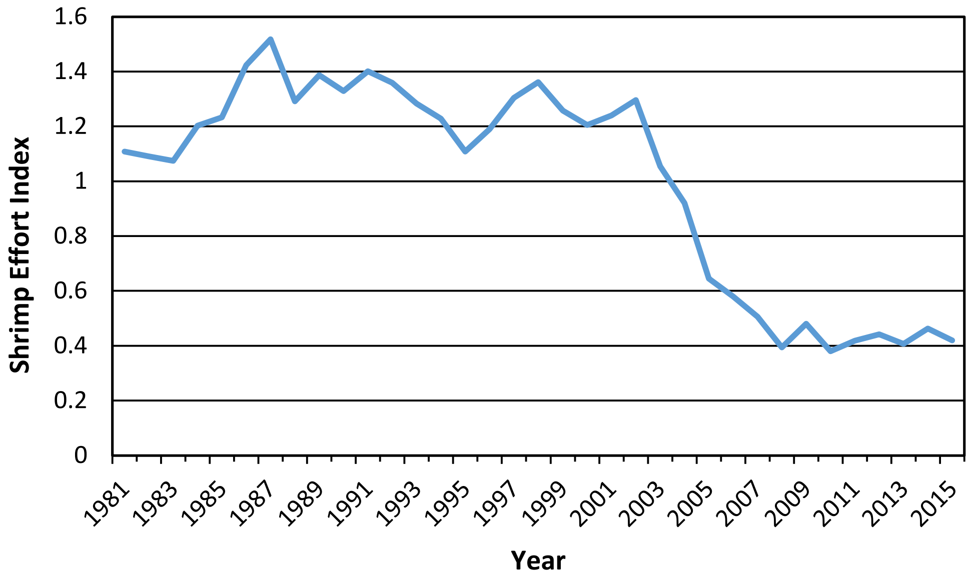
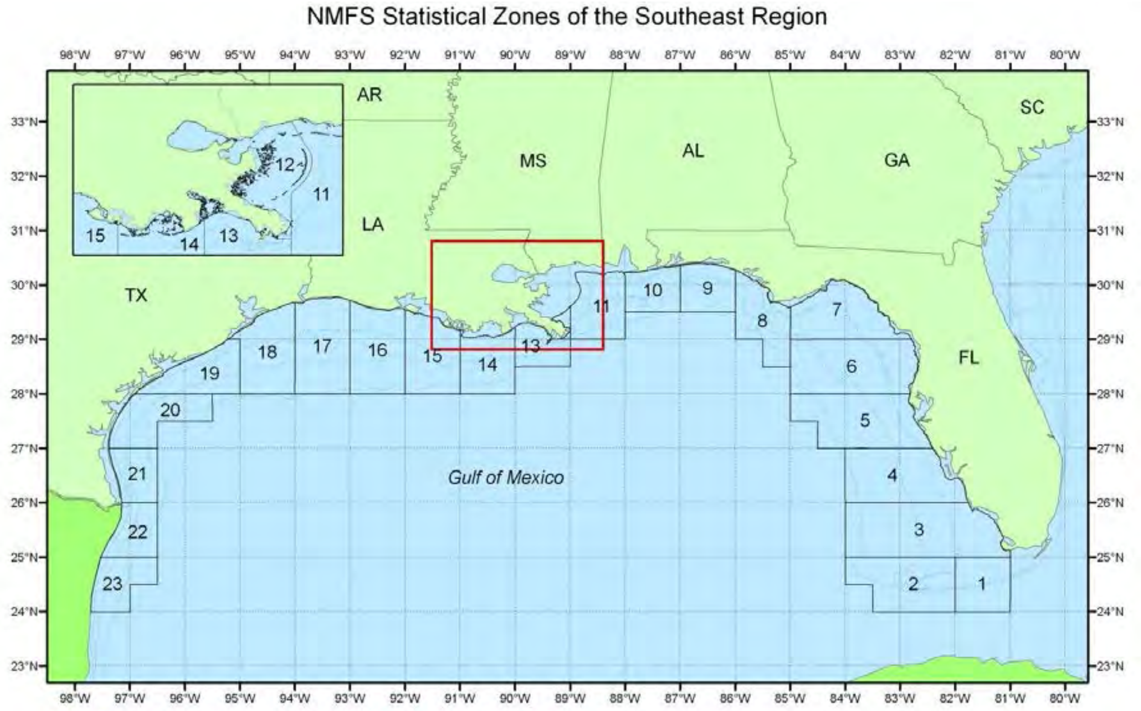


Figure 4.14 Estimate of shrimping effort in the Gulf of Mexico from 1981-2015 provided by NOAA Galveston Lab.



Note: Stat zone 12 expands east to include Chandeleur Islands (see inset)

Figure 4.15 National Marine Fisheries Service Gulf Shrimp Landing Statistical Zones used for SEAMAP sampling with trawls.

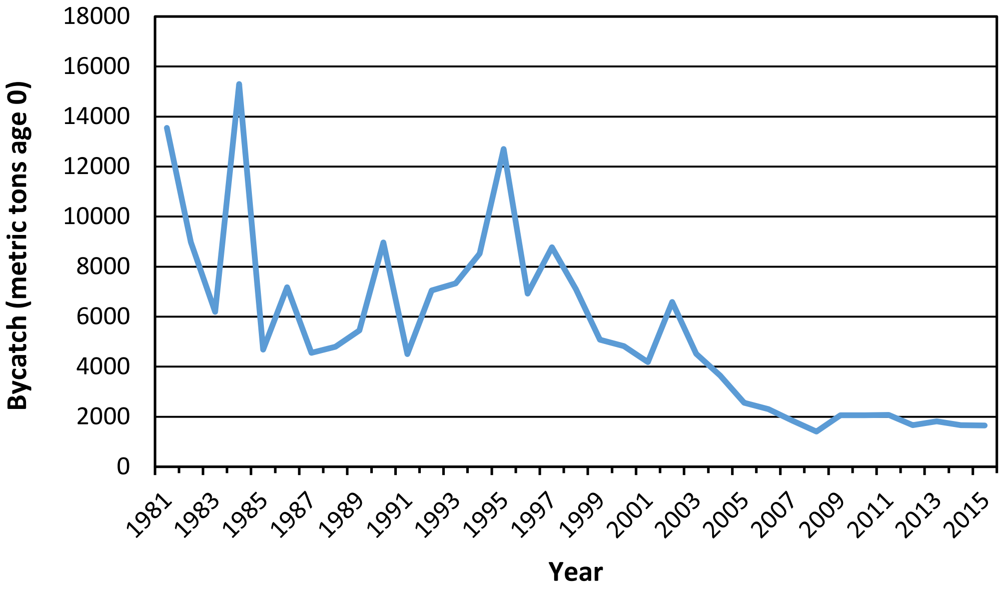


Figure 4.16 Estimate of Gulf Menhaden bycatch estimated using shrimping effort from 1081-2015 provided by NOAA Galveston Lab.

5.0 Fishery-Independent Data Collection and Treatment

Data collected in Texas, Louisiana, Mississippi, Alabama, and Florida were considered for use in order to calculate two coast-wide indices of juvenile abundance based on bag seine data and trawl data. Gill net data were available from each state except Florida to calculate an adult index of abundance. Each state conducts separate surveys, which collect Gulf Menhaden, however Gulf Menhaden are not the target species. Below is a brief description of the data for each individual state sampling program. Tables 5.1-5.4 provide specifics on the states fishery-independent gears. In addition, SEAMAP plankton and trawl data were considered for creation of an index.

5.1 Seines

5.1.1 Texas Seine Data

Texas Parks and Wildlife Department's (TPWD) fishery-independent bag seines are utilized to determine relative abundance, size, species composition, and temporal and spatial distribution of various life history stages of fish and invertebrates in Texas coastal waters.

5.1.1.1 Survey Methods (Including Coverage, Intensity)

Each bay system and Gulf area in Texas serves as a non-overlapping stratum with a fixed number of samples per month (Figure 5.1). Sample locations are drawn independently and without replacement for each combination of gear, stratum, and month (season). Bag seine sample locations are randomly selected from grids (1-minute latitude by 1-minute longitude) that contains >15.2 m of shoreline. Each selected grid is subdivided into 144 5-second gridlets. All gridlets containing >15.2 m of shoreline are used to randomly choose sample sites. Prior to September 1984, sites were randomly selected from 100 fixed stations in each bay system, with random site selection since September 1984.

Bag seines are used in each of ten Texas estuarine systems: Sabine Lake, Galveston, Cedar Lakes, East Matagorda, Matagorda, San Antonio, Aransas, Corpus Christi, upper Laguna Madre, and lower Laguna Madre (Figure 5.1). Bag seines have been employed in seven Texas bay systems since October 1977; sample collection began in the East Matagorda Bay system February 1983, Sabine Lake in January 1986, and Cedar Lakes in January 1996.

Bag seines are pulled parallel to the shoreline for 15.2 m. The area swept (0.03 ha) is determined using distance pulled and actual width of the bag seine when pulled. One half of the monthly bag seine samples are collected during each half (days 1-15 and 16-31) of the month to ensure good temporal distribution of samples. No grid is sampled more than once in a month. Prior to October 1981, six bag seine samples were collected each month in each bay system (except during June 1978 when no samples were collected). From October 1981 through March 1988, 10 bag seine samples were collected each month in each bay system, with half of the samples collected during each half of the month. From April 1988 through December 1989, 12 bag seine samples were collected each month in each bay system. Beginning January 1990, 16 bag seine samples were collected each month in each bay system. Beginning January 1992, 20 samples were collected in each bay system each month, except in East Matagorda Bay and Cedar Lakes where 10 samples were collected per month.

5.1.1.2 Biological Sampling Methods (Including Coverage, Intensity)

Lengths [total (TL) or standard (SL)] of organisms caught are recorded. In bag seines, up to 19 specimens are measured for each species in each sample collected. Surface salinity (ppt), water temperature (°C), dissolved oxygen (ppm), and turbidity [Nephelometric Units (NTU)] are measured for each bag seine sample.

5.1.1.3 Ageing Methods

TPWD does not collect hard parts for age determination of Gulf Menhaden at this time.

5.1.1.4 Use for an Index

Bag seine data from Texas were examined for use in combination with data from other states to create an index for use in the base run. However, after analyzing coast-wide length frequencies of Gulf Menhaden (*B. patronus*) from TPWD bag seines and other monitoring gears, the presence of larger individuals than previously reported in literature or commercial landings was questioned. In general, Finescale Menhaden (*B. gunteri*) grows to a considerably larger size than Gulf Menhaden (*B. patronus*), making the presence of larger individuals of Gulf Menhaden in the Texas data questionable due to potential identification issues with adult fish and consequently juvenile fish, because juvenile individuals are more difficult to identify to species level than adults. The assessment panel also explored the catches of Finescale Menhaden in each of the gears as well. Few catches of Finescale Menhaden occur in the gears that are catching juvenile individuals, but some adult individuals are captured with the gill net gear. If the adults are being sampled, where are the juveniles? The lack of small individuals captured in the seine and trawl gears again brought into question species identification. Since the last benchmark assessment, the state of Texas analyzed genetic information from a sample of large fish from their survey gears. Of the 46 samples taken and classified as Gulf Menhaden, 43 samples were Finescale Menhaden (Section 3.1.1). As a consequence, the assessment panel decided to exclude TPWD data with a recommendation that further DNA testing should be conducted across their size and spatial range to clarify this issue.

5.1.2 Louisiana Seine Data

The Louisiana seine is generally used to sample juvenile finfish, shellfish, and other marine organisms to monitor relative abundance, size distribution, and seasonal and long-term trends but is used more for environmental characterization.

5.1.2.1 Survey Methods (Including Coverage, Intensity)

The sampling design for Louisiana seines consists of fixed stations selected by coastal study areas to target areas known to have fish and shellfish when the sampling programs started (Figure 5.2).

At some sampling stations, land loss due to subsidence, storms or anthropogenic activities, has forced the station locations to move inland (e.g., shoreline seines, gill nets). However, these stations were excluded from all of the analyses because they are not long-term stations. The seine survey has been conducted from 1986 to present at fixed sampling locations. Although the survey period for the seine data is 1986-2017, there were a few years in the late 80s and early 90s when length measurements were not required and thus not recorded in some of the coastal study areas, which lead to systematic differences between areas. After 1991, the Department reinstituted the taking of length measurements; however, implementation didn’t become consistent across all CSAs until late 1995. In October of 2010, additional fixed sampling locations were added to this survey allowing for more spatial coverage within each CSA. Prior to October 2010, samples were collected monthly from January-August and twice monthly from September-December. Beginning in October of 2010, sampling frequency was changed to quarterly and continued at this frequency until July of 2014. In July of 2014, sampling frequency reverted back to monthly, and included all pre- and post-2010 sampling locations.

The seine is 50 ft in length, 6 ft in depth and has a 6x6 ft bag in the middle of the net. The nylon, tarred ace webbing, has a mesh size of 1⁄4 in bar. A lead and float line runs the entire length of the seine. The ends of the seine are held open with 6-ft poles, which are attached to the float and lead lines. Seine sampling techniques can be subdivided into two general types: soft bottom and hard bottom. Sampling methodology utilized at each station is identified. The line is anchored to the shoreline by tying the end to a push pole, paddle, anchor, or other structure. The boat is quietly reversed until the line is fully extended. At this point the boat is turned 90° astern (parallel to the shoreline) and the seine is fed out over the boat's bow while making sure the cork line and bag are not tangled. As the end of the seine is placed overboard, the boat proceeds shoreward and is anchored or tied to the bank. The seine is hauled in by the two tow lines, with care being taken to keep the lead line on the bottom. Once on shore, the catch in the wings of the net is shaken down to the bag, and removed. Gear specifications for the seines can be found in Table 5.2.

5.1.2.2 Biological Sampling Methods (Including Coverage, Intensity)

All organisms collected in seine samples are identified to species and counted. Sizes of up to 30 randomly selected individuals of targeted species are measured to the nearest mm total length. More specimens are measured if measurement of 30 (or general inspection of the sample) indicates that there may be more than one mode of length. The remaining individuals of these species are counted. Other non-target species are counted and weighed in aggregate. Water temperature and salinity are measured at each station during each sampling event.

5.1.2.3 Ageing Methods

LDWF does not collect hard parts for age determination of Gulf Menhaden at this time.

5.1.2.4 Use for an Index

Fishery-independent data from the Louisiana seines were combined with the data from other states to create an index for use in the base run (Tables 5.5 and 5.6; see Section 5.6.1).

5.1.3 Mississippi Seine Data

5.1.3.1 Survey Methods (Including Coverage, Intensity)

Mississippi Department of Marine Resources (MDMR) and the Gulf Coast Research Laboratory (GCRL) collect fishery-independent seine data, which has been collected since January 1974. Seines are sampled at fixed stations (Figure 5.3) and do not target any specific species. Seines are 50-ft bag seines with ¼-in bar mesh. Bag seines are set by hand and pulled at various distances from the shoreline depending on the topography of the bottom of each station. No changes in methodology have occurred over time.

5.1.3.2 Biological Sampling Methods (Including Coverage, Intensity)

All samples are returned to GCRL. Target species (commercially important species of fish and shellfish) were sorted from samples, measured, and weighed up to a minimum aliquot of 50 specimens. The minimum and maximum sizes were measured when the total number of a species exceeded 50. When 50 or fewer animals of a species were present, all were measured. For non-target species, only the smallest and largest specimens were measured for each taxon. The total number (calculated in instances where aliquots were used) and total weight of both target and non-target species were recorded. Since 2009, all species (vertebrates and invertebrates) are sorted from samples, measured, and weighed with a minimum aliquot of 20 specimens. The minimum and maximum sizes were measured when the total number of a species exceeded 20. When 20 or fewer animals of a species are present, all specimens are measured. Total numbers (calculated in instances where aliquots were used) and total weights of all species are recorded.

5.1.3.3 Ageing Methods

Mississippi does not collect hard parts for age determination of Gulf Menhaden at this time.

5.1.3.4 Use for an Index

Fishery-independent seine data from Mississippi were combined with the data from other states to create an index for use in the base run (Tables 5.5 and 5.6; see Section 5.6.1).

5.1.4 Alabama Seine Data

5.1.4.1 Survey Methods (Including Coverage, Intensity)

Seines have been used at fixed stations from 1981 to the present (Figure 5.4). The seine gear has not changed over time. Seines are 4 ft by 50 ft bag seines with bag dimension of 4 ft^3. The mesh is knotless $^3/_{16}$-in mesh. Seines are pulled 60 ft toward shore, which means all pulls are perpendicular to shore. Stations are fixed at sites, collected monthly, and numerous stations have been added or dropped over time, although some long running stations are consistent throughout the time series. The target species for the seine survey was juvenile mullet for two specific stations (34 and 38), otherwise no particular species was targeted. Station 34 was dropped due to shifting of the shoreline, which made the site inaccessible. Current stations are: 36, 37, 38, and 132. All seine sites have a sandy shoreline to which the seine can be drawn.

5.1.4.2 Biological Sampling Methods (Including Coverage, Intensity)

Samples taken during seining are preserved in 5% formalin solution in the field and held in solution until processing. Large specimens, if caught, are measured for appropriate length, weighed using a spring scale, and released alive at the collection site. The entire sample is returned to the lab and sorted to species level. In November of 1998, sampling was altered to quarterly and after a period of evaluation was returned to monthly in October 2000. Lab processing prior to 2010 entailed measuring up to 50 individuals by species in mm SL and obtaining the weight of the entire catch of each species on a bench scale. Current lab processing entails weighing and measuring up to 20 individuals in mm SL for finfish and obtaining the weight of the 20 individuals and the entire catch of each species on a bench scale. Water temperature (°C), salinity (ppt), and dissolved oxygen (Mg/L) are sampled at the surface for each station when the sample is taken.

5.1.4.3 Ageing Methods

AMRD does not collect hard parts for age determination of Gulf Menhaden at this time. The standard length of most Gulf Menhaden collected in the seine is less than 40mm and considered to be young-of-year.

5.1.4.4 Use for an Index

Seine fishery independent data from Alabama were combined with the data from other states to create an index for use in the base run (Tables 5.5 and 5.6; see Section 5.6.1). Samples that were taken from east of 88° longitude were excluded due to the potential hybridization between *B. patronus* and *B. smithi* east of Perdido Bay towards Apalachicola, Florida (see Section 1.3 for more details on the biogeographic break in the northern Gulf).

5.1.5 Florida Seine Data

5.1.5.1 Survey Methods (Including Coverage, Intensity)

Two sampling designs (stratified-random and fixed-station) were initially employed by the Florida Fish and Wildlife Conservation Commission's (FFWCC) Fisheries-Independent Monitoring (FIM) program to assess the status of fishery stocks in Florida estuaries. Fixed-station samples, however, cannot be statistically expanded to describe the fishery stocks beyond the actual sampling sites, while stratified-random samples can be extrapolated to describe an entire estuary. Monthly fixed-station sampling, therefore, was terminated in 1996. Monthly stratified-random sampling with seines is currently conducted year-round using 70-ft bag seines and 600-ft haul seines. Numerous estuaries have been sampled by the FIM program but not all are continuous. Figure 5.5 indicates the location and duration of the various collections in Florida. The primary sampling areas since 1997 along the west Florida coast are Apalachicola, Cedar Key, Tampa Bay, and Charlotte Harbor.

For stratified random sampling, estuarine systems are subdivided into zones delineated primarily on geographic and logistical criteria but which also define areas of greater biological and hydrographic homogeneity than the system as a whole. Zones are identified as being either bay or riverine. Both bay and riverine zones are subdivided into grids based upon a 1 x 1 minute cartographic grid that is overlaid on the entire system. Grids are further subdivided into micrograids using a 10 x 10 cell grid overlay.

In bay zones, grids have been stratified by depth and may be further stratified by habitat type. Depth identifies the gear types (70-ft bay set seine, or 600-ft haul seine) that can be used to sample each grid.

Habitat stratification is gear and estuary specific. In estuaries that stratify 70 ft bay set seines by habitat, stratification is by the presence or absence of submerged aquatic vegetation and by the occurrence of a shoreline within the grid. In estuaries that stratify the 600-ft haul seines by habitat, stratification is based on the presence or absence of overhanging vegetation within the grid.

In riverine zones, micrograids are stratified by depth and may be further stratified by habitat type and salinity gradient. As with bay zones, depth identifies microgrids where the 70 ft boat set seines can be deployed. In some estuaries, the 70 ft boat set seines are further stratified by the presence or absence of overhanging vegetation within the microgrid. Rivers may also be stratified into subzones to ensure that the entire salinity gradient of the river is sampled each month.

Differences in the scale of stratification between bay and riverine zones results in slightly different definitions of the primary sampling unit (sampling site) between the two zone types. Bay zone stratification has only been taken to the grid level, so the grid is randomly selected based upon strata, but the microgrid is simply a random number between 0 and 99. Therefore, the primary sampling unit in bay zones is a randomly selected microgrid within a randomly selected grid. In riverine zones, where stratification has been taken to the microgrid level, microgrids are randomly selected based on strata; the primary sampling unit, therefore, is a randomly selected microgrid. The number of sites to be sampled each month, for each gear and stratum within a given zone, is proportional to the total number of sampling sites that can be sampled within a particular stratum by a gear in an estuarine system. All sampling sites are selected and sampled without replacement each month. After site selections have been made for a month, zone boundaries are removed and sample sites are grouped to optimize sampling logistics. Once sampling groups have been identified, the order in which these groups are sampled during a given month is randomized.

The 70-ft seine has been used for fishery independent sampling from 1989 to the present. The seine used is a 21.3-m (~70 ft), 1.8-m (~6ft) deep center bag seine with 3-mm ($^{1}/_{8}$-inch) delta mesh. It typically collects juvenile and small adult fish and macroinvertebrates along bay edges, river banks, shallow tidal flats, and most areas where water depth is less than 1.5 m (~5ft) for bay sets and less than 1.8 m (~6ft) for in boat sets. Two techniques are currently employed by the FIM program to cover specific habitats. The bay set seine technique samples areas where the water depth is less than 1.5m, such as tidal flats, mangrove fringes, sea wall habitats, sloping beaches, and banks. The boat set seine technique samples riverine areas and tidal creeks where water depth typically increases rapidly from the shoreline, making it impossible to use the bay technique.

The 600-ft haul seine was incorporated into the FIM program in 1996 and is deployed only in bay zones. The seine used is 183-m (~600ft), 3.0-m (~10ft) deep center bag seine with 25-mm (~1 inch) stretch knotted nylon mesh. The haul seine typically collects subadult and adult fish and macroinvertebrates along bay edges, shallow tidal flats and most areas where water depth is less than 2.5-m (~8ft).

5.1.5.2 Biological Sampling Methods (Including Coverage, Intensity)

The number of gear deployments has varied through the years in response to funding and improvements in sampling design. In total there were 2,534 deployments of the 70-ft seine during 2016: Charlotte Harbor (408 bay sets and 504 boat sets), Tampa Bay (408 and 432 bay and boat sets, respectively), Cedar Key (252 and 168 bay and boat sets, respectively), and Apalachicola Bay (204 bay sets and 156 boat sets).

Over 850 deployments with the 183-m haul seine were made during 2016: Charlotte Harbor (204), Tampa Bay (240), Cedar Key (192), and Apalachicola Bay (216).

Vertical profiles for water quality parameters (temperature, dissolved oxygen, pH, and salinity) are recorded at each sampling site. With each gear deployment, the submerged and shoreline habitats (type and percent of each vegetation, and total percent cover), and the type and quantity of bycatch collected are characterized.

Fishery samples collected by the FFWCC's FIM program are processed following a standard set of protocols. All species of fish and select macroinvertebrates are worked up for each sample. Specimens are identified to lowest practical taxonomic level (generally species). *Brevoortia* spp. are only identified to genus because of hybridization (Dahlberg 1970). Specimens are counted, and a subset of each taxon is measured (standard length, SL) prior to release. If samples contain large numbers of specimens (>1,000) sub-sampling with a two-way Motoda box splitter may be conducted. A minimum number of individuals (10 individuals for each species <150 mm SL, and 20 individuals for each species >150 mm SL) are randomly selected to be measured. If multiple size classes of a taxon exist, then the minimum number of specimens from each size class are measured. More than the minimum number of specimens are measured when a broad range in sizes exists with no clear size classes. If a sample has been sub-sampled and a taxon was present in both the split and unsplit portions, the minimum number of specimens are measured from each size class within both the split and unsplit portions. If multiple size classes were measured, then the number collected within each size class is counted separately.

5.1.5.3 Ageing Methods

FFWCC does not collect hard parts for age determination of Gulf Menhaden at this time.

5.1.5.4 Use for an Index

Seine fishery-independent data from Florida were not combined with the data from other states to create an index of juvenile abundance for use in the base run. Because FFWCC does not separate menhaden out to the species level and the high degree of mixing with other species of menhaden with Gulf Menhaden on the eastern edge of its range, these data were not used for index creation.

5.2 Gill nets

5.2.1 Texas Gill Net Data

5.2.1.1 Survey Methods (Including Coverage, Intensity)

Each bay system and Gulf area in Texas serves as a non-overlapping stratum with a fixed number of samples per season for gill nets (Figure 5.1 and 5.6). Sample locations are drawn independently and without replacement for each combination of gear, stratum, and month (season). Gill net sample locations are randomly selected from grids (1-minute latitude by 1-minute longitude) that contains >15.2 m of shoreline. Each selected grid is subdivided into 144, 5-second gridlets. All gridlets containing >15.2 m of shoreline are used to randomly choose sample sites. Prior to September 1984, sites were randomly selected from 100 fixed stations in each bay system, with random site selection since September 1984.

Gill nets are utilized to determine relative abundance, size, species composition, and temporal and spatial distribution of various life history stages of fish and invertebrates in Texas coastal waters. Brief descriptions of each gear are included in Table 5.1. Gill nets are set perpendicular to shorelines and target subadult and adult finfish.

Monofilament gill nets are used in each of ten Texas estuarine systems: Sabine Lake, Galveston Bay, Cedar Lakes, East Matagorda Bay, Matagorda Bay, San Antonio Bay, Aransas Bay, Corpus Christi Bay, upper Laguna Madre, and lower Laguna Madre (Figure 5.6). Gill nets have been systematically used in seven Texas bay systems since November 1975; East Matagorda Bay was added in fall 1976, Sabine Lake in spring 1986, and Cedar Lakes in spring 1995.

Gill net samples are collected overnight during each spring and fall season. The spring season begins with the second full week in April and extends for 10 weeks. The fall season begins with the second full week in September and extends for 10 weeks. Between three and five nets are set each week in each bay, except in East Matagorda Bay where only two sets are made during each week, and Cedar Lakes, where only one set is made each week. Prior to fall 1981, no more than 18 overnight gill net sets occurred in each season in each bay system. Since fall 1981, 45 gill nets were set during each season in each bay system except East Matagorda Bay. In East Matagorda Bay from fall 1981 to spring 1984, not less than six nor more than 12 gill nets were set each season; since fall 1984, 20 nets were set each season. In Cedar Lakes, 20 nets were set each season until 2000, when 10 nets were set each season. Each sampling week extends from 1 h before sunset on Sunday through 4 h after sunrise the following Sunday. Gill nets are set perpendicular to shore with the smallest mesh shoreward. Nets are set within 1 hr before sunset and retrieved within 4 h after the following sunrise. Total fishing time is recorded (nearest 0.1 hr).

5.2.1.2 Biological Sampling Methods (Including Coverage, Intensity)

All organisms greater than 5 mm total length caught in gill nets are counted and identified to the lowest phylogenetic unit (genus and species are preferred). Up to nineteen individual Gulf Menhaden from each gill net sample are randomly selected and measured to the nearest 1 mm.

Surface salinity (‰), water temperature (°C), dissolved oxygen (ppm), and turbidity [Nephelometric Units (NTU)] are measured at the set and pickup for each gill net. Latitude and longitude, start and completion times, and shallow and deep water depths are recorded for each sample, as is presence or absence of vegetation.

5.2.1.3 Ageing Methods

TPWD does not collect hard parts for age determination of Gulf Menhaden at this time.

5.2.1.4 Use for an Index

Gill net data collected by TPWD in Texas' state waters were examined for use in combination with data from other states to create and index for use in the base run. However, after analyzing coast-wide length frequency of Gulf Menhaden (*B. patronus*) from TPWD gill nets, the presence of large individuals (anomalously large individuals that exceeded the maximum lengths reported in literature or commercial landings) was questioned (Figure 5.7). Finescale Menhaden (*B. gunteri*) grow to a considerably larger size than Gulf Menhaden (*B. patronus*) making the presence of larger individuals of Gulf Menhaden in the Texas data questionable due to potential identification issues with adult and consequently juvenile fish too. The assessment panel also explored the catches of Finescale Menhaden in each of the other gears as well. Few catches of Finescale Menhaden occur in the gears that are catching juvenile individuals, but some individuals are captured with the gill net gear. The lack of small individuals captured in the seine and trawl gears again brought into question species identification across the entire size range. Since the last benchmark assessment, the state of Texas analyzed genetic information from a sample of large fish from their survey gears (Section 3.1.1). Of the 46 samples taken and identified as Gulf Menhaden, 43 samples were determined, using genetics tools, to be Finescale Menhaden. Additionally, the set time for the Texas gill net was substantially longer than the set time of the gill nets deployed by the other states, which would make it difficult to standardize with other data sets. As a consequence of the genetic testing, length frequencies, and differences in deployment, the assessment panel decided to exclude TPWD data for use in a gill net index. The assessment panel recommended that further study be conducted across the size and spatial range of Gulf Menhaden to clarify species identification and the potential for hybridization.

5.2.2 Louisiana Gill Net Data

LDWF utilizes a 750-ft experimental monofilament gill net to sample finfish in order to obtain indices of abundance, size distribution of finfish, and ancillary life history information on selected species.

5.2.2.1 Survey Methods (Including Coverage, Intensity)

The sampling design for Louisiana gill nets consists of fixed stations selected by coastal study areas to target areas known to have fish or shellfish when the sampling programs started (Figure 5.8).

At some sampling stations, land loss due to subsidence, storms or anthropogenic activities, has forced the station locations to move inland. The gillnet survey was conducted from 1986 to April of 2013 at fixed sampling locations within each CSA. The 1¼ in. and 1¾ in. bar mesh were not included until 1988. In October of 2010, additional fixed stations were added to this survey allowing more spatial coverage within basins and all old and new stations were sampled monthly. Beginning in April of 2013, the survey design was modified so that sampling locations are now selected randomly from all the established stations within each basin. These new stations were excluded from the analysis because they are not long-term stations. Although the survey period for the gill net data is 1986-2017, there were a few years in the late 1980s and early 1990s when length measurements were not required and thus not recorded in some of the coastal study areas, which lead to systematic differences between areas. After 1991, the LDWF reinstituted the taking of length measurements; however, implementation didn't become consistent across all CSAs until late 1995. Gill net sample sites are visited on a monthly basis from October through March and on a semi-monthly basis from April through September across all CSAs.

The experimental gill nets are 750 ft long, 8 ft deep, and comprised of five 150 ft panels. The five panels consist of 1-, 1¼-, 1½-, 1¾-, and 2-in bar mesh or 2.0-, 2.5-, 3.0-, 3.5-, and 4.0-in stretch mesh. The float line is $^3/_8$-in diameter hollow braided polypropylene and the lead line is #60 75 lead core, $^5/_{16}$-in diameter lead core line. Large floats and anchor weights are attached to both ends of the float line and lead line, respectively. Gill net deployment begins with the 1-in bar mesh end. After the float and weight are tossed overboard adjacent to or on a shoreline or reef, the gill net is deployed over the transom of the net well. The net may be set parallel to the shoreline or reef or in a crescent shape. Enough room is left on one side of the net to allow the net skiff to enter and then maneuver within the net. Fish are forced to strike the net by running the net skiff around both the inside and outside of the net a minimum of two or three times in gradually tightening circles. The net is then retrieved and pulled aboard from the downwind or down current end.

5.2.2.2 Biological Sampling Methods (Including Coverage, Intensity)

All organisms captured in gill nets are removed and placed in baskets corresponding to each mesh size or panel of the net. Organisms are noted as gilled or tangled (i.e., those fish which have not penetrated individual meshes to the back of the operculum). Up to 30 individuals of each target species are individually measured (TL in mm) per panel; remaining individuals of these species are counted and the entire sample is weighed in aggregate per panel. Other non-target species are counted and weighed in aggregate per panel. Water temperature and salinity are measured at each station during each sampling event.

5.2.2.3 Ageing Methods

LDWF does not collect hard parts for age determination of Gulf Menhaden at this time.

5.2.2.4 Use for an Index

Fishery-independent data from the Louisiana gill net samples were used to create an index of abundance for use in the base run (Tables 5.7 and 5.8). The assessment panel deemed the Louisiana gill net data appropriate for capturing true fluctuations in population abundance and appropriate for use in the assessment for the following reasons:

1. The sampling stations are within the range of the population of interest.

The gill net sampling stations cover a portion of the range of the Gulf Menhaden population and a portion of the range of the commercial fishery; however, the coverage is large enough to sample the large scale dynamics that are occurring in the population. Also, the area of coverage is off the coast of Louisiana, which is the heart of the range of Gulf Menhaden.

2. Length samples indicate that the gill net sampling program captures Gulf Menhaden smaller and larger than the commercial fishery.

The specimens collected during gill net sampling are both smaller and larger than the specimens collected by the port agents from the commercial reduction fishery (Figure 5.9). This indicates that the gill net sampling is collecting a wider range in sizes, and likely ages, than the commercial fishery and is a better representation of the population as a whole in the Gulf of Mexico.

3. The standardized abundance index created from the gill net index is correlated with the catch at age-2 from the fishery (see Section 5.6.3 below for further discussion).

The final, standardized abundance index created from the gill net data correlates with an index based on the catch at age-2 from the reduction fishery. This provides corroborative evidence that the two pieces of separate information are picking up on a similar signal from the true population abundance.

4. Best available data were used to create an index of adult abundance.

The gill net sampling was not meant to target Gulf Menhaden specifically; however, the data provide adequate information to create an index for the assessment. These data are the best data available for creation of an index. Other data are available, such as fishery-dependent data or gill net data from other states. However, concerns about hyperstability in the fishery-dependent data are warranted, and the other fishery-independent data from the states has questionable species identification or a shorter time period. It is believed that the Louisiana gill net data do not suffer from hyperstability of its CPUE. Thus, the Louisiana gill net data are the best data available to provide an adult abundance index, which is critical for the statistical catch at age model.

5.2.3 Mississippi Gill Net Data

Mississippi Department of Marine Resources (MDMR) and the Gulf Coast Research Laboratory (GCRL) have collected fishery-independent gill net data since October 2005.

5.2.3.1 Survey Methods (Including Coverage, Intensity)

Gill nets have been sampled at fixed stations (Figure 5.3), but random stations have also been added since May of 2008. Gill net sampling does not target any specific species. Gill nets are 750 ft long consisting of five panels measuring 150-ft each. Mesh sizes include 2.0-, 2.5-, 3.0-, 3.5-, and 4.0-in stretch mesh. Gill nets are deployed from the shoreline angling out then turning parallel to the shoreline. The end of the net is turned back towards the shore to form a small hook. The net has a soak time of one hour. The only sampling change since the inception of gill net sampling was the addition of random stations in May 2008. Five areas were divided up into a grid system with grids being randomly drawn for each area once a month.

5.2.3.2 Biological Sampling Methods (Including Coverage, Intensity)

All fish sampled in gill nets (including menhaden since the fall of 2008) are brought back to the lab for processing and are separated by each mesh size and bagged for future analysis. Since 2011, MDMR has measured all Gulf Menhaden sampled for total length (TL), fork length (FL), and standard length (SL) in mm. Weights of individual Gulf Menhaden were recorded in grams. For gill nets deployed by GCRL, all menhaden lengths are recorded as total length (TL) in mm. When more than one Gulf Menhaden specimen was collected at a station a range of lengths was recorded consisting of the smallest and largest length. Weights were recorded in grams. Temperature, salinity, and dissolved oxygen were sampled at each sampling location during each sample.

5.2.3.3 Ageing Methods

Mississippi does not collect hard parts for age determination of Gulf Menhaden at this time.

5.2.3.4 Use for an Index

Gill net fishery independent data from Mississippi were combined with the data from Alabama to consider the creation of an index of abundance for use in a sensitivity run (Tables 5.7 and 5.8; see Section 5.6.3 for more information).

5.2.4 Alabama Gill Net Data

A gill net survey has been implemented from 2001 to the present (Figure 5.4). In 2000, a trial period of gears, set types, and locations were explored for assessing multiple finfish species. Gear and study design were decided upon in 2001 and implemented in May 2001. Gill nets used for sampling in Alabama are either small mesh gill nets (2001 to current) or large mesh gill nets (2004 to current). The small mesh gill net is composed of five panels (8 X 150 ft) of graduated mesh sizes (750 ft total). Mesh sizes begin with a 2-inch stretch mesh and increase by ½-inch increments up to 4 in. Each mesh is color coded by a corresponding float (blue = 2.0, red =2.5, white = 3.0, green = 3.5, and gold = 4.0). Each large mesh gill net is presently composed of four panels (8 X 150 ft) of graduated mesh sizes (600 ft total). Mesh sizes begin with a 4.5-in stretch mesh and increase by ½-inch increments up to 6 in. Meshes are color coded by a corresponding float (blue = 4.5, red =5, white = 5.5, and green = 6). The configuration of the large mesh net was changed for 2005 when a 4-in mesh was dropped to remove duplicative sampling with this mesh.

5.2.4.1 Survey Methods (Including Coverage, Intensity)

Nets are soaked for a period of one hour and sets do not target any specific species. Stations are selected using stratified random sampling with sampling sites being allocated based on variation in samples. A target of 240 sets per year (120 for each net configuration) is maintained annually.

Area 1, upper Mobile Bay, is characterized by brackish waters with submersed aquatic vegetation (SAV) beds along the northern boundary and eastern shore. Sand and mud sediments are prevalent in the upper reaches giving way to mostly sand substrate in the middle of the bay. Oyster reefs are patchy and common along the western and center portions of the upper bay. Gaillard Island is a man-made island that is bordered by large rip-rap and sandy bottoms.

Area 2, Lower Mobile Bay shorelines are sandy giving way to mud in the deeper portions. Large oyster reefs are present in several locations both on the east and western portions in 8-12 ft of water.

Area 3, Mississippi Sound is quite diverse. Site A has an undeveloped shoreline with extensive savannah and marshes. Due to connectivity to the open Gulf through Petit Bois Pass, the salinity stays high and fosters growth of numerous SAV beds on the open flats. Site B houses two ports (Bayou La Batre and Coden Bayou), which serve as harbors for commercial fishing and ship building industries. In spite of this, the mud and sand bottoms provide substrate for numerous oyster resources. Site C has an undeveloped shoreline with extensive savannah and marshes and shares an expansive oyster reef in lower Mobile Bay. This area is subject to the fresh water inputs flowing down the west side of Mobile Bay. The northern shore of Dauphin Island is sandy with sparse SAV beds and tidal pools that wax and wane with tropical events.

Area 4, Perdido Bay and Little Lagoon comprise this area. Little lagoon (site A) is almost entirely influenced by tides in and out of its Gulf inlet. Water depth averages about 3 feet and SAV are numerous in the clear water. The majority of the shoreline is bordered by residential development and seawall. Site B has muddy water and substrate and is bordered for the most part by marsh and savannahs. The remainder of Area 4 has clear, higher salinity waters. SAV beds are numerous. Substrate is sand even in the deeper portions.

5.2.4.2 Biological Sampling Methods (Including Coverage, Intensity)

While nets are being retrieved fish are removed from the net and placed in boxes corresponding to mesh size. Field processing entails identification to species, measuring up to 10 individuals in mm FL or TL (depending on species) from each mesh size per species and obtaining a total count by mesh size per species. Samples are bagged, labeled, placed on ice, and are returned for lab processing. Lab processing includes length, weight, ovary weight, sexing, and otolith extraction (although otoliths have not been removed for Gulf Menhaden; see below Section 5.2.4.3). Surface water temperature, salinity, dissolved oxygen, and GPS coordinates are recorded at each site during each sample taken. While the net is deployed, the water depth at the midpoint of the mesh is recorded as mesh depth.

5.2.4.3 Ageing Methods

The AMRD does not age Gulf Menhaden samples collected during fishery-independent monitoring. However, recent protocols have been implemented to begin collecting scales from Gulf Menhaden retrieved from the gill net sampling program, but no age data exist for the purposes of this analysis.

5.2.4.4 Use for an Index

Gill net fishery independent data from Alabama were combined with the data from Mississippi for consideration in creating an index of abundance for use in the base run (Tables 5.7 and 5.8; see Section 5.6.3). Due to differences in setting the gear (strike versus passive) the assessment panel decided to separate Alabama and Mississippi from Louisiana for gill net index considerations. In addition, samples that were taken from east of 88° longitude were excluded due to the potential hybridization between *B. patronus* and *B. smithi* east of Perdido Bay towards Apalachicola, Florida (see Section 1.3 for more details on the geographic break in the northern Gulf).

5.3 Inshore Trawls

5.3.1 Texas Inshore Trawl Data

5.3.1.1 Survey Methods (Including Coverage, Intensity)

Each bay system and Gulf area serves as non-overlapping strata with a fixed number of samples per month (Figure 5.1). Sample locations are drawn independently and without replacement for each combination of gear, stratum, and month.

Bay trawl sample locations are randomly selected from grids containing water $\geq$1 m deep in at least ⅓ of the grid and are known to be free of obstructions. Large bays (Galveston, Matagorda, San Antonio, Aransas, and Corpus Christi) are stratified into two zones: Zone 1 (upper bay nearest mouths of rivers) and Zone 2 (lower bay farthest from rivers) to ensure good spatial distribution of samples. Smaller bays (Sabine Lake, East Matagorda Bay, upper Laguna Madre and lower Laguna Madre) are not stratified. One half of the monthly trawl samples in each zone in each bay system are collected during each half (days 1-15 and 16-31) of the month to ensure good temporal distribution of samples. Trawls are towed in a circular pattern near the center of each grid. All tow times are 10 minutes in duration. No grid is sampled more than once per month. Trawl samples have been collected in three bays since January 1982 and seven bays since May 1982. Trawl samples commenced in Sabine Lake beginning January 1986, and in East Matagorda Bay beginning April 1987. Since inception, sample size has been 10 trawls per month per zone.

5.3.1.2 Biological Sampling Methods (Including Coverage, Intensity)

All organisms greater than 5 mm total length caught in trawls are counted and identified to the lowest phylogenetic unit (genus and species are preferred). Up to nineteen individual Gulf Menhaden from each trawl sample are randomly selected and measured to the nearest 1 mm.

Bottom salinity, water temperature, dissolved oxygen, and turbidity are measured prior to each trawl sample. Latitude and longitude, start and completion times, and shallow and deep water depths are recorded for each sample, as is presence or absence of vegetation.

5.3.1.3 Ageing Methods

TPWD does not collect hard parts for age determination of Gulf Menhaden at this time.

5.3.1.4 Use for an Index

Trawl data from Texas were examined for use in combination with data from other states to create an index for use in the base run. However, after analyzing coast-wide length frequencies of Gulf Menhaden (*B. patronus*) from TPWD trawls and other monitoring gears, the presence of larger individuals than previously reported in literature or commercial landings was questioned. In general, Finescale Menhaden (*B. gunteri*) grows to a considerably larger size than Gulf Menhaden (*B. patronus*) making the presence of larger individuals of Gulf Menhaden in the Texas data questionable due to potential identification issues with adult and consequently juvenile fish too, because juvenile individuals are more difficult to identify to species level than adults. The assessment panel also explored the catches of Finescale Menhaden in each of the other gears as well. Few catches of Finescale Menhaden occur in the gears that are catching juvenile individuals, but some individuals are captured with the gill net gear. If the adults are being sampled, where are the juveniles? The lack of small individuals captured in the seine and trawl gears again brought into question species identification across the entire size range. Since the last benchmark assessment, the state of Texas analyzed genetic information from a sample of large fish from their survey gears. Of the 46 samples taken and classified as Gulf Menhaden, 43 samples were Finescale Menhaden (Section 3.1.1). As a consequence of the genetic testing and concern over species identification, the assessment panel decided to exclude TPWD data and a recommendation that DNA testing be conducted across the size and spatial range of Gulf Menhaden to clarify species identification was made.

5.3.2 Louisiana Inshore Trawl Data

The 16-ft flat otter trawl is used to sample penaeid shrimp, blue crabs, finfish (bottomfish), and other marine organisms in the larger inshore bays and in Louisiana's territorial waters at fixed stations.

5.3.2.1 Survey Methods (Including Coverage, Intensity)

Trawl data from the LDWF marine fisheries-independent sampling program dates back to 1965 for some areas. The survey period for 16-ft trawl data is 1967-2017. The 16-ft trawl inshore sampling is conducted monthly during January-March and August-September, then semi-monthly during April-July and December. The 6-ft trawl samples are conducted beginning the first week of April and taken weekly through the first week of May, then they are sampled from the second week of June through the first week of July. The 20-ft trawls (offshore) are sampled monthly in January, March, May, and November with semi-monthly samples being conducted in April and December. New fixed sampling stations were also added in October of 2010. Revisions to sampling frequency were initiated in 2013 to more efficiently gather the required data. Beginning in 2013, nearshore stations previously sampled with 16-ft trawls were sampled with 20-ft trawls and additional offshore sample sites were added throughout Louisiana’s offshore waters.

The trawl body is constructed of ¾ in bar mesh No. 9 nylon mesh while the tail is constructed of ¼-in bar mesh knotted 35-lb tensile strength nylon and is 54-60 in long. The trawl is hung on $^3/_8$-in PDP rope with four 3.0- X 1.5-in spongex floats on the corkline and with a minimum of 3.5 ft extra rope on the corkline and leadline. The trawl has 16 ft and 20 ft of webbing along the cork and lead lines, respectively. Trawls are dipped in green plastic nylon net dip. The trawl boards are constructed of ¾-in marine plywood and measure 24 in across the top, 14 in at the back, and 10 in at the front with a 4-in rounded corner. The bridle is constructed of four lengths of galvanized $^3/_{16}$-in chain while the bottom slide consists of a $^3/_8$-in by 2-in, flat iron bar. The 16-ft trawl is attached to a ½-in diameter nylon rope or stainless steel tow line and bridle. The length of the bridle is 2-3 times the trawl width. Tow line length is normally at least 4-5 times the maximum depth of water. The trawl is towed for ten minutes (timed from when the trawl first begins to move forward to when it stops forward movement) at a constant speed and in a weaving or circular track to allow the prop wash to pass on either side of the trawl.

5.3.2.2 Biological Sampling Methods (Including Coverage, Intensity)

All organisms collected in trawls are identified by species, counted, and up to 50 of each species measured in 5-mm intervals. Finfish are measured for total length (tip of snout to tip of longest lobe of compressed caudal fin).

5.3.2.3 Ageing Methods

LDWF does not collect hard parts for age determination of Gulf Menhaden at this time.

5.3.2.4 Use for an Index

Trawl fishery independent data from the state of Louisiana were considered with the data from other states. However, during the last stock benchmark assessment for Gulf Menhaden (SEDAR 2013a), the assessment panel determined that this gear was not suited to catch menhaden well and would not be as representative as the seine gear for age-0 individuals. The current assessment panel agreed with this determination, and no new data have arisen to change these decisions so these data were excluded.

5.3.3 Mississippi Inshore Trawl Data

Trawl data have been collected from January 1974 to the present. Trawls are run at fixed stations (Figure 5.3) and do not target any specific species.

5.3.3.1 Survey Methods (Including Coverage, Intensity)

Tows are 10 minutes at each station and no changes in methodology have occurred over time. The trawl has a 16-ft head rope and a 20-ft foot rope. The nets are made of nylon netting of the following size mesh and thread: 1.5 in stretch mesh #9 thread body, $1\frac{3}{8}$-in stretch mesh #18 thread cod end (80x100 deep) fully rigged with 2.0-in O.D. nylon net rings for purse rope, and no lazyline. Head and footropes of $\frac{3}{8}$-in diameter poly-dac net rope with legs extended 3 ft 6 in and rope thimbles spliced in at each end. Six 1.5 x 2.5 in sponge floats spaced evenly on bosom of headrope with $\frac{1}{8}$ in galvanized chain hung loop style on footrope. Nets treated in latex net dip on completion. Purse rope rigged on nets. Inner liner composed of $\frac{3}{8}$ in stretch mesh #63 knotless nylon netting inserted and hogtied in cod end to hold small specimens.

5.3.3.2 Biological Sampling Methods (Including Coverage, Intensity)

All samples are returned to GCRL. Target species (commercially important species of fish and shellfish) were sorted from samples, measured, and weighed up to a minimum aliquot of 50 specimens. The minimum and maximum sizes were measured when the total number of a species exceeded 50. When 50 or fewer animals of a species were present, all were measured. For non-target species, only the smallest and largest specimens were measured for each taxon. The total number (calculated in instances where aliquots were used) and total weight of both target and non-target species were recorded. Since 2009, all species (vertebrates and invertebrates) are sorted from samples, measured, and weighed for a minimum aliquot of 20 specimens. The minimum and maximum sizes are measured when the total number of a species exceeded 20. When 20 or fewer animals of a species are present, all specimens are measured. Total numbers (calculated in instances where aliquots were used) and total weights of all species are recorded.

5.3.3.3 Ageing Methods

Mississippi does not collect hard parts for age determination of Gulf Menhaden at this time.

5.3.3.4 Use for an Index

Trawl fishery independent data from the state of Mississippi were considered with the data from other states. However, during the last stock benchmark assessment for Gulf Menhaden (SEDAR 2013a), the assessment panel determined that this gear was not suited to catch menhaden well and would not be as representative as the seine gear for age-0 individuals. The current assessment panel agreed with this determination, and no new data have arisen to change these decisions so these data were excluded from this assessment.

5.3.4 Alabama Inshore Trawl Data

5.3.4.1 Survey Methods (Including Coverage, Intensity)

AMRD from 1981 to the present has towed trawls at fixed stations (Figure 5.4). The trawl gear has been consistent over time. Trawls are 16-ft, with 1.25-in stretch mesh (front) and 1.5-in stretch mesh (bag) with a $^3/_{16}$-in liner. Trawls are towed for 10 minutes at each station. Stations are currently fixed at 24 sites, collected monthly, and numerous stations have been added or dropped over time. In November of 1998, sampling was altered to quarterly and after a period of evaluation was returned to monthly in October 2000. Station habitat varies from within channel, to mud, sand, and grass flats. Three stations within the Mobile Ship Channel are at depths between 40-45 feet depending on the maintenance activities of the corps. The other station depths are less than 14 feet.

5.3.4.2 Biological Sampling Methods (Including Coverage, Intensity)

Prior to 2007 trawl samples were preserved in 10% formalin, and after 2007 samples were frozen until processing. If caught, large adults were measured for appropriate length, weighed using a spring scale, and released. Lab processing prior to 2010 entailed measuring up to 50 individuals by species in mm SL and obtaining the weight of the entire species catch on a bench scale. Current lab processing entails weighing and measuring up to 20 individuals in mm SL for finfish and obtaining the weight of the 20 individuals and the entire species catch on a bench scale. Water temperature (°C), salinity (ppt), and dissolved oxygen (Mg/L) are sampled at maximum depth for each station when the sample is taken.

5.3.4.3 Ageing Methods

AMRD does not collect hard parts for age determination of Gulf Menhaden at this time. Most specimens are less than 70mm SL and are considered to be young-of-year.

5.3.4.4 Use for an Index

Trawl fishery independent data from the state of Alabama were considered with the data from other states. However, during the last stock benchmark assessment for Gulf Menhaden (SEDAR 2013a), the assessment panel determined that this gear was not suited to catch menhaden well and would not be as representative as the seine gear for age-0 individuals. The current assessment panel agreed with this determination, and no new data have arisen to change these decisions. Thus, trawl data were not included in this assessment.

5.3.5 Florida Inshore Trawl Data

Two sampling designs (stratified-random and fixed-station) were initially employed by the FFWCC FIM program to assess the status of fishery stocks in Florida estuaries. Fixed-station samples, however, cannot be statistically expanded to describe the fishery stocks beyond the actual sampling sites, while stratified-random samples can be extrapolated to describe an entire estuary. Monthly fixed-station sampling, therefore, was terminated in 1996. Monthly stratified-random sampling is currently conducted year-round using 20-ft trawls. Numerous estuaries have been sampled by the FIM program but not all are continuous. Figure 5.8 indicates the location and duration of the various collections in Florida. The primary sampling areas since 1997 along the west Florida coast are Apalachicola, Cedar Key, Tampa Bay, and Charlotte Harbor.

For stratified random sampling, estuarine systems are subdivided into zones delineated primarily on geographic and logistical criteria but which also define areas of greater biological and hydrographic homogeneity than the system as a whole. Zones are identified as being either bay or riverine. Both bay and riverine zones are subdivided into grids based upon a 1 x 1 minute cartographic grid that is overlaid on the entire system. Grids are further subdivided into microgrids using a 10 x 10 cell grid overlay. In both bay and river zones, grids have been stratified by depth. River zones may be further stratified into subzones to ensure that the river's entire salinity gradient is sampled each month.

Trawls have been used for fishery independent sampling in Florida from 1989 to the present. A 6.1-m (20-ft) otter trawl with 38-mm (~1.5 inches) stretch mesh and 3-mm ($^1/_8$ in) delta mesh liner is used in the FIM program to sample areas of the estuarine system between 1.8 m and 7.6 m in depth. In addition to sampling areas of the bay not accessible to seines, trawls tend to collect epibenthic fish and macroinvertebrates that are larger than those typically collected in 70-ft seines. Trawl tows are either five (river zones) or ten (bay zones) minutes in duration. The otter trawl is conical in shape with a wide elliptical mouth opening, which gradually tapers backwards toward a narrow bag. Each side of the trawl mouth has lines attached to weighted doors. A tow line is tethered to each of these doors and is used to pull the net through the water. The trawl mouth is leaded at the base and floated on top. Running from the base of the doors is a long chain that is pulled just ahead of the mouth of the trawl. This is called a tickler chain and serves the purpose of scaring bottom organisms into the water column where they can be collected by the trawl. When the net is fishing, the doors are spread apart by the forward motion of the boat. This forward action opens the mouth of the trawl. Organisms on the bottom stirred up by the tickler chain and those already present in the water column are funneled down the trawl toward the bag where they are trapped. The bag is lined with a small-mesh liner and tied off at the end to prevent escapement of organisms.

5.3.5.1 Biological Sampling Methods (Including Coverage, Intensity)

The number of gear deployments has varied through the years in response to funding and improvements in sampling design. In total there were 1,116 deployments of the 20-ft otter trawl during 2016: Charlotte Harbor (360), Tampa Bay (348), Cedar Key (180), and Apalachicola (228).

Vertical profiles for water quality parameters (temperature, dissolved oxygen, pH, and salinity) are recorded at each sampling site. With each gear deployment, the nearest shoreline habitat (type and percent of each vegetation, and total percent cover), and the type and quantity of bycatch collected are characterized.

Fishery samples collected by the FFWCC's FIM program are processed following a standard set of protocols. All species of fish and select macroinvertebrates are worked up for each sample. Specimens are identified to lowest practical taxonomic level (generally species). *Brevoortia* spp. are only identified to genus because of hybridization (Dahlberg 1970). Specimens are counted, and a subset of each taxon is measured (standard length, SL) prior to release. If samples contain large numbers of specimens

(>1,000) sub-sampling with a two-way Motoda box splitter may be conducted. A minimum number of individuals (10 individuals for each species <150 mm SL, and 20 individuals for each species >150 mm SL) are randomly selected to be measured. If multiple size classes of a taxon exist, then the minimum number of specimens from each size class are measured. More than the minimum number of specimens are measured when a broad range in sizes exists with no clear size classes. If a sample has been sub-sampled and a taxon was present in both the split and unsplit portions, the minimum number of specimens are measured from each size class within both the split and unsplit portions. If multiple size classes were measured, then the number collected within each size class is counted separately.

5.3.5.2 Ageing Methods

FFWCC does not collect hard parts for age determination of Gulf Menhaden at this time.

5.3.5.3 Use for an Index

Trawl fishery-independent data from Florida were not considered because FFWCC does not separate menhaden out to the species level and because of a high degree of mixing with other species of menhaden with Gulf Menhaden on the Eastern edge of its range. Thus, these data were not used for consideration for index creation.

5.4 Alabama Juvenile Survey

5.4.1 Survey Methods (Including Coverage and Intensity)

Sampling under current design began in June of 2016 (Table 5.4). Six tidally influenced river systems were the target sampling areas. The push net is a small flat 2-seam trawl suspended from booms extending forward of the boat's bow. Aluminum trawl doors are attached to the head and footrope to maintain the net opening. Mesh is a $1^{3}/_{8}$-in stretch treated nylon webbing with a ½-in stretched delta mesh in the cod end. Net body is approximately 11-ft in length and cod end is 4-ft in length. To maintain the net near the surface, the gear is suspended from booms extending forward of the bow and the gear fishes just under the vessel.

The net is pushed for a 5-minute interval within riverine environments during hours past sunset. Fishing time begins once lines are dogged off and doors are in a fishing position off the bow of the vessel just under the water's surface. Mean vessel speed through the water while sampling is monitored in mph on the vessels depth finder and is recorded in knots prior to picking up the net.

Upon retrieving the net, the doors are pulled forward to pulleys on the end of the booms and the tail bag is retrieved first with the lazy line and then the remainder of the net is hauled in, shaken down, contents bagged and labeled for processing in the lab.

5.4.2 Biological and Physical Sampling Methods

Prior to sampling, environmental data are taken at the surface. An YSI meter measures for surface salinity, temperature, and dissolved oxygen. GPS start coordinates (DD.DDDDD), date, time (24 hr), site name, repetition number, and sampler's initials are recorded for each sample. During sampling, water speed is monitored by an Airmar P66 transducer equipped with a paddle wheel. Vessel speed is registered as 1.66 MPH while sampling and speed through the water is verified periodically by a General Oceanic flow meter equipped with a standard rotor to be averaging 2.5 knots.

For each sample, no more than 20 lengths and weights per species/sample are measured for the appropriate total or fork length (mm) and weight (grams). All individuals are counted unless that number appears greater than 500. Then, the combined weight of the 20 may be used to calculate a mean weight, which then can be used to extrapolate the number of individuals from the total weight as long as the lengths of the 20 are similar to the remaining sample. Total count and weight of individuals is recorded on the field data sheet. **Note:** total weight is an aggregate weight of all organisms and may not equal the sum of individual weights.

5.4.3 Ageing Methods

Surface trawls capture Gulf Menhaden 20-140 mm FL, which is based upon mesh size in the cod end and vessel speed. Most menhaden captured were in the 20-65 mm FL range. Based upon the length range, it is estimated that all menhaden within this size range are age-0s and are comprised of multiple spawning events of that year class.

5.4.4 Use for an Index

Surface trawl fishery independent data from the state of Alabama were considered for use in the stock assessment. However, based upon the short time series and limited spatial coverage, it was not included in the assessment, but demonstrated promise as a reliable method to potentially index Gulf Menhaden, especially since the survey specifically targets pelagic fishes (anchovies and menhaden).

5.5 SEAMAP Trawl Survey

5.5.1 Survey Methods (Including Coverage and Intensity)

The Southeast Monitoring and Assessment Program (SEAMAP) is a multi-agency collaboration within the Gulf of Mexico to collect fishery independent sampling data. SEAMAP surveys use trawl gear to collect fishery independent data (i.e. finfish, shrimp, and other invertebrates). State and federal agencies collaboratively coordinate the scheduling of cruise dates and the selection of stations to be sampled by each agency, which results in a coordinated program with common sampling protocols and gear. The program has been operating since 1982 and ranges from Texas to Florida (Figure 5.10). The spatial and temporal extent of SEAMAP covers a greater scale than other data sources under consideration for index creation, and the spatial extent encompasses the range of the commercial menhaden fishery (Figure 5.11).

The Summer and Fall SEAMAP Shrimp/Groundfish surveys have used the same design from 1987 to 2009. Sampling protocols were changed beginning in 1987. At least one day and one night set were located within each depth/statistical unit beginning in 1987 (Craig 2001). Prior to 1987, sets were randomly located within 10x10 minute grid cells, and were set only at night (Craig 2001). The 5,896 samples set prior to 1987 were excluded from the analysis. The removal of surveys prior to 1987 had no noticeable influence on length distributions of captured menhaden because only 35 captured menhaden lengths were recorded prior to 1987. Similarly, the effect of excluding sets taken prior to 1987 on spatial distributions of sampling locations was negligible. Sampling protocols were again changed in 2009. Federal agencies implemented a fixed tow time of 30 minutes for trawls in 2009, and changed the way sampling locations were chosen. Additionally, the designation of “day” and “night” stations was removed. State agencies implemented the changes in 2010; however Texas maintained a 10 minute tow time rather than switching to 30 minutes. Sets taken after 2009 were included because changes in tow time were accounted for by catch-per-unit-effort.

Currently, SEAMAP sampling stations are chosen using a random design with proportional allocation by bottom area within shrimp statistical zones. Stations are sampled 24-hours a day, with a tow time (bottom time) of 30 minutes per station for agencies other than Texas. A 42-foot SEAMAP trawl with $1\frac{5}{8}$-in stretched mesh is lowered to depth at each station and the towline is set at a 5:1 cable length water depth. The desired vessel speed while towing is 2.5-3.0 knots. Texas uses a different sized trawl than the rest of the agencies. However, because of the potential for species misidentification, Texas SEAMAP data were excluded from all analyses.

5.5.2 Biological and Physical Sampling Methods

Temperature (air and water) was collected for each sampling station. Weight of the catch was recorded for individual species and for the catch as a whole. The number of individuals per species was also recorded. Up to 20 individuals of a species are measured for length with the appropriate measurement being used depending upon the species.

5.5.3 Ageing Methods

SEAMAP does not collect hard parts for age determination of Gulf Menhaden at this time.

5.5.4 Use for an Index

SEAMAP survey data were explored for use in the last benchmark assessment for Gulf Menhaden (SEDAR 2013a). During that time, the assessment panel determined that too few menhaden were caught with the trawl gear during the survey to be useful for an index. Figure 5.12 shows the low portion positive from the survey and is a copy of a figure from the benchmark assessment (SEDAR 2013a). The assessment panel discussed these data again at the data workshop and determined that the conclusion from the last stock assessment still applied: 1) the number of menhaden caught/the proportion of positive tows was too low, and 2) that this trawl gear is not suitable for capturing menhaden successfully given the habitat it samples and the nature of the gear.

5.6 SEAMAP Ichthyoplankton Survey

5.6.1 Survey Methods (Including Coverage, Intensity)

Plankton survey activities were initiated in the Gulf by NMFS in 1977 as part of the Marine Resources Monitoring Assessment and Prediction program or MARMAP (Sherman et al. 1983, Richards 1987). Most of the plankton sampling during those early annual surveys (1977-1981) was conducted in open Gulf waters in April and May using essentially the same gear and methods as are in use today. Starting in

1982 resource surveys, including plankton surveys carried out by the NMFS Mississippi Laboratories, were incorporated into SEAMAP (Sherman et al. 1983, Stuntz et al. 1983). Through this joint Federal-State program coordinated through the GSMFC, the NMFS, and the states of Louisiana, Mississippi, Alabama, and Florida, plankton sampling is conducted cooperatively during resource surveys in the Gulf.

The goal of plankton surveys under SEAMAP has been to assemble a time series of data on the occurrence, abundance, and geographical distribution of fish eggs and larvae, as well as to collect data on selected physical properties of their pelagic habitat. These data can then be used to more precisely describe the spawning times and areas of Gulf fishes and the relationship of their early life stages to environmental (abiotic) factors. Furthermore it was anticipated (and shown now to be true) that this time series of annual abundance estimates could eventually provide a valuable fishery-independent index of spawning stock size for additional Gulf species as was first demonstrated for tuna from pre-SEAMAP plankton surveys. Larval indices of abundance based on SEAMAP plankton survey data have been developed for Atlantic Bluefin Tuna (Scott et al. 1993), King Mackerel (Gledhill and Lyczkowski-Shultz 2000), Red Snapper (SEDAR 2009, Hanisko et al. 2007), Vermilion Snapper (SEDAR 2005a), and Gray Triggerfish (SEDAR 2005b). After larval identifications have been verified (as necessary) nominal and model-generated indices of larval abundance over the SEAMAP time series are now routinely provided to SEFSC stock assessment scientists.

The overall SEAMAP sampling area covers the entire northern Gulf from the 10-m isobath out to the EEZ, and comprises approximately 300 designated sampling stations. Most stations are located at 30-nautical mile or ~56 km intervals in a fixed, systematic, 2-dimensional latitude-longitude grid of transects across the Gulf. SEAMAP plankton data have been collected primarily during four survey periods: spring (April to early June, annually, 1982 to present), summer (June and July, annually, 1982 to present), late summer/early fall (typically in September, annually, 1986 to present) and fall (October and November, annually, 1982 to 2014). The spring survey covers only open Gulf waters (within the EEZ), while the summer and fall (trawl) surveys encompass only continental shelf waters from south Texas to Mobile Bay, Alabama. The late summer/early fall survey encompasses the continental shelf waters from south Texas to south Florida. A winter survey was initiated in 2007, and conducted annually through 2009. However, since 2009 the survey only has only been conducted during 2012, 2013 and 2015. Sampling for the winter survey either occurs during late January to February or late February and March.

The standard sampling gear and methodology used to collect plankton samples during SEAMAP surveys are similar to those recommended by Kramer et al. (1972), Smith and Richardson (1977), and Posgay and Marak (1980). Plankton sampling protocols and guidelines for the two standard SEAMAP gears used during resource surveys (bongo and neuston nets) are described in detail in the SEAMAP Field Operations manual (SEAMAP 2001). A 61-cm (outside diameter) bongo net fitted with 0.335-mm mesh netting is fished in an oblique tow path from a maximum depth of 200 m or to 2-5 m off the bottom at station depths less than 200 m. A single or double, 2x1 m pipe frame neuston net fitted with 0.950-mm mesh netting is the other standard gear employed and is towed at the surface with the frame half submerged for 10 minutes.

Maximum bongo tow depth is calculated using the amount of wire paid out and the wire angle at the 'targeted' maximum tow depth or is directly observed using a SBE 19 or Seacat to view and record bongo net depth in real time throughout the tow. A mechanical flow meter is mounted off-center in the mouth of each bongo net to record the volume of water filtered. During surveys in 1982 and part of 1983 a flow meter was placed on only one side of the bongo gear. Water volume filtered during bongo net tows ranges from ~20-600 m^3 but is typically 30-40 m^3 at the shallowest stations and 300-400 m^3 at the deepest stations.

5.6.2 Biological Sampling Methods (Including Coverage and Intensity)

Since the inception of SEAMAP, most plankton samples have been sorted for fish eggs and larvae, and specimens have been initially identified (mostly to the family level) at the Sea Fisheries Institute, Plankton Sorting and Identification Center (MIR ZSIOP), in Gdynia and Szczecin, Poland under a Joint Studies Agreement between the NMFS and the Sea Fisheries Institute. During the period 1989-2002 plankton samples collected by the LDWF were processed by Louisiana state biologists following SEFSC SEAMAP protocols in use at MIR ZSIOP. Vials of eggs and identified larvae, plankton displacement volumes, total egg counts; and counts and body length measurements of identified larvae are sent to the SEAMAP Archive at the Fish and Wildlife Research Institute (FWRI) in St. Petersburg, Florida. No attempt has been made to identify menhaden larvae to species although the larvae of all three Gulf species have now been described. Identification of menhaden larvae (to the genus level) has been possible over the entire time series of SEAMAP collections.

5.6.3 Ageing Methods

SEAMAP does not age Gulf Menhaden samples collected during fishery-independent monitoring because the samples contain larval menhaden only.

5.6.4 Use for an Index

While larval Gulf Menhaden were captured during the SEAMAP ichthyoplankton sampling, these data were not deemed as best for creating a juvenile index for Gulf Menhaden. First, Gulf Menhaden larvae and plankton occur most frequently in winter when SEAMAP sampling is less frequent. Wide fluctuations in abundance likely indicates a high degree of variability in the onset of menhaden spawning prior to the expected peak between December and February. Therefore, the SEAMAP Fall Trawl survey results were not representative of the core adult spawning stock and a lack of coincidence with the peak spawning of menhaden limits its ability to track changes in adult spawning stock biomass. It is also important to note that as of 2014, plankton sampling during the SEAMAP Fall Trawl survey has been discontinued.

The SEAMAP Winter Plankton survey, initiated in 2007, is now the sole SEAMAP plankton survey conducted during the spawning season of menhaden and may provide additional information regarding the spawning and spawning conditions of menhaden larvae during winter months. Unfortunately, the short time series and inconsistent scheduling of the survey does not currently allow for index development. Thus, these data were considered, but not put forward for use in the base run.

5.7 Indices of Abundance

5.7.1 Seine Index

The seine index was explored by the assessment panel as an option for a recruitment index for the base run. Coastwide (LA, MS, and AL) and Louisiana-only models were created and compared using different standardization approaches. The data used the months of January-June, which were the months with the greatest catches of small fish. There was little difference between standardizations of the data with respect to the trend over time.

5.7.1.1 Data Compilation for Use in an Index

Seine data from Texas, Louisiana, Mississippi, Alabama, and Florida were explored for creation of a recruitment index for use in the base run. These data were meant to reflect juvenile abundance throughout the range of Gulf Menhaden in the Gulf of Mexico. Data from each state were compiled individually before being grouped coastwide. Texas, Florida, and Alabama samples East of Perdido Bay (88° longitude – see Section 1.4) were excluded from the index standardization due to concerns about species misidentification with other *Brevoortia* species. For Mississippi and Louisiana, only data from the long-term sampling stations were retained.

In order for the seine index to represent only juvenile catch, only the months of January through June were used for the index. As the year progressed, larger and larger individuals were available to being sampled by the gear, and some of those individuals may not have been recruitments from the current year (Figure 5.13). The assessment panel decided to use those months where the catches were of individuals less than 100 mm FL.

Data records for each state were examined and explored to determine if any confounding factors would have an effect on the index's measure of relative abundance. The examination revealed no confounding factors. Each state deploys seines somewhat differently. However, the effect of any differences was accounted for by including state as an explanatory variable in the final index analysis rather than to calibrate the different state collection methods. Seine gear methods were consistent within states for the samples considered.

The number of years of data available differs by state. Louisiana had the longest data set. However, changes in the protocols for length sampling precluded use of data collected prior to 1996. Mississippi only had two long-term stations. Mississippi data were limited to the same years as available from Louisiana. The Alabama data were available from 2001-present.

5.7.1.2 Standardization

CPUE was modeled using the delta-GLM approach (cf., Lo et al. 1992, Dick 2004, Maunder and Punt 2004). In particular, the fits of lognormal and gamma models for positive CPUE were compared, and the combination of predictor variables that best explained CPUE patterns (both for positive CPUE and 0/1 CPUE) were examined. Jackknife estimates of variance were computed using the 'leave one out' estimator (Dick 2004). All analyses were performed in the R programming language, with much of the code adapted from Dick (2004).

Response and explanatory variables:

CPUE – Catch per unit effort (CPUE) has units of catch/seine and was calculated as the number of Gulf Menhaden caught per seine set.

YEAR – A summary of the total number of trips per year and a summary of the total number of trips with positive Gulf Menhaden catch per year is provided in Table 5.6.

STATE – State was defined as the state where the survey occurred (Louisiana, Mississippi, or Alabama). The total number of trips by year and state and the total number of trips with Gulf Menhaden catches by year and region is provided in Table 5.5.

MONTH – Month was used as a factor as catches may be different between months of the year (January, February, March, April, May, and June).

TEMPERATURE – Temperature was a continuous environmental factor that was thought to have an influence on juvenile Gulf Menhaden catches.

SALINITY – Salinity was a continuous environmental factor that was thought to have an influence on juvenile Gulf Menhaden catches.

BERNOULLI SUBMODEL: One component of the delta-GLM is a logistic regression model that attempts to explain the probability of either catching or not catching Gulf Menhaden during a particular sampling event. First, a model was fit with all main effects in order to determine which effects should remain in the binomial component of the delta-GLM. Stepwise AIC (Venables and Ripley 1997) with a backwards selection algorithm was then used to eliminate those that did not improve model fit. In this case, the stepwise AIC procedure did not remove any of the explanatory variables.

POSITIVE CPUE SUBMODEL: Then, to determine predictor variables important for predicting positive CPUE, the positive portion of the model was fitted with all main effects using both the lognormal and gamma distributions. Stepwise AIC (Venables and Ripley 1997) with a backwards selection algorithm was then used to eliminate those that did not improve model fit. Backwards model selection did not eliminate any variables for the lognormal distribution, and the model did not converge for the gamma distribution.

Then both components of the model were fit together (with the code adapted from Dick 2004) using the lognormal distribution with CPUE as the dependent variable. All factors were included for both the Bernoulli submodel and the positive CPUE submodel (lognormal).

5.7.2 Trawl Index

The trawl survey data and resultant index were initially discussed by the assessment panel as an option for a recruitment index. At the data workshop, the decisions and analyses from the last benchmark assessment for Gulf Menhaden (SEDAR 2013a) were discussed and the updated data were considered. However, the trawl data were not recommended for further exploration for the assessment because trawls are not an optimal gear to capture menhaden and because the seine index was the preferred recruitment index. No new information has arisen since the last benchmark to indicate that the trawl index would provide a better recruitment index.

5.7.3 Gill Net Index

5.7.3.1 Data Compilation for Use in an Index

Gill net data from Louisiana, Mississippi, and Alabama were considered for creation of adult Gulf Menhaden abundance indices for use in the base run. Florida does not collect consistent gill net data, and data from Texas were excluded because of the potential for species mis-identification. Because of differences in gear specifications and deployment, the Louisiana data were considered separately from the Mississippi and Alabama data.

5.7.3.1.1 Louisiana Data

Data records for Louisiana were examined to determine if any confounding factors would have an effect on the ability of the index to reflect relative abundance. Nothing became apparent that would affect the ability of the data to reflect relative abundance, and in fact, the threads of evidence supported the use of the gill net index based on Louisiana data. See section 5.2.2.4 above for more specific information.

Following the approach in SEDAR 32A (2013a), data were available from Louisiana from 1986-2017 for each month January through December. However, because of gear changes in the first two years of the survey, the years 1986-1987 were excluded from the analysis. The months January-March and October-December were also excluded from the analysis because those months had reduced sampling and much smaller catches of Gulf Menhaden compared to the months April through September (which has double the sample effort). Any stations that had never caught a menhaden were also excluded; while non-long-term stations were also excluded.

If values were missing for any of the factors below, then the trip was deleted, and the model was fit with the remaining trips.

5.7.3.1.2 Mississippi and Alabama Data

Data records for Mississippi and Alabama were combined and examined to determine if any confounding factors would have an effect on the ability of the index to reflect relative abundance. Nothing became apparent that would affect the ability of the data to reflect relative abundance. The biggest challenge with data from many states is the gear differences both in size and deployment. The gears across the states were relatively similar and mesh size differences could be accounted for using mesh size as a factor, thus the gill net index based on Mississippi and Alabama data was further explored.

Different states have different numbers of years of data available. Alabama gill net data are available from 2002 to 2017, and Mississippi gill net data are available from 2008 to 2017. The combined data from both Mississippi and Alabama were complete and include the abiotic variables sea surface temperature (°C) and surface salinity (ppt) from 2009-2017 for both states. Prior to that time a majority of these data were missing from the Mississippi data. For the Alabama data, all stations east of Perdido Bay in Alabama were excluded because of concerns over species identification. All months were included in the index. Finally, because the state of Mississippi does not record individual lengths for Gulf Menhaden, the assessment panel assumed that the lengths samples from Alabama would be representative of lengths that are likely sampled in Mississippi.

5.7.3.2 Standardization

The gill net dataset from Louisiana was analyzed for potential use in the base run of the assessment, and the combined gill net dataset from Mississippi and Alabama was analyzed for potential use in the sensitivity runs.

5.7.3.2.1 Standardization for Louisiana

CPUE was modeled using the delta-GLM approach (cf., Lo et al. 1992, Dick 2004, Maunder and Punt 2004). In particular, the fits of lognormal and gamma models for positive CPUE were compared and combination of predictor variables that best explained CPUE patterns (both for positive CPUE and 0/1 CPUE) were examined. Jackknife estimates of variance were computed using the 'leave one out' estimator (Dick 2004). All analyses were performed in the R programming language, with much of the code adapted from Dick (2004).

Response and explanatory variables:

> *CPUE* – Catch per unit effort (CPUE) has units of catch/set. Set was used as the unit of effort because Louisiana gill nets are fished as strike nets, set and retrieved with little to no soak time and fish are driven into the net by the boat.
>
> *YEAR* – A summary of the total number of trips per year is provided in Table 5.7, and a summary of the total number of trips with positive Gulf Menhaden catch per year is provided in Table 5.8.
>
> *MONTH* – Month was used as a factor as catches may be different between months of the year (April, May, June, July, August, and September).
>
> *TEMPERATURE* – Temperature was a continuous environmental factor that was thought to have an influence on Gulf Menhaden catches.
>
> *SALINITY* – Salinity was a continuous environmental factor that was thought to have an influence on Gulf Menhaden catches.
>
> *MESH SIZE* – Mesh size was a factor that was thought to have an influence on Gulf Menhaden catches. This factor accounted for differences in catch due to differences in panel catchability.
>
> *STATION* – Station was a factor that was thought to have an influence on Gulf Menhaden catches, specifically because some stations have habitats that may be more or less likely to catch menhaden.
>
> *CSA (COASTAL STUDY AREA)* – CSA was a factor that was thought to have an influence on Gulf Menhaden catches. Similar to station, some CSAs have habitats that should be more or less like to catch menhaden.

BERNOULLI SUBMODEL: One component of the delta-GLM is a logistic regression model that attempts to explain the probability of either catching or not catching Gulf Menhaden during a particular sampling event. First, a model was fit with all main effects in order to determine which effects should remain in the binomial component of the delta-GLM. Stepwise AIC (Venables and Ripley 1997) with a backwards selection algorithm was then used to eliminate those that did not improve model fit. In this case, the stepwise AIC procedure did not remove any of the predictor variables.

POSITIVE CPUE SUBMODEL: Then, to determine predictor variables important for predicting positive CPUE, the positive portion of the model was fitted with all main effects using both the lognormal and gamma distributions. Stepwise AIC (Venables and Ripley 1997) with a backwards selection algorithm was then used to eliminate those that did not improve model fit. Backwards model selection eliminated month as a factor from the lognormal distribution, and the model did not converge for the gamma distribution.

Then, both components of the model were fit together (with the code adapted from Dick 2004) using the lognormal distribution with CPUE as the dependent variable. All of the factors were included for both the Bernoulli submodel and the positive CPUE submodel (lognormal) except month.

5.7.3.2.2 Standardization for Mississippi and Alabama

The combined data from both Mississippi and Alabama were complete in terms of the inclusion of all predictor variables including sea surface temperature (°C) and surface salinity (ppt) from 2009-2017. Log(CPUE + 1) was modeled:

$$\log(CPUE + 1) = Month + Year + Station + Panel + SST + Salinity.$$

We note that each of the independent variables (Month, Year, Station, and Panel) in the analysis are categorical and SST and Salinity are continuous variables. The linear model coefficients were modeled using a hierarchical structure in the Bayesian framework where each of the individual "state" linear model coefficients come from a "common population" group distribution.

5.8 Indices of Abundance

Overall, two final indices of abundance were put forward for use in the base run: 1) a recruitment index based on the seine survey data from Louisiana, Mississippi, and western Alabama, and 2) an adult abundance index based on the Louisiana gill net survey data. Both indices were deemed appropriate and likely to reflect true, underlying population dynamics given the correlations with other corroborative evidence. Below is a discussion on how these decisions were made.

5.8.1 Juvenile Indices of Abundance

The seine index was explored as a potential index of recruitment in the base run of the model. The seine index showed large year classes of juveniles in 1996, 2010, 2011, 2014, and 2016 (Figure 5.14, Table 5.9). The residuals for the Bernoulli portion of the model were normally distributed across years, months, states, and salinities (Figures 5.15-5.18). The residuals for the positive CPUE portion of the model were normally distributed across years, months, state, temperature, and salinity (Figures 5.19-5.20). The density plot of positive catches and the QQ plot provide information on the adequacy of the lognormal distribution (Figures 5.21-5.22). The other distribution tested, gamma, did not converge. Thus, the scaled, standardized index based on the seine data is the best data and science available to produce an index of recruitment for the Gulf Menhaden stock assessment.

The seine data and resultant index are the best available information on recruitment abundance. Seine index samples are collected closer to shore in the best recruit habitats, the length compositions are predominately smaller fish, and the gear is similar from state to state. Additionally, the seine data were compared against catches by the commercial fishery at age-1. The correlation between the recruitment index and the catch at age-1 index with a one-year lag was 0.42. This provides another piece of corroborative evidence that the seine index,

Lastly, the seine data were standardized using the same factors by several different methods (Figure 5.23). The methods included the nominal index, glm index, glmm index, tmb index, gam, and a delta-glm. Each was configured using the same data but allowed for random effects or fixed effects or both. Each method produced a standardized index that was scaled to its mean. Ultimately, the different methods produced very similar indices with respect to trends over time.

5.8.2 Adult Indices of Abundance

The assessment panel considered an index based on gill net data available from Mississippi and Alabama. However, because of the short time period of adequate sample sizes from 2009-2017, an index based on these data was deemed inadequate for the base run, but suitable for a sensitivity analysis.

The assessment panel considered an index based on Louisiana gill net data. The gill net index based on the Louisiana data showed an increasing trend from the late 1980s to the mid-1990s, then a stable trend from the mid-1990s to the mid-2000s, and large adult abundances in the most recent years except for 2010 (Figure 5.24, Table 5.9). The uncertainty surrounding the index was consistently small over the years (Table 5.13, Figure 5.25-5.26). The proportion of positive trips per year ranged from 0.12 to 0.26 (Figure 5.27). The residuals for the Bernoulli portion of the model were normally distributed across years, months, and mesh sizes (Figures 5.28-5.29). The residuals for the positive CPUE portion of the model were normally distributed across years, months, and mesh sizes (Figures 5.30-5.31). The density plot of positive catches and the QQ plot indicate that the lognormal distribution is not ideal, but none of the other distributions tested matched the distribution better. Thus, the scaled, standardized index based on the Louisiana gill net data is the best data and science available to produce an index of adult abundance for the Gulf Menhaden stock assessment.

The Louisiana gill net index was correlated with age-2 catch index from the commercial reduction fishery, and the correlation was 0.68 for the years 1988-2017. The Louisiana gill net index was deemed the most appropriate adult abundance index by the assessment panel because the positive correlation between the index and catches of a similar age class, and because those data are the best data available to provide that information to the assessment model (see Section 5.2.2.4). Given the corroborative evidence available, the Louisiana gill net index likely reflects the true, underlying dynamics of the population.

Lastly, gill net data were standardized using the same factors by several different methods (Figure 5.34). The methods included the nominal index, glm index, glmm index, tmb indes, gam, and a delta-glm. Each was configured using the same data but allowed for random effects or fixed effects or both. Each method produced a standardized index that was scaled to its mean. Ultimately, the different methods produced very similar indices with respect to trends over time.

5.8.2.1 Length Compositions

All lengths recorded during gill net sampling were standardized to fork length using the length-length conversions in Section 3.4. Yearly length compositions were provided as the proportion in each length class for a given year from 1996-2017 (Table 5.10). Some incomplete length records exist for years prior to 1996, but lengths were not recorded for all CSAs in Louisiana until 1996. Annual length composition for the combined Mississippi-Alabama gillnet index 2009-2017 are in Table 5.11. Table 5.12 provides the summary statistics for the Mississippi-Louisiana gillnet.

Lengths from the Louisiana gill net index will be used to estimate selectivity for the gill net index and will be used to help define the functional form of selectivity for reduction fishery. The Louisiana gill nets capture both larger and smaller individuals than the commercial reduction fishery (Figure 5.9), which is evidence that the commercial reduction fishery selectivity may be dome-shaped. In addition, it looked as if cohorts may have been captured by the gill net sampling; however, the apparent cohorts were determined to be size-specific selection of individuals by mesh size (Figure 5.35). Additional evidence for the potential of dome-shaped selectivity for the commercial reduction fishery was investigated further by looking at the only other data available, the age and length data from the fishery. Based on the age and length data from the fishery, dome-shaped selectivity is also suspected because the CV in lengths with age is decreasing as ages get larger, which is unexpected (Figure 5.36; Schueller et al. 2014). In Figure 5.36, there appears to be a size at which the reduction fishery is no longer capturing menhaden. Given these pieces of data, the functional form of the selectivity for the reduction fishery appears to be dome-shaped. However, the extent of the dome is unknown.

The assessment panelists discussed plausible reasons that one might expect to see dome-shaped selectivity in the commercial reduction fishery. The first possible reason may be fishery targeting. If the fishery targets the largest schools to set a purse seine on, those schools are likely comprised of the most abundant ages or sizes of fish, which would likely be younger fish. Thus, even though schools of age-3 and -4 individuals may be present in an area, the schools are not harvested because they are smaller than the optimum school size for the fishery to set on. The second possible reason is based on work completed by Simpson and Scott (2011), where one would expect dome-shaped selectivity with a spatially heterogenous stock such as Gulf Menhaden.

Table 5.1 Fishery-independent gear descriptions by state for gill nets. Length of gear is in feet, all mesh sizes are in stretch mesh in inches, and net height is in feet.

State	Texas	Louisiana	Mississippi	Alabama	Florida
Length	600	750	750	750(1), 600 (2)	NA
Mesh size/type	3,4,5,6	2,2.5,3,3.5,4	2,2.5,3,3.5,4	(1)2,2.5,3,3.5,4 (2) 4.5,5,5.5,6	
	stretch	stretch	stretch	stretch	
Net height	4	8	6	8	
Effort	hours	strike net	1 hour	1 hour	
Rough size ranges	243-289	100-200	180-220	95-241	
Fish length units	TL	TL	TL	FL	

**Note that the rough size ranges are in the length units specified.

Table 5.2. Fishery-independent gear descriptions by state for seines.

State	Texas	Louisiana	Mississippi	Alabama	Florida	
Gear length	60-ft bag seine	50-ft bag seine	50-ft bag seine	50-ft bag seine	70-ft bag seine	600 ft haul seine
Gear height			4 ft	4 ft	6 ft	10 ft
Legs length	60ft	50ft	50 ft	50ft	32 ft (64 ft total)	295 ft (590 ft total)
Bag dimensions	1.8 m wide	6ft by 6ft	4ftx4ftx4ft	4x4x4ft	6x6x6ft	10x10x10ft
Mesh size	½in	¼in bar mesh	0.6 cm=0.24in	3/16in knotless	1/8in knotless	1in stretch
Effort	3229 ft^2	982 ft^2	3432 ft^2	2400 ft^2	723 ft^2 (boat set) 1507 ft^2 (bay set)	44,347 ft^2
Rough size ranges	38-74	25-44	21-54	45	20-60 mm	80 - 800
length units	TL	TL	SL	SL	SL	SL

**Note that the rough size ranges are in the length units specified.

Table 5.3. Fishery-independent gear descriptions by state for trawls.

State	Texas	Louisiana	Mississippi	Alabama	Florida
Gear name	20-ft trawl	16-ft flat trawl	16-ft trawl	16-ft flat 2-seam trawl	20-ft trawl
Door Length	48 in	24 in	36 in	24 in	36 in
Door Height	18 in	14 in	18 in	12.5 in	18 in
Leg length	1.5 ft	1 ft	3 ft	6ft	4ft
Net Footrope			20 ft	17.8 ft	21.5 ft
Net Headrope	20 ft	16 ft	16 ft	14.2 ft	20 ft
Bag Length		4.9 ft	4.9 ft	2 ft	7 ft
Mesh Body/Front	1.5 in stretch	1.5 in stretch	1.5 in stretch	1.37 in stretch	1.5 in stretch
Mesh Cod/Bag	1.5 in stretch	0.5 in stretch	¼ in knotless bar	1.75 in cover and 3/16 in knotless bar liner	1/8 in knotless bar
No. of weights	1 per foot	¼ in chain along the footrope webbing	¼ in chain along the footrope webbing	3/16 in chain, 17 links = 1 chain, 7 chains along footrope	¼ in chain along the footrope webbing
Weight size	2 oz/ weight			7 chains=4 lbs	
No. of Floats		4	4	2	4
Float Dimensions		2.5 in x1 in	2.5 in x1 in	3 in x3 in	2.5 in x1 in
Tickler Length	none	none	none	none	24 ft of ¼ in chain
Effort	10 minute tow	10 minute tow	10 minute tow	10 minute tow	timed tow
Rough size range (mm)	116-151 67-123	20-85	37-85	50-70	21-64
Fish length units	TL	TL	SL	SL	SL

**Note that the rough size ranges are in the length units specified.

Table 5.4. Fishery-independent gear descriptions for AL surface trawl.

Gear Component	Specifications
Gear name	11-ft flat 2-seam trawl
Door Length	24 in - aluminum
Door Height	12. in
Leg length	1ft
Net Footrope	8.3 ft
Net Headrope	9.3 ft
Bag Length	4 ft
Mesh Body/Front	1.37 in stretch
Mesh Cod/Bag	1.5 in cover and ½ in stretch Delta liner
No. of weights	3/16 in chain, 17 links = 1 chain, 3 chains along footrope
Weight size	3 chains= 1.88 lbs
No. of Floats	5
Float Dimensions	4.5 in x 2.6 in
Tickler Length	none
Effort	5 minute tow
Rough size range (mm)	20-140
Fish length units	FL

Table 5.5 Total number of seines for each state as input into the calculation of the seine index.

Year	Seine Samples			
	LA	MS	AL	Total
1996	256	12	10	278
1997	248	12	10	270
1998	292	12	10	314
1999	296	12	4	312
2000	306	12	4	322
2001	327	12	36	375
2002	332	11	35	378
2003	343	12	36	391
2004	297	12	35	344
2005	329	12	29	370
2006	329	12	30	371
2007	319	12	33	364
2008	317	12	31	360
2009	327	12	31	370
2010	315	12	28	355
2011	268	12	35	315
2012	227	14	23	264
2013	202	12	24	238
2014	189	12	24	225
2015	597	12	24	633
2016	602	12	24	638
2017	609	12	23	644

Table 5.6 Total number of seines that caught Gulf Menhaden (positive) for each state as input into the calculation of the seine index.

Year	Positive Seine Samples			
	LA	MS	AL	Total
1996	164	12	4	180
1997	146	11	5	162
1998	180	11	7	198
1999	165	9	2	176
2000	123	8	1	132
2001	169	8	26	203
2002	170	6	24	200
2003	177	10	22	209
2004	150	8	22	180
2005	168	10	17	195
2006	166	5	11	182
2007	175	5	15	195
2008	175	9	12	196
2009	182	10	22	214
2010	203	9	16	228
2011	179	10	24	213
2012	166	13	11	190
2013	129	11	8	148
2014	121	9	13	143
2015	330	6	11	347
2016	382	9	11	402
2017	333	10	11	354

Table 5.7 Number of trips by state and year for the fishery-independent data collected by gill nets. For the state of LA, there are 5 meshes per gill net set.

Year	Louisiana	Mississippi	Alabama
1988	401		
1989	456		
1990	488		
1991	427		
1992	467		
1993	410		
1994	500		
1995	523		
1996	527		
1997	524		
1998	574		
1999	590		
2000	609		
2001	626		
2002	609		315
2003	606		341
2004	599		340
2005	565		250
2006	577		250
2007	613		170
2008	598		180
2009	636	216	210
2010	564	216	100
2011	737	217	180
2012	785	216	285
2013	407	216	260
2014	405	216	255
2015	396	216	310
2016	383	216	360
2017	392	216	265

Table 5.8 Number of positive meshes by state and year for the fishery-independent data collected by gill nets. For LA, there are five meshes per net.

Year	Louisiana	Mississippi	Alabama
1988	435		
1989	332		
1990	364		
1991	311		
1992	325		
1993	247		
1994	365		
1995	351		
1996	400		
1997	474		
1998	481		
1999	481		
2000	625		
2001	580		
2002	556		152
2003	518		183
2004	436		169
2005	521		112
2006	617		116
2007	549		73
2008	710		87
2009	789	80	93
2010	402	77	43
2011	828	86	69
2012	968	130	140
2013	406	108	107
2014	411	98	114
2015	362	90	155
2016	314	120	164
2017	353	60	92

Table 5.9 Seine and LA gill net abundance indices and associated coefficient of variation (*CV*) for use in the base run.

Year	Seine	Seine CV	LA gill net	LA gill net CV
1988			0.95	0.08
1989			0.54	0.09
1990			0.59	0.09
1991			0.58	0.10
1992			0.44	0.09
1993			0.35	0.10
1994			0.62	0.10
1995			0.50	0.10
1996	1.47	0.27	0.57	0.08
1997	0.59	0.27	0.85	0.08
1998	0.89	0.27	0.76	0.08
1999	0.53	0.29	0.71	0.08
2000	0.84	0.30	1.07	0.07
2001	0.75	0.26	1.09	0.08
2002	0.48	0.26	0.87	0.07
2003	0.75	0.25	0.83	0.07
2004	0.50	0.27	0.65	0.08
2005	0.66	0.26	1.01	0.08
2006	0.88	0.27	1.17	0.07
2007	0.74	0.27	0.86	0.07
2008	0.28	0.28	2.10	0.07
2009	1.01	0.25	1.91	0.06
2010	1.39	0.25	0.60	0.08
2011	3.28	0.25	1.44	0.06
2012	1.03	0.25	1.78	0.06
2013	1.00	0.29	1.49	0.09
2014	1.76	0.31	1.82	0.09
2015	1.15	0.22	1.17	0.09
2016	1.48	0.21	1.26	0.10
2017	0.53	0.22	1.43	0.10

Table 5.10 Annual sample length compositions in mm FL for Gulf Menhaden caught in Louisiana gill nets from 1996-2017 with fish being the sample size in number of fish measured and sets being the sample size in number of gill net sets.

Fish	Sets	Year	Annual Menhaden Length Increments								
			(80,90]	(90,100]	(100,110]	(110,120]	(120,130]	(130,140]	(140,150]	(150,160]	(160,170]
2,529	225	1996	0.010	0.020	0.010	0.020	0.070	0.160	0.160	0.090	0.110
3,566	247	1997	0.000	0.010	0.000	0.020	0.060	0.140	0.140	0.110	0.110
3,299	276	1998	0.000	0.010	0.010	0.020	0.070	0.170	0.190	0.120	0.110
3,184	262	1999	0.000	0.010	0.010	0.030	0.080	0.160	0.140	0.090	0.110
4,736	326	2000	0.000	0.010	0.010	0.020	0.070	0.140	0.110	0.070	0.070
4,343	279	2001	0.000	0.010	0.010	0.010	0.060	0.110	0.100	0.080	0.120
3,566	295	2002	0.000	0.010	0.010	0.030	0.060	0.140	0.140	0.080	0.090
3,661	293	2003	0.000	0.010	0.010	0.030	0.090	0.190	0.190	0.100	0.090
3,000	256	2004	0.000	0.010	0.020	0.040	0.110	0.180	0.170	0.110	0.100
4,069	271	2005	0.000	0.010	0.010	0.030	0.060	0.150	0.180	0.120	0.120
5,142	345	2006	0.010	0.010	0.010	0.020	0.080	0.160	0.150	0.150	0.100
3,870	298	2007	0.010	0.010	0.010	0.010	0.050	0.130	0.170	0.150	0.140
6,708	325	2008	0.000	0.010	0.010	0.020	0.040	0.120	0.140	0.100	0.120
6,554	362	2009	0.000	0.010	0.010	0.020	0.040	0.090	0.140	0.110	0.110
2,547	219	2010	0.000	0.010	0.010	0.030	0.070	0.140	0.120	0.080	0.090
6,996	421	2011	0.000	0.010	0.020	0.030	0.080	0.160	0.150	0.080	0.080
8,458	486	2012	0.000	0.000	0.010	0.020	0.060	0.160	0.180	0.110	0.110
3,471	215	2013	0.000	0.020	0.010	0.020	0.060	0.120	0.140	0.110	0.140
3,981	211	2014	0.000	0.000	0.020	0.010	0.040	0.130	0.160	0.090	0.090
2,833	189	2015	0.010	0.010	0.010	0.030	0.090	0.180	0.160	0.060	0.060
2,820	166	2016	0.000	0.010	0.000	0.020	0.050	0.120	0.200	0.160	0.130
3,337	188	2017	0.000	0.010	0.010	0.010	0.060	0.170	0.170	0.100	0.110

Table 5.10 Con't

Fish	Sets	Year	Annual Menhaden Length Increments								
			(170,180]	(180,190]	(190,200]	(200,210]	(210,220]	(220,230]	(230,240]	(240,250]	(250,260]
2,529	225	1996	0.110	0.070	0.050	0.040	0.040	0.020	0.010	0.000	0.000
3,566	247	1997	0.120	0.090	0.070	0.060	0.030	0.020	0.010	0.000	0.000
3,299	276	1998	0.110	0.070	0.040	0.030	0.020	0.010	0.010	0.000	0.000
3,184	262	1999	0.110	0.090	0.060	0.060	0.030	0.020	0.000	0.000	0.000
4,736	326	2000	0.120	0.120	0.080	0.080	0.060	0.030	0.010	0.000	0.000
4,343	279	2001	0.130	0.090	0.080	0.080	0.060	0.040	0.020	0.010	0.000
3,566	295	2002	0.100	0.090	0.060	0.070	0.060	0.030	0.010	0.010	0.000
3,661	293	2003	0.130	0.070	0.020	0.020	0.020	0.010	0.000	0.000	0.000
3,000	256	2004	0.080	0.070	0.040	0.040	0.020	0.010	0.000	0.000	0.000
4,069	271	2005	0.130	0.080	0.040	0.040	0.020	0.010	0.000	0.000	0.000
5,142	345	2006	0.110	0.080	0.050	0.040	0.020	0.010	0.000	0.000	0.000
3,870	298	2007	0.130	0.080	0.040	0.030	0.020	0.010	0.000	0.000	0.000
6,708	325	2008	0.150	0.110	0.080	0.060	0.030	0.010	0.010	0.000	0.000
6,554	362	2009	0.120	0.120	0.080	0.080	0.050	0.020	0.010	0.000	0.000
2,547	219	2010	0.110	0.100	0.080	0.060	0.050	0.020	0.010	0.000	0.000
6,996	421	2011	0.100	0.100	0.060	0.060	0.040	0.020	0.000	0.000	0.000
8,458	486	2012	0.120	0.070	0.050	0.050	0.030	0.010	0.000	0.000	0.000
3,471	215	2013	0.130	0.100	0.050	0.060	0.030	0.010	0.000	0.000	0.000
3,981	211	2014	0.120	0.130	0.090	0.060	0.040	0.010	0.000	0.000	0.000
2,833	189	2015	0.110	0.100	0.070	0.070	0.040	0.010	0.000	0.000	0.000
2,820	166	2016	0.110	0.080	0.040	0.040	0.030	0.000	0.000	0.000	0.000
3,337	188	2017	0.130	0.100	0.050	0.030	0.020	0.010	0.000	0.000	0.000

Table 5.11 Annual sample length compositions in mm FL for Gulf Menhaden caught in gill nets from 2009-2017 in Alabama gillnets. These data are used to provide the length-composition information for the combined Mississippi-Alabama gillnet index.

Fish	Sets	Year	Annual Menhaden Length Increments								
			(80, 90]	(90, 100]	(100, 110]	(110, 120]	(120, 130]	(130, 140]	(140, 150]	(150, 160]	(160, 170]
415	42	2009	0.0000	0.0000	0.0072	0.0000	0.0145	0.0289	0.0434	0.0747	0.0843
154	20	2010	0.0065	0.0000	0.0065	0.0325	0.026	0.0844	0.1883	0.2532	0.0649
297	36	2011	0.0067	0.0034	0.0471	0.1111	0.0741	0.0572	0.0943	0.0337	0.0337
1162	89	2012	0.0000	0.0017	0.0138	0.0258	0.0258	0.0706	0.0964	0.0972	0.0757
799	67	2013	0.0013	0.0025	0.015	0.0075	0.005	0.03	0.1439	0.1402	0.0876
813	75	2014	0.0000	0.0012	0.0062	0.0037	0.0025	0.0074	0.0406	0.0775	0.1378
1084	79	2015	0.0018	0.0074	0.0212	0.0341	0.0812	0.0775	0.0683	0.0618	0.0775
1065	98	2016	0.0047	0.0038	0.0009	0.0066	0.0413	0.1239	0.2000	0.0779	0.0545
645	91	2017	0.0093	0.0062	0.0109	0.0434	0.0806	0.124	0.1426	0.0977	0.0636

Table 5.11 Con’t

Fish	Sets	Year	Annual Menhaden Length Increments							
			(170, 180]	(180 ,190]	(190, 200]	(200, 210]	(210, 220]	(220, 230]	(230, 240]	(240, 250]
415	42	2009	0.1108	0.1566	0.1590	0.1470	0.1108	0.0386	0.0145	0.0000
154	20	2010	0.0779	0.0844	0.0325	0.0649	0.0260	0.0390	0.0065	0.0000
297	36	2011	0.0505	0.0943	0.1313	0.1246	0.0875	0.0303	0.0202	0.0000
1162	89	2012	0.1015	0.0981	0.1222	0.1334	0.0904	0.0344	0.0103	0.0000
799	67	2013	0.1176	0.1452	0.1114	0.0851	0.0576	0.0426	0.0063	0.0013
813	75	2014	0.1820	0.2325	0.1132	0.0959	0.0566	0.0197	0.0098	0.0037
1084	79	2015	0.1365	0.1559	0.0895	0.0904	0.0424	0.0277	0.0083	0.0111
1065	98	2016	0.0845	0.1005	0.1080	0.1033	0.0469	0.0197	0.0085	0.0056
645	91	2017	0.0729	0.0992	0.1008	0.0822	0.0434	0.0171	0.0031	0.0016

Table 5.11 Con’t

Fish	Sets	Year	Annual Menhaden Length Increments				
			(250, 260]	(260, 270]	(270, 280]	(280, 290]	(290, 300]
415	42	2009	0.0048	0.0024	0.0024	0.0000	0.0000
154	20	2010	0.0000	0.0000	0.0065	0.0000	0.0000
297	36	2011	0.0000	0.0000	0.0000	0.0000	0.0000
1162	89	2012	0.0000	0.0009	0.0000	0.0009	0.0009
799	67	2013	0.0000	0.0000	0.0000	0.0000	0.0000
813	75	2014	0.0049	0.0000	0.0000	0.0025	0.0025
1084	79	2015	0.0028	0.0009	0.0000	0.0009	0.0028
1065	98	2016	0.0038	0.0009	0.0019	0.0009	0.0009
645	91	2017	0.0000	0.0000	0.0016	0.0000	0.0000

Table 5.12 MS/AL gill net abundance indices and associated coefficient of variation (*CV*) for use in a sensitivity run.

Year	MS AL gill net	MS AL gill net CV
2009	0.75	0.35
2010	0.62	0.37
2011	0.75	0.4
2012	1.38	0.59
2013	1.2	0.48
2014	0.98	0.47
2015	1.28	0.55
2016	1.4	0.56
2017	0.65	0.31

Figure 5.1 Chart of Texas bay systems.

Figure 5.2 Map of the Louisiana Department of Wildlife and Fisheries' Coastal Study Areas (i.e., management units) which are generally delineated by river basins.

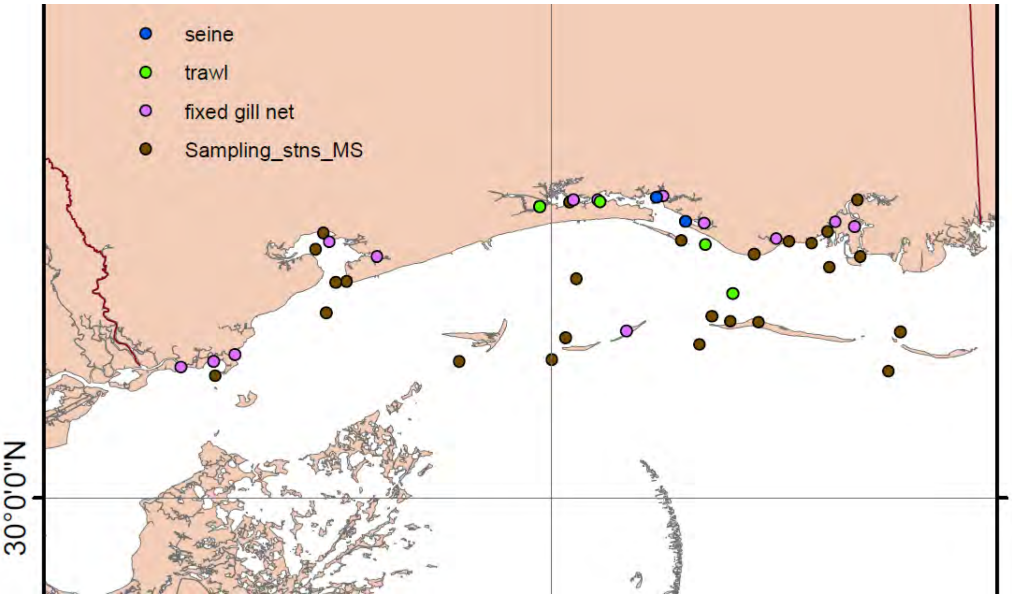


Figure 5.3 Fixed seine, trawl, and gill net stations for fishery-independent sampling conducted by Mississippi Department of Marine Resources.

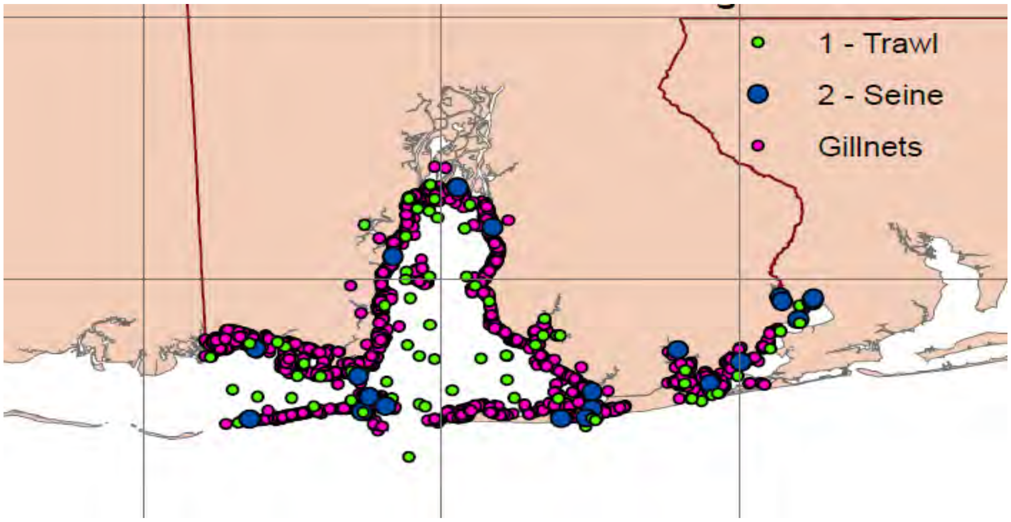


Figure 5.4 Fishery-independent sampling stations for trawls, seines, and gill nets for the Alabama Marine Resources Division.

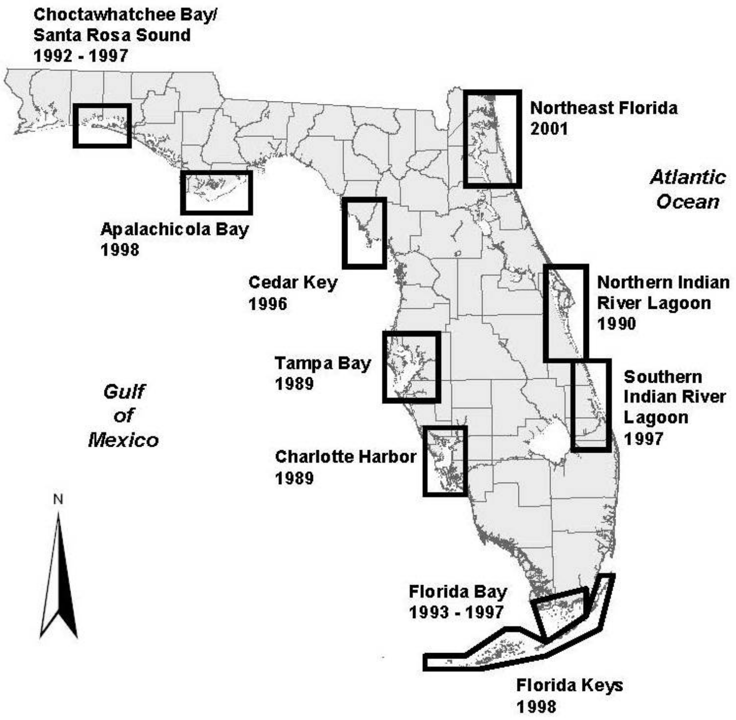


Figure 5.5 Locations of Fisheries-Independent Monitoring (FIM) program field laboratories for FWC. Years indicate initiation of sampling. If sampling was discontinued at a field lab, the last year of sampling is also provided.

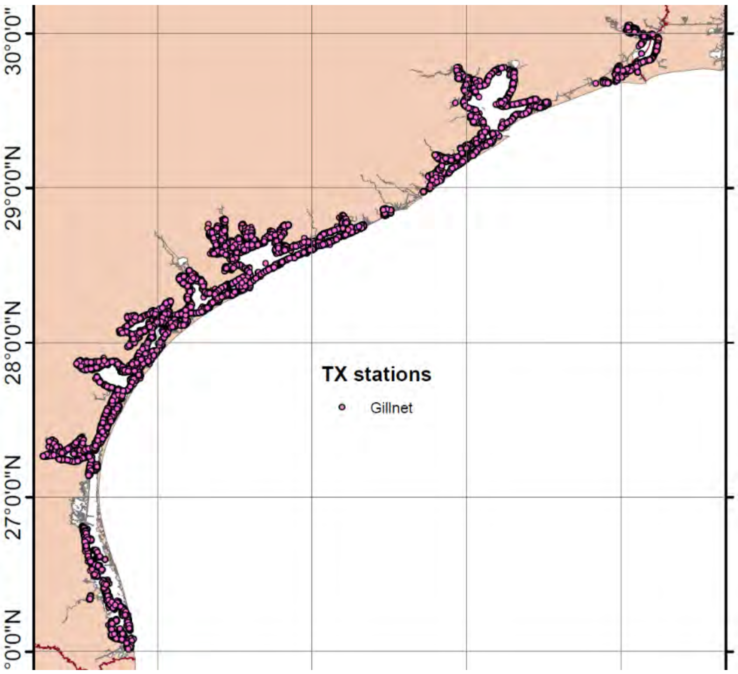


Figure 5.6 Texas sampling locations for the gill net data.

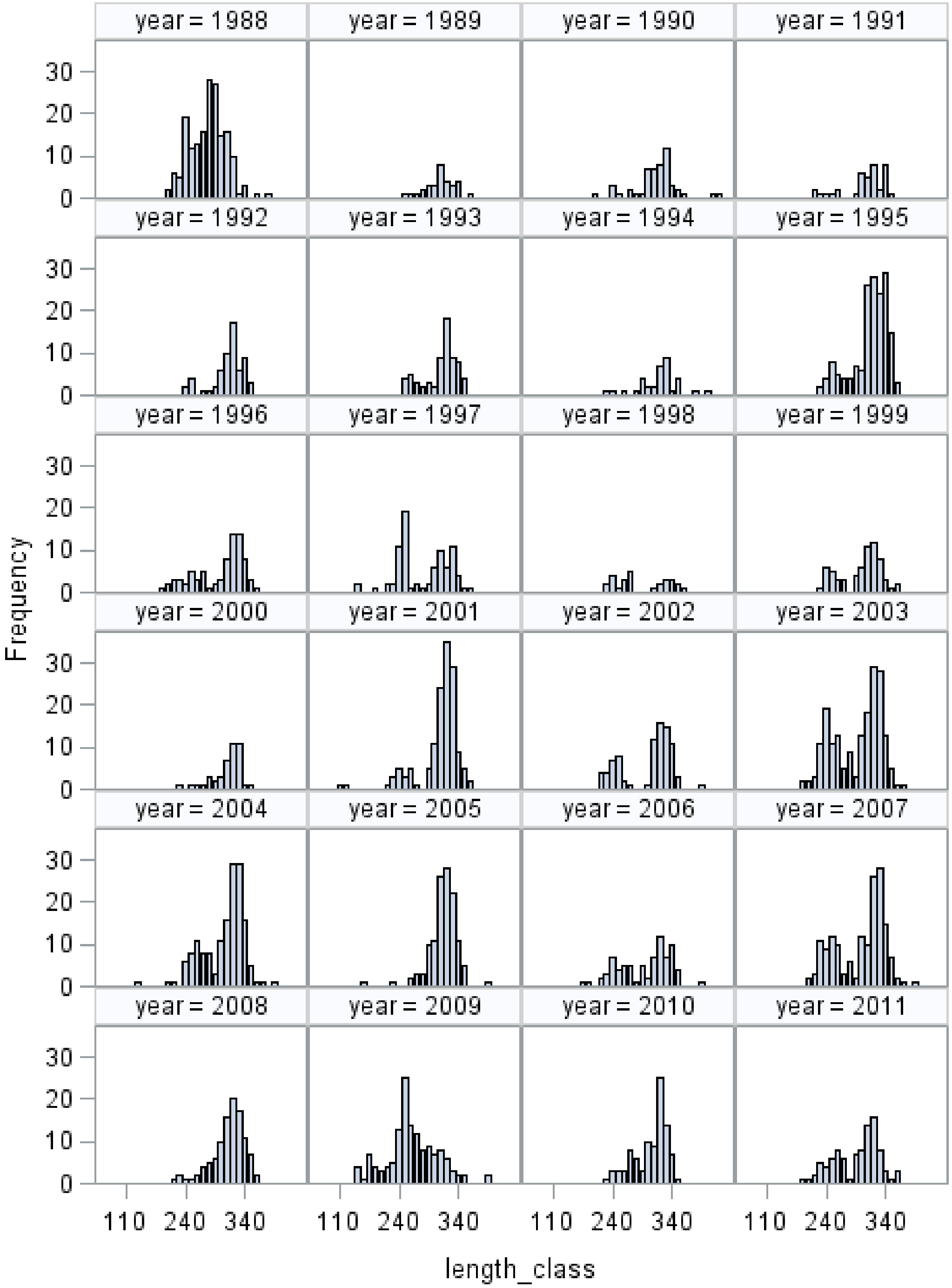


Figure 5.7 Length frequencies of Gulf Menhaden from Texas gill net sampling.

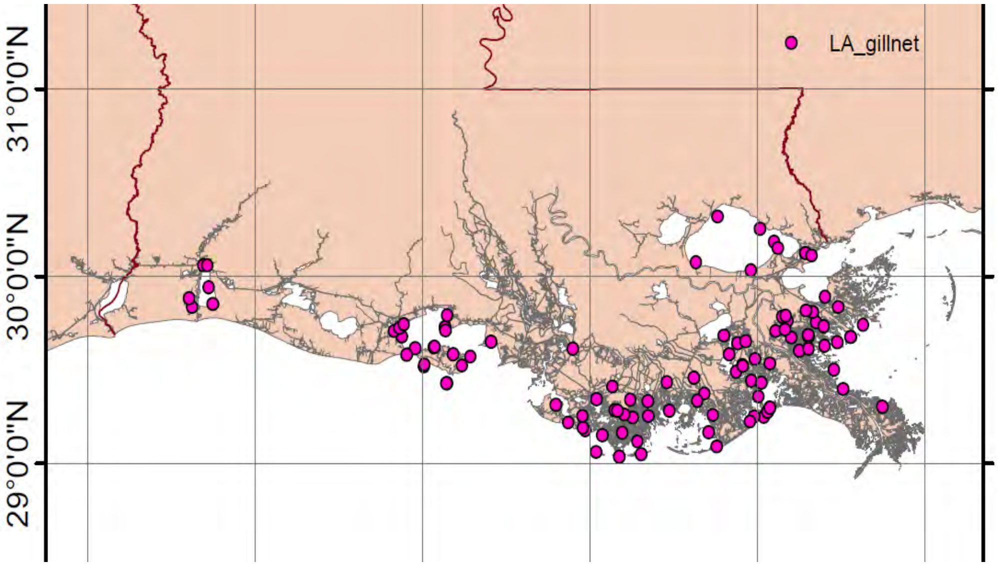


Figure 5.8 Louisiana gill net sampling stations across all Coastal Study Areas.

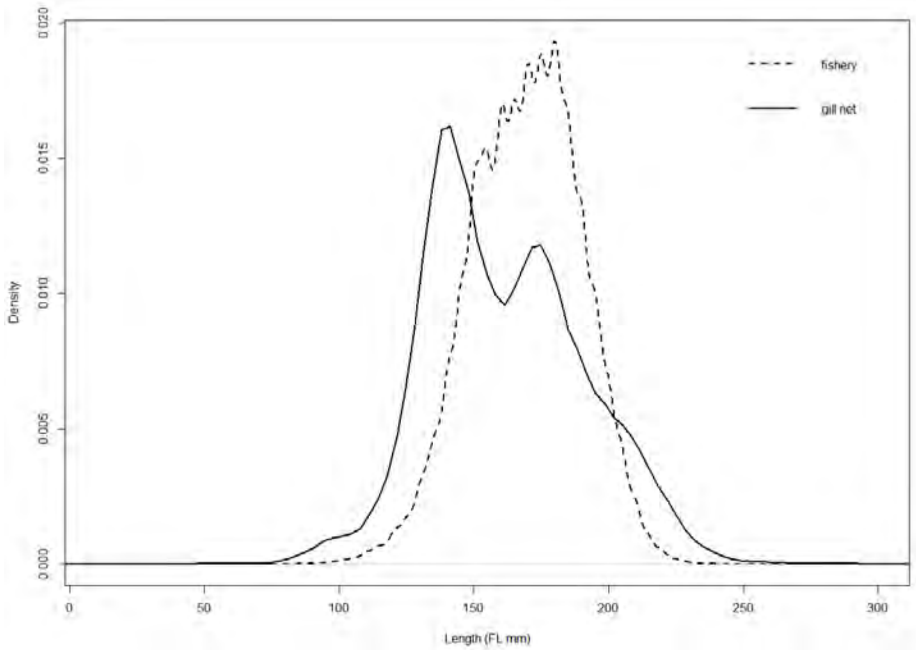


Figure 5.9 Density plots of length sampled by Louisiana gill nets from 1996-2011 and by the commercial reduction fishery from 1977-2011 (*from* SEDAR 2013a).

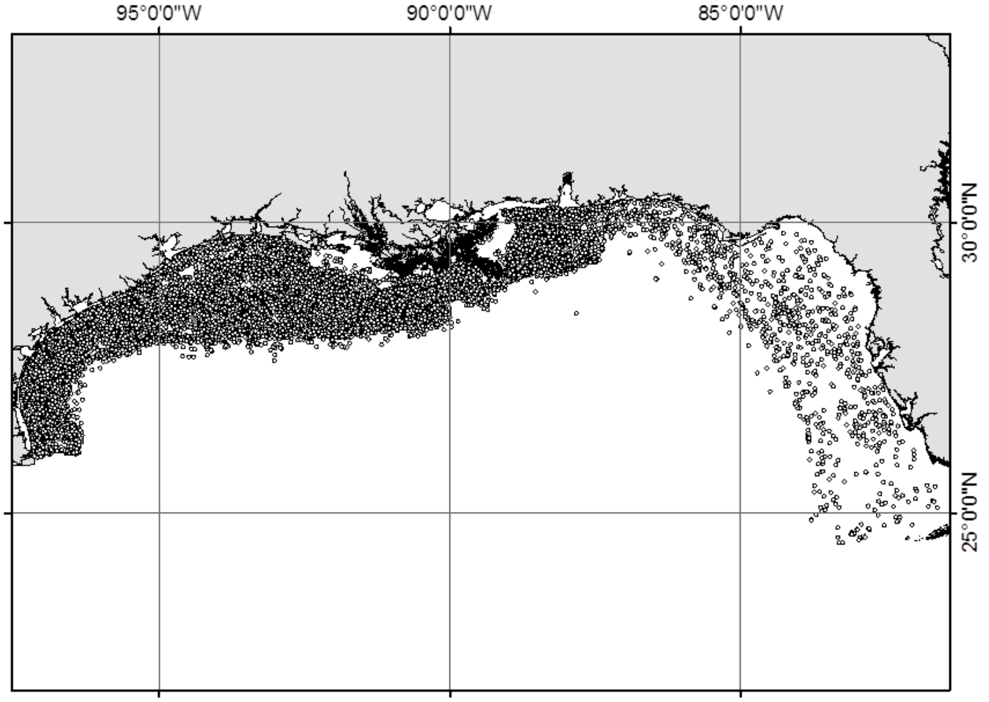


Figure 5.10 Spatial distribution of SEAMAP sets (open circles) in the Gulf of Mexico during 1982-2011, for all months, sampling agencies, locations, and depths (*from* SEDAR 2013a).

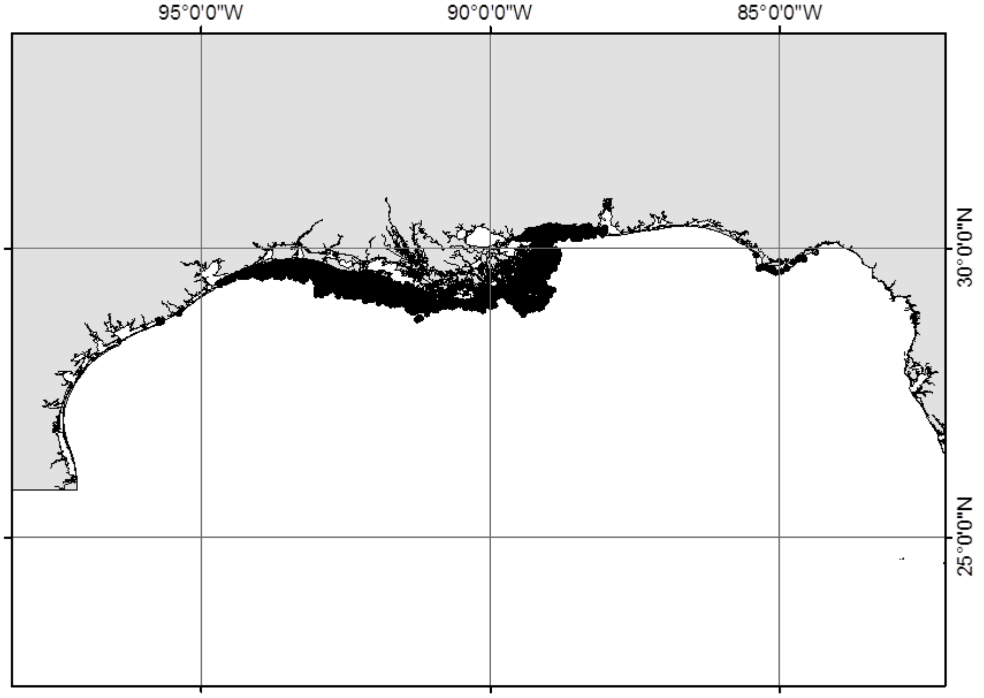


Figure 5.11 Spatial distribution of sets from the commercial menhaden fishery during 1986-2011 (*from* SEDAR 2013a).

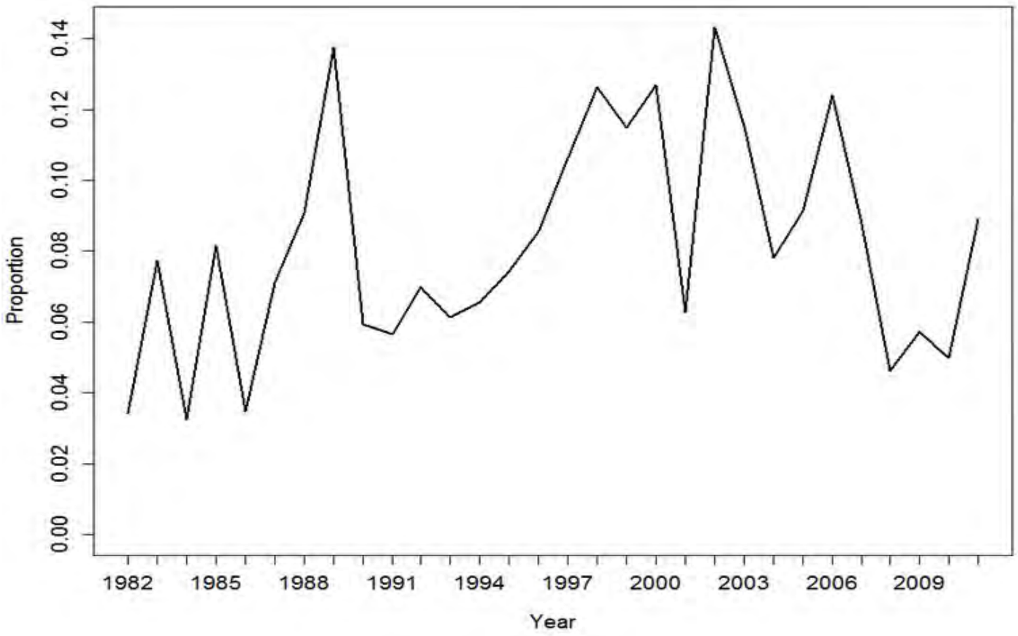


Figure 5.12 Proportion of SEAMAP sets within a year that captured at least one menhaden during 1982-2011 for all months, sampling agencies, locations, and depths (*from* SEDAR 2013a).

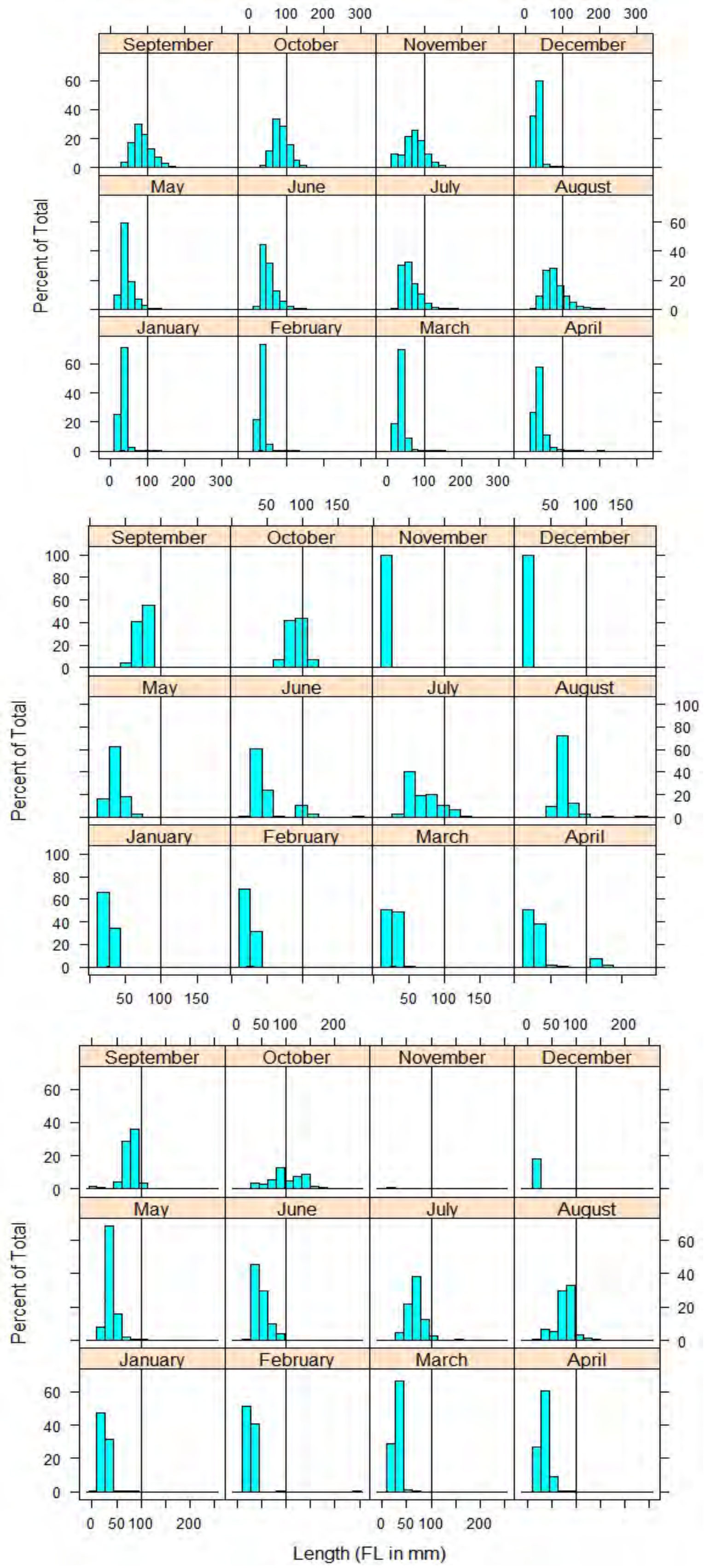


Figure 5.13 Lengths of Gulf Menhaden in the LA (upper panel), MS (middle panel), and AL (lower panel) seine surveys by month. The vertical line indicates a length of 100 mm FL.

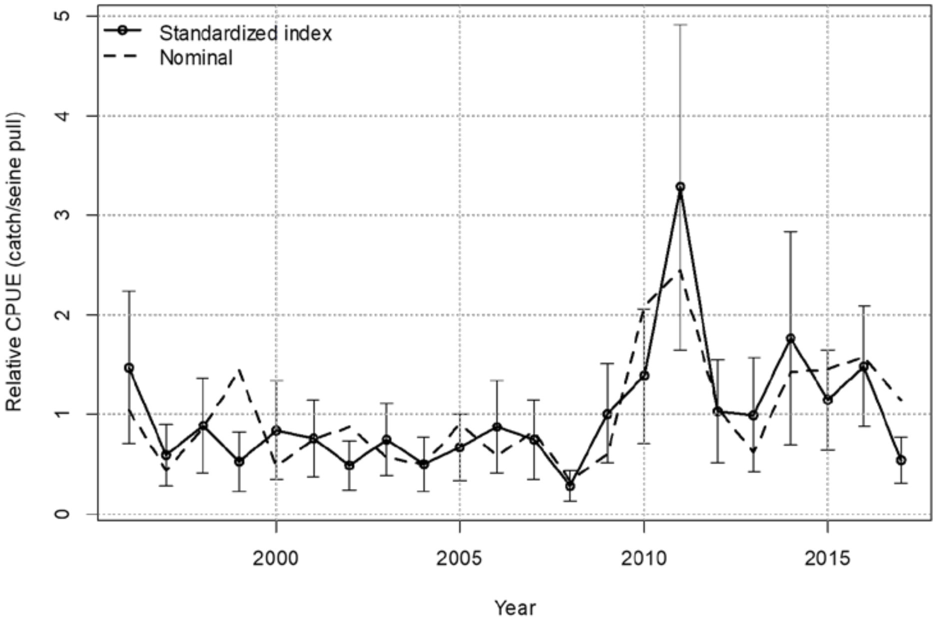


Figure 5.14 The scaled, standardized and scaled, nominal Gulf Menhaden seine index for 1988-2017 representing juvenile abundance.

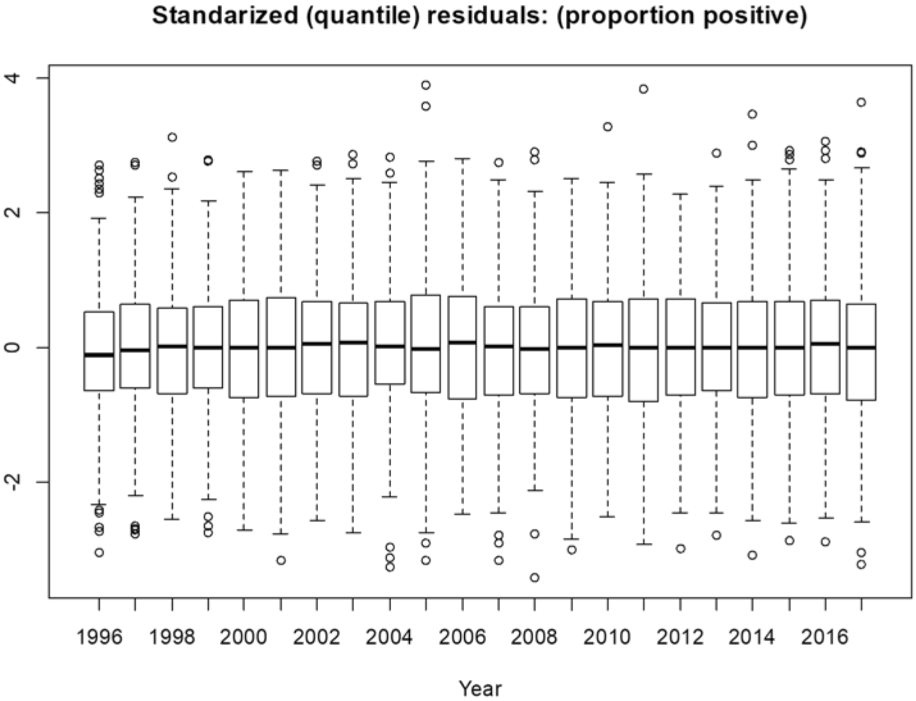


Figure 5.15 Residual plot for the proportion positive by year for the seine index.

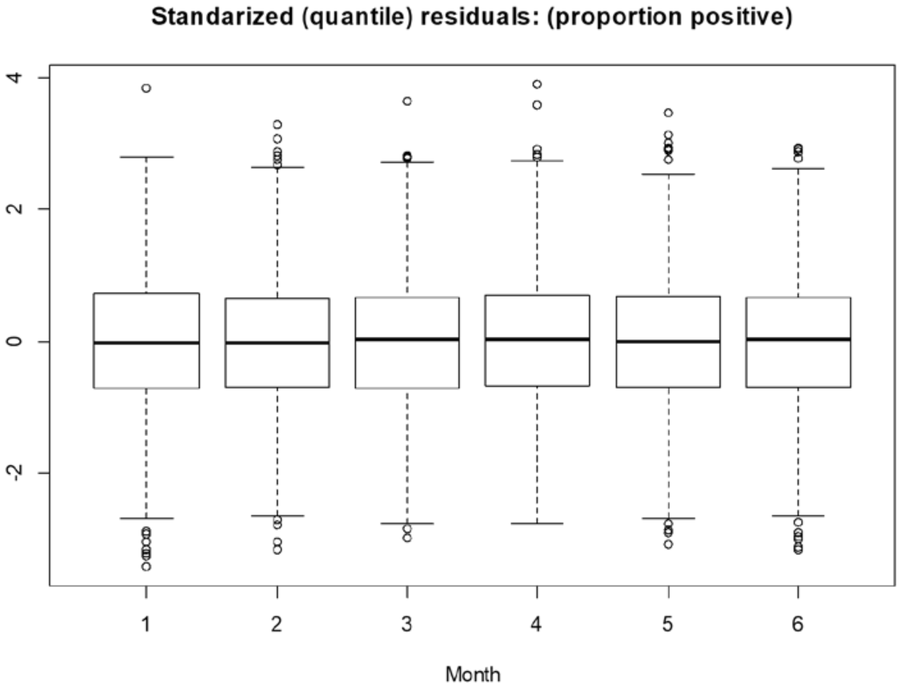


Figure 5.16 Residual plot for the proportion positive by month (January-June) for the seine index.

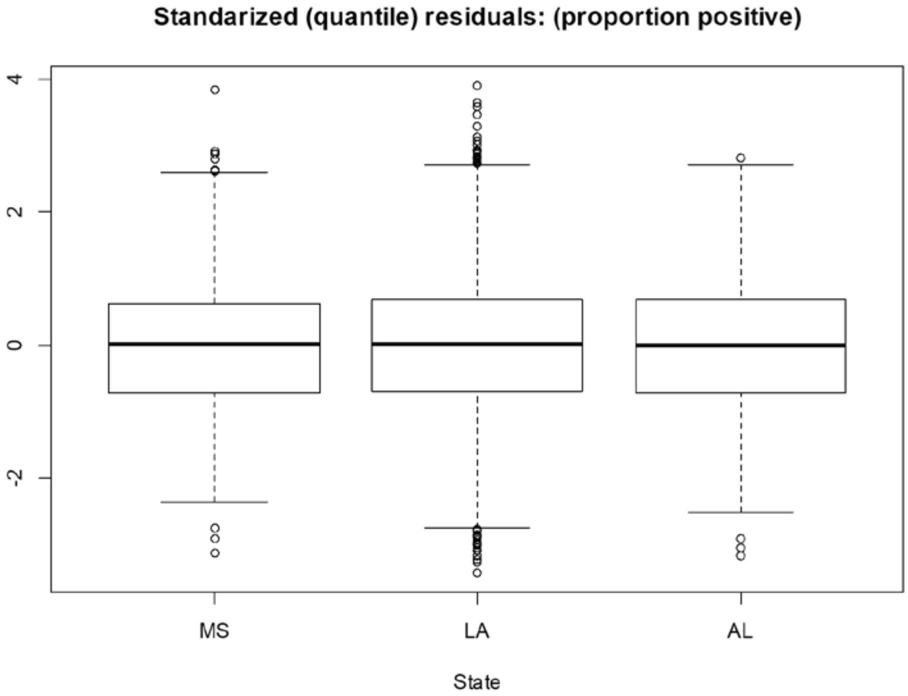


Figure 5.17 Residual plot for the proportion positive by state for the seine index.

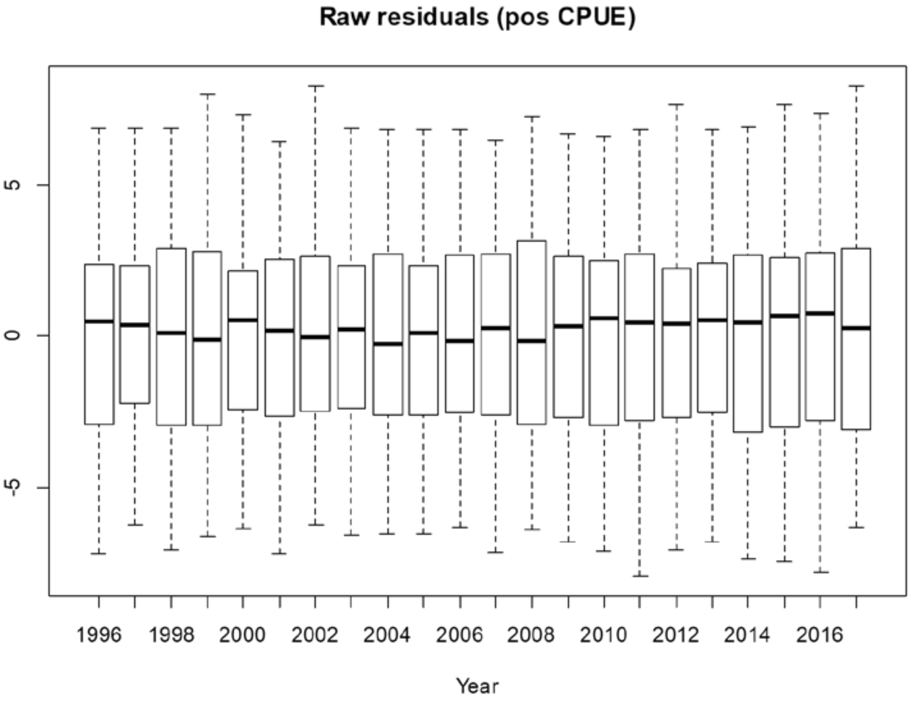


Figure 5.18 Raw residuals for the positive catches by year for the seine index.

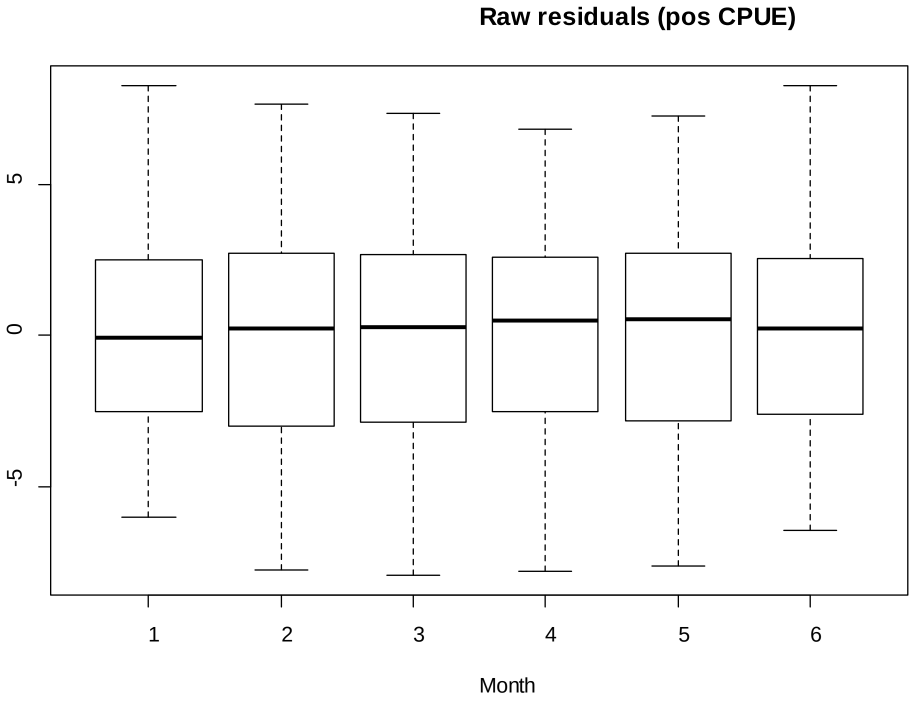


Figure 5.19 Raw residuals for the positive catches by month (January-June) for the seine index.

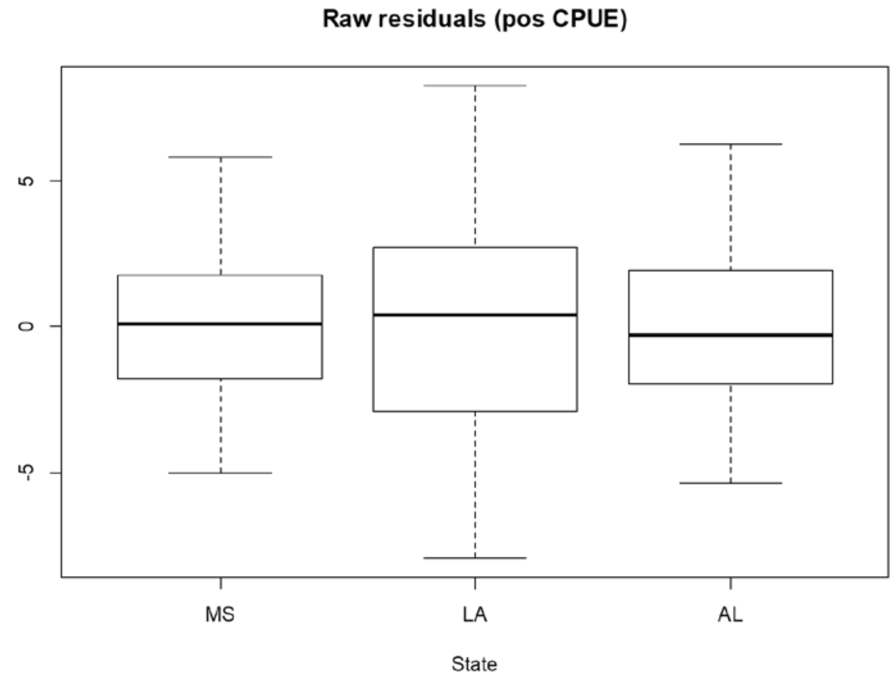


Figure 5.20 Raw residuals for the positive catches by state for the seine index.

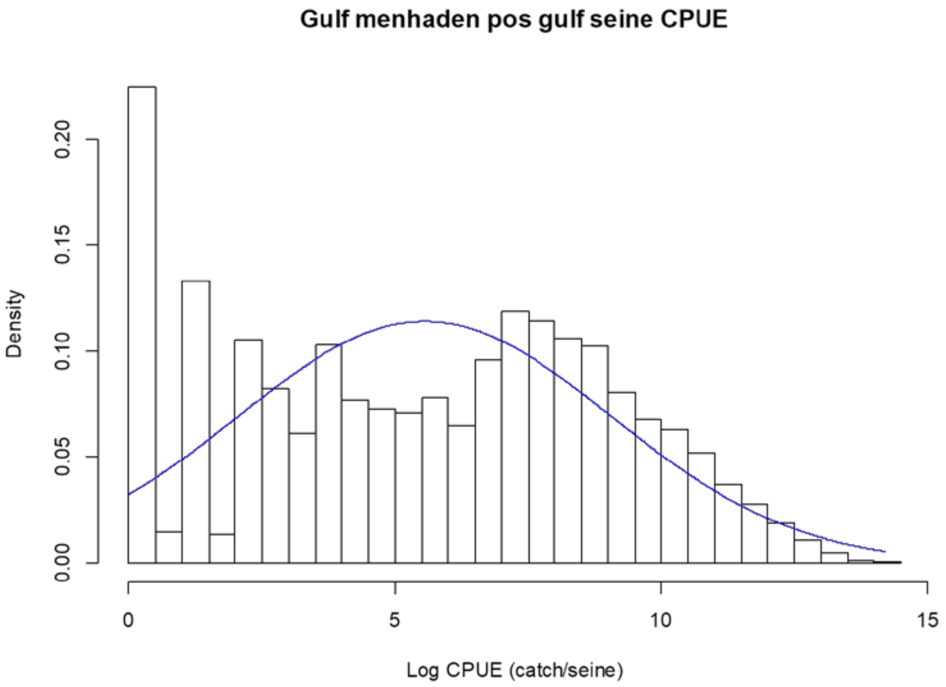


Figure 5.21 Density plot of the positive catches for the seine index.

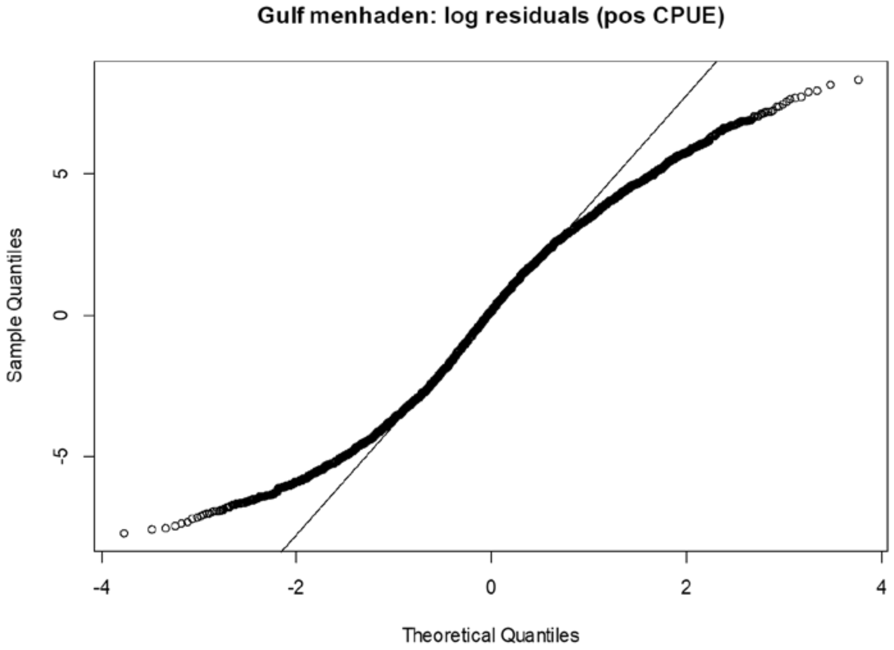


Figure 5.22 QQ plot of the positive catches for the seine index.

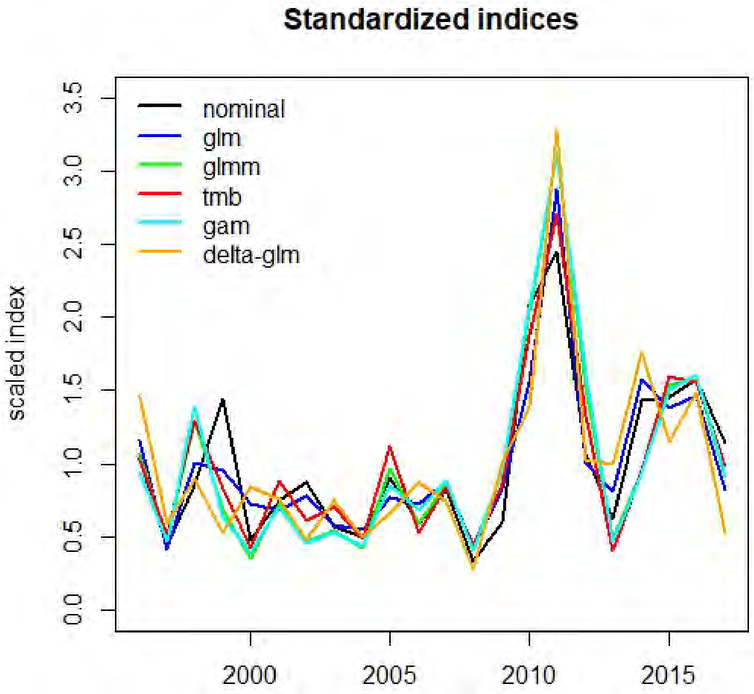


Figure 5.23 Seine data standardized using several methods including nominal, glm, glmm, tmb, gam, delta-glm.

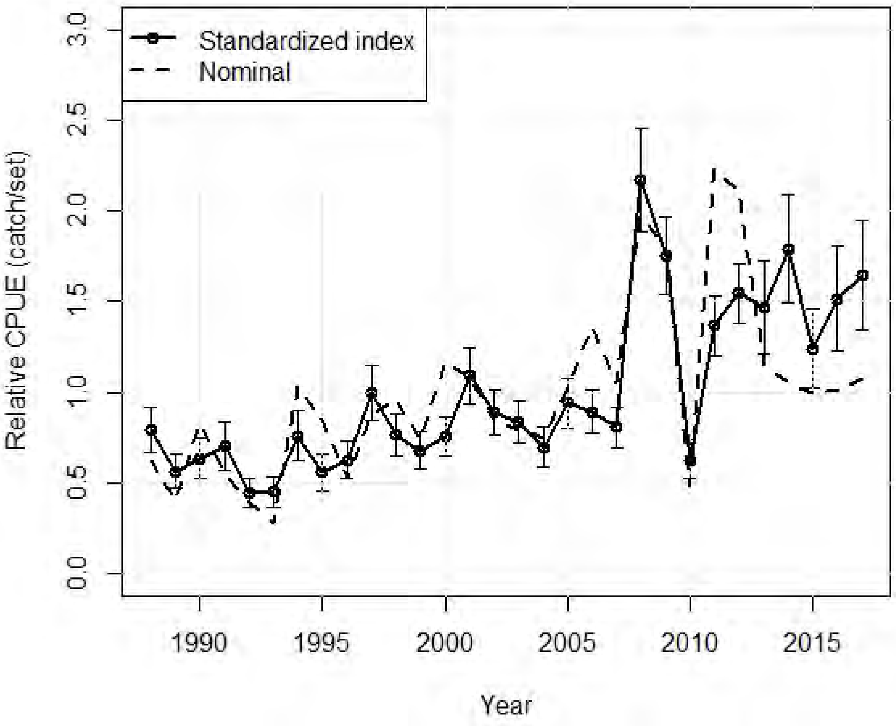


Figure 5.24 The scaled, standardized and scaled, nominal Gulf Menhaden gill net index for 1988-2017 representing adult abundance.

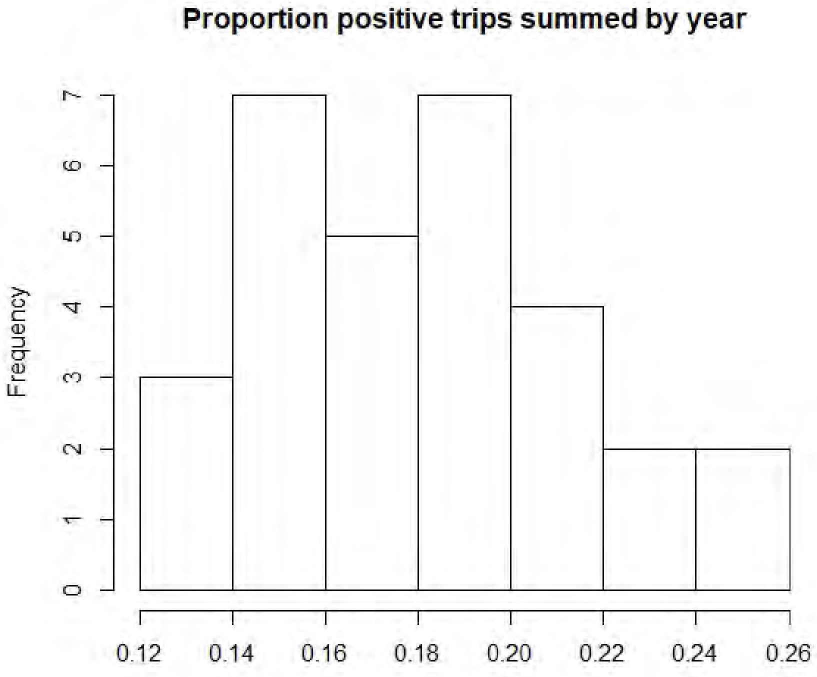


Figure 5.25 Frequency plot of the proportion positive for the years 1988-2017, which were included in the Louisiana gill net index.

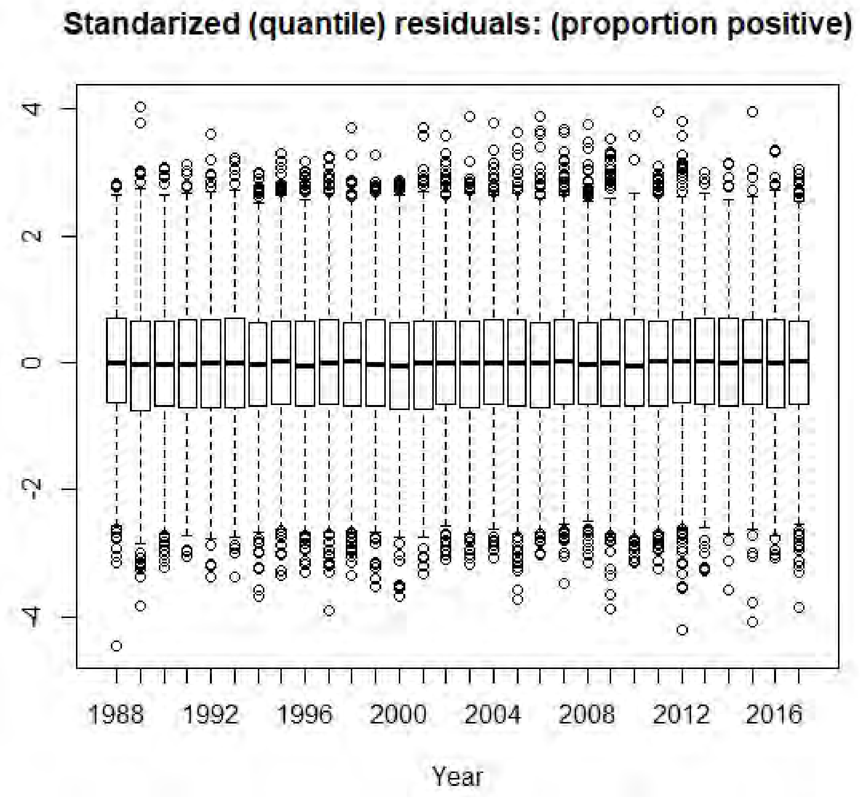


Figure 5.26 Residual plot for the proportion positive by year for the Louisiana gill net index.

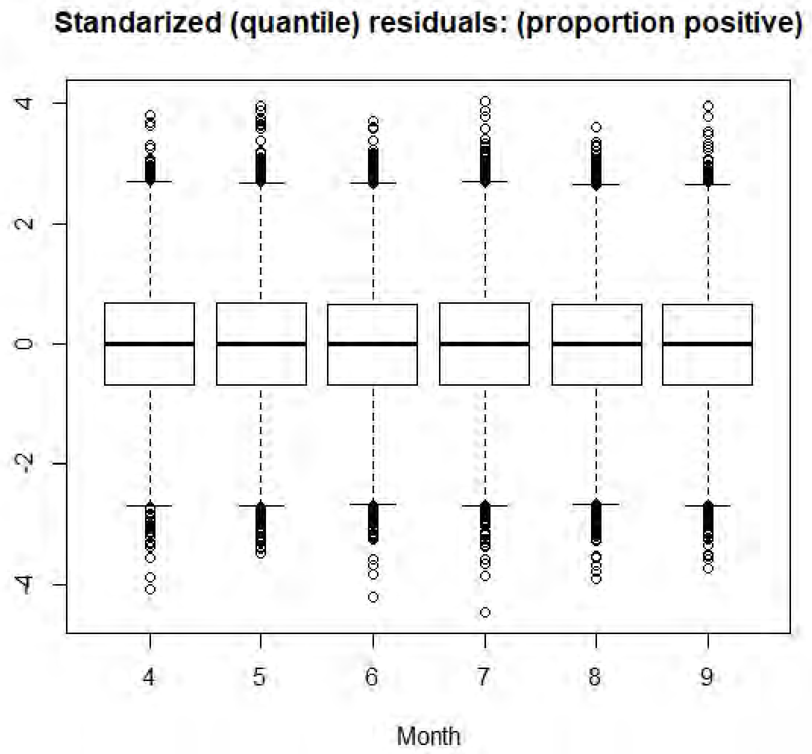


Figure 5.27 Residual plot for the proportion positive by month (April-September) for the Louisiana gill net index.

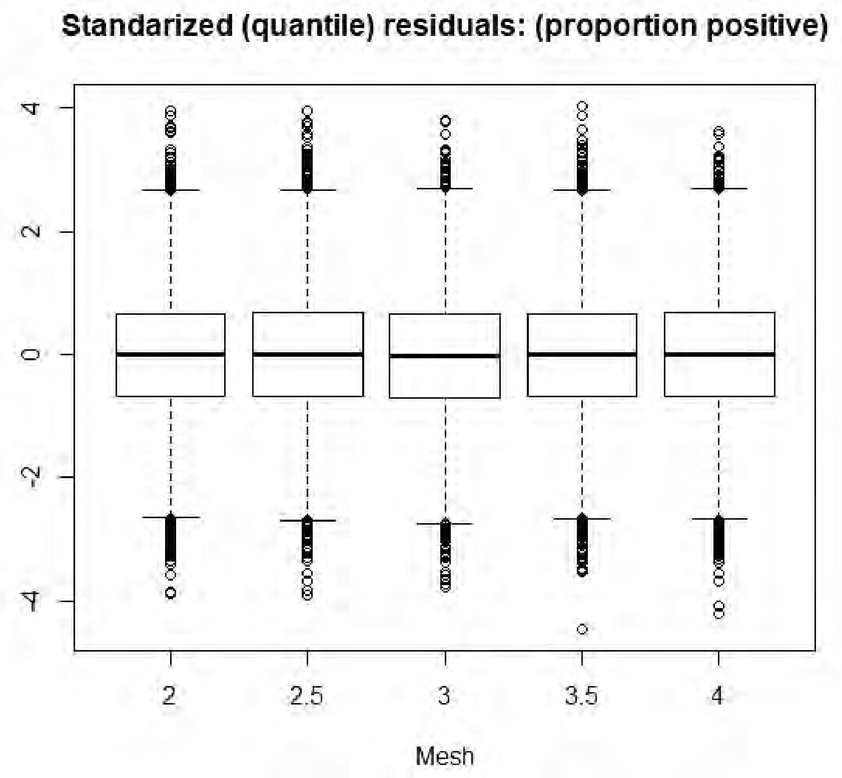


Figure 5.28 Residual plot for the proportion positive by mesh size for the Louisiana gill net index.

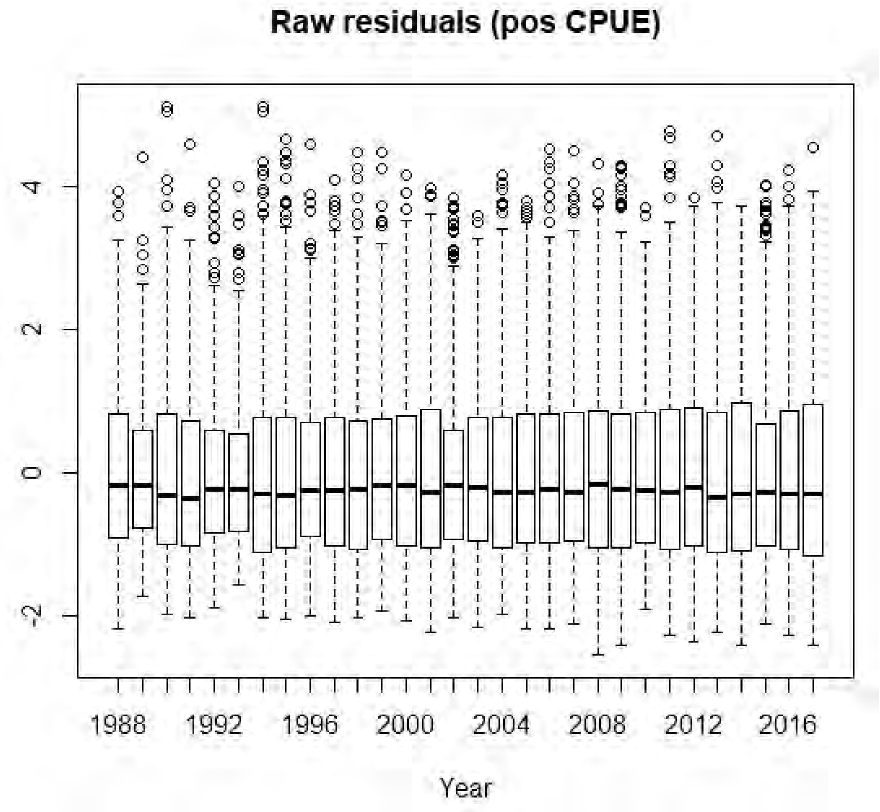


Figure 5.29 Raw residuals for the positive catches by year for the Louisiana gill net index.

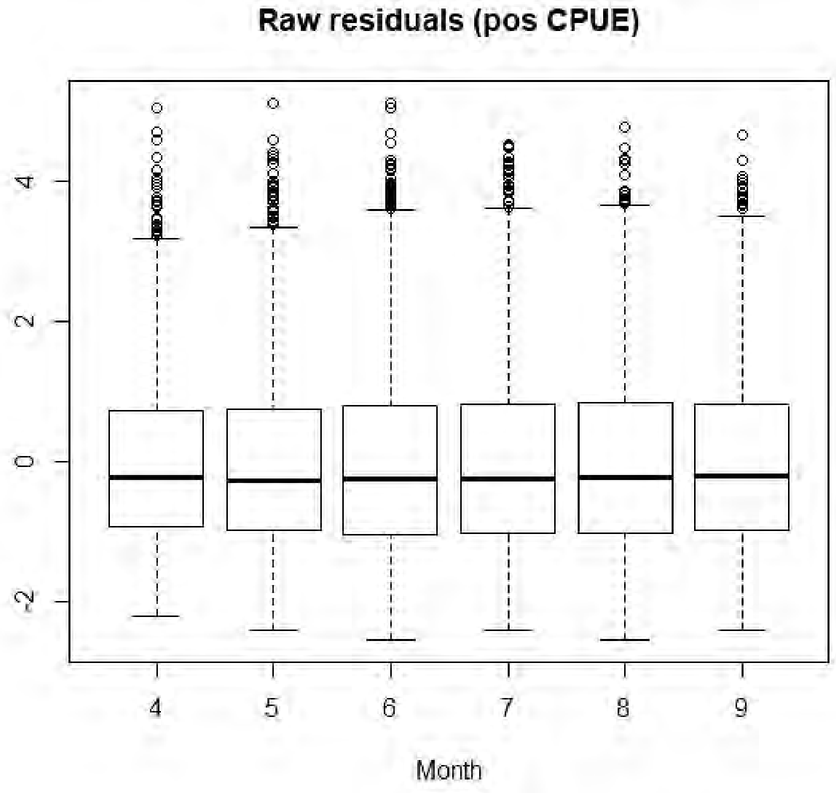


Figure 5.30 Raw residuals for the positive catches by month (April-September) for the Louisiana gill net index.

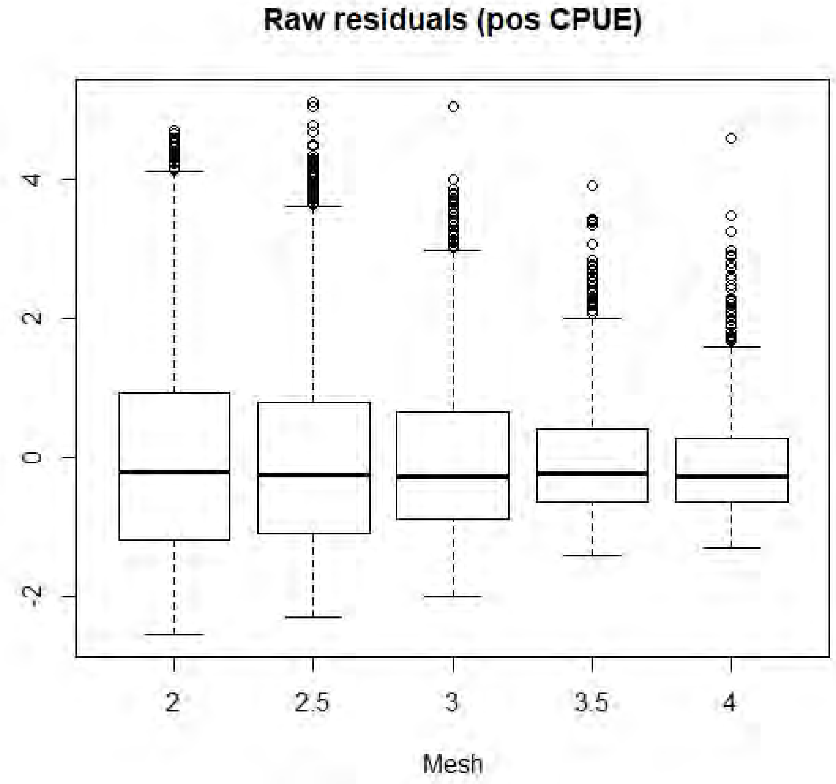


Figure 5. 31 Raw residuals for the positive catches by mesh size for the Louisiana gill net index.

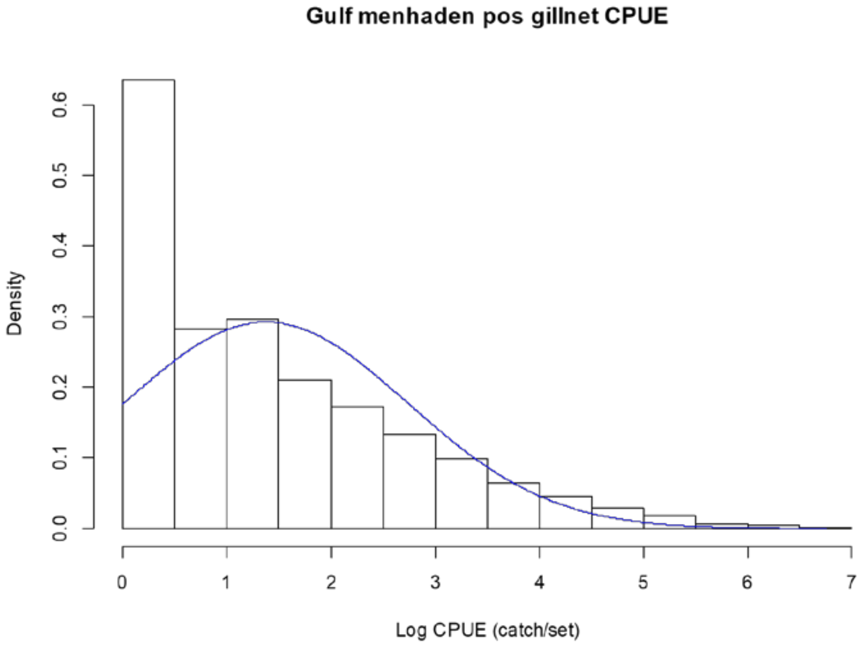


Figure 5.32 Density plot of the positive catches for the Louisiana gill net index.

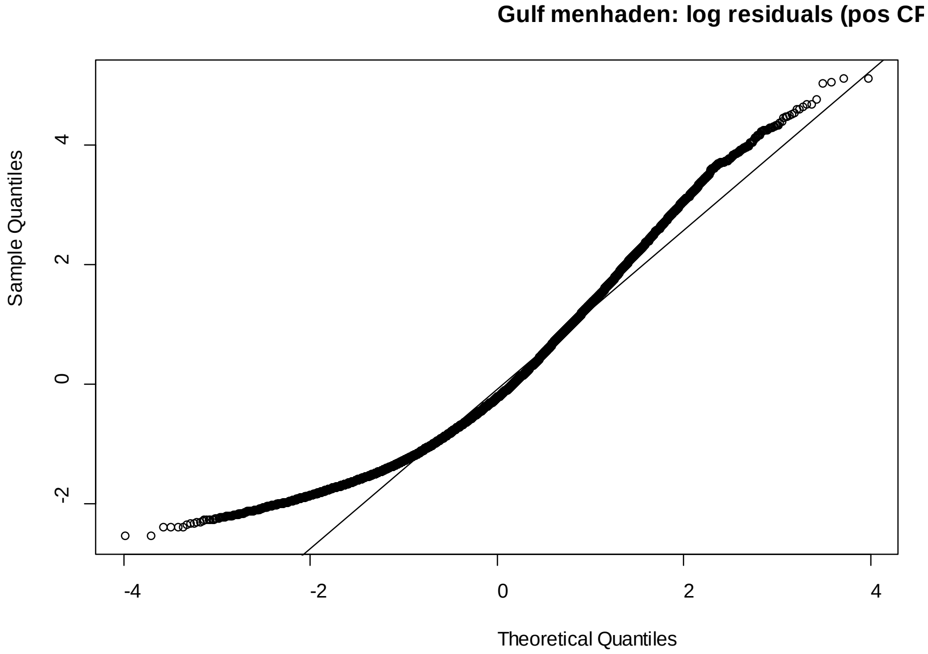


Figure 5.33 QQ plot of the positive catches for the Louisiana gill net index.

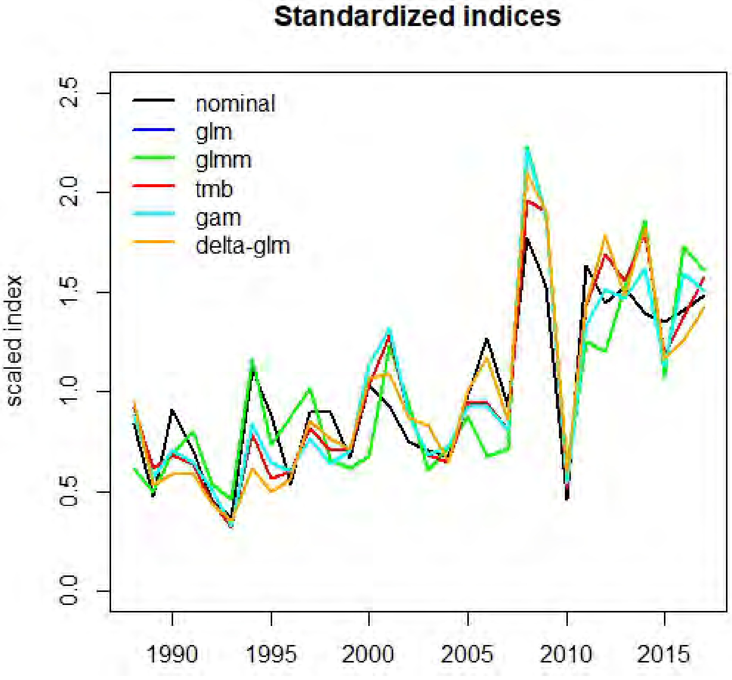


Figure 5.34 Gill net data standardized using several methods including nominal, glm, glmm, tmb, gam, delta-glm.

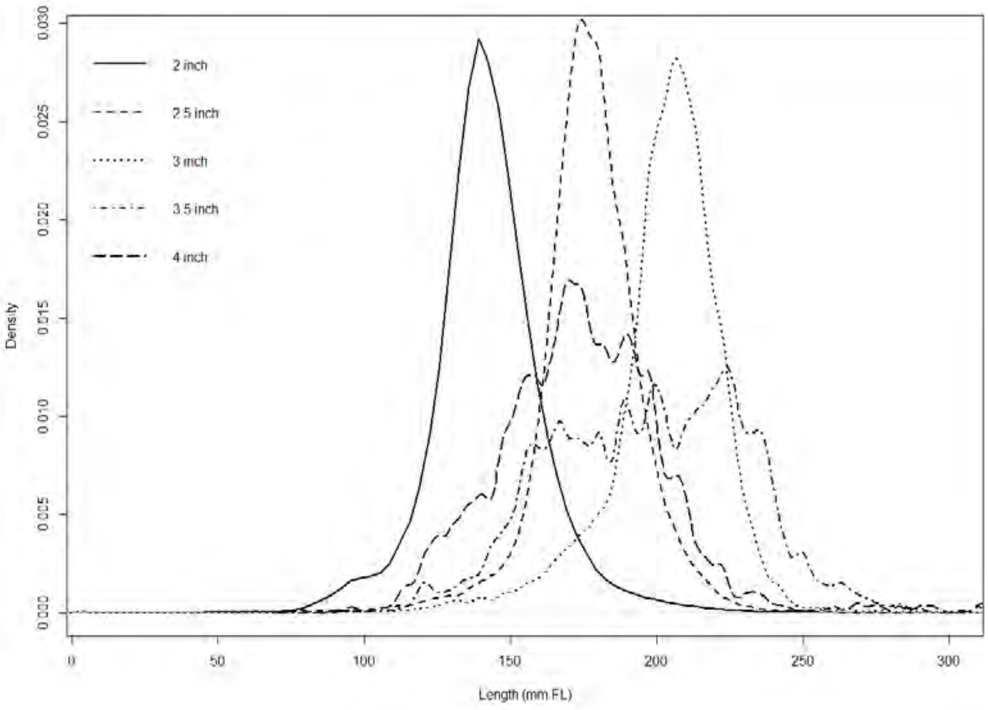


Figure 5.35 Probability density functions of the Louisiana gill net survey length samples in mm FL by mesh size.

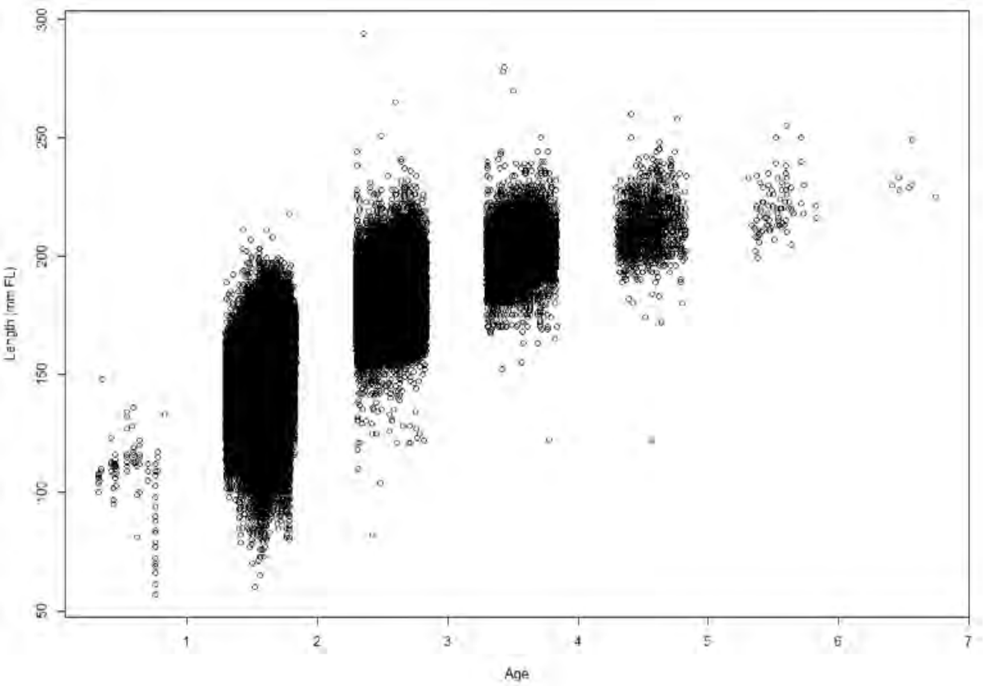


Figure 5.36 Age versus length in mm FL for the commercial reduction fishery for the years 1977-2011 (*from* SEDAR 2013a).

6.0 Methods

6.1 Assessment Model Descriptions

In this section, we identify one modeling approach that was considered as the potential base model for the Gulf Menhaden stock assessment. The modeling approach is an age-structured statistical catch-at-age model called the Beaufort Assessment Model (BAM). During the assessment workshop (AW), the pros-and-cons of different approaches were discussed in detail. The panel selected the statistical catch-at-age model as the base (preferred) model for the current assessment in order to use all of the available data and to avoid making assumptions about fishery selectivity and life history.

6.1.1 Beaufort Assessment Model (BAM)

The essence of a 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 (e.g., gear selectivity) are also simulated. Quantities to be estimated are systematically varied from starting values until the simulated population's characteristics match available data on the real population as closely as possible. Such data include total catch by year, observed age composition by year, observed indices of abundance, and observed length composition by year. The method of forward projection has a long history in fishery models. It was introduced by Pella and Tomlinson (1969) for fitting production models. Additionally, forward projection was used by Fournier and Archibald (1982) and Deriso et al. (1985) in their CAGEAN model and by Methot (1989) in his stock-synthesis model. Forward-projecting age-structured models share many attributes with ADAPT-style tuned and untuned VPAs. The model developed for this assessment is an elaboration of the CAGEAN and stock-synthesis models and very similar in structure to models used for assessments of Gulf of Mexico Cobia (Williams 2001, SEDAR 2013b), South Atlantic Red Porgy (SEDAR 2002), South Atlantic Black Sea Bass (SEDAR 2003, SEDAR 2005c, SEDAR 2011b, SEDAR 2013c), South Atlantic Snowy Grouper and Tilefish (SEDAR 2004b, SEDAR 2011b), South Atlantic Red Snapper (SEDAR 2008a, ASMFC 2010), and Atlantic Menhaden (ASMFC 2010), as well as many others (Williams and Shertzer 2015). The BAM was the forward-projecting age-structured model used in the previous Gulf Menhaden benchmark assessment (SEDAR 2013a), and has multiple options for benchmark computation, has many model diagnostics, and can account for uncertainty through sensitivity runs and Monte Carlo bootstrapping.

6.2 Model Configuration for Base and Uncertainty Exploration

6.2.1 Assessment Model – Base Model: Age Structured Catch-at-Age Model

The Beaufort Assessment Model (BAM) used for this assessment is a statistical catch-at-age model (Quinn and Deriso 1999), implemented with the AD Model Builder software (developed by Otter Research Ltd – http://otter-rsch.com; Williams and Shertzer 2015).

6.2.1.1 Spatial and Temporal Coverage

The BAM model is not a spatially-explicit model and assumes a single population of Gulf Menhaden. Catches are assumed to come from one population. Commercial reduction fishery catches have ranged from Florida to Texas with the majority of recent catches coming from Louisiana waters. The abundance index data for Gulf Menhaden, which includes the seine recruitment index and the gill net adult abundance index, are assumed to be measures of the coastwide population, as reflected by the age-specific selectivity vector applied to each survey. Some historical data are available on Gulf Menhaden movement dynamics and patterns, which indicates a mixed coastwide population (Pristas et al. 1976, Ahrenholz 1981; Section 3.1.2). Anderson (2016) suggests that a single genetic stock exists in the Gulf with exceptionally high diversity noting the greatest genetic variability toward the population's center, west of the Mississippi River to Galveston Bay (Section 3.1.1). As a result, the panel assumed one coastwide stock to model for the stock assessment.

The BAM model for Gulf Menhaden employs annual time steps, modeling the years 1977-2017. The 1977 starting year reflects the first year of age composition data that were used, includes sufficient generations, and was supported by several other analyses and data sets. The other analyses and data sets supporting the decision to start with 1977 included work done by Nicholson and Schaaf (1978) on scale legibility, a VPA completed during previous assessments, principal component analysis (PCA) of the age composition data, and re-ageing of scales across 12 historical years. First, Nicholson and Schaaf (1978) determined that length data could be used to help estimate age from scales with lower legibility. In addition, the number of scales sampled from each individual increased from six to ten, to improve the chances of sampling a scale that was legible for age determination (J. Smith personal communication). Second, the VPA-based stock assessments completed in the past always showed an unexplained break around the 1976 time period (Vaughan et al. 2000). Third, during the last benchmark assessment for Gulf Menhaden, a PCA was done on the age composition to see if any years exhibited differences from the rest (SEDAR 2013a). That analysis showed that the earliest years of age composition data grouped separately and were different from the remainder of the years. Fourth, an analysis was completed during the last benchmark assessment (SEDAR 2013a) whereby scales from a dozen years over the decades of 1970s into the 2000s were re-aged by the original scale reader, Mrs. Ethel A. Hall (Section 4.2.7.2). Based on the second age readings, the years 1972 and 1974 were significantly different from the first age reading done in those respective years. All of the other years in the study were not significantly different, which called into question the validity of the years 1972 and 1974. In addition, there were no selectivity changes in the fishery that could account for the difference in the age structure sampled. Based on all of these analyses and evidence, there is an apparent difference in the age composition data from 1964-1976, which led to exclusion of those data for the current base run of the statistical catch-at-age model, which thus started in 1977. In order to account for the uncertainty related to not using the age composition data for 1964-1976, a sensitivity run was completed (Section 6.2.1.6).

6.2.1.2 Selection and Treatment of Indices

As mentioned above, two sources of information were used for abundance indices in the statistical catch-at-age model. Fishery-independent gill net data were used to develop an adult abundance index. The adult gill net index sampling presumably catches mostly age-1 to 4+ Gulf Menhaden, with the majority of them presumed to be age-2+. The index was derived from data collected by the state of Louisiana, which is the center of the stock distribution. The adult gill net index was treated in the model as a representation of the coastwide stock, following the age-specific selectivity vector estimated within the model. The age-specific selectivity vector was estimated within the model as a logistic function. The level of error for this index was determined by a jackknife analysis done on the adult gill net index data records. The jackknife procedure estimated low error in the index, thus the assessment panel decided to set the error at 0.25 for each year based on work from the state of Louisiana (West and Zhang 2018).

In the BAM model, the estimates of the product of total numbers of fish at the midpoint of the year, a single catchability parameter, and the selectivity schedule were fit to the adult gill net index value in that same year. The error in this abundance index was assumed to follow a lognormal distribution.

The other source of abundance information used in the BAM model was a seine index. The seine index was derived from data from state surveys that were not designed to capture Gulf Menhaden. However, the seine index was treated as a Gulf Menhaden recruitment index in the stock assessment model, because the gear tends to capture primarily age-0 menhaden. The level of error for this index was determined by a jackknife analysis done on the seine index data records. In the model, the seine index was treated as an age-0 recruitment index, by fitting the product of the model estimated annual age-0 numbers on April 1 and a single catchability parameter to the computed index values. The index was matched with April as that was the period of highest catches of menhaden by that gear and the midpoint of the data used for creation of the index. The error in the recruitment index was assumed to follow a lognormal distribution.

6.2.1.3 Parameterization

The ADMB model code and input data file for the base run are attached as Appendices A.1, A.2, and A.3. A summary of the model equations may be found in Table 6.1. The major characteristics of the model formulation were as follows:

- *Natural mortality*: The age-specific natural mortality rate was assumed constant. A Lorenzen curve was scaled such that the age-2 mortality was 1.10 y^{-1}, or the mean value from a tagging study (Ahrenholz 1981).
- *Stock dynamics*: The standard Baranov catch equation was applied. This assumes exponential decay in cohort size because of fishing and natural mortality processes.
- *Growth/Sex Ratio/Maturity/Fecundity*: The ratio of males to females, percent of females mature, and fecundity were fixed in the model. The von Bertalanffy growth parameters (L_∞, K, and t_0) were fixed to values estimated using a bias correction and the fishery-dependent data (Schueller et al. 2014). No fishery-independent age data were available on which to base the population growth curve. The weight-at-age during spawning and during the middle of the fishery were input into the model and were based on the overall estimates of the parameters for the weight-length equation. The ratio of males to females was assumed to be 1:1. The maturity was fixed over time with zero percent of individuals being mature at age-0, 80% of individuals being mature at age-1, and one hundred percent of individuals being mature at age-2 and older. Annual age-specific fecundity was fixed in the model. This was calculated using the length-specific batch fecundity for the length-at-age of fish in each age class in the model at January 1 multiplied by the length-specific estimate of the proportion mature. This age-specific value was multiplied by the age-specific spawning frequency to determine annual age-specific fecundity (Brown-Peterson et al. 2017).
- *Recruitment:* Spawning was assumed to occur on January 1 in the model; hence the spawning time in months was 0.0. Recruitment to age-0 was estimated in the assessment model for each year with a set of annual deviation parameters, conditioned about a Beverton-Holt stock recruitment curve, and estimated in log-space. The steepness of the stock-recruitment curve was fixed at 0.99. The likelihood profile across steepness values showed that steepness should go to the upper bound (Figure 6.1). Therefore, the AW panel decided to fix steepness at 0.99 and then

explore the uncertainty in steepness in sensitivity runs.

- *Biological benchmarks*: Formal benchmarks were adopted for Gulf Menhaden during the last benchmark stock assessment. Further discussion of benchmarks can be found in Section 6.2.1.8.
- *Fishing*: One fishery was explicitly modeled. The fishery that was explicitly modeled was a combination of the commercial reduction fishery, which consisted of ~99% of all landings, the bait fishery, and the recreational fishery. Because the bait and recreational landings were such a small proportion of the landings in each year, they were combined with the reduction fishery landings. In addition, the bait and recreational fisheries are not sampled for biological information; thus, the assessment workshop panel assumed that the commercial reduction fishery was representative of all landings, which is a reasonable assumption. Fishing mortality rates were estimated for each year.
- *Selectivity functions*: Selectivity for the commercial reduction fishery used a parameter for each age, with most parameters being fixed values. Selectivity was dome-shaped for the commercial reduction fishery for all years 1977-2017 (see Section 5.8.2.1) with two time periods being estimated for age-1 selectivity (1977-1996 and 1997-2017). Dome-shaped selectivity was set up such that age-0 selectivity was 0.0, age-2 selectivity was 1.0, ages- 3 and -4 were 0.87, and age-1 selectivity was estimated for the two time periods of 1977-1996 and 1997-2017. The use of dome-shaped selectivity for the commercial reduction fishery was thoroughly explored (Section 5.8.2.1) and discussed during the assessment process. Selectivity for ages-3 and -4 were freely estimated during initial stages of the assessment. While the AW panel believed the reduction fishery selectivity to be dome-shaped, the AW panel does not know the extent of the doming. In addition, the ability of the data to inform estimation of age-3 and -4 selectivity was explored through likelihood profiles (Figures 6.2 and 6.3). Thus, the minimum and maximum extents of doming were determined to have a rather broad range. The value used by the assessment panel was the midpoint of the range based on the likelihood profiles when combining both ages-3 and -4+, since age-4+ selectivity was not well defined (Figure 6.4). However, these selectivity values were explored in both the sensitivity runs and Monte Carlo bootstrapping. Selectivity for the seine index was 1.0 for age-0 and 0.0 for all other ages, which reflects that the seine index was a recruitment index. Selectivity for the gill net index was age varying, but constant over time. The gill net index selectivity was estimated as a logistic function. See Section 5.8.2.1 for further discussion.
- *Discards*: Discards of Gulf Menhaden were believed to be negligible and were therefore ignored in the assessment model.
- *Abundance indices*: The model used two indices of abundance that were modeled separately: a recruitment (age-0) index series (1996-2017; seine index) and an adult index series (1988-2017; gill net index).
- *Ageing error matrix*: An ageing error matrix was not used for the base run of the stock assessment, but was included in the sensitivity runs.
- *Fitting criterion*: The fitting criterion was a total likelihood approach in which total catch, the observed age compositions from the commercial reduction fishery, the observed length compositions from the gill net index, and the patterns of the abundance indices (both seine and gill net indices) were fit based on the assumed statistical error distribution and the level of assumed or measured error (Section 6.2.1.4).
- *Model testing*: Experiments with a reduced model structure indicated that parameters estimated from the BAM model were unbiased and could be recovered from simulated data with little noise (cf., SEDAR 2008a). Additionally, the general model structure has been extensively peer

reviewed. As an additional measure of quality control, code and input data for Gulf Menhaden were examined by multiple analysts to ensure accuracy. This combination of testing and verification procedures suggests that the assessment model has been implemented correctly and provides an accurate assessment of Gulf Menhaden stock dynamics.

6.2.1.4 Weighting of Likelihoods

The likelihood components in the BAM model include reduction landings, reduction catch-at-age, a gill net adult index, a seine recruitment index, and gill net length compositions. For each of these components, a statistical error distribution was assumed as follows:

Likelihood Component	Error Distribution	Error Levels
Reduction landings	Lognormal	Constant CV = 0.04
Reduction catch at age	Dirichlet multinomial	Annual number of trips sampled
Gill net index length compositions	Dirichlet multinomial	Annual number of sets sampled
Gill net index	Lognormal	Annual CV values = 0.25
Seine index	Lognormal	Annual CV values from 0.21 to 0.31

Iterative reweighting was used to weight the index data components by setting the weights such that the standard deviation of the normalized residuals was near one and a half (Francis 2011). This required upweighting the gill net index to a weight of 4.0, while the seine index weight remained at 1.0. This put the two indices' standard deviations of the normalized residuals near 1.5. Upweighting the gill net index led the model to fit the index more closely, which led to model stability and the ability to estimate the other parameters.

6.2.1.5 Estimating Precision (e.g. ASEs, Likelihood profiling, MCB)

The BAM model was implemented in the AD Model Builder software, which allowed for easy calculation of the inverse Hessian approximated precision measures. However, in this case where some key values were fixed (e.g., natural mortality), it is believed that precision measures from the inverse Hessian matrix are underestimates of the true precision. Instead, the BAM model employed a parametric bootstrap procedure in which the input data sources were re-sampled using the measured or assumed statistical distribution and error levels provided. The data sources that were re-sampled in 5,000 bootstrap iterations included landings, gill net index, seine index, gill net length compositions, commercial reduction age compositions, natural mortality, and selectivity of age-3 and -4+ for the commercial reduction fishery. The landings, gill net index, and seine index were all re-sampled using multiplicative lognormal error using the CVs specified in the model input for each respective component. Uncertainty in the landings and indices was applied using a parametric bootstrap. To implement this approach in the MCB runs, random variables (x_s,y) were drawn for each year y of time series s from a normal distribution with a mean of 0 and a variance of $\sigma^{2s,y}$. Each observation was then perturbed from the original values ($O_{s,y}$) using the equation:

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

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

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

The gill net length compositions and commercial reduction age compositions were recreated for each year by distributing the number of fish sampled for each year to each length or age based on the probability observed. Variability in natural mortality was included as a random uniform distribution from 0.69 to 1.51 for age-2. The Lorenzen curve was then scaled to the random age-2 value. The selectivity for ages-3 and -4+ for the commercial reduction fishery was a uniform distribution between 0.68 and 0.95 and was the most likely range of values based on the likelihood profiling.

6.2.1.6 Sensitivity Analyses

A total of 21 sensitivity runs were completed with the BAM model. These sensitivity runs represent those involving input data and those involving changes to the model configuration.

6.2.1.6.1 Sensitivity to Input Data

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

Run Number	Sensitivity Examined
gm-017	Ageing error based on rereads
gm-018	Ageing error based on blind reads
gm-023	Vector of fecundity based on the low confidence interval from Brown-Peterson et al. 2017
gm-024	Vector of fecundity based on the high confidence interval from Brown-Peterson et al. 2017
gm-028	Excluded the seine index
gm-029	Excluded gill net index and gillnet length compositions
gm-030	Included MS/AL gill net index and associated length compositions
gm-034	Life history and growth inputs based on data from 1977-1996
gm-035	Life history and growth inputs based on data from 1997-2017
gm-041	Age-2 *M* scaled to minimum value estimated in the tagging study
gm-042	Age-2 *M* scaled to maximum value estimated in the tagging study

Natural mortality is always a source of uncertainty in stock assessments. To test the sensitivity of the model output to assumptions about natural mortality, sensitivity run numbers gm-041 and gm-042 were completed. In runs 041 and 042, natural mortality values were scaled such that age-2 mortality was the upper bound based on the tagging data (Ahrenholz 1981), and age-2 mortality was the lower bound based on the tagging data, respectively. These two sensitivity runs addressed uncertainty in the scale of *M*.

To explore the uncertainty related to data components included in the model, several sensitivity runs were completed with data sources excluded or included. First, a run was done without the gill net index and gill net length compositions (gm-029). Second, a run was done without the seine index (gm-028).

Finally, a run was done which included a gill net index based on data from the states of Mississippi and Alabama, as well as the associated length compositions (gm-030). Each of these runs explored the effects of indices on the overall results of the model.

Four additional runs were completed to look at the uncertainty surrounding the population growth parameters and life history information. Because no age data are available for any other gear besides the commercial reduction fishery, population growth parameters were based on limited external data including the Brown-Peterson et al. (2017) information on fecundity. Two sensitivity runs were completed with the assumption that the population fecundity was based on the low or high confidence interval values from the Brown-Peterson et al. (2017) paper, which allowed for exploration of changes in the number of eggs produced per adult. Additionally, two runs were completed using two different von Bertalanffy curves for estimating life history and growth information. The two curves were based on commercial reduction fishery data for 1977-1996 and 1997-2017. Based on analyses of the growth data, there appeared to be a possible shift in the von Bertalanffy parameters during the mid-1990s; however, this was only apparent from the mean estimated values, but not when the confidence intervals were observed. The assessment panel determined that there wasn't a difference in the values over time given the confidence intervals, but decided to run sensitivity analyses to determine the impacts of that decision (gm-034 and gm-035).

Finally, two additional runs were completed that looked at two different ageing error matrices. The base run of the stock assessment does not include any ageing error, so each of these runs was to look at the effects of ageing error from two different perspectives. First, an ageing error matrix based on rereading of scales over four decades was to look at the possibility of age reader drift over time (gm-017). Second, an ageing error matrix based on reading of scales blind between two readers was used to look the precision between the readers (gm-018).

6.2.1.6.2 Sensitivity to Model Configuration

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

Run Number	Sensitivity Examined
gm-019	Steepness fixed at 0.75
gm-020	Weight of 1.0 for the gill net index data component
gm-021	Weight of 3.0 for the gill net index data component
gm-022	Weight of 5.0 for the gill net index data component
gm-025	Age-3 and -4+ commercial reduction selectivity fixed at 1.0
gm-026	Age-3 and -4+ commercial reduction selectivity fixed at 0.73
gm-027	Age-3 and -4+ commercial reduction selectivity fixed at the midpoint of the likelihood profile for each parameter
gm-031	Start year of the model was 1996
gm-032	Start year of model was 1964, included 1964-1976 age composition data
gm-033	Start year of model was 1948

In order to explore the effect that weighting the likelihood components had on the fit to the various data components as well as estimated parameters, three sensitivity runs were completed (gm-020, gm-021, and gm-022). Each of these runs changed the weight on the gill net index, which was an influential index in the stock assessment.

A sensitivity run was also completed which modified the fixed value of steepness for the Beverton-Holt stock-recruitment curve (gm-019). Therefore, a sensitivity run was completed with steepness fixed at 0.75.

Selectivity is always an uncertainty in stock assessments, and that uncertainty was explored with three sensitivity runs related to the commercial reduction selectivity. The first was to fix the selectivity for ages-3 and -4+ individuals to a value of 1.0 (gm-025). The second was to fix the selectivity for age-3 and -4+ individuals to a value of 0.73, which is near the midpoint of the range of values based on the likelihood profiles (gm-026). Lastly, a sensitivity run was completed that fixed the selectivity of age-3 and age-4+ selectivity to the midpoint of the likelihood profile for each parameter (gm-027).

Additional data were available before 1977, so to explore the effects of leaving those data out of the base run, two sensitivity runs were completed with the runs having a start year prior to 1977. The first had a start year of 1964, which is the first year that the age composition data are available (gm-032). The second had a start year of 1948, which is the first year with reliable landings estimates (gm-033). Lastly, a sensitivity analysis was run with a start year of 1996 (gm-031). This run explored excluding data that had apparent shifts (including the growth data) to determine the impact on the overall outcomes.

6.2.1.7 Retrospective Analyses

Retrospective analyses were completed by running the BAM model in a series of runs sequentially omitting years 2017 to 2013, as indicated below:

Run Number	Sensitivity Examined
gm-036	Retrospective analysis with modeling ending in 2016
gm-037	Retrospective analysis with modeling ending in 2015
gm-038	Retrospective analysis with modeling ending in 2014
gm-039	Retrospective analysis with modeling ending in 2013
gm-040	Retrospective analysis with modeling ending in 2012

None of these runs required additional constraints to converge.

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

The assessment panel provided options for *F*-based and *SSB*-based (*SSB* in fecundity) benchmarks for the current Gulf Menhaden stock assessment in Section 7.1.6 and Table 7.10. The quantities F_{MSY}, SSB_{MSY}, B_{MSY}, and *MSY*, estimated by the method of Shepherd (1982), were infinite and increased to the maximum allowed value of *F* within the model of 10.0 y^{-1}. Thus, estimates of *MSY* and associated benchmarks typically used in the federal system were not provided. Although the GSMFC's Menhaden Advisory Committee (MAC) has the ability to recommend reference points to the Gulf States, they are not constrained to the Magnuson-Stevens Act. The assessment panel recommends that the MAC discuss the goals and objectives for fishery management for Gulf Menhaden and potential alternative references points based on management needs. Some standard F_{MSY} proxies, such as SPR based metrics, were also not suitable candidates for use as benchmarks given that *F* values were above 10 for the benchmarks in the current fishery management plan ($F_{30\%}$ and $F_{35\%}$; VanderKooy and Smith 2015). As a consequence, the assessment panel suggested the use of the following *F*-based benchmarks: $F=M$ for the threshold and $F=0.75M$ as the target. The natural mortality associated with the *F*-based benchmarks was the geometric mean natural mortality for ages-0 to -2, which is the bulk of the incoming fishery in future years. These *F*-based metrics were suggested because they are used in other areas such as category 3 and 4 stocks in ICES (Patterson 1992, Gabriel and Mace 1999, Mace 2001, ICES 2018). In addition, the suggested *F*-based metrics are similar in value to metrics that would have been suggested considering historical interpretation of the fishery. Specifically, the assessment panel discussed that fishing in the 1980s was likely to impact the population, although not to the point of being overfished. Thus, the panel suggested avoiding *F* values in the range of values estimated during that time period or to use them as a threshold. The panel also noted that the current fishing mortality rates (during late 2000s and 2010s) appear to be in a good range (*F* ranging from 0.48 to 0.99) with little impact on the population; thus the assessment panel thought that those values for the target fishing mortality rate were in an appropriate range.

All equilibrium benchmark calculations were based upon current fishery selectivity, *M*-at-age (which was constant over time), weight-at-age, and fecundity-at-age from the model inputs (1977-2017).

As was also the case in previous Gulf Menhaden stock assessments, population fecundity (*FEC*, number of maturing or ripe eggs) was used as the measure of reproductive capacity. The assessment panel suggested the following options for *SSB* or *FEC* based metrics: the *SSB* value at 25% and 50% of the equilibrium value when $F=0$, which is a measure of reproductive capacity (*SSB* [spawning stock biomass]=*FEC*). These two values are also used on the West Coast as recommendations for the threshold and target values, respectively (PFMC 2016) and are similar to what is used for Pacific herring (DFO 2017). The *SSB*-based metrics were not paired with the *F*-based metrics because the spread in the associated *SSB* metric was smaller than one standard deviation of the variability in the *SSB* time series. Because the *SSB* metrics associated with the *F* based metrics were so close together, managers would run the risk of drastic changes in stock status from year to year as the *SSB* changed over time. However, the recommended *SSB* metrics have *F* values that are high and are 4.71 and >10 for the *SSB* target and threshold, respectively. That being said, the assessment panel recommended these SSB based metrics because the panel thought that it was unlikely that the fishery had caused the population to decrease to a point that the population would have been unable to recover given the species life history and protracted spawning season.

Table 6.1 General definitions, input data, population model, and negative log-likelihood components of the BAM forward-projecting statistical age-structured model used for Gulf Menhaden. Estimated parameters are denoted using hat (^) notation, and predicted values are denoted using breve (˘) notation.

General Definitions	Symbol	Description/Definition
Year index: *y* = {1977,..,2017}	y	
Age index: *a* = {0,...,4+}	a	
Length index: *l* = {85,...,295+}	l	
Fishery weight at age	w_a	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 with an L_∞ that is bias corrected using Schueller et al. 2014
Maturity at age	m_a	From data workshop; based on Brown-Peterson et al. 2017
Fecundity at age	γ_a	From data workshop; based on Brown-Peterson et al. 2017
Observed age-0 CPUE *y* = {1996,...,2017}	$U_{1,y}$	Based on numbers of age-0 fish from state seine surveys
Observed gill net CPUE *y* = {1988,...,2017}	$U_{2,y}$	Based on gill net survey from Louisiana
Selectivity for U_2	$\hat{s}'_a$	Estimated as a logistic function
Coefficient of variation for *U*	c_U	Based on annual estimates from samples for U_1 and U_2; for U_2, the value was fixed at 0.25
Observed length compositions	$\tau_{l,y}$	Computed as percent of length composition at length (*l*) for each year (*y*)
Length composition sample sizes	n_y^l	Number of sets sampled in each year (*y*)
Observed age compositions	$p_{a,y}$	Computed as percent age composition at age (*a*) for each year (*y*)
Age composition sample sizes	n_y^a	Number of trips sampled in each year (*y*)
Observed fishery landings	L_y	Reported landings in weight for each year (*y*)
Coefficient of variation for *L*	c_L	Fixed at 0.04, from Data Workshop
Natural mortality	M_a	From Data Workshop, varies with age and is constant across time. Age-2 scaled to empirically based value from Arhenholz (1981).
Fishery selectivity	$\hat{s}_a$	Fixed at 0.0 for age-0, fixed at 1.0 for age-2, fixed at 0.87 for ages-3 and -4+, and estimated for age-1. Two time blocks for age-1 (1977-1996 and 1997-2017).
Fishing mortality (fully selected)	$F_{a,y}$	$F_{a,y} = \hat{s}_a \hat{F}_y$ where F_y values for each year are estimated parameters
Total mortality	$Z_{a,y}$	$Z_{a,y} = M_a + F_{a,y}$

Table 6.1 Con’t

General Definitions	Symbol	Description/Definition
Fecundity per recruit at *F* = 0	ϕ	$\phi = \sum_{a=0}^{4+} N_a m_a \gamma_a 0.5 \Big/ N_0$ where $N_{a+1} = N_a \exp(-Z_a)$ and $N_{4+} = N_3 \exp(-Z_3) / [1 - \exp(-Z_{4+})]$ and the sex ratio is assumed to be 1:1.
Population numbers	$N_{a,y}$	$N_{0,1977} = \frac{\hat{R}_0 (0.8 \varsigma \hat{h} S_{equil} - 0.2 \Phi_0 (1 - \hat{h}))}{(\hat{h} - 0.2) S_{equil}} \exp(\hat{R}_{1977})$ $\hat{N}_{1+,1977}$ $N_{0,y+1} = \frac{0.8 \hat{R}_0 \hat{h} S_{y+1}}{0.2 \Phi_0 \hat{R}_0 (1 - \hat{h}) + (\hat{h} - 0.2) S_{y+1}} \exp(\hat{R}_{y+1})$ $N_{a+1,y+1} = N_{a,y} \exp(-Z_{a,y})$ $N_{A,y} = N_{A-1,y-1} \frac{\exp(-Z_{A-1,y-1})}{1 - \exp(-Z_{A-1,y-1})}$
Population fecundity	ε_y	$\varepsilon_y = \sum_{a=0}^{4+} N_{a,y} m_a \gamma_a 0.5$
Population biomass (age-1+)	B_y	$B_y = \sum_{a=1}^{4+} N_{a,y} w_a^p$
Predicted catch-at-age	$\breve{C}_{a,y}$	$\breve{C}_{a,y} = \frac{F_{a,y}}{Z_{a,y}} N_{a,y} [1 - \exp(-Z_{a,y})]$
Predicted landings	$\breve{L}_y$	$\breve{L}_y = \sum_{a=0}^{4+} \breve{C}_{a,y} w_a$
Predicted age composition	$\breve{p}_{a,y}$	$\breve{p}_{a,y} = \breve{C}_{a,y} \Big/ \sum_{a=0}^{4+} \breve{C}_{a,y}$
Predicted age-0 CPUE	$\breve{U}_{1,y}$	$\breve{U}_{1,y} = N_{0,y} \hat{q}_1$ where q_1 is an estimated constant catchability parameter
Predicted gill net CPUE	$\breve{U}_{2,y}$	$\breve{U}_{2,y} = \sum_{a=0}^{4+} N_{a,y} \hat{s}'_a \hat{q}_2$ where q_2 is an estimated constant catchability parameter
Predicted length composition	$\breve{\tau}_{l,y}$	$\breve{\tau}_{l,y} = \hat{s}'_a N_{a,y} * prob(l) \Big/ \sum_{a=0}^{4+} \hat{s}'_a N_{a,y}$ where *prob*(*l*) is the probability of an individual of an age *a* being length *l*

Table 6.1 Con’t

General Definitions	Symbol	Description/Definition
Negative Log-Likelihood		
Dirichlet multinomial age composition	Λ_f	*A* = *Θn* where *n* is sample size and *Θ* is the adjustment $L = \frac{\Gamma(A)}{\Gamma(n+A)} \prod \left[\frac{\Gamma(no+Ap)}{\Gamma(Ap)}\right]$ where *A* and *n* are defined above, *o* is observed data, and *p* is predicted data. $NLL = \Lambda_f = -[ln\Gamma(A) - ln\Gamma(n+A)] - \sum_{ages}[ln\Gamma(no+Ap)] + \sum_{ages}[ln\Gamma(Ap)]$ And the effective sample size, n_{eff}, is calculated as $n_{eff} = \frac{1+\square n}{1+\square}$
Lognormal indices	Λ_f	$\Lambda_f = \sum_{U} \sum_{y} \frac{\left[\log(U_{u,y}+x) - \log(\breve{U}_{u,y}+x)\right]^2}{2\sigma^2_{U,y}}$ where w_U is a preset weighting factor for both the seine and gill net indices, *x* is fixed at an arbitrary value of 0.001, and $\sigma_U = \sqrt{\log(1+(c_U/w_U)^2)}$
Lognormal landings	Λ_f	$\Lambda_f = \sum_{y} \frac{\left[\log(L_y+x) - \log(\breve{L}_y+x)\right]^2}{2\sigma^2_L}$ where λ_f is a preset weighting factor (w_L) equal to 1.0, *x* is fixed at an arbitrary value of 0.001, and $\sigma_L = \sqrt{\log(1+(c_L/w_L)^2)}$.
Dirichlet multinomial length compositions	Λ_f	Where the likelihood is the same as that for the age compositions, but sample sizes, observed data, and predicted data are for the length compositions.
Lognormal recruitment deviations	Λ_f	$\Lambda_f = \lambda_f \left[R^2_{1977} + \sum_{y>1977} \frac{\left[(R_y - R_{y-1}) + (\hat{\sigma}^2_R/2)\right]^2}{2\hat{\sigma}^2_R} \right]$ where λ f is a preset weighting factor of 1.0.

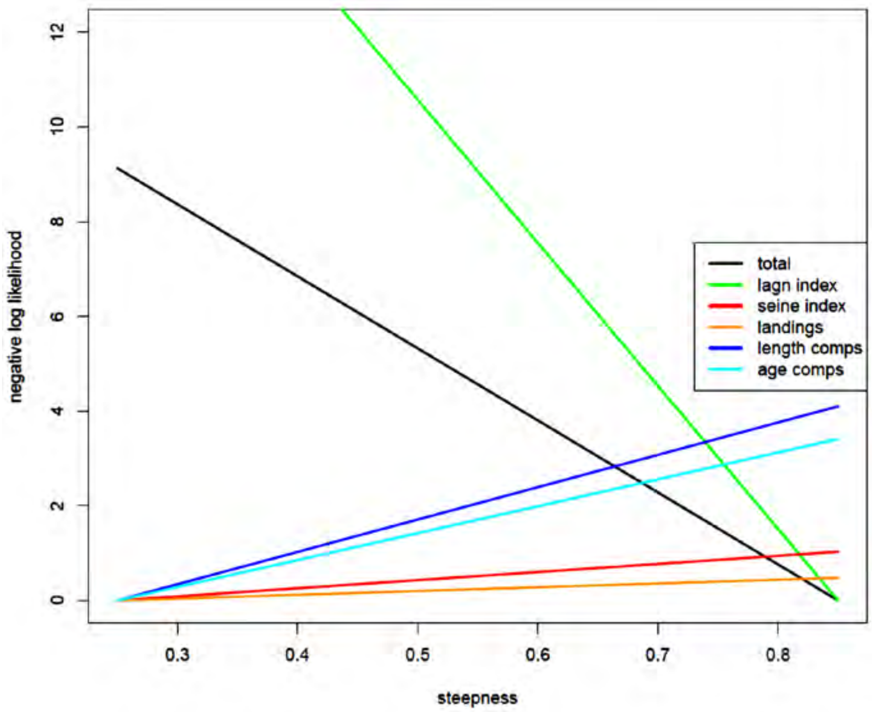


Figure 6.1 Likelihood profile across a range of values for steepness.

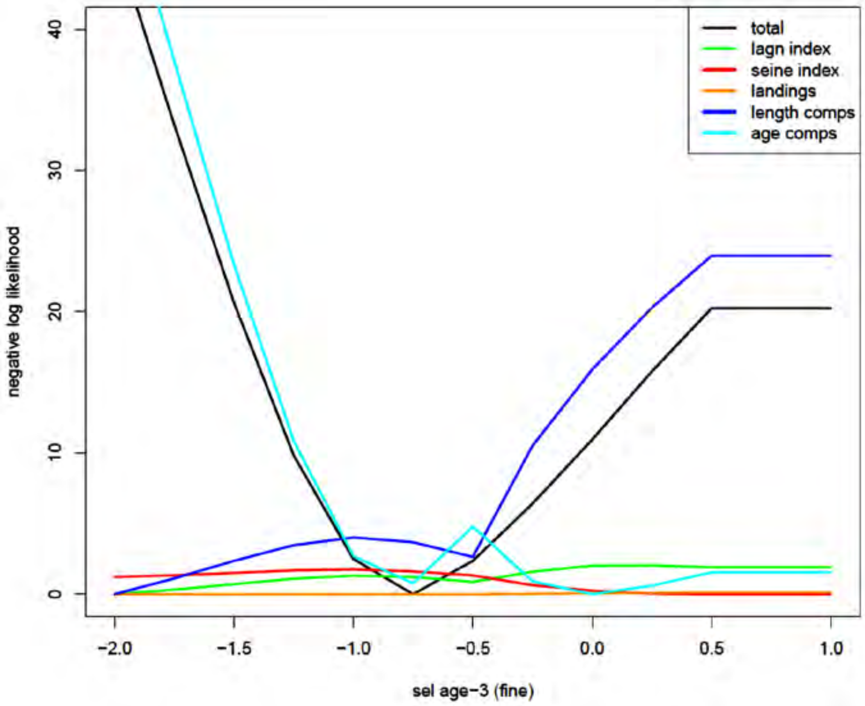


Figure 6.2 Likelihood profile of age-3 selectivity for the commerical reduction fishery.

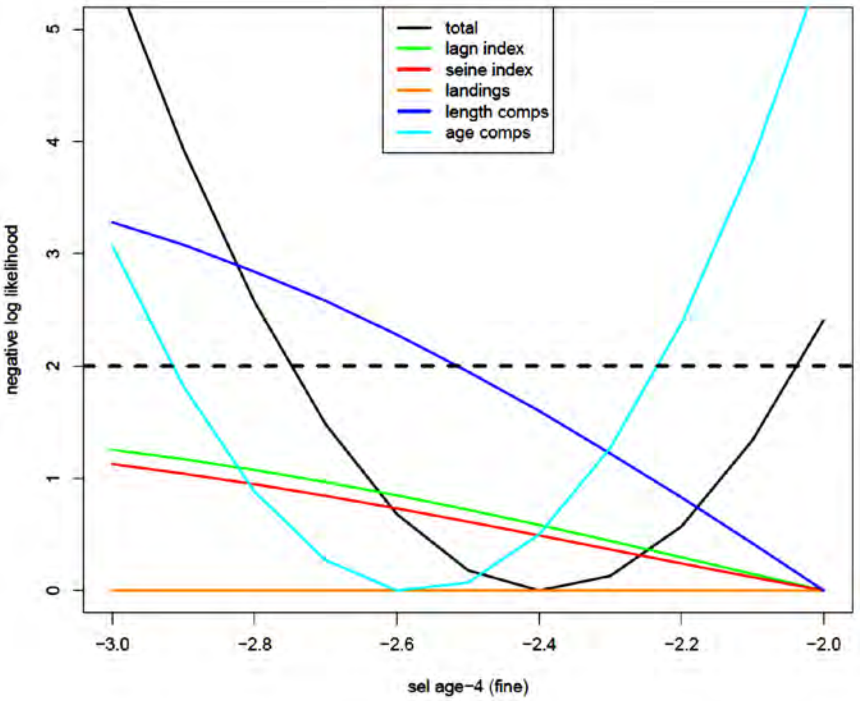


Figure 6.3 Likelihood profile of age-4+ selectivity for the commerical reduction fishery. The dashed black line indicates the range of values within two likelihood components.

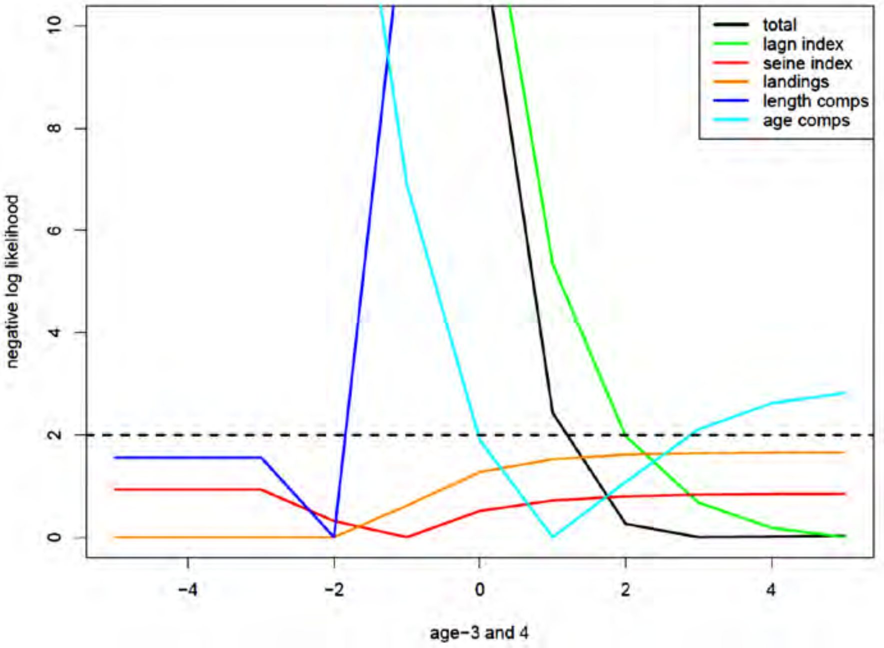


Figure 6.4 Likelihood profile of ages-3 and -4+ selectivity combined for the commerical reduction fishery. The dashed black line indicates the range of values within two likelihood components.

7.0 Base Model Results

7.1 Results of Base BAM Model

7.1.1 Goodness of Fit

Goodness-of-fit was governed in the BAM assessment model by the likelihood components in the objective function (Table 6.1). The relative fit among the likelihood components was governed by the weighting terms and the assumed error levels for each data source (see Section 6.2.1.4). During the Assessment Workshop, goodness of fit was also judged for each data source through examination of the model residuals.

Observed and model-predicted landings for the reduction fishery (1977–2017; Figure 7.1) were compared for the base model run. Reduction fishery landings, which are known fairly precisely, fit very well. Patterns in the annual comparisons of observed and predicted proportion catch-at-age for the reduction fishery (Figure 7.2) indicate a good overall model fit to the observed data. The bubble plot for the reduction fishery (Figure 7.3) indicates that the model fit does fairly well estimating age-1 during the time series. There is no patterning observed in the bubble plot that would cause concern.

Observed and predicted coastwide seine recruitment indices were compared for the base model run (1996–2017; Figure 7.4). The residual pattern suggests that the recruitment index data did not fit well when relatively large or small year classes occurred. Visual examination of the fit suggests that the overall pattern fit reasonably well, with the BAM model capturing some of the lows and highs observed in the index values.

The observed and predicted gill net index (1988–2017; Figure 7.5) values appear to fit well. The general patterns are captured. However, the model has a difficult time fitting estimates to the observed high values in 2008 and 2009 and the subsequent low value in 2010. Patterns in the annual comparisons of observed and predicted proportion gill net measurements at length for the gill net index (Figure 7.6) indicate a good overall model fit to the observed data. The bubble plot for the gill net index length compositions (Figure 7.7) indicates that the model fit fairly well.

7.1.2 Parameter Estimates (Include Precision of Estimates)

7.1.2.1 Selectivities and Catchability

Fishing mortality was related to an overall level of fishing and the selectivity (or availability) of Gulf Menhaden to the fishery. Model estimates of selectivity (availability) for the fishery are shown graphically in Figure 7.8. Selectivity parameters were estimated for age-1 during the time blocks 1977-1996 and 1997-2017 and fixed for all other ages. The selectivity for age-1 for 1977-1996 was estimated in logit space and was estimated at -0.97 (0.28 in normal space) with a standard error (SE) of 0.10. The selectivity for age-2 for 1997-2017 was estimated in logit space and was estimated at -1.79 (0.14 in normal space) with a SE of 0.09.

Selectivity for the gill net index was estimated as a two parameter logistic function as shown in Figure 7.9. The slope of the selectivity curve was estimated at 22.81 with a 337.9 SE, and the L_{50} of the selectivity curve was estimated at 1.12 with a 1.80 SE. Selectivity for the gill net index was used to fit the gill net length composition data and represents the ages of fish that were captured by the gill net index.

The base BAM model estimates a single, constant catchability parameter for each of the abundance indices, reflecting the assumption that expected catchability for these CPUE indices is believed to be constant with time. This is certainly a good assumption for the fishery-independent recruitment index and gill net adult index since they are based on consistent, scientific survey collections, although the surveys are at fixed stations and target other species. Log-catchability was estimated at -4.47 (0.011 back transformed) for the seine index with a 0.07 SE, while the log-catchability of the gill net index was -1.01 (0.37 back transformed) with a 0.10 SE.

7.1.2.2 Fishing Mortality Rate

Highly variable fishing mortalities were noted throughout the entire time series, with the highest fishing mortalities in the 1980s and 1990s, with a decline in fishing mortality during the 2000s. In the most recent decade, the full fishing mortality rate has ranged between 0.48 and 0.99 (Table 7.1; Figure 7.10). However, the only age that is fully selected is age-2, thus the fishing mortality rate on other ages is much smaller. In the most recent decade, full fishing mortality on age-1 has ranged from 0.06 to 0.14 (Table 7.2). The estimate of full fishing mortality rate for 2017 is 0.63 (Table 7.1).

7.1.2.3 Abundance, Fecundity, and Recruitment Estimates

The base BAM model estimated population numbers-at-age (ages 0-4+) for 1977–2017 (Figure 7.11 and Table 7.3). From these estimates, along with growth and reproductive data, estimates of reproductive capacity were computed. Population fecundity was the preferred measure of reproductive output. Population fecundity (*FEC*, number of maturing ova) was lower in the late 1980s and through the 1990s and was higher during the early 1980s and after 2005 with *FEC* values since 2005 being as high as values in the earliest part of the time series (Figure 7.12 and Table 7.4). The time period 1977-2017 produced a median population fecundity of 2.9×10^{15} ova with a minimum of 1.4×10^{15} and a maximum of 4.2×10^{15} and an interquartile range of 2.3×10^{15} to 3.5×10^{15} (Table 7.4). The estimate for population fecundity in 2017 was 4.2×10^{15}, which was the highest value in the time series. Throughout the time series, the age-1 and -2 fish produced most of the total estimated number of eggs spawned annually (Figure 7.13); however, in more recent years, ages-3 and -4 have contributed more significantly to the overall number of eggs.

Age-0 recruits of Gulf Menhaden (Figure 7.14 and Table 7.5) were highest during the 1970s and early 1980s and from the mid-2000s on and were lowest during the mid-1980s to the mid-2000s. The largest year-classes were in 1984, 2010, and 2016. The annual estimated recruitment values are shown in Figure 7.15. The recent estimates of recruitment for 2010 and 2016 are high, but the large recruitment classes have shown up in other data sources. The estimate of recruits to age-0 in 2010 (190 billion) was the third highest recruitment value during the time series; while the estimate for 2016 of 212 billion was the highest recruitment value during the time series. A plot of the fecundity (mature ova) to the recruits at age-0 indicated a weak relationship, suggesting Gulf Menhaden recruitment was only marginally governed by population fecundity (Figure 7.16). The only recruitment parameter estimated in the model was log of R_0, which was estimated at 4.76 with a standard deviation of 0.03.

7.1.2.4 Weighting of the Data Components

All of the likelihood component weights in the model were set to 1.0. For the age and length composition data, a Dirichlet multinomial likelihood was used where weighting parameters were estimated for each data component, with sample size represented by the annual number of trips adjusted by an estimated variance inflation factor (Thorson et al 2017). For the age compositions, the Dirichlet multinomial parameter was estimated as -3.09 with a SE of 0.13, while for the length compositions, the Dirichlet multinomial parameter was estimated as -0.83 with a SE of 0.12.

The standard deviations of the normalized residuals (SDNR) and likelihood values for the gill net index were explored across a range of weights in order to explore the trade-off of upweighting the index such that the SDNR was greater than 1.0 (Figures 7.17-21). Upweighting of the gill net index gave the model stability as the gill net index is a significant source of information on the trend of the population over time, while reduced weights on this data component led to the index not being fit well. Good fits to gill net index resulted in a stable model that was able to estimate the other parameters well and was especially influential on the estimation of R_0. Thus, the assessment panel decided that the assessment model should fit the adult data best because those data inform the part of the population managers are most interested in. As a result, the gill net index was upweighted to 4.0, which resulted in an SDNR of 1.48, while the seine index SDNR was 1.52.

7.1.3 Sensitivity Analyses

The results of the sensitivity runs suggest that the base BAM model is fairly robust to model choices made in the base run and data choices made by the assessment panel (Figures 7.17-7.21). The sensitivity runs associated with natural mortality mostly scaled the outputs from the model. Specifically, the runs that used the minimum and maximum values of *M* from the tagging study (gm-041 and gm-042) scaled the values of full *F*, recruitment, and fecundity. Overall, the behaviors observed from the sensitivity runs changing the input of natural mortality were as expected.

Changes to the stock-recruitment curve did not have much effect on the overall results from the model. The run with steepness set to 0.75 (gm-019) resulted in very minor to no changes to the full *F*, recruitment, and fecundity. Overall, the behaviors observed from the sensitivity run changing the input for the stock-recruitment curve were as expected.

The sensitivity runs that explored changes in the commercial reduction fishery selectivity had little effect on the overall results from the model. The run with ages-3 and -4+ selectivity fixed at 1.0 (gm-025) and the run with ages-3 and -4+ fixed at the midpoint from the likelihood profiles (gm-027) bound the results expected from dome to flat topped selectivity for the assessment. The base run and the sensitivity run with the age-3 and -4+ selectivity fixed at 0.73 (gm-026) are both between the results from those two runs. Overall, the behaviors observed from the sensitivity runs changing the selectivity for the commercial reduction fishery were very minimal, and the model was quite robust to these changes.

The start year of the model had no effect on the estimates of full *F*, recruitment, nor fecundity during 1977-2017 when the model started in 1948, 1964, and 1977 (gm-033, gm-032, and the base run). However, when the start year of the model was 1996 (gm-031), then there were slight differences in the fecundity, full fishing mortality rate, and recruitment. Specifically, when the model started in 1996, the fecundity and recruitment all decreased slightly, while the fishing mortality rate increased slightly. Overall, the start year did not have a large impact on the determination of population parameters in the more recent time period of interest.

Several runs were completed that changed data inputs for the indices including omitting the seine index (gm-028), omitting the gill net index and associated length compositions (gm-029), and including a gill net index based on data from Mississippi and Alabama along with the associated length composition data (gm-030). The runs that omitted the seine index and included the Mississippi and Alabama gill net index had very similar trends and values to the base run with virtually no differences. The run that omitted the gill net index and associated length compositions was quite different from the base run and had different trends. This sensitivity run demonstrates the influence of the gill net index and the associated length compositions on the results of the stock assessment. This is not an unexpected outcome because the gill net index provides the information on the dynamics of the adult population.

The gill net index is an influential data component; thus the assessment panel also explore the weighting of that data component as part of the sensitivity runs. Three runs were done that included setting the gill net index weight to 1.0 (gm-020), 3.0 (gm-021), and 5.0 (gm-022). The run that resulted in the most significant differences from the base run was the run with the weight set to 1.0. In general, trends were different for the fishing mortality rate, but similar for fecundity, biomass, and recruitment. This is expected since the higher the weight, the more closely the model is fitting the gill net index and thus, different trends in the resultant estimates.

Life history and growth information was explored through four sensitivity runs: fecundity values based on the lower confidence interval in Brown-Peterson et al. 2017 (gm-023), fecundity values based on the upper confidence interval in Brown-Peterson et al. 2017 (gm-024), all life history and growth information based on the data from 1977-1996 (gm-034), and all life history and growth information based on the data from 1997-2017 (gm-035). Recruitment and fishing mortality rate were virtually unchanged from the base run for all of these sensitivity runs. Fecundity was different for these runs, which makes sense since all of these runs modified the fecundity by age vector used as a data input into the stock assessment. Overall, these runs resulted in expected model behaviors.

Finally, two additional runs were completed that looked at ageing error. The first was gm-017 where ages were reread from a series of years spanning four decades to look for ageing drift over time, and the second was gm-018 where ages were read blind by two different readers (no information on size). These two runs exhibited both trend and scale differences from the base run when looking at fecundity, recruitment, and fishing mortality rate. Each ageing error matrix was different and impacted the spread of the different ages differently. However, the overall outcomes for the stock assessment and status did not change even with these runs, which were some of the most different from the base run.

The overall trend in the results from 1977-2017 was seen in most of the sensitivity runs. Some sensitivity runs resulted in differing year to year variability depending upon the data sources that were used, which is expected. Some of the sensitivity runs did change the overall scale of the assessment. For example, scaling natural mortality scaled other model components. This is a typical stock assessment result.

Concern arose from the assessment panel that some of the sensitivity runs might represent different states of nature. However, based on the MCB runs discussed below (Section 7.1.5) and the likelihood values and parameter estimates (Table 7.6), the sensitivity runs are simply bounds on the uncertainty rather than distinct states of nature. The assessment panel specified these sensitivity runs as the bounds on the uncertainty (for example, commercial reduction age-3 and -4 selectivity set at the mean from the likelihood profiles and 1.0). The output distributions from the estimated parameters are smooth distributions that are not bimodal, which suggests that these runs are simply the bounds on the uncertainty of the assessment given the assumptions and data inputs.

Because the benchmarks that have been adopted for Gulf Menhaden as well as FMSY were functionally infinite (greater than 10 for fishing mortality rate), a new suite of suggested benchmarks was calculated and presented for the sensitivity runs (Table 7.7; Figures 7.22-7.25). Even with the differences in the sensitivity runs, all of the runs, given the suite of benchmarks presented, did not result in overfishing or overfished conditions with respect to stock status (Tables 7.7), with the single exception of the run with low natural mortality. The run with low natural mortality resulted in the stock status of overfishing, but not of overfished.

7.1.4 Retrospective Analyses

The retrospective was run peeling off data back to 2012 (Figures 7.26-7.35). The results indicate that the model is stable to terminal year data. The terminal full fishing mortality rate has no retrospective pattern of concern (Figure 7.26). The resulting recruitment, fecundity, and biomass show no pattern, similar to full *F* (Figures 7.27-7.29; Tables 7.8). The fits to the indices are fairly good regardless of the terminal year of the model (Figures 7.30-7.31).

The magnitude of stock status outcomes did not vary much in this set of retrospective model runs. In particular, the ratio of full fishing mortality to the suite of potential benchmarks in the terminal year showed no variation in stock status (Figures 7.32 and 7.34). The ratio of *SSB* to the suite of *SSB* metrics also did not vary much (Figures 7.33 and 7.35).

7.1.5 Uncertainty Analysis

Uncertainty was examined in our results in two distinct ways: by considering each data source, in turn, in a series of sensitivity runs (Sections 7.1.3 and 7.1.4), and by using a MCB procedure. The parametric bootstrap procedure was run for 5,000 iterations. For some iterations, the model did not converge; if this was true, then that particular iteration was not included in the results. In addition, some runs had high values for some parameter estimates; thus, runs with the upper and lower percentiles of natural mortality and R_0 were removed. The assessment panel determined that 51% of runs met the convergence criteria and were included in the analysis of the results. Some of the runs with low natural mortality had to estimate very high R_0 values to fit the data, which led to some instability and increased uncertainty (Figure 7.36). As a result, those runs were censored from the final analysis. Finally, to determine the number of uncertainty runs that needed to be done to stabilize the SE of the outputs, we plotted the SE in landings, fecundity, and the suggested threshold fishing mortality rate to determine when the SE stabilized (Figure 7.37). Given these plots, any number of runs greater than 1,000 appear to provide sufficient stability in the SE, and are thus sufficient for estimating the uncertainty of the outputs from the stock assessment model.

The resulting estimates from the 2,557 runs have been summarized in Figures 7.12, 7.14 and 7.38 and

Tables 7.4, 7.5, and 7.9, showing the 90% confidence region. In general, the MCB results are fairly symmetrical distributions about the base run results. The uncertainty was quite large and was dependent upon the uncertainty specified in the input data.

7.1.6 Reference Point Results – Parameter Estimates and Sensitivity

Benchmarks for Gulf Menhaden in the current Fishery Management Plan (FMP – VanderKooy and Smith 2015) are based on SPR and are $F_{30\%}$, $F_{35\%}$, $SSB_{30\%}$, and $SSB_{35\%}$ (with *SSB* measured by fecundity) and were estimated as a fishing mortality rate greater than 10 (Table 7.10). Thus, the assessment panel suggests a suite of options to make a general statement about the likely stock status for Gulf Menhaden. The assessment panel highly recommends that managers work to clearly define the goals for the fishery and to specify objectives for the fishery. Once that has been completed, the appropriateness of the suggested benchmarks can be evaluated. Below is the proposed suite of options.

Spawner-per-recruit (*SPR*) and yield-per-recruit (*YPR*; mt) estimates as a function of full fishing mortality rates are shown in Figures 7.39 and 7.40. These plots are offered as a reference for other fishing mortality rates. For example, the terminal year fishing mortality rate estimate (F_{2017}) of 0.63 is approximately 75% of SPR (Figure 7.41). Alternatively, the age-1+ biomass in the terminal year is 1.02 of B_0, in 2016 it is 0.69 of B_0, and in 2015 it is 0.76 of B_0. Over the entire time series, the age-1+ biomass divided by B_0 averaged 0.68, and over the past decade, the age+1 biomass divided by B_0 averaged 0.79.

The base BAM model estimates for the suite of benchmark options presented and terminal year values are indicated in Table 7.10. The terminal year was considered the geometric mean of 2015-2017 given that the terminal year of an assessment is the most uncertain. The benchmark options suggested by the assessment panel includes a fishing mortality rate target of $F=0.75M$, a fishing mortality rate threshold of $F=M$, a fecundity based target of 50% of *SSB* at *F*=0, and a fecundity based threshold of 25% of *SSB* at *F*=0. Based on the suite of benchmarks presented in this section, the results suggest that the current stock status is not overfished and overfishing is not occurring for the base run and for most of the sensitivity runs and uncertainty analysis (Table 7.10). The 2017 fishing mortality rate was estimated to be below the target fishing mortality rate, as suggested by the assessment panel, and the 2017 fecundity value was estimated to be above the target SSB. Time series of $F/F_{F=M}$, $F/F_{F=0.75M}$, $SSB/SSB_{25\%\ at\ F=0}$, and $SSB/SSB_{50\%\ at\ F=0}$ are also shown in Figures 7.42, 7.43, 7.44, and 7.45, along with the cumulative probability density functions for the thresholds in Figures 7.46. The history of fishing mortality rates in these figures suggests that overfishing likely occurred in the late 1980s and 1990s, but generally, overfishing is unlikely to be occurring in the present. The population may have been considered overfished in one year (1992), given the uncertainty provided in the MCBs. However, these are the currently suggested benchmarks based partially on information accumulated since that time, not those within the FMP nor were they in place historically. As a result, during the 1980s and 1990s when overfishing was occurring using these suggested benchmarks, it wasn't occurring according to the benchmarks in use at that time; in addition, the stock was not near the overfished status. Finally, the equilibrium landings values associated with the fishing mortality rate threshold and target are 717,000 mt and 623,000 mt, respectively.

The uncertainty in the terminal year stock status indicators was expressed using the results of the 2,557 bootstrap runs of the base BAM model, which already excluded runs because of convergence and unstable parameter space. The results indicate that the fecundity estimates for the terminal three years are well above $SSB_{25\%\ at\ F=0}$, with not a single bootstrap estimate falling below 1.0 (Figure 7.47). The results for the geometric mean fishing mortality rate across 2015-2017 suggests that the base run estimate is below $F_{F=M}$ with 19% of the bootstrap runs exceeding the threshold in the most recent years (Figure 7.47). However, those runs that exceeded the fishing mortality rate threshold were runs that had low natural mortality compared to runs with higher natural mortality rates, which is shown in Figure 7.48. Specifically, all of the runs that had overfishing occurring had low natural mortality rates (histogram of *M* on respective panel), which were used to demonstrate uncertainty, but are not the most likely outcomes.

A phase plot for fishing years 1977 to 2017 with fishing mortality benchmarks of $F=M$ (threshold) and $F=0.75M$ (target) was generated to compare years based on the current benchmark options (Figure 7.49). The plot includes the associated spawning stock biomass (fecundity) benchmarks of $SSB_{25\%\ at\ F=0}$ (threshold) and $SSB_{50\%\ at\ F=0}$ (target). Some distinct phases of the stock and fishery relative to reference points can be identified as the decades are identified in the phase plot – the largest fishery (plants and vessels) in the 1970's and 1980's, the heaviest exploitation in the late 1980's through the 1990's, and the consolidated, present day fishery from the 2000s through the 2010s.

To be complete, the assessment panel included the benchmarks in the current FMP for the base run in Table 7.10. However, note that the benchmarks were not defined because they resulted in values outside of the range of fishing mortality rates explored. In addition, plots of the SPR based thresholds versus the fishing mortality rate and fecundity (SSB) have been provided in Figures 7.50 through 7.54; again, note that the benchmarks were not defined because they resulted in values outside of the range of fishing mortality rates explored.

The estimation of F_{MSY} was functionally infinite, meaning that the maximum *F* value allowed was 10, and F_{MSY} had still not been maximized. F_{MSY} was infinite because of the nature of the fishery and the population dynamics of the stock. Almost all fish reach maturity and spawn before being harvested by the commercial reduction fishery. Because the stock spawns in the winter and fishing doesn't begin until late April, all fish are allowed to spawn before the fishing season starts. Fish mature at age-1, and the bulk of the fishery take is of age-2 individuals. A very small proportion of the age-1 fish are captured by the fishery, thus, those fish are allowed to escape the fishery, mature, and spawn before being captured the next year. Therefore, Gulf Menhaden may be considered as something similar to an annual crop (although you need to wait 2 years). Once the fish have spawned as age-1 and -2 individuals, the fish can be harvested because they have already contributed to the recruitment that year. An infinite value of F_{MSY} will apply as long as the fishery selectivity and season remain unchanged. If the fishery harvests before spawning occurs (either by harvesting earlier than late April or by harvesting age-0 individuals), then F_{MSY} will likely be reduced.

Overall, the base run provides evidence that the stock, as most of the uncertainty and sensitivity runs show, is either a stable or increasing stock structure. The assessment panel determined that the Gulf Menhaden stock in the Gulf of Mexico is not undergoing overfishing and is not overfished.

Table 7.1 Estimated annual full fishing mortality rate from the base BAM model.

Year	Full *F*	Year	Full *F*
1977	0.86	1998	1.20
1978	1.07	1999	1.64
1979	0.93	2000	1.06
1980	1.06	2001	0.97
1981	0.74	2002	1.26
1982	0.91	2003	1.29
1983	1.20	2004	1.33
1984	1.62	2005	0.88
1985	1.11	2006	0.92
1986	1.01	2007	0.87
1987	1.33	2008	0.48
1988	1.21	2009	0.62
1989	1.45	2010	0.99
1990	1.24	2011	0.96
1991	1.35	2012	0.71
1992	1.51	2013	0.63
1993	1.49	2014	0.53
1994	1.71	2015	0.93
1995	1.23	2016	0.80
1996	1.48	2017	0.63
1997	1.44		

Table 7.2 Estimated full fishing mortality rates at age from the base BAM model.

Year	0	1	2	3	4+
1977	0.00	0.24	0.86	0.75	0.75
1978	0.00	0.29	1.07	0.93	0.93
1979	0.00	0.26	0.93	0.81	0.81
1980	0.00	0.29	1.06	0.93	0.93
1981	0.00	0.20	0.74	0.65	0.65
1982	0.00	0.25	0.91	0.79	0.79
1983	0.00	0.33	1.20	1.05	1.05
1984	0.00	0.45	1.62	1.41	1.41
1985	0.00	0.31	1.11	0.97	0.97
1986	0.00	0.28	1.01	0.88	0.88
1987	0.00	0.37	1.33	1.16	1.16
1988	0.00	0.33	1.21	1.05	1.05
1989	0.00	0.40	1.45	1.26	1.26
1990	0.00	0.34	1.24	1.08	1.08
1991	0.00	0.37	1.35	1.17	1.17
1992	0.00	0.42	1.51	1.32	1.32
1993	0.00	0.41	1.49	1.30	1.30
1994	0.00	0.47	1.71	1.49	1.49
1995	0.00	0.34	1.23	1.07	1.07
1996	0.00	0.21	1.48	1.29	1.29
1997	0.00	0.21	1.44	1.25	1.25
1998	0.00	0.17	1.20	1.04	1.04
1999	0.00	0.23	1.64	1.42	1.42
2000	0.00	0.15	1.06	0.92	0.92
2001	0.00	0.14	0.97	0.85	0.85
2002	0.00	0.18	1.26	1.09	1.09
2003	0.00	0.18	1.29	1.12	1.12
2004	0.00	0.19	1.33	1.15	1.15
2005	0.00	0.13	0.88	0.76	0.76
2006	0.00	0.13	0.92	0.80	0.80
2007	0.00	0.12	0.87	0.75	0.75
2008	0.00	0.07	0.48	0.42	0.42
2009	0.00	0.09	0.62	0.54	0.54
2010	0.00	0.14	0.99	0.87	0.87
2011	0.00	0.14	0.96	0.84	0.84
2012	0.00	0.10	0.71	0.62	0.62
2013	0.00	0.09	0.63	0.55	0.55
2014	0.00	0.08	0.53	0.46	0.46
2015	0.00	0.13	0.93	0.81	0.81
2016	0.00	0.11	0.80	0.69	0.69
2017	0.00	0.09	0.63	0.55	0.55

Table 7.3 Estimated numbers of Gulf Menhaden (billions) at the start of the year from the base BAM model.

Year	0	1	2	3	4+
1977	174.83	25.33	2.56	0.42	0.09
1978	154.15	32.91	5.66	0.36	0.09
1979	94.09	29.01	6.95	0.65	0.06
1980	178.62	17.71	6.37	0.91	0.11
1981	173.28	33.62	3.75	0.73	0.15
1982	126.85	32.62	7.77	0.59	0.17
1983	143.67	23.88	7.20	1.04	0.13
1984	208.81	27.04	4.86	0.72	0.15
1985	128.21	39.30	4.91	0.32	0.08
1986	148.36	24.13	8.20	0.54	0.05
1987	83.25	27.92	5.19	1.00	0.09
1988	92.43	15.67	5.48	0.45	0.12
1989	101.70	17.40	3.19	0.55	0.07
1990	79.92	19.14	3.31	0.25	0.06
1991	50.80	15.04	3.86	0.32	0.04
1992	116.87	9.56	2.94	0.33	0.04
1993	106.63	22.00	1.79	0.22	0.04
1994	75.16	20.07	4.14	0.13	0.03
1995	123.09	14.15	3.55	0.25	0.01
1996	113.32	23.17	2.86	0.35	0.03
1997	91.82	21.33	5.31	0.22	0.04
1998	149.87	17.28	4.92	0.42	0.03
1999	128.15	28.21	4.13	0.49	0.06
2000	102.85	24.12	6.33	0.27	0.05
2001	114.43	19.36	5.88	0.73	0.05
2002	75.58	21.54	4.78	0.74	0.12
2003	116.02	14.23	5.10	0.45	0.10
2004	121.83	21.84	3.36	0.47	0.07
2005	80.82	22.93	5.12	0.30	0.06
2006	179.48	15.21	5.74	0.71	0.06
2007	163.89	33.78	3.78	0.76	0.12
2008	31.30	30.85	8.46	0.53	0.15
2009	126.42	5.89	8.17	1.74	0.16
2010	190.14	23.80	1.53	1.46	0.40
2011	149.38	35.79	5.85	0.19	0.28
2012	146.84	28.12	8.85	0.75	0.08
2013	93.34	27.64	7.20	1.45	0.16
2014	137.71	17.57	7.16	1.28	0.34
2015	114.36	25.92	4.62	1.40	0.37
2016	212.41	21.53	6.43	0.60	0.29
2017	77.74	39.98	5.45	0.96	0.16

Table 7.4 Estimated annual fecundity (billions of eggs) from the base BAM model and percentiles from the bootstrap runs.

Year	BAM Base run	5 percentile	50 percentile	95 percentile
1977	2,389,286	1,767,466	2,517,957	3,844,845
1978	3,489,171	2,640,819	3,635,247	5,346,039
1979	3,588,319	2,730,254	3,711,935	5,379,426
1980	2,855,186	2,229,287	2,975,314	4,161,632
1981	3,321,851	2,460,652	3,438,084	5,023,800
1982	4,029,025	3,127,215	4,135,619	5,674,758
1983	3,483,943	2,816,099	3,578,692	4,726,230
1984	3,112,044	2,499,860	3,201,662	4,258,105
1985	3,735,710	2,803,834	3,769,238	5,267,368
1986	3,473,052	2,676,839	3,456,391	4,665,552
1987	3,304,348	2,368,740	3,146,245	4,453,693
1988	2,377,372	1,654,044	2,195,645	3,103,055
1989	2,031,192	1,405,266	1,903,296	2,735,684
1990	2,055,099	1,388,838	1,887,501	2,796,601
1991	1,909,787	1,357,347	1,784,164	2,488,246
1992	1,370,600	952,603	1,260,225	1,790,081
1993	1,906,592	1,359,865	1,877,736	2,719,223
1994	2,218,088	1,590,583	2,063,277	2,856,083
1995	1,747,057	1,209,817	1,665,202	2,382,249
1996	2,246,776	1,583,285	2,191,565	3,179,030
1997	2,576,761	1,783,127	2,405,261	3,444,877
1998	2,301,128	1,614,811	2,195,111	3,187,983
1999	2,903,076	2,017,582	2,734,143	3,998,875
2000	2,990,255	1,973,332	2,753,218	4,091,823
2001	2,759,151	1,853,048	2,551,265	3,728,269
2002	2,725,068	1,866,141	2,534,604	3,608,858
2003	2,193,443	1,533,792	2,056,764	2,954,279
2004	2,324,820	1,544,509	2,140,046	3,259,328
2005	2,686,462	1,724,165	2,455,614	3,756,134
2006	2,457,882	1,596,341	2,230,451	3,386,130
2007	3,335,601	2,003,031	3,025,638	4,815,299
2008	4,019,115	2,412,931	3,556,644	5,496,175
2009	2,778,950	1,768,286	2,430,889	3,544,036
2010	2,642,436	1,728,850	2,488,431	3,787,062
2011	3,766,159	2,413,443	3,410,265	5,296,025
2012	3,955,084	2,409,724	3,487,685	5,489,878
2013	3,900,958	2,313,815	3,415,044	5,387,105
2014	3,271,193	2,019,550	2,897,172	4,428,848
2015	3,370,955	2,113,654	3,001,865	4,577,015
2016	3,102,648	1,925,334	2,781,064	4,307,280
2017	4,177,789	2,448,232	3,867,315	6,306,011

Table 7.5 Estimated annual recruitment of age-0 (billions) fish from the base BAM model and percentiles from the bootstrap runs.

Year	BAM Base run	5 percentile	50 percentile	95 percentile
1977	174.8	88.0	177.8	384.9
1978	154.1	76.1	157.1	336.6
1979	94.1	46.9	96.5	207.2
1980	178.6	87.7	181.1	388.6
1981	173.3	87.5	174.9	357.4
1982	126.9	66.4	128.9	257.1
1983	143.7	75.5	144.7	289.6
1984	208.8	103.7	205.5	421.9
1985	128.2	64.1	125.4	252.1
1986	148.4	68.4	138.4	284.8
1987	83.2	35.4	77.0	165.8
1988	92.4	43.3	89.1	189.9
1989	101.7	45.2	91.2	201.5
1990	79.9	38.5	78.7	157.5
1991	50.8	20.6	46.7	107.3
1992	116.9	58.9	117.6	243.8
1993	106.6	43.9	93.2	198.6
1994	75.2	36.8	77.1	166.8
1995	123.1	57.8	120.1	258.3
1996	113.3	46.3	100.9	222.3
1997	91.8	43.8	93.0	203.3
1998	149.9	65.7	138.0	301.6
1999	128.2	51.5	116.2	272.1
2000	102.9	44.2	99.1	224.9
2001	114.4	50.0	107.1	234.5
2002	75.6	33.2	73.2	164.9
2003	116.0	48.5	106.6	243.1
2004	121.8	49.6	110.4	261.9
2005	80.8	31.7	74.3	185.2
2006	179.5	69.2	164.6	387.5
2007	163.9	58.4	140.5	344.5
2008	31.3	12.4	30.2	80.6
2009	126.4	58.3	127.6	293.1
2010	190.1	72.8	165.2	397.2
2011	149.4	55.6	132.3	320.3
2012	146.8	53.7	132.1	317.6
2013	93.3	37.2	89.7	219.8
2014	137.7	54.6	122.7	294.1
2015	114.4	45.4	105.9	255.0
2016	212.4	86.4	201.7	463.1
2017	77.7	31.9	71.9	170.7

Table 7.6 Table of likelihood components and estimates of R_0, catchability, and CV of length from the sensitivity runs that were completed.

Run	total	unweighted	landings	gill net index	seine index	length comps	age comps	Initial age structure	SR fit	R_0	q gill net	q seine	Len CV
Base run (gm-016)	52704.63	52715.11	1.61	31.84	24.41	15142.42	37514.83	0.61	-11.09	116.51	0.37	0.01	0.15
age error – rereads (gm-017)	52702.98	52714.01	1.63	10.19	26.66	15139.18	37536.35	0.45	-11.48	103.37	0.6	0.01	0.16
age error – blind (gm-018)	52799.22	52807.93	0.8	10.76	27.09	15141.77	37627.51	0.24	-8.95	120.45	0.38	0.01	0.15
h = 0.75 (gm-019)	52704.53	52715.12	1.62	31.88	24.4	15142.38	37514.84	0.61	-11.2	122.18	0.37	0.01	0.15
LAgn index wt=1.0 (gm-020)	52611.61	52624.6	0.44	22.72	19.4	15118.54	37463.51	1.02	-14.01	123.46	0.26	0.01	0.14
LAgn index wt=3.0 (gm-021)	52683.55	52695.2	1.22	39.88	20.9	15133.54	37499.65	0.74	-12.38	121.37	0.3	0.01	0.15
LAgn index wt=5.0 (gm-022)	52716.58	52726.24	1.82	21.86	27.1	15149.99	37525.46	0.54	-10.2	113.58	0.42	0.01	0.15
low fec (gm-023)	52704.63	52715.11	1.61	31.84	24.41	15142.42	37514.83	0.61	-11.09	116.51	0.37	0.01	0.15
high fec (gm-024)	52704.63	52715.11	1.61	31.84	24.41	15142.42	37514.83	0.61	-11.09	116.51	0.37	0.01	0.15
cR sel age-3 & 4 = 1.0 (gm-025)	52704.28	52714.82	1.66	29.58	24.46	15142.3	37516.82	0.63	-11.17	115.47	0.38	0.01	0.15
cR sel age-3 & 4 = 0.73 (gm-026)	52706.84	52717.24	1.52	34.98	24.33	15142.51	37513.89	0.58	-10.97	118.28	0.35	0.01	0.15
cR sel age-3 & 4 at midpt (gm-027)	52706.80	52717.24	1.56	34.68	24.19	15142.77	37514.05	0.61	-11.04	118.44	0.35	0.01	0.15
Exclude seine index (gm-028)	52677.36	52687.14	1.27	25.16	0	15142.77	37517.93	0.62	-10.39	118.36	0.37	0	0.15
Exclude LAgn index and comps (gm-029)	37458.81	37471.49	0.25	0	20.89	0	37450.34	1.01	-13.68	116.82	0	0.01	0.17
Include MS/AL index (gm-030)	54232.96	54243.49	1.64	32.09	24.27	15143.17	37514.29	0.61	1.49	116.52	0.37	0.01	0.15
Start year 1996 (gm-031)	32488.24	32493.8	1.59	26.57	24.3	15136.42	17304.92	0.25	-5.81	106.99	0.44	0.01	0.15
Start year 1964 (gm-032)	59804.38	59816.71	1.89	34.78	24.03	15142.07	44613.94	0.95	-13.29	105.87	0.37	0.01	0.15
Start year 1948 (gm-033)	59795.87	59814.77	1.93	34.64	24.03	15142.04	44612.13	0	-18.9	101.11	0.38	0.01	0.15
1977-1996 life history (gm-034)	52708.69	52719.58	1.55	26.4	24.25	15153	37514.37	0.58	-11.47	134.05	0.41	0.01	0.14
1997-2017 life history (gm-035)	52702.96	52713.46	1.54	31.94	24.33	15141.74	37513.92	0.65	-11.15	103.44	0.36	0.01	0.15
low M (gm-041)	52722.88	52733.55	3.46	28.5	26.51	15146.69	37528.39	0.6	-11.27	32.15	0.57	0.04	0.15
high M (gm-042)	52696.72	52705.51	0.29	32.11	24.04	15139.29	37509.79	0.38	-9.17	841.26	0.16	0	0.15

Table 7.7 Estimates of $F_{threshold}$, F_{target}, $SSB_{threhold}$, and SSB_{target} along with the geometric mean of 2015-2017 divided by each benchmark from the sensitivity runs and retrospective analyses that were completed.

Run	$F_{threshold}$	F_{target}	$SSB_{threshold}$	SSB_{target}	F(2015-17) /$F_{threshold}$	F(2015-17) /F_{target}	SSB(2015-17) /$SSB_{threshold}$	SSB(2015-17) /SSB_{target}
Base run (gm-016)	1.32	0.99	1244281	2488562	0.59	0.79	2.83	1.42
age error – rereads (gm-017)	1.32	0.99	1103967	2207933	0.97	1.30	2.52	1.26
age error – blind (gm-018)	1.32	0.99	1286333	2572665	0.71	0.95	2.75	1.37
h = 0.75 (gm-019)	1.32	0.99	1323819	2647638	0.59	0.79	2.66	1.33
LAgn index wt=1.0 (gm-020)	1.32	0.99	1318459	2636918	0.48	0.64	3.13	1.57
LAgn index wt=3.0 (gm-021)	1.32	0.99	1296131	2592263	0.52	0.69	2.96	1.48
LAgn index wt=5.0 (gm-022)	1.32	0.99	1213008	2426015	0.64	0.85	2.76	1.38
low fec (gm-023)	1.32	0.99	821694.8	1643390	0.59	0.79	2.83	1.42
high fec (gm-024)	1.32	0.99	1666867	3333733	0.59	0.79	2.83	1.42
cR sel age-3 & 4 = 1.0 (gm-025)	1.32	0.99	1233147	2466293	0.59	0.78	2.81	1.40
cR sel age-3 & 4 = 0.73 (gm-026)	1.32	0.99	1263221	2526443	0.59	0.78	2.87	1.43
cR sel age-3 & 4 at midpt (gm-027)	1.32	0.99	1264938	2529876	0.57	0.76	2.87	1.44
Exclude seine index (gm-028)	1.32	0.99	1264001	2528001	0.60	0.79	2.79	1.40
Exclude LAgn index and comps (gm-029)	1.32	0.99	1247577	2495155	0.64	0.86	2.70	1.35
Include MS/AL index (gm-030)	1.32	0.99	1244339	2488678	0.60	0.80	2.83	1.41
Start year 1996 (gm-031)	1.32	0.99	1142587	2285173	0.71	0.94	2.73	1.36
Start year 1964 (gm-032)	1.32	0.99	1130652	2261304	0.60	0.79	3.09	1.55
Start year 1948 (gm-033)	1.32	0.99	1079833	2159666	0.60	0.80	3.21	1.61
1977-1996 life history (gm-034)	1.32	0.99	1123696	2247393	0.60	0.80	2.61	1.31
1997-2017 life history (gm-035)	1.32	0.99	1291184	2582369	0.59	0.78	3.02	1.51
low M (gm-041)	0.83	0.62	1324646	2649291	1.45	1.94	1.47	0.74
high M (gm-042)	1.94	1.45	2513583	5027165	0.18	0.23	4.33	2.17
Retrospective 2016 (gm-036)	1.32	0.99	1244281	2488562	0.58	0.77	2.78	1.39
Retrospective 2015 (gm-037)	1.32	0.99	1244281	2488562	0.65	0.86	3.35	1.68
Retrospective 2014 (gm-038)	1.32	0.99	1244281	2488562	0.36	0.47	3.24	1.62
Retrospective 2013 (gm-039)	1.32	0.99	1244281	2488562	0.47	0.63	3.05	1.52
Retrospective 2012 (gm-040)	1.32	0.99	1244281	2488562	0.43	0.57	4.31	2.15

Table 7.8 Table of likelihood components and estimates of R_0, catchability, and CV of length from the retrospective runs that were completed.

Run	total	unweighted	landings	gill net index	seine index	length comps	age comps	initial N	SR fit	q gill net	q seine	R_0	len CV
Base run (gm-016)	52704.63	52715.11	1.61	31.84	24.41	15142.42	37514.83	0.61	-11.09	0.37	0.01	116.51	0.15
Retrospective 2016 (gm-036)	51612.26	51622.63	1.57	31.46	23.51	14688.32	36877.77	0.64	-11.01	0.37	0.01	118.32	0.15
Retrospective 2015 (gm-037)	50431.51	50441.34	1.51	29.89	22.33	14300.2	36087.41	0.66	-10.49	0.37	0.01	117.97	0.15
Retrospective 2014 (gm-038)	48982.12	48991.53	1.44	30.84	20.24	13833.21	35105.8	0.72	-10.13	0.35	0.01	121.18	0.15
Retrospective 2013 (gm-039)	47590.65	47600.25	1.37	29.99	20.27	13319.41	34229.21	0.67	-10.27	0.34	0.01	118.92	0.15
Retrospective 2012 (gm-040)	46462.43	46470.98	1.11	28.56	13.75	12794.96	33632.61	0.72	-9.28	0.34	0.01	121.95	0.15

Table 7.9 Estimated annual full *F* from the base BAM model and percentiles from the bootstrap runs.

Year	BAM Base run	5 percentile	50 percentile	95 percentile
1977	0.86	0.59	0.82	1.09
1978	1.07	0.74	1.02	1.33
1979	0.93	0.67	0.90	1.16
1980	1.06	0.77	1.03	1.32
1981	0.74	0.55	0.72	0.94
1982	0.91	0.70	0.89	1.10
1983	1.20	0.94	1.17	1.42
1984	1.62	1.24	1.58	1.94
1985	1.11	0.85	1.11	1.38
1986	1.01	0.79	1.03	1.26
1987	1.33	1.03	1.45	1.93
1988	1.21	0.96	1.36	1.87
1989	1.45	1.10	1.61	2.23
1990	1.24	0.95	1.39	1.92
1991	1.35	1.08	1.51	2.04
1992	1.51	1.19	1.71	2.37
1993	1.49	1.12	1.54	2.11
1994	1.71	1.37	1.91	2.58
1995	1.23	0.96	1.35	1.88
1996	1.48	1.17	1.69	2.35
1997	1.44	1.18	1.67	2.33
1998	1.20	0.95	1.43	2.06
1999	1.64	1.28	1.91	2.65
2000	1.06	0.86	1.27	1.80
2001	0.97	0.78	1.16	1.72
2002	1.26	1.03	1.48	2.13
2003	1.29	1.02	1.51	2.15
2004	1.33	1.03	1.58	2.27
2005	0.88	0.72	1.05	1.52
2006	0.92	0.73	1.10	1.61
2007	0.87	0.67	1.07	1.65
2008	0.48	0.40	0.57	0.83
2009	0.62	0.51	0.78	1.12
2010	0.99	0.79	1.21	1.82
2011	0.96	0.76	1.11	1.57
2012	0.71	0.56	0.88	1.31
2013	0.63	0.50	0.80	1.24
2014	0.53	0.42	0.65	0.94
2015	0.93	0.73	1.15	1.71
2016	0.80	0.62	0.98	1.51
2017	0.63	0.48	0.76	1.21

Table 7.10 Summary of benchmarks and the geometric mean of the three terminal years from the stock assessment (2015-2017) values estimated for the base BAM model. Fecundity was used as the metric for *SSB*.

Benchmarks and Terminal Years Geometric Means	Base BAM Model Estimates
R_0	116.5
Y at F_{MSY}	infinite
$F_{2015\text{-}2017}$	0.78
$F_{30\%}$	>10.0
$F_{35\%}$	>10.0
$F_{F=M}$	1.32
$F_{F=0.75M}$	0.99
F at $SSB_{25\%\ at\ F=0}$	>10.0
F at $SSB_{50\%\ at\ F=0}$	4.71
$SSB_{2015\text{-}2017}$	3,522,173
$SSB_{30\%}$	<2,074,992
$SSB_{35\%}$	<2,074,992
$SSB_{25\%\ at\ F=0}$	1,244,281
$SSB_{50\%\ at\ F=0}$	2,488,562
SSB at $F_{F=M}$	3,212,045
SSB at $F_{F=0.75M}$	3,408,847

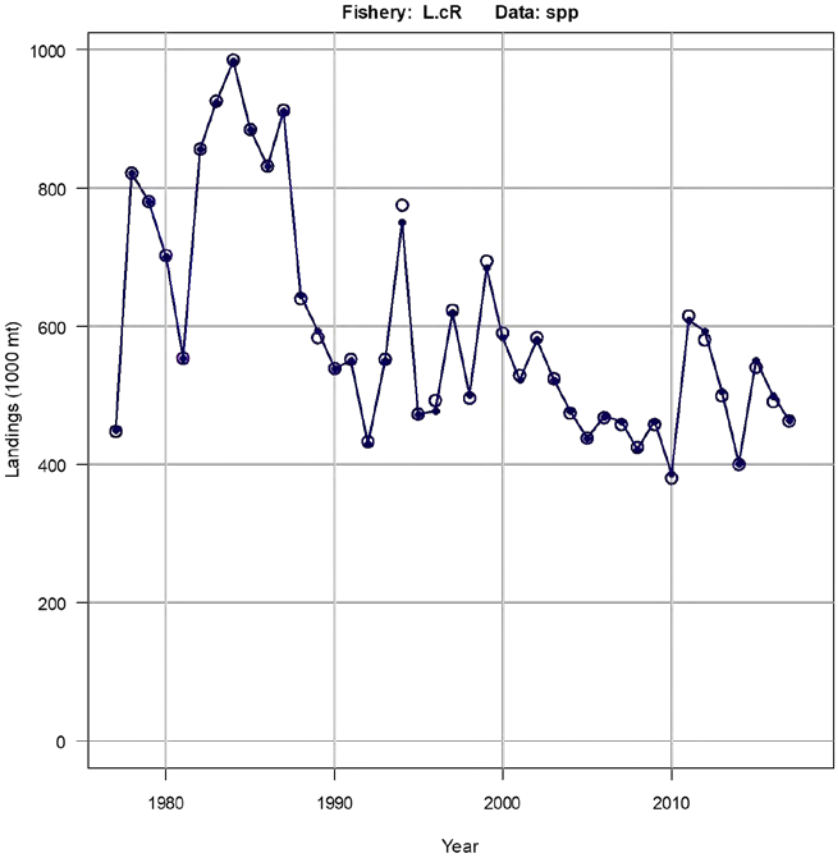


Figure 7.1 Observed and predicted landings for the commercial reduction fishery from 1977-2017.

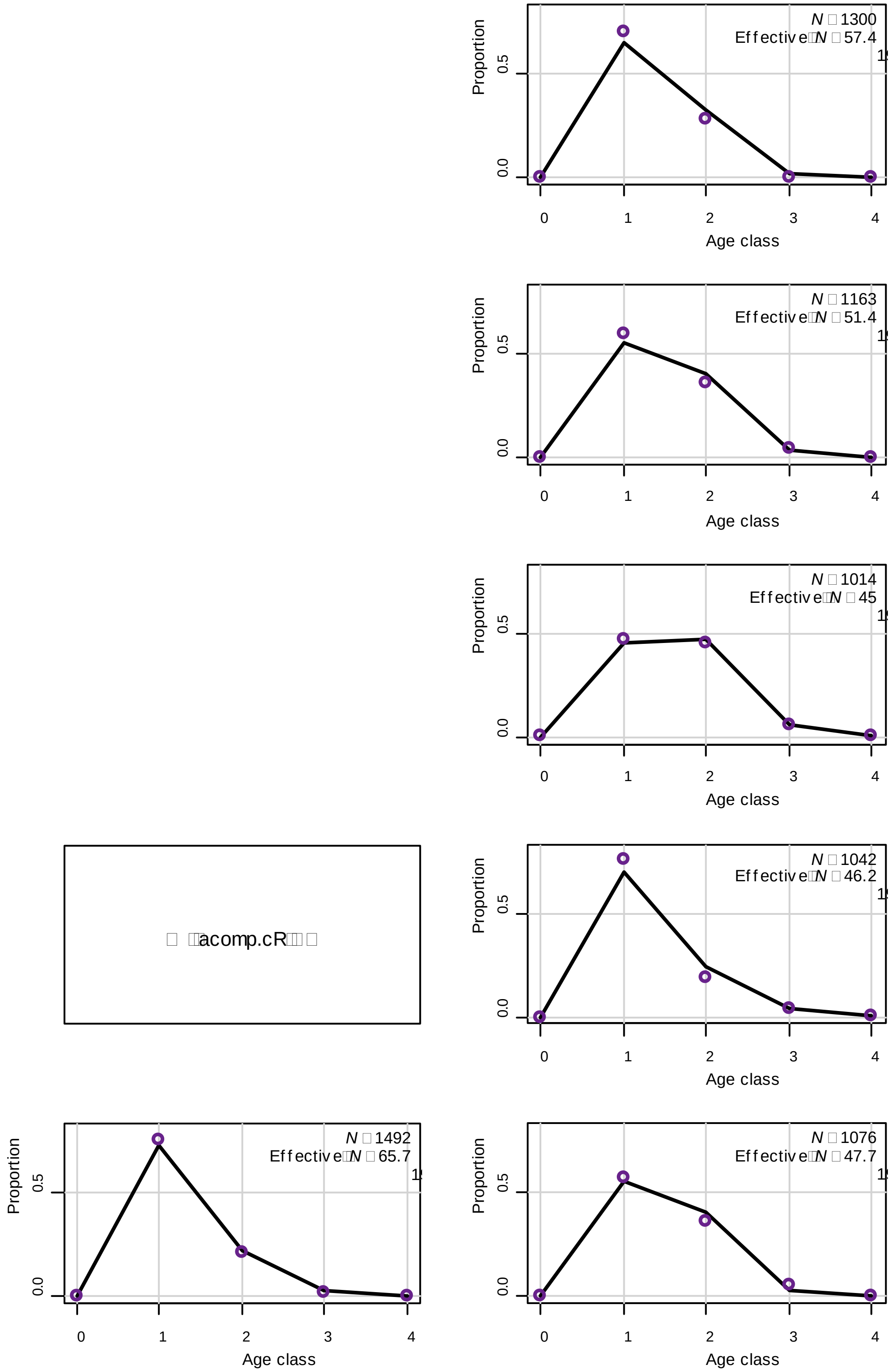


Figure 7.2 Observed and predicted age compositions for the commercial reduction fishery from 1977-2017. Each panel includes the year and associated sample size in the upper right corner.

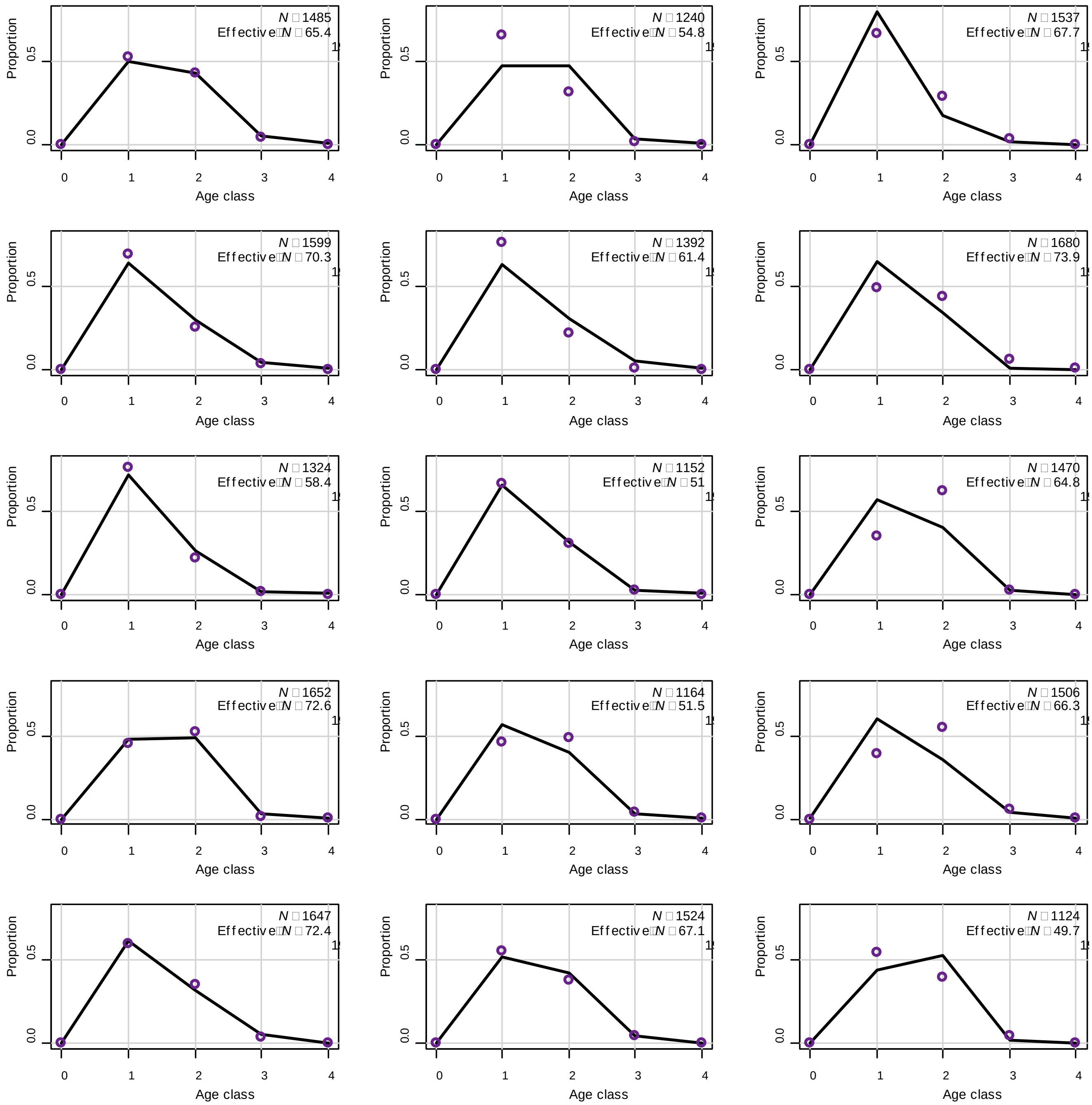


Figure 7.2 (Cont.)

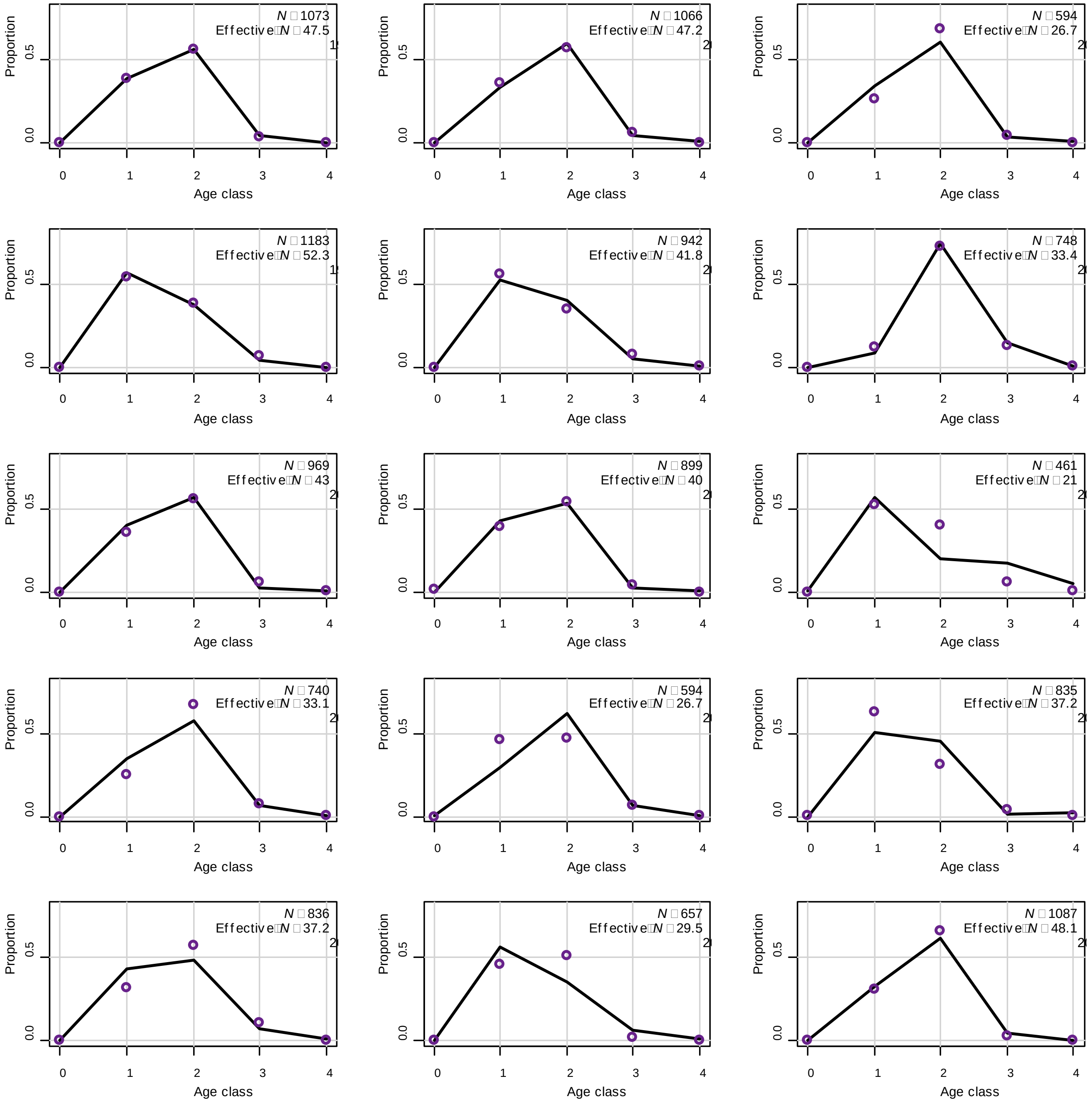


Figure 7.2 (Cont.)

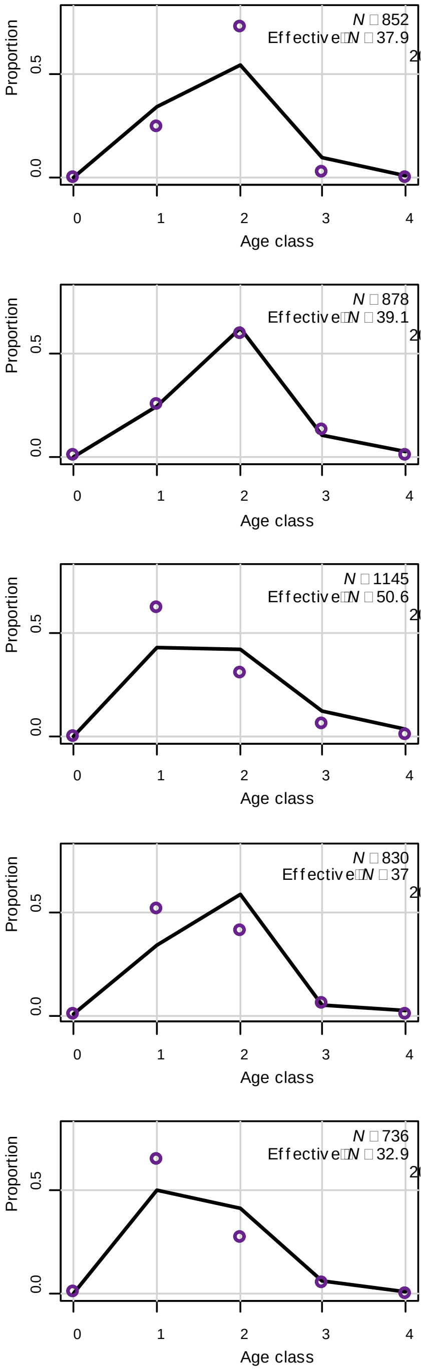


Figure 7.2 (Cont.)

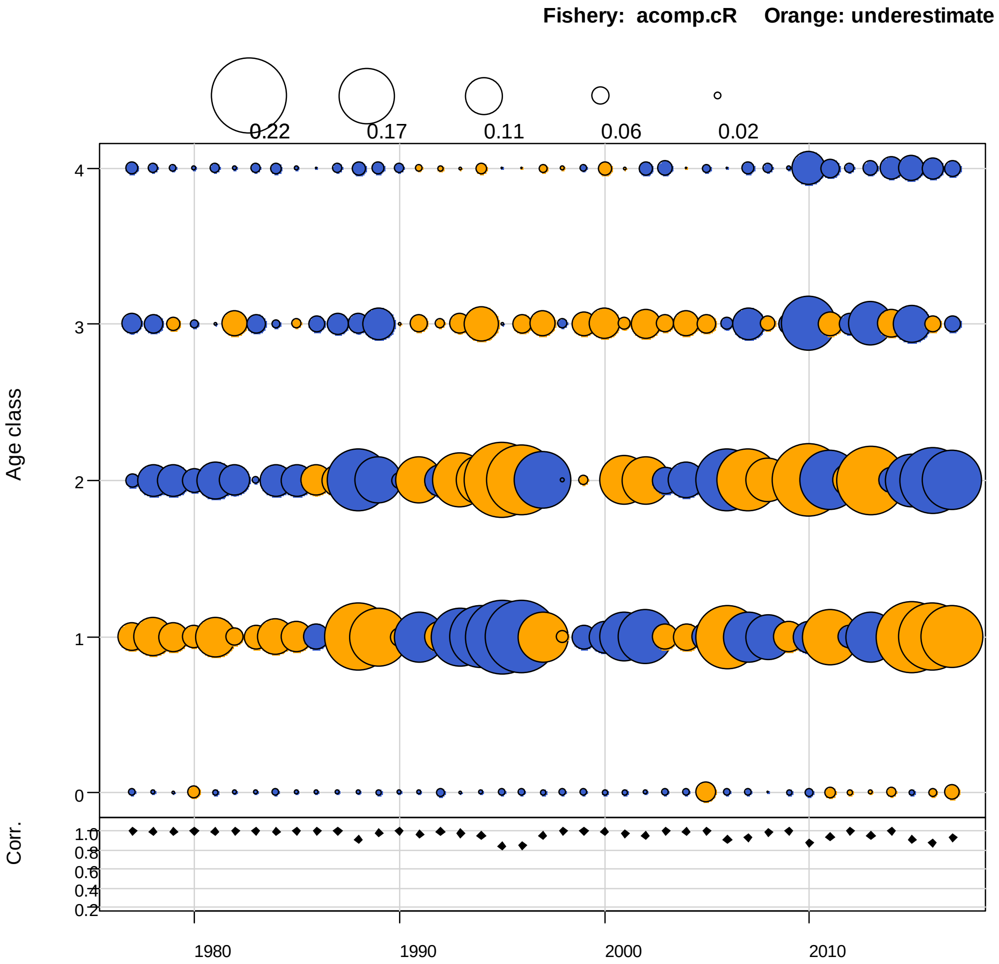


Figure 7.3 Bubble plot of residuals for the age compositions for the commercial reduction fishery from 1977-2017. Light colored circles are underestimated while dark colored circles are overestimated. The bottom panel is the correlation between predicted and observed data.

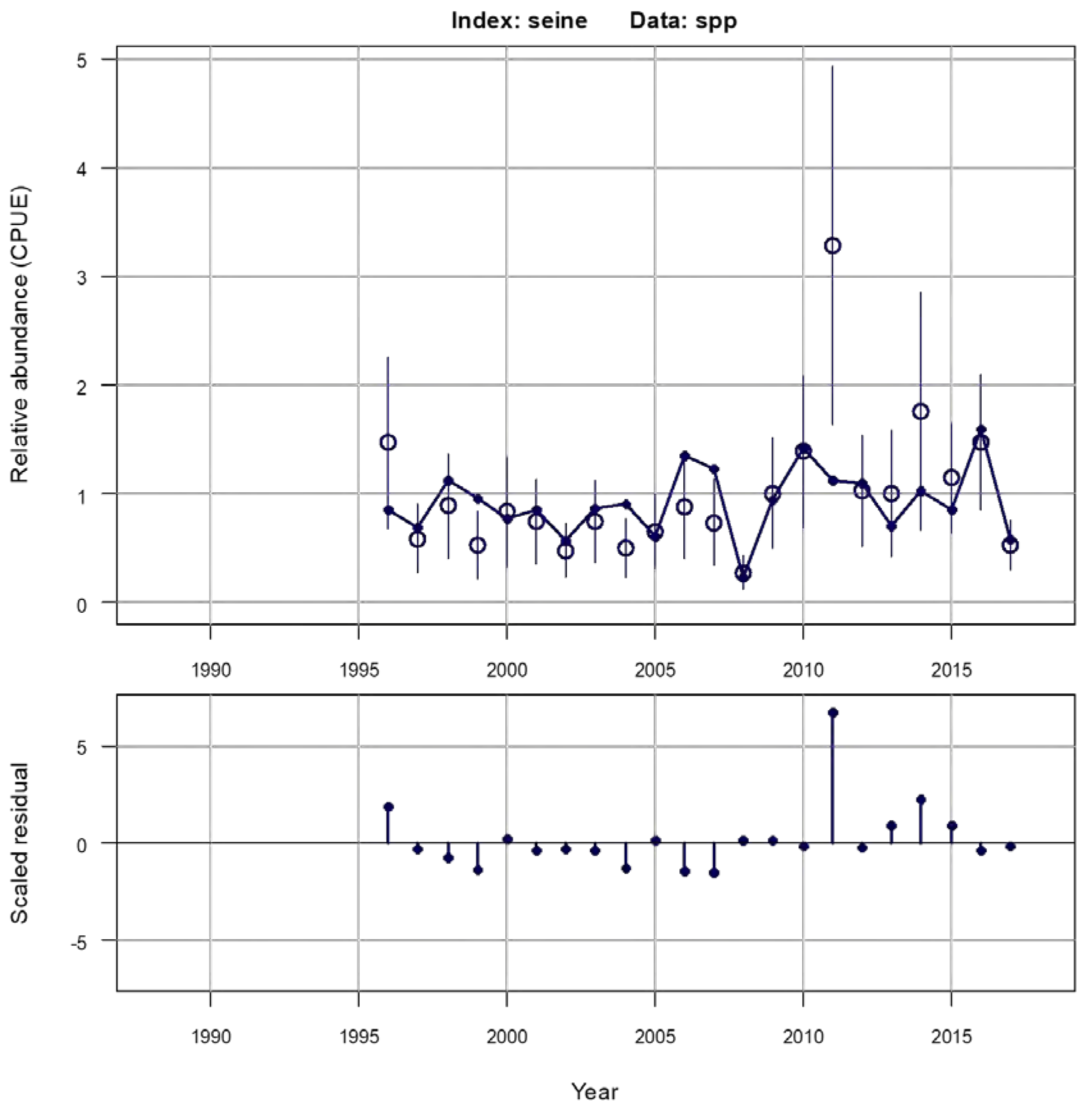


Figure 7.4 Observed and predicted seine index, which was a juvenile abundance or age-0 recruitment index, for 1996-2017.

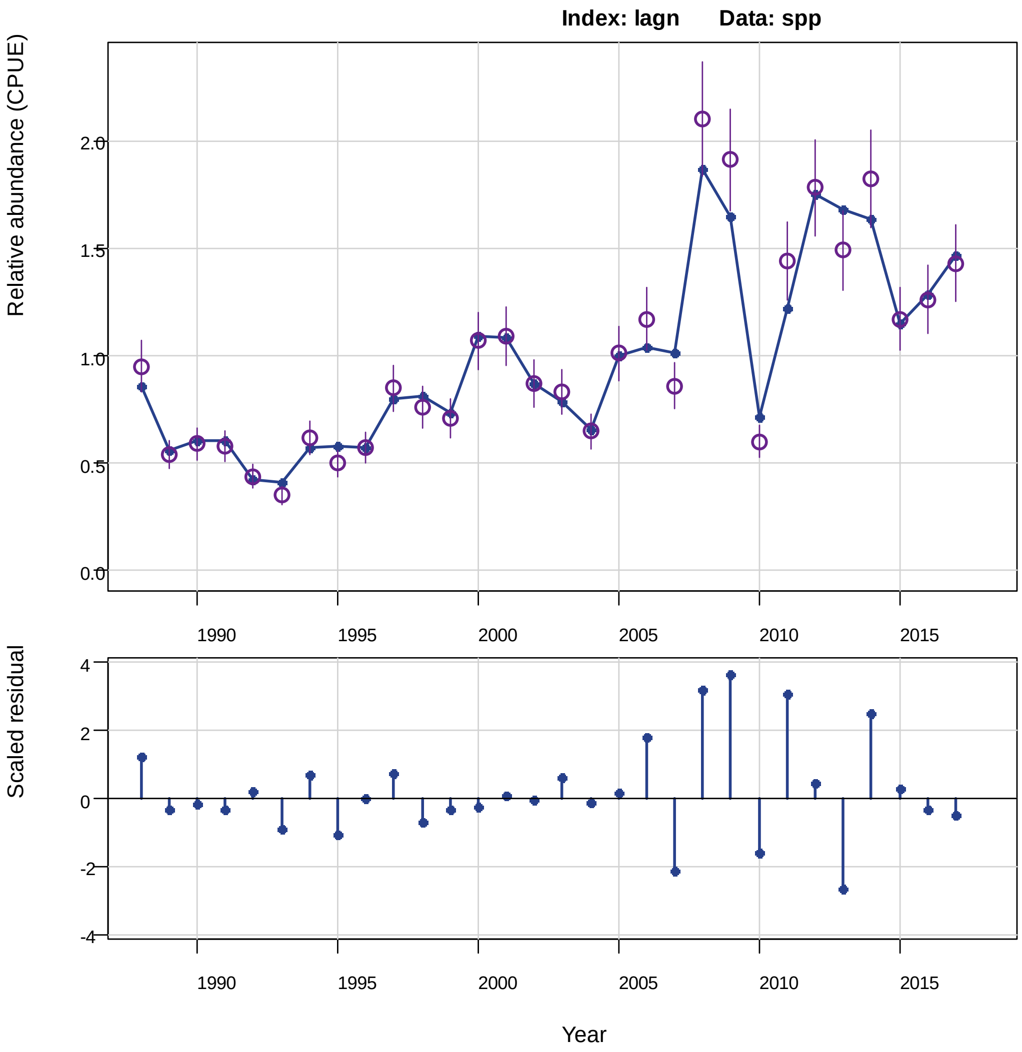


Figure 7.5 Observed and predicted gill net index, which was an adult abundance index, for 1988-2017.

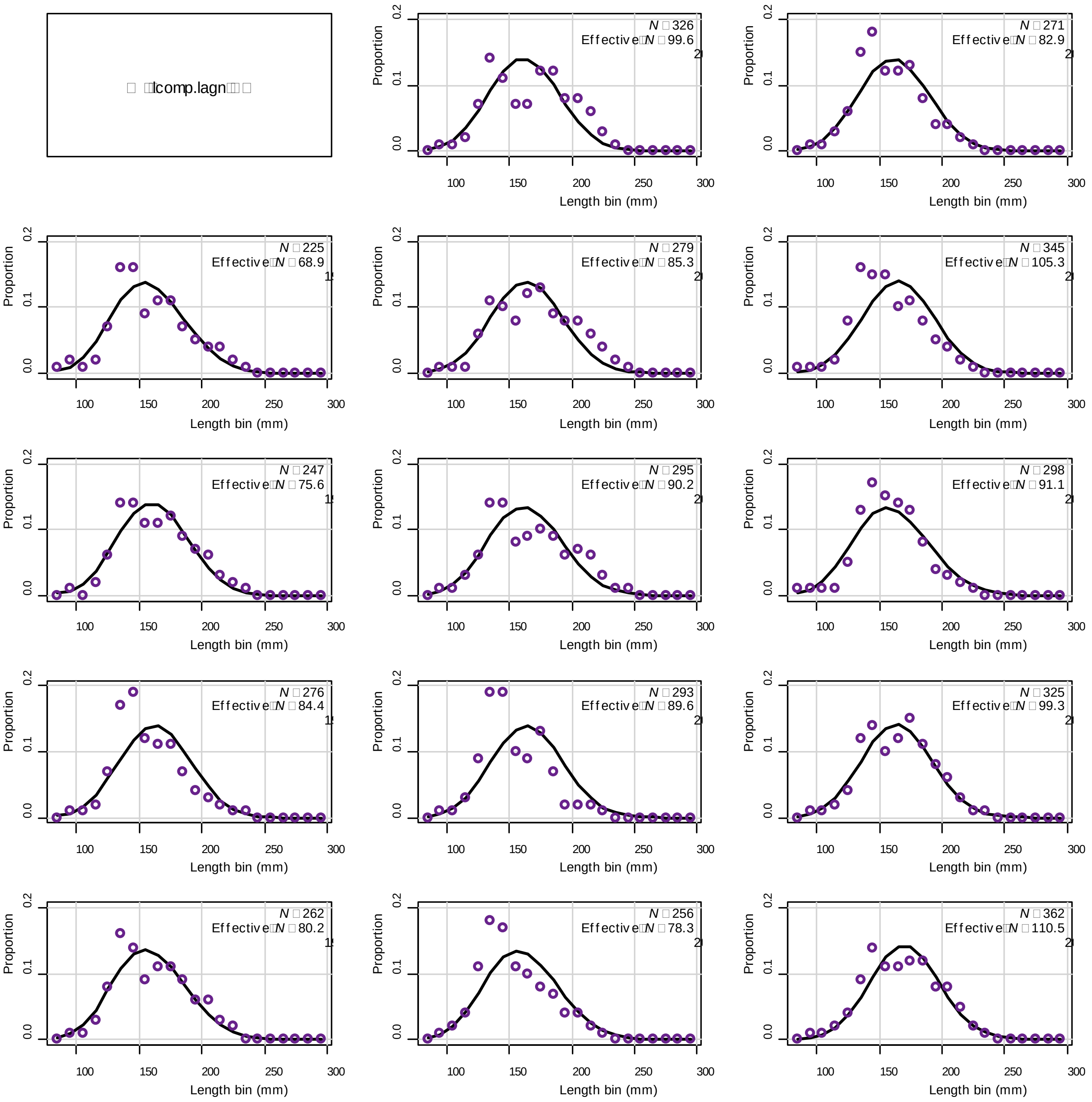


Figure 7.6 Observed and predicted length compositions for the gill net index from 1996-2017. Each panel includes the year and associated sample size in the upper right corner.

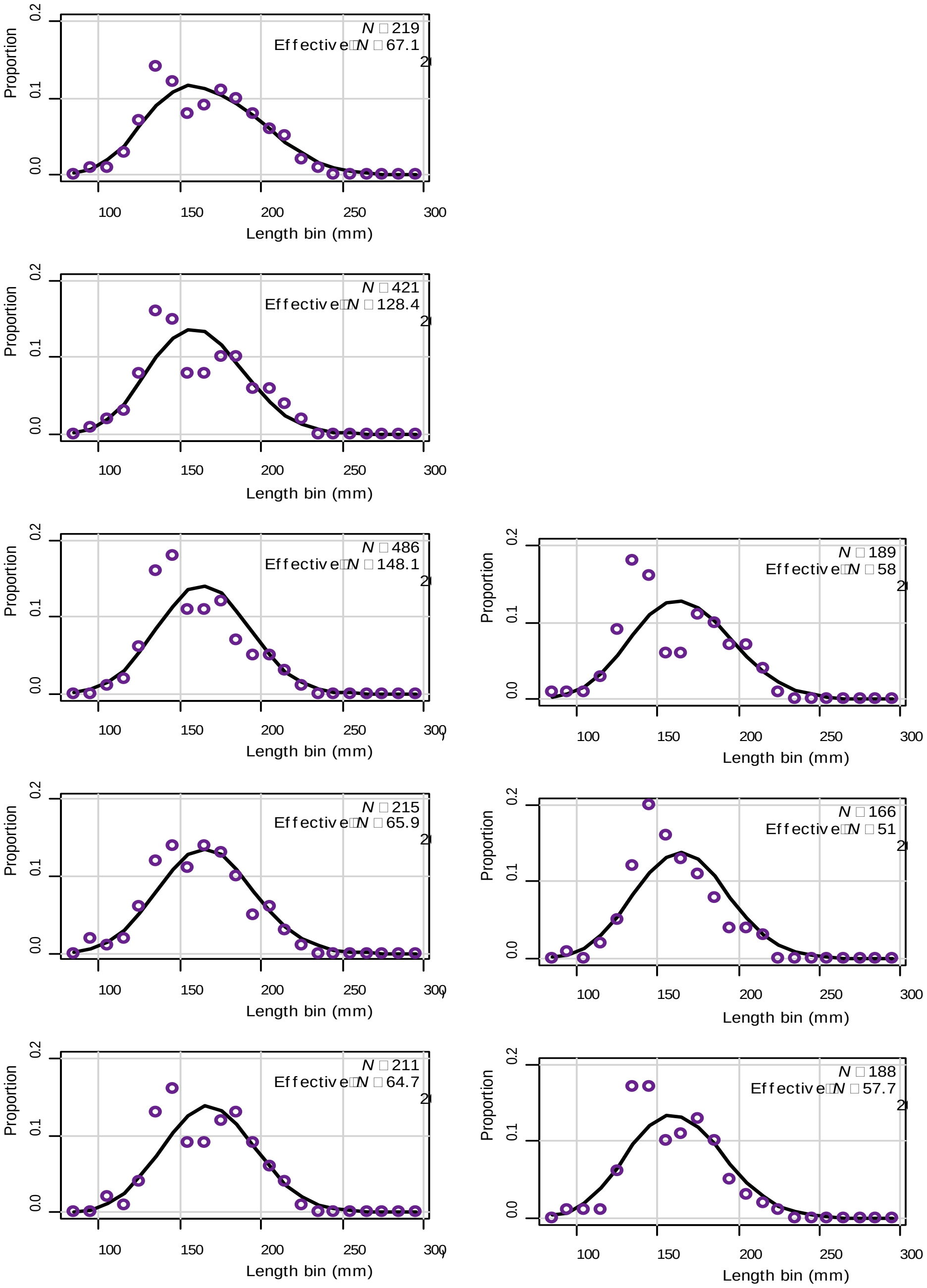


Figure 7.6 (Cont.)

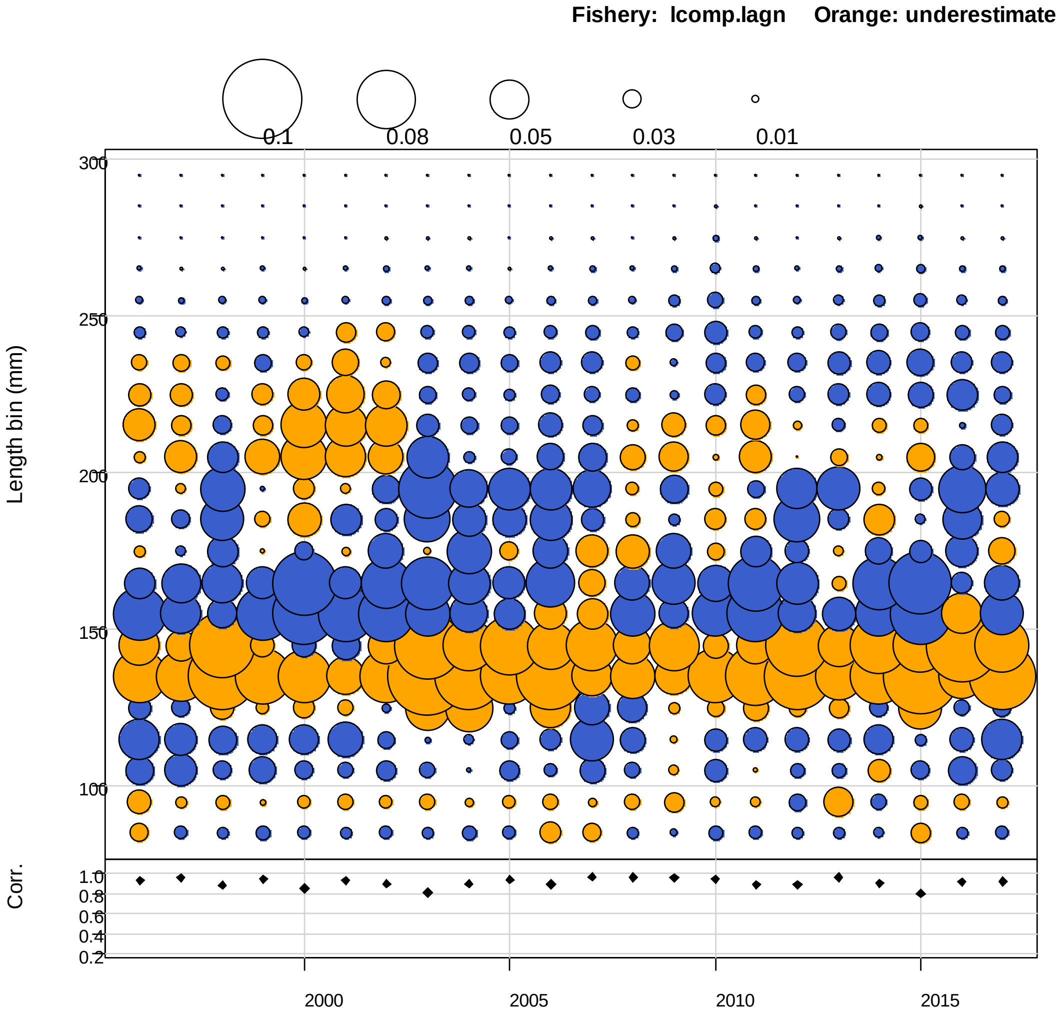


Figure 7.7 Bubble plot of residuals for the length compositions for the gill net index from 1996-2017. Light colored circles are underestimated while dark colored circles are overestimated. The bottom panel is the correlation between predicted and observed data.

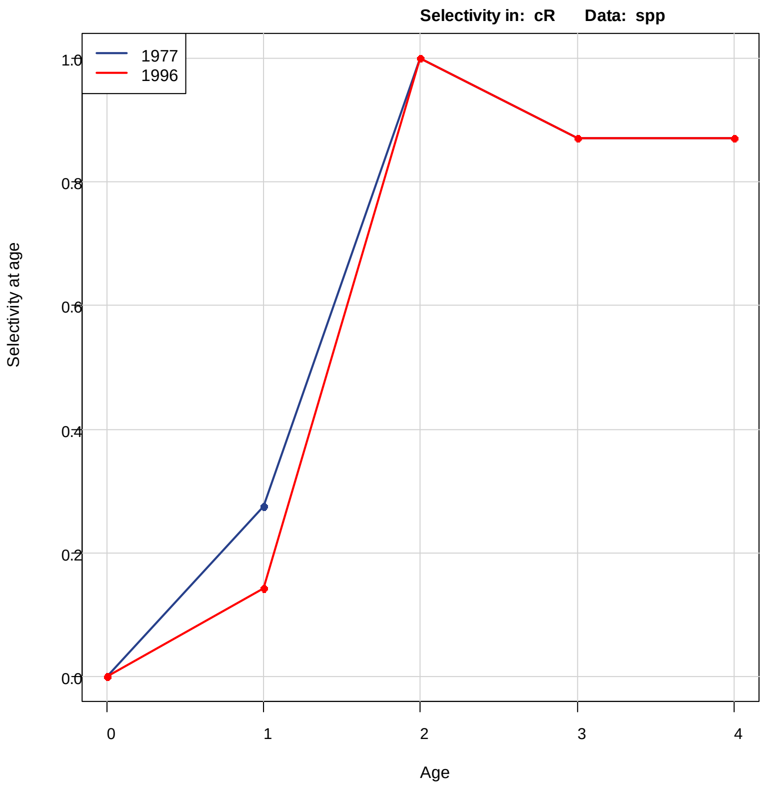


Figure 7.8 Estimated selectivity for the commercial reduction fishery for age one during two different time blocks, 1977-1995 and 1996-2017. Age-0 was assumed to be 0.0, age-2 was assumed to be 1.0, and ages-3 and -4+ were assumed to be 0.87.

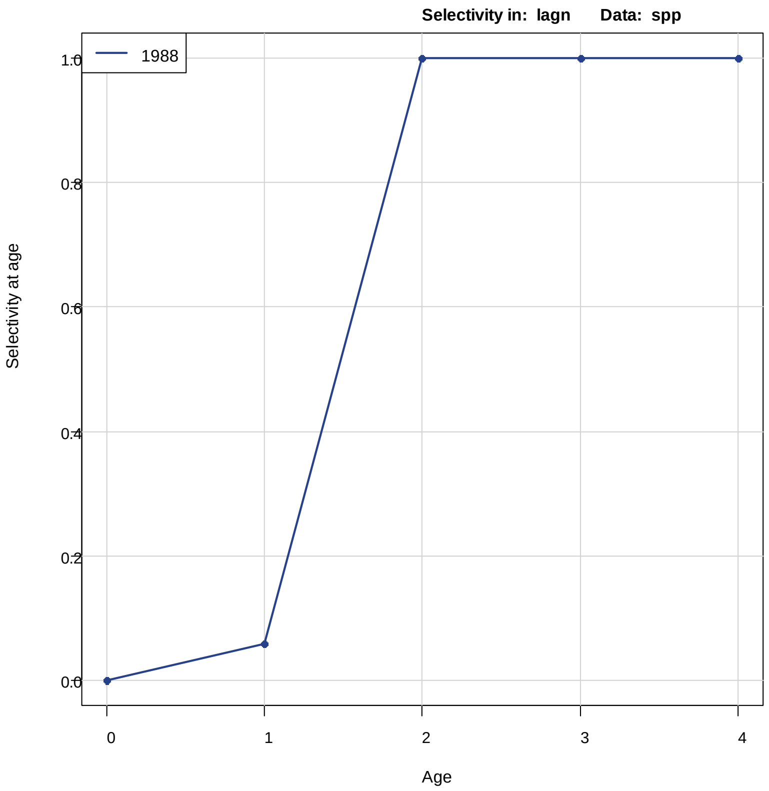


Figure 7.9 Estimated selectivity for the gill net index across the entire time series.

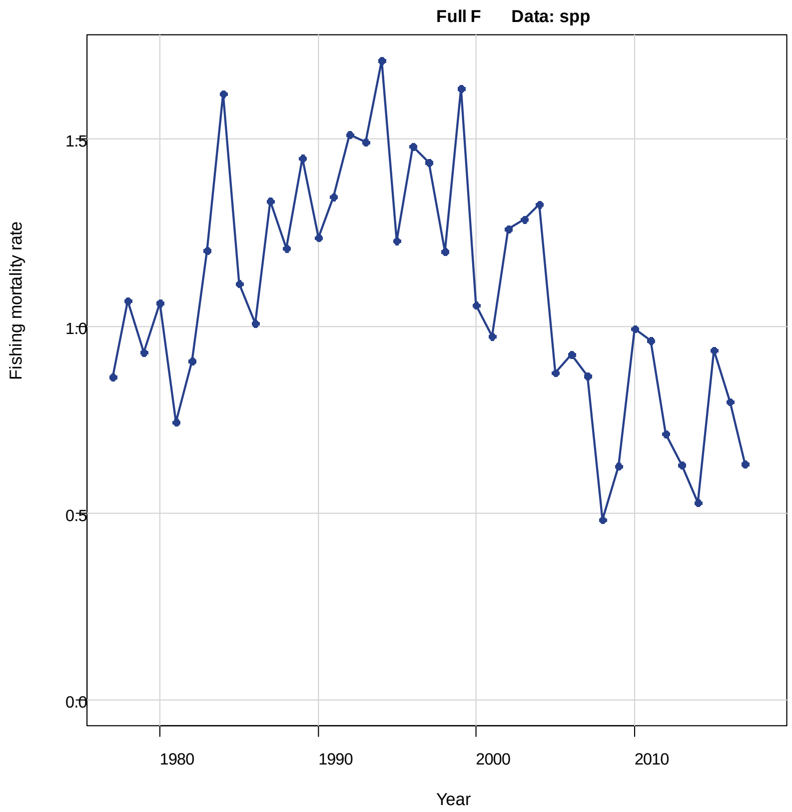


Figure 7.10 Estimated full fishing mortality rate for the commercial reduction fishery from 1977-2017.

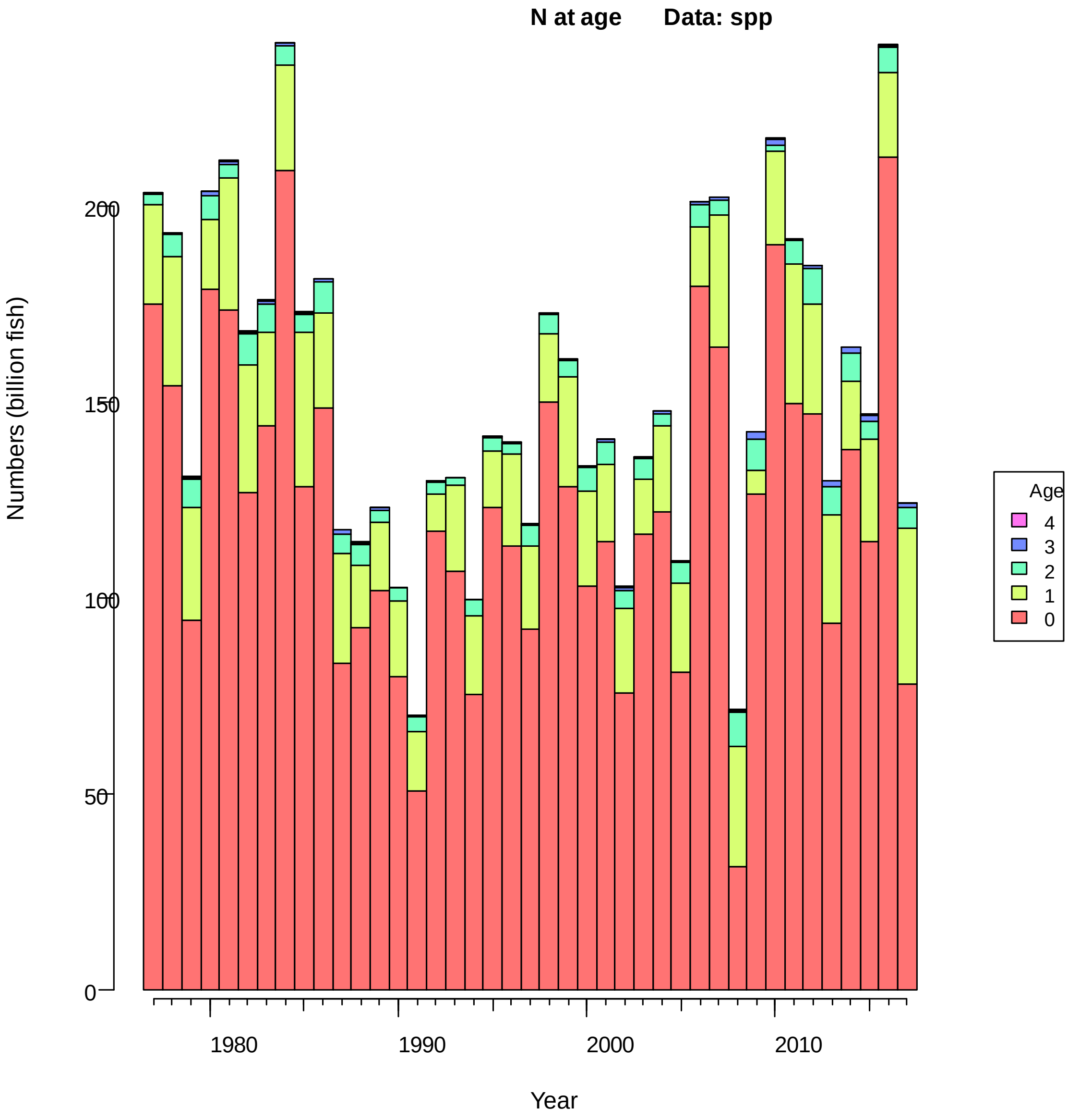


Figure 7.11 Estimated numbers at age of Gulf Menhaden (billions) at the start of the fishing year from the base BAM model.

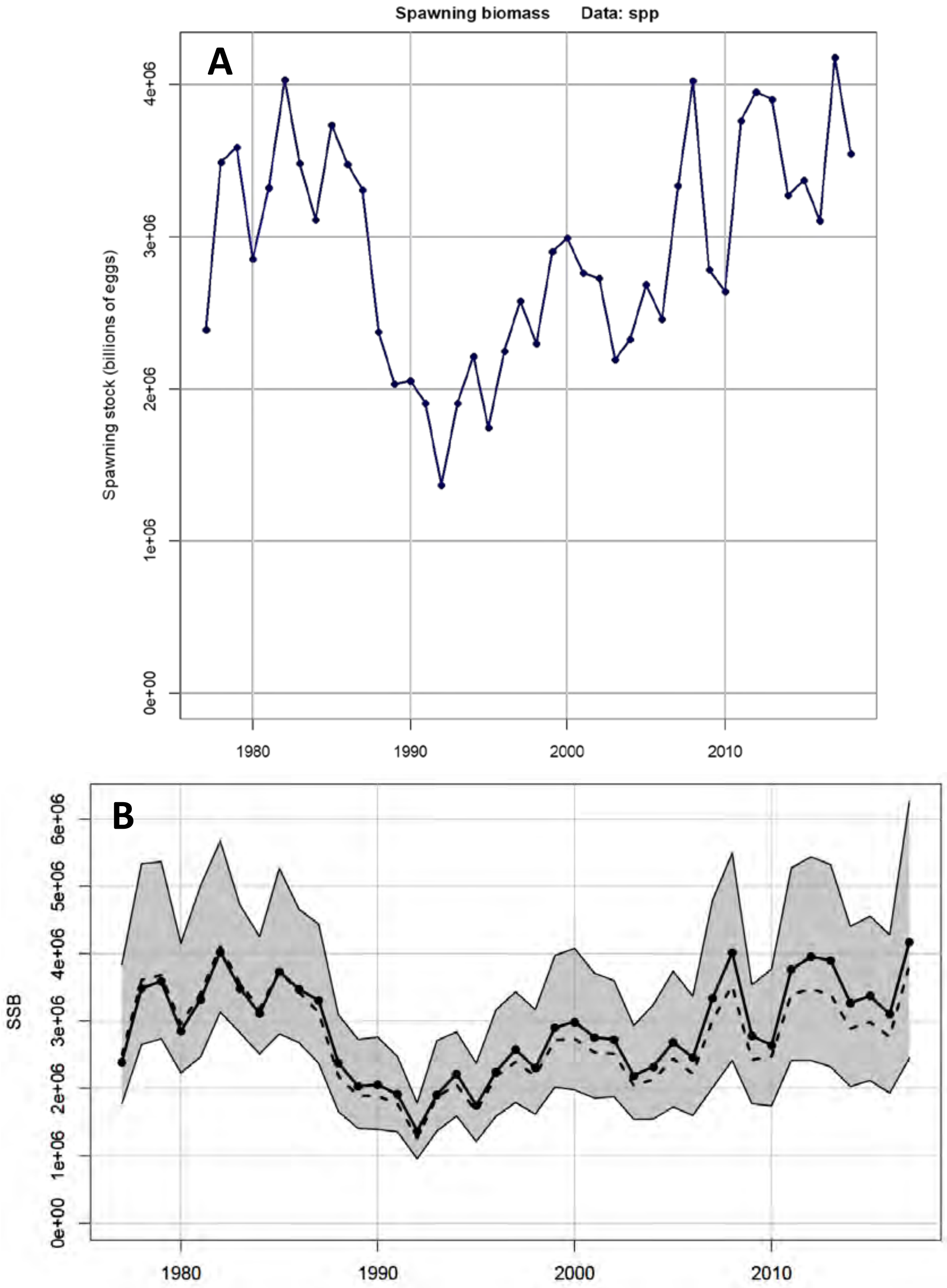


Figure 7.12 Estimated annual fecundity (billions of eggs) from the base BAM model for 1977-2017 with a one year ahead prediction for 2018 (panel A). SSB was represented by fecundity in this assessment. Estimated annual recruitment to age-0 (billions) from the base BAM model (connected points) and the median from the MCB runs (dashed line; panel B). Shaded area represents the 90% confidence interval of the bootstrap runs after runs were eliminated.

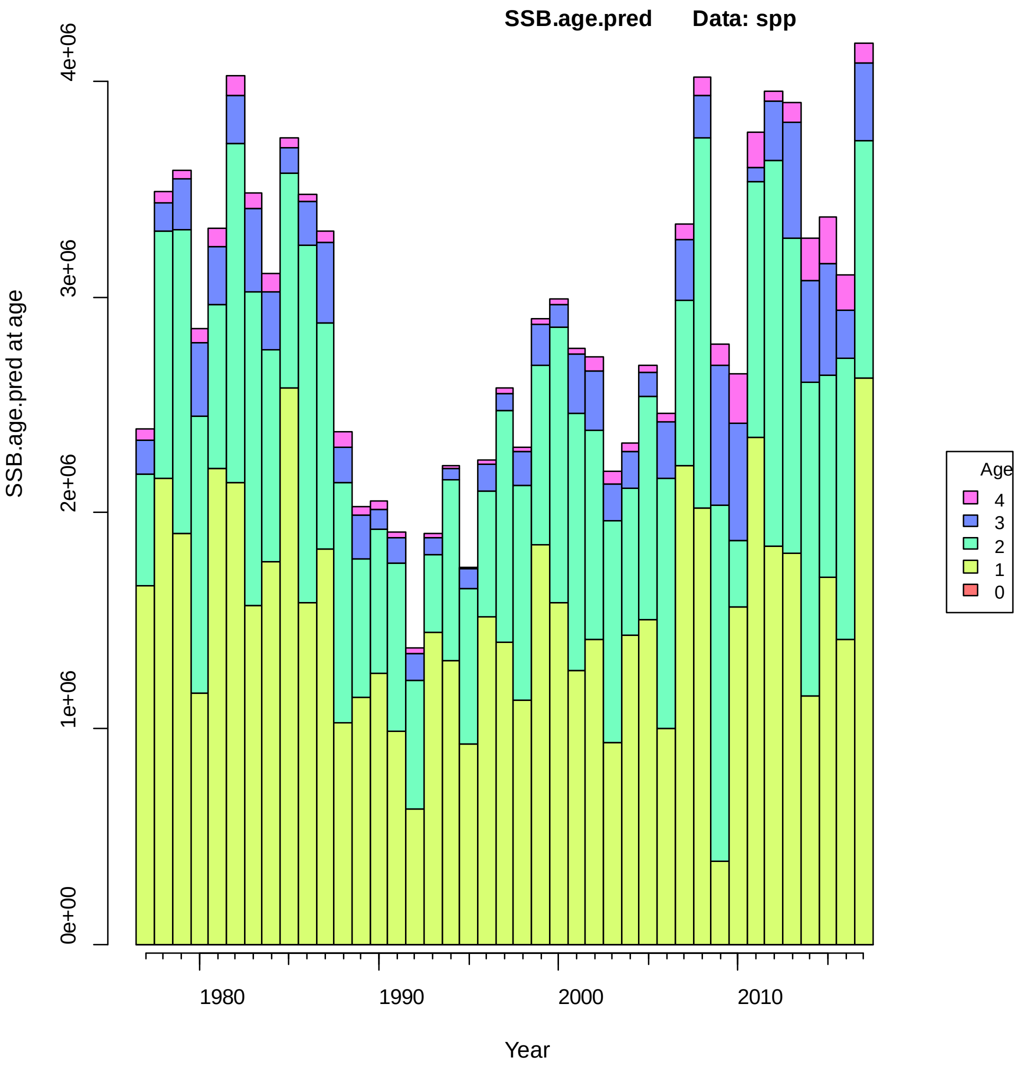


Figure 7.13 Estimated total fecundity (billions of mature ova) at age for Gulf Menhaden at the start of the fishing year from the base run of BAM.

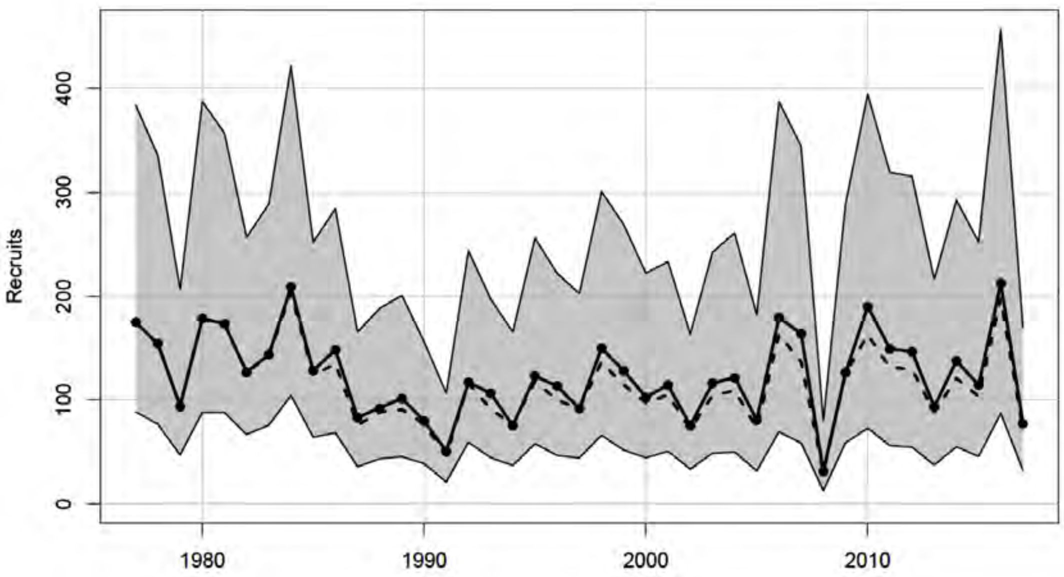


Figure 7.14 Estimated annual recruitment to age-0 (billions) from the base BAM model (connected points) and the median from the MCB runs (dashed line). Shaded area represents the 90% confidence interval of the bootstrap runs after runs were eliminated.

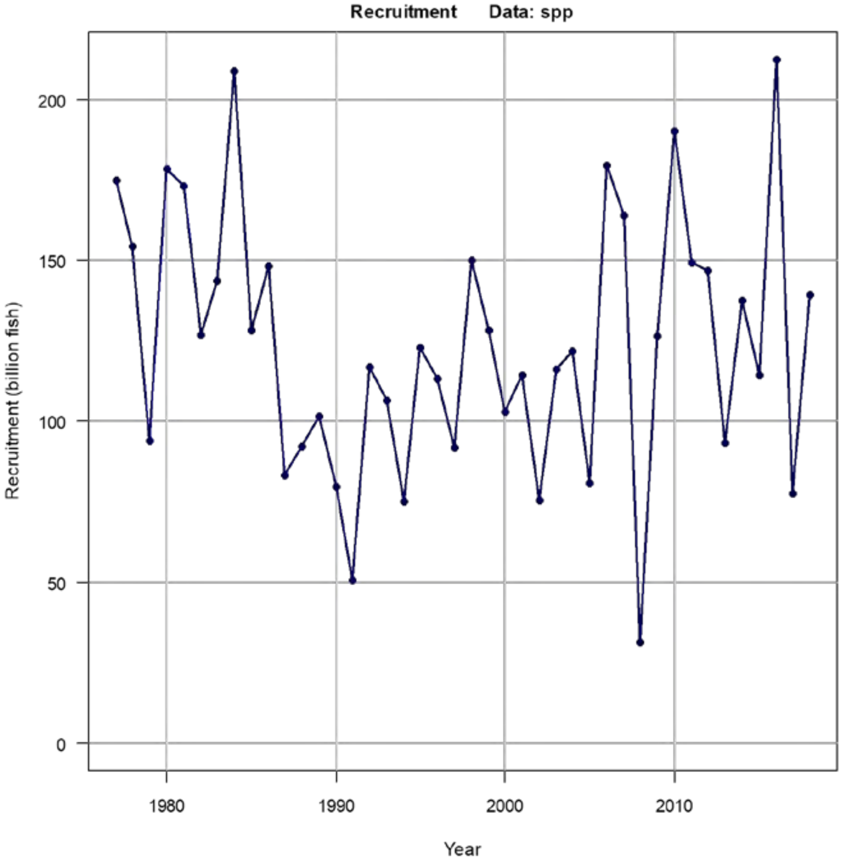


Figure 7.15 Estimated annual recruitment to age-0 (billions) from the base BAM model (connected points) for 1977-2017 with a one year ahead prediction for 2018.

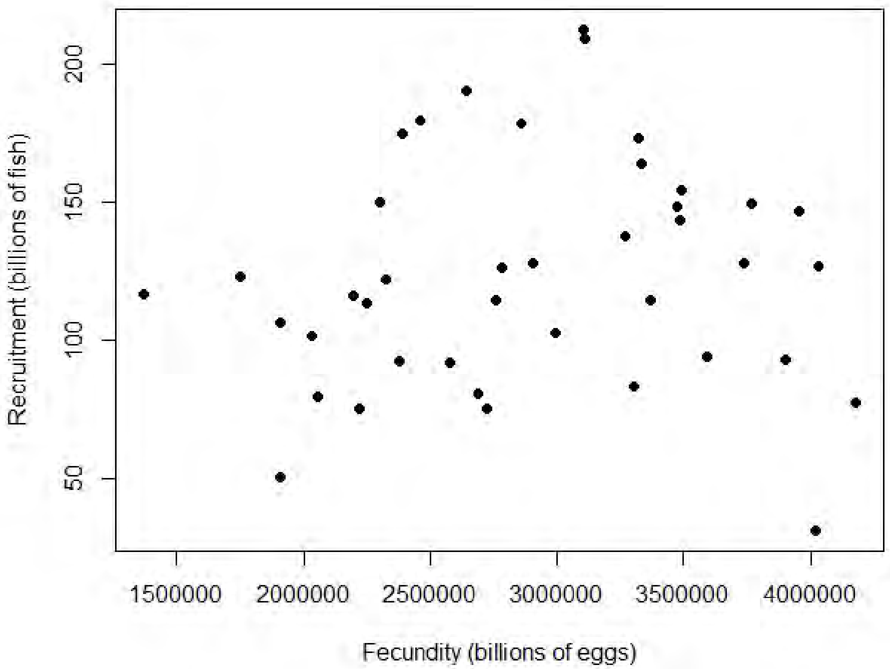


Figure 7.16 Plot of the fecundity (billions of eggs) versus the recruitment at age-0 in billions of fish.

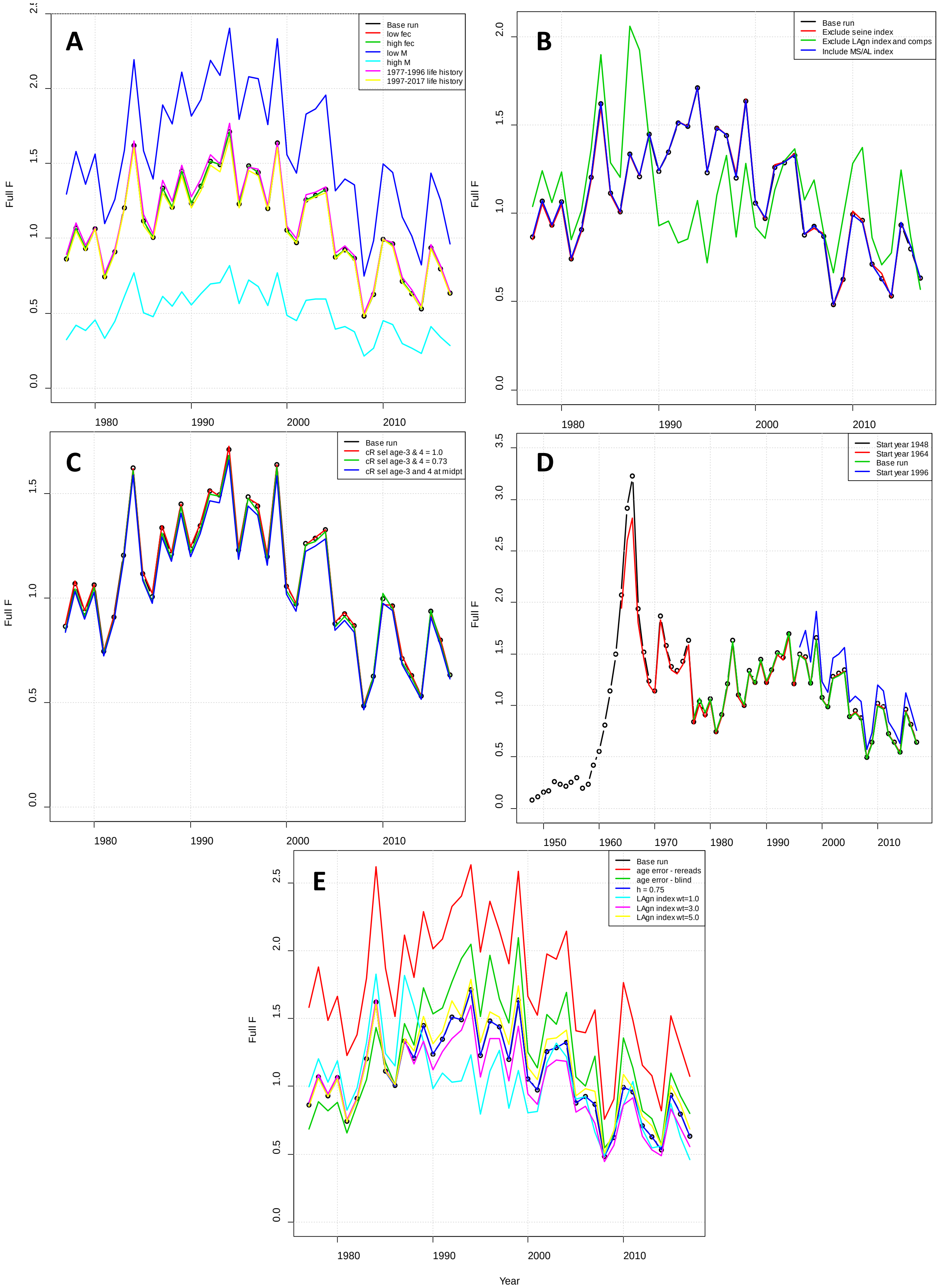


Figure 7.17 Estimated full fishing mortality rate for sensitivity runs related to changes in the input growth and life history data (panel A), to changes in the index data included or excluded (panel B), to changes in selectivity (panel C), to changes in start year of the model (panel D), and to changes in other model components (panel E).

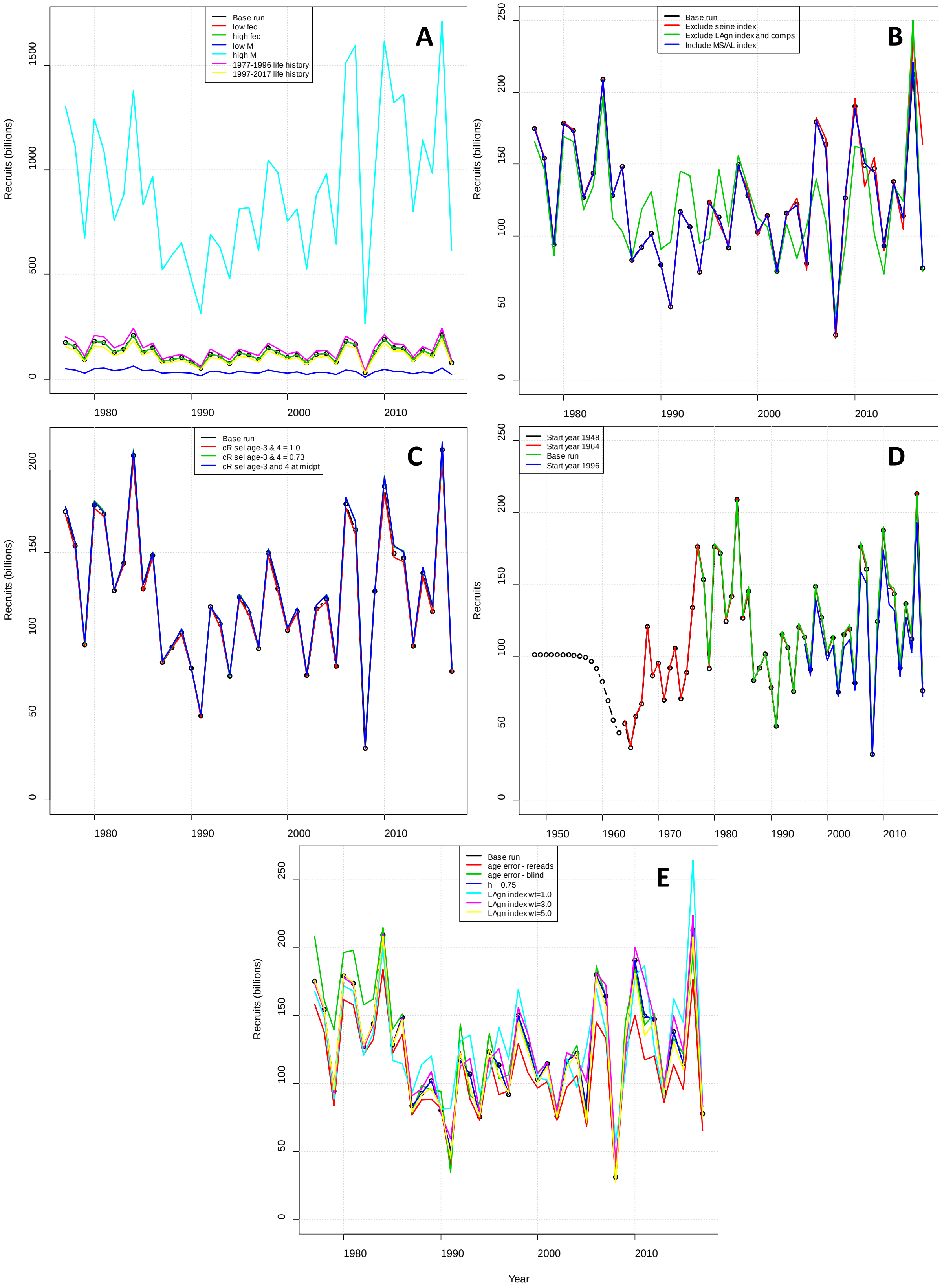


Figure 7.18 Estimated recruitment for sensitivity runs related to changes in the input growth and life history data (panel A), to changes in the index data included or excluded (panel B), to changes in selectivity (panel C), to changes in start year of the model (panel D), and to changes in other model components (panel E).

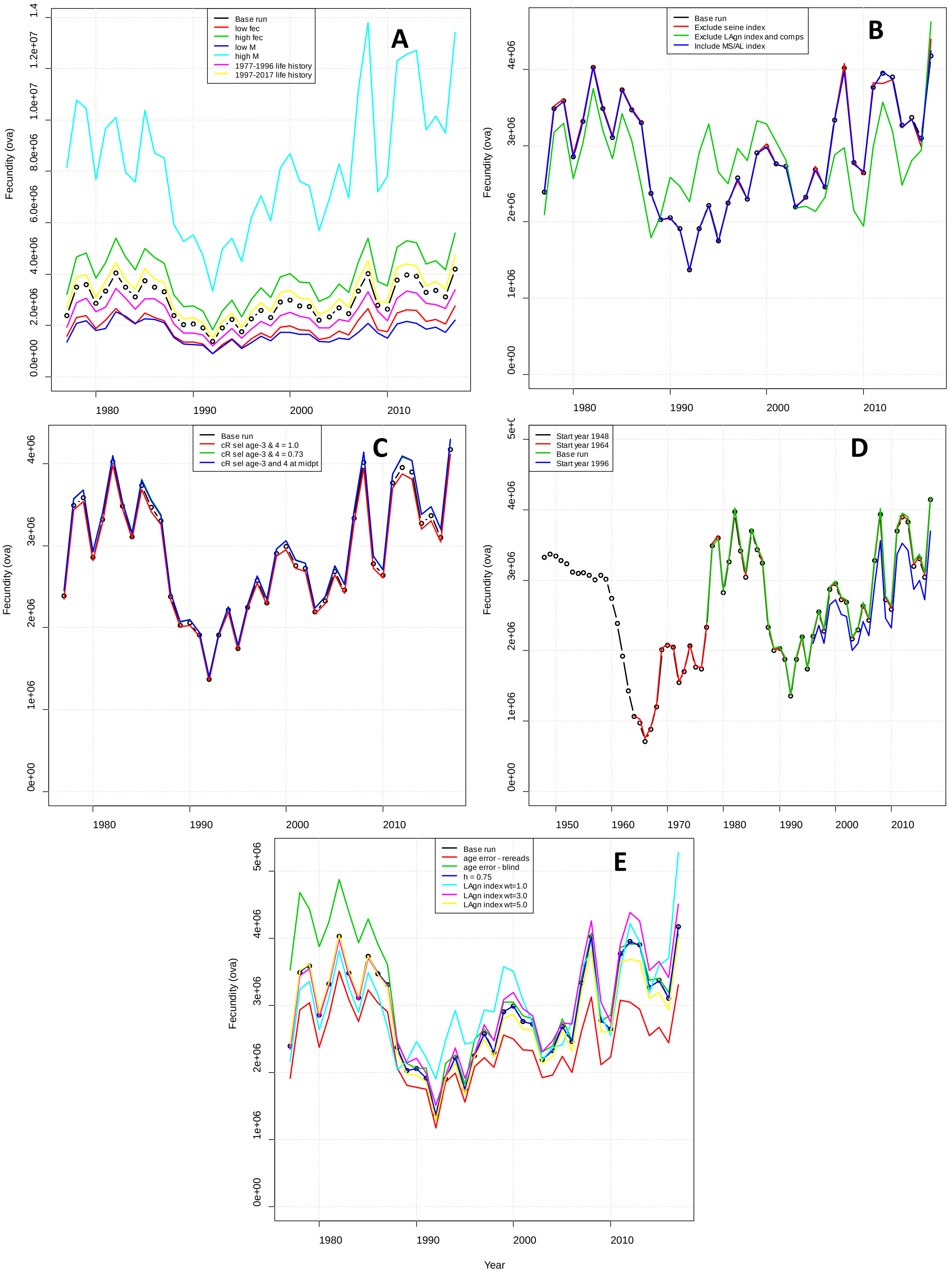


Figure 7.19 Estimated fecundity (SSB) for sensitivity runs related to changes in the input growth and life history data (panel A), to changes in the index data included or excluded (panel B), to changes in selectivity (panel C), to changes in start year of the model (panel D), and to changes in other model components (panel E).

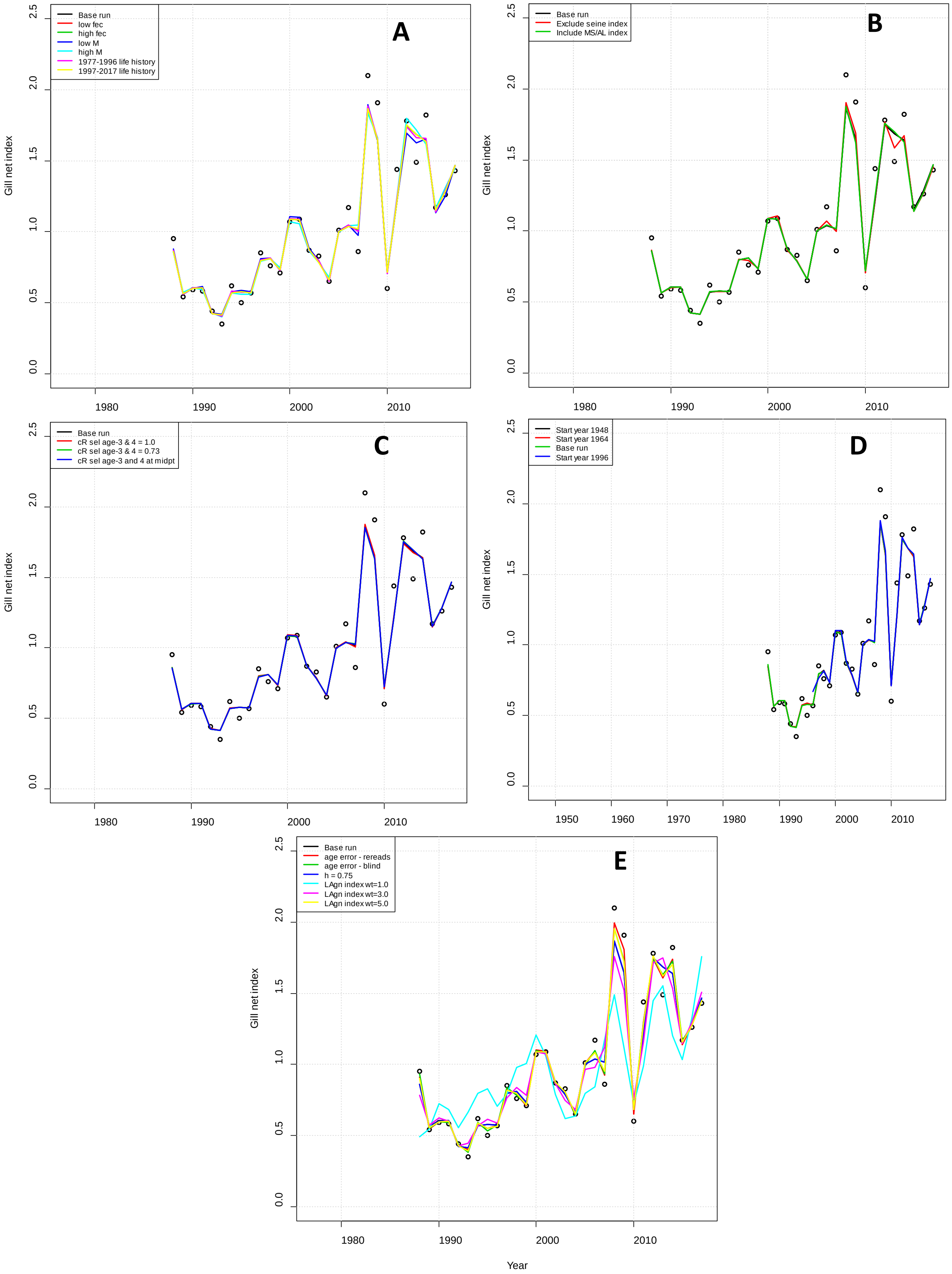


Figure 7.20 Fit to the gill net index for sensitivity runs related to changes in the input growth and life history data (panel A), to changes in the index data included or excluded (panel B), to changes in selectivity (panel C), to changes in start year of the model (panel D), and to changes in other model components (panel E).

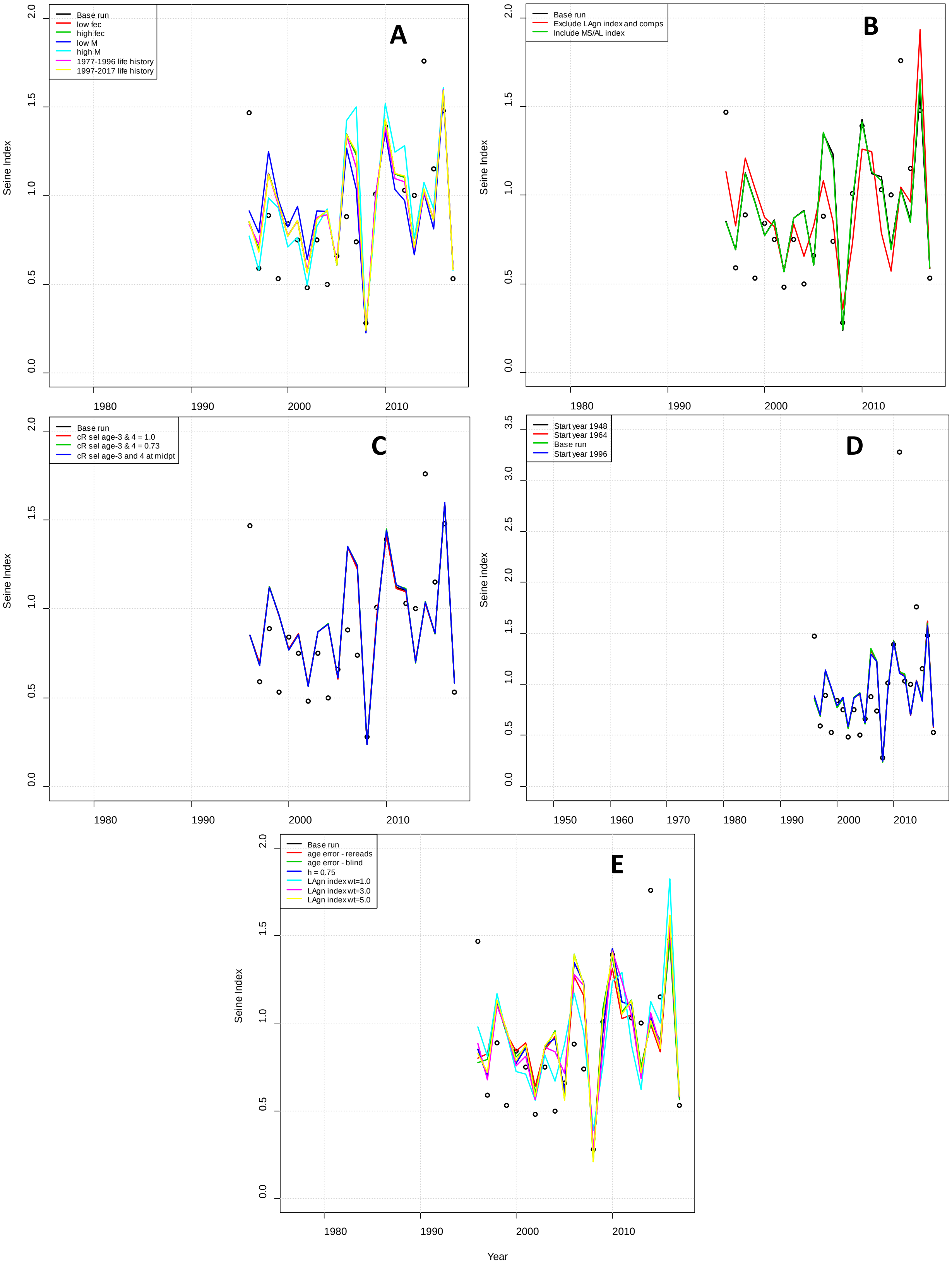


Figure 7.21 Fit to the seine index for sensitivity runs related to changes in the input growth and life history data (panel A), to changes in the index data included or excluded (panel B), to changes in selectivity (panel C), to changes in start year of the model (panel D), and to changes in other model components (panel E).

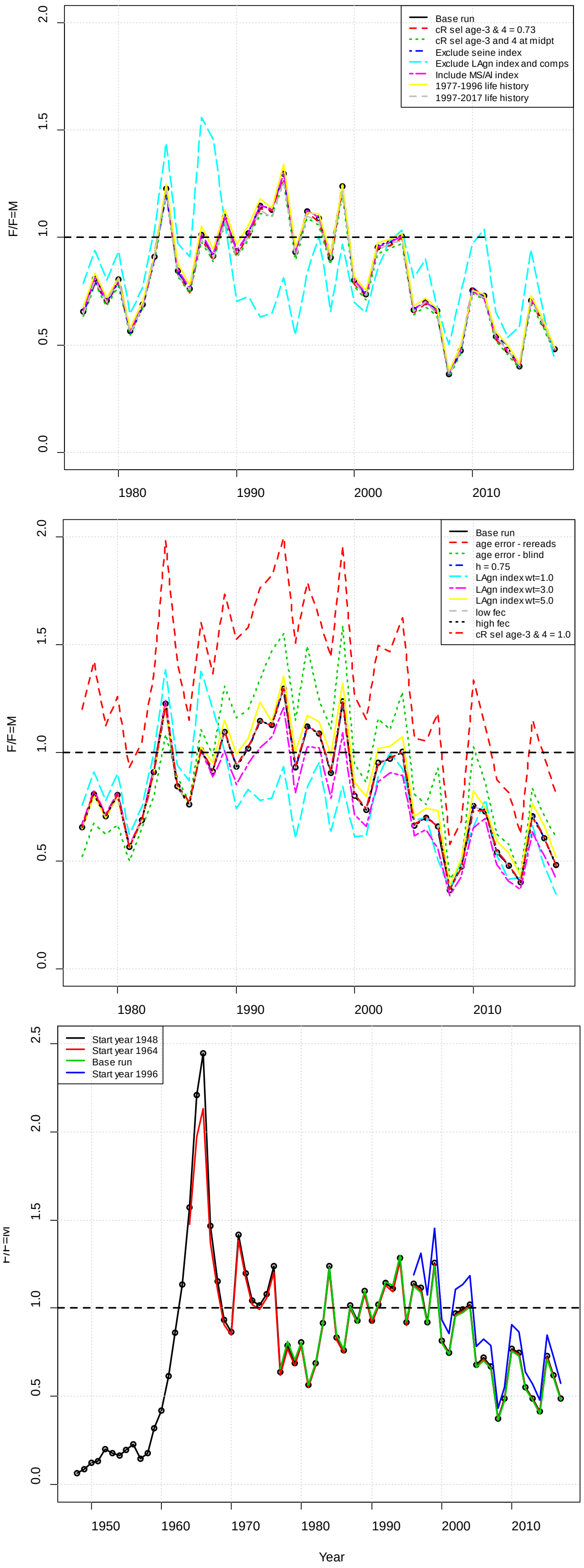


Figure 7.22 Fishing mortality rate over $F_{F=M}$ for sensitivity runs related to changes in the input growth and life history data, to changes in the index data included or excluded, to changes in selectivity, to changes in start year of the model, and to changes in other model components.

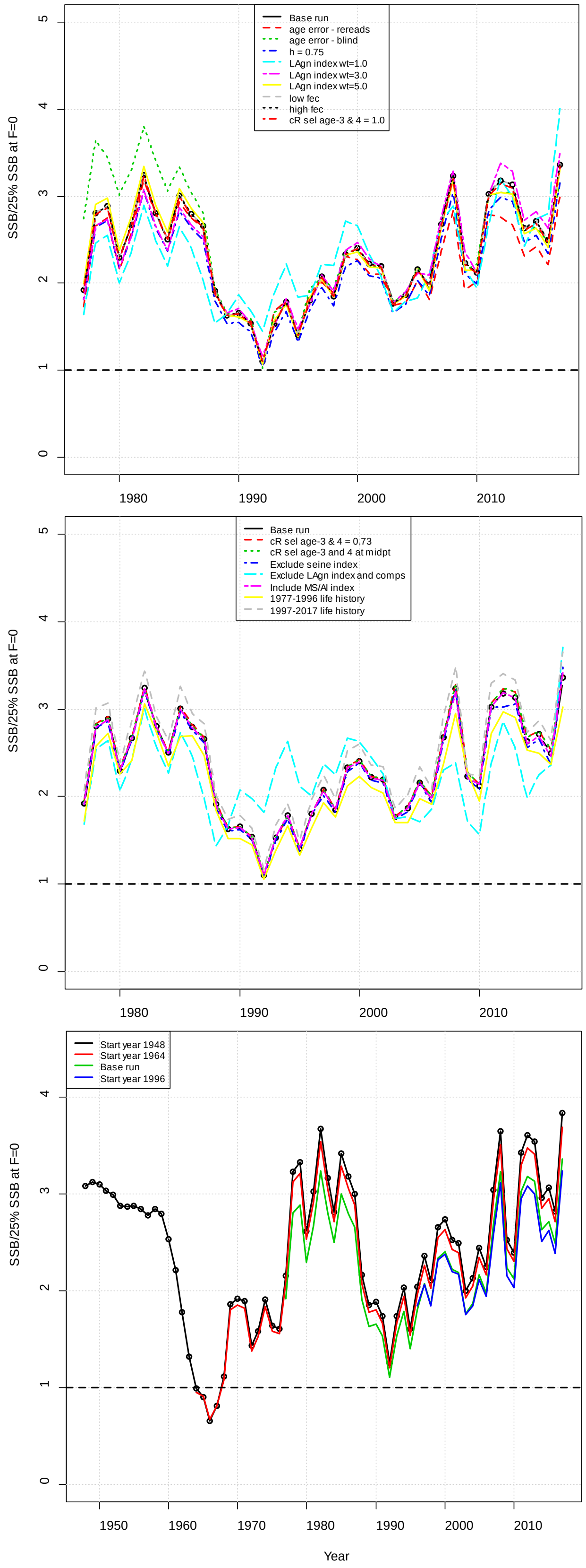


Figure 7.23 Fecundity (*SSB*) over the *SSB* threshold for sensitivity runs related to changes in the input growth and life history data, to changes in the index data included or excluded, to changes in selectivity, to changes in start year of the model, and to changes in other model components.

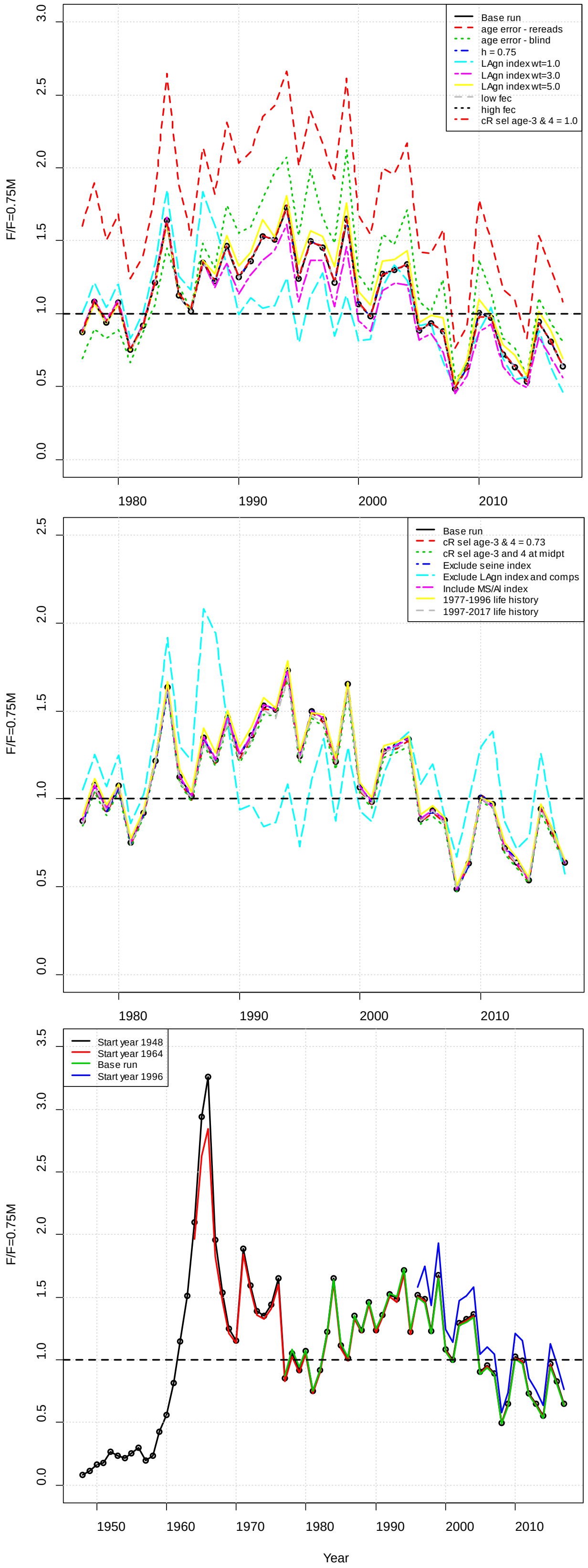


Figure 7.24 Fishing mortality rate over $F_{F=0.75M}$ for sensitivity runs related to changes in the input growth and life history data, to changes in the index data included or excluded, to changes in selectivity, to changes in start year of the model, and to changes in other model components.

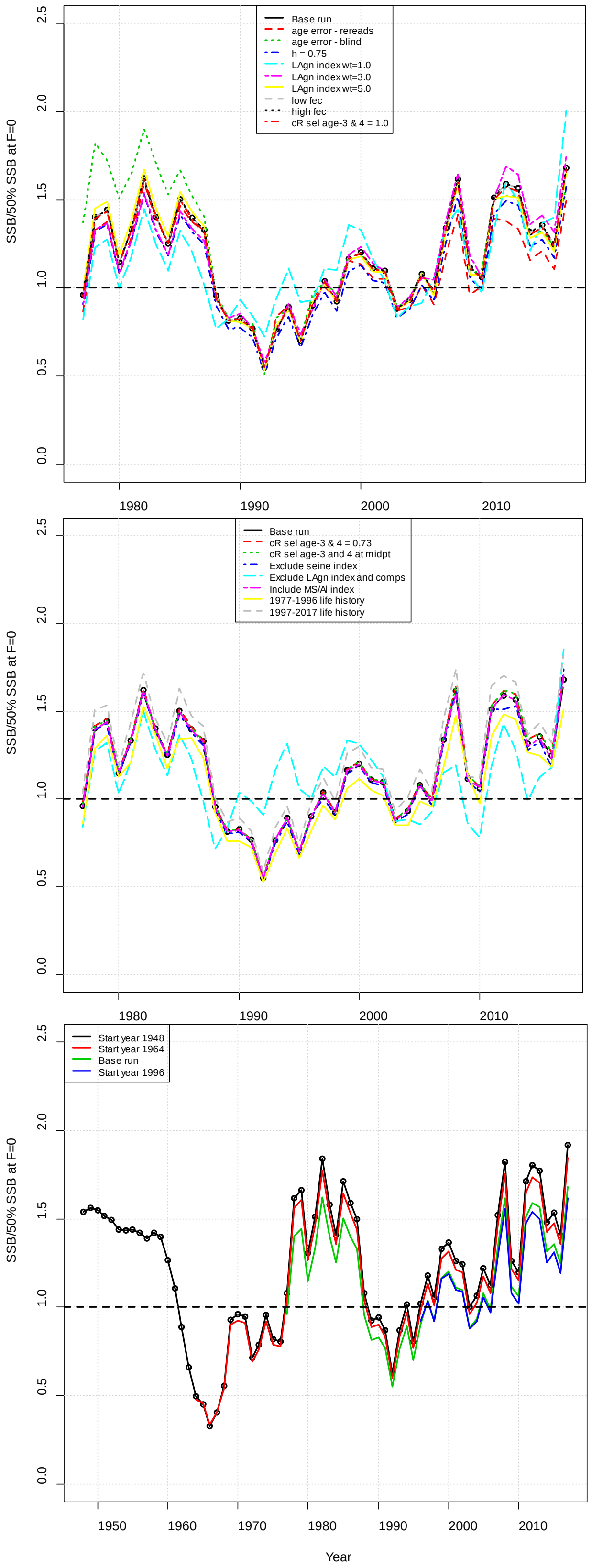


Figure 7.25 Fecundity (*SSB*) over the *SSB* target for sensitivity runs related to changes in the input growth and life history data, to changes in the index data included or excluded, to changes in selectivity, to changes in start year of the model, and to changes in other model components.

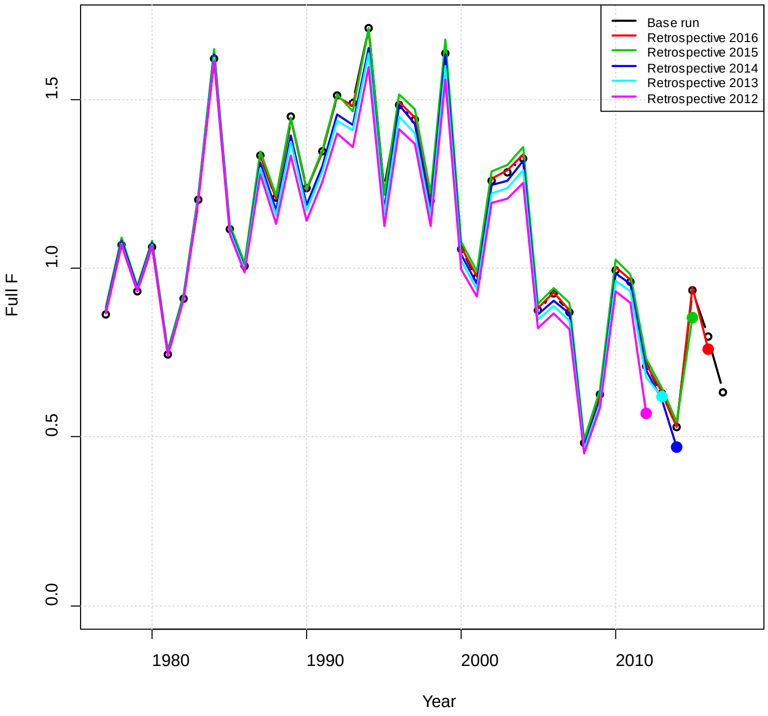


Figure 7.26 Full fishing mortality rate over time for the retrospective analysis.

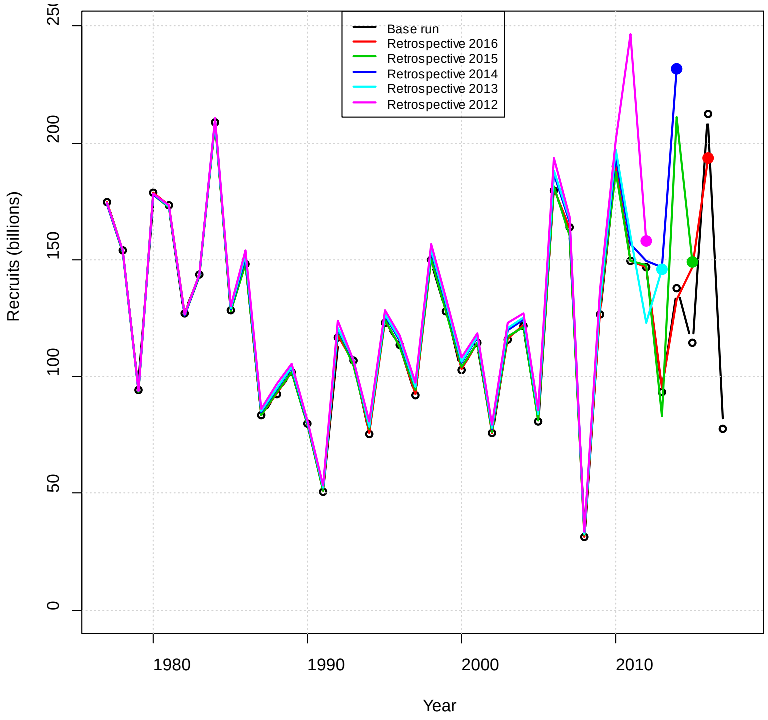


Figure 7.27 Annual recruitments estimated in the base run of BAM and for the retrospective analysis.

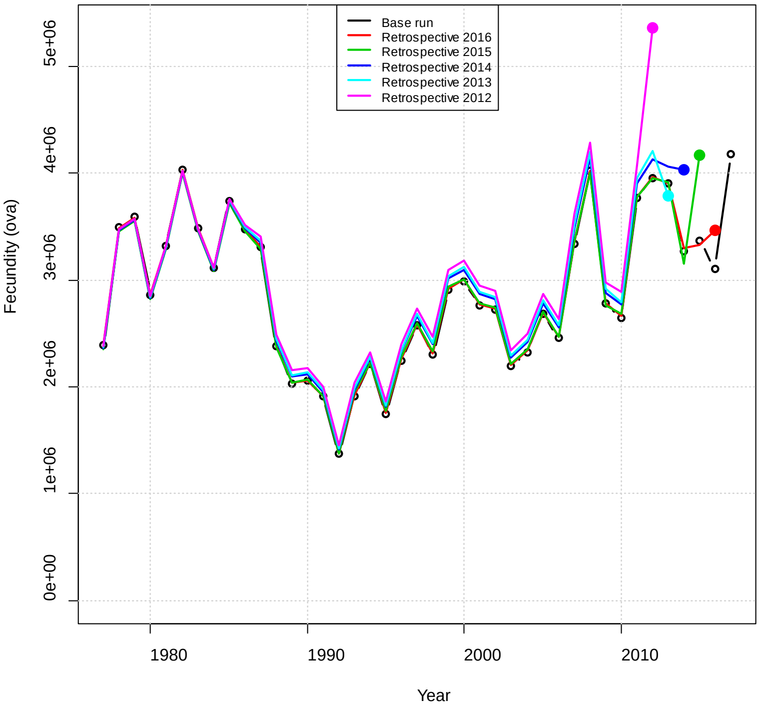


Figure 7.28 Annual fecundity (billions of eggs) estimated in the base run of BAM and for the retrospective analysis.

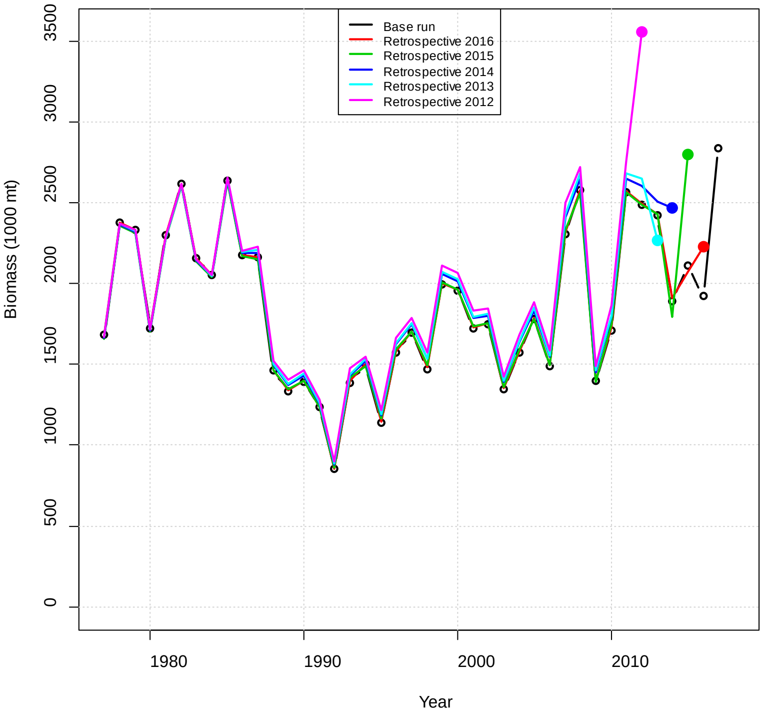


Figure 7.29 Annual age-1+ biomass estimated in the base run of BAM and for the retrospective analysis.

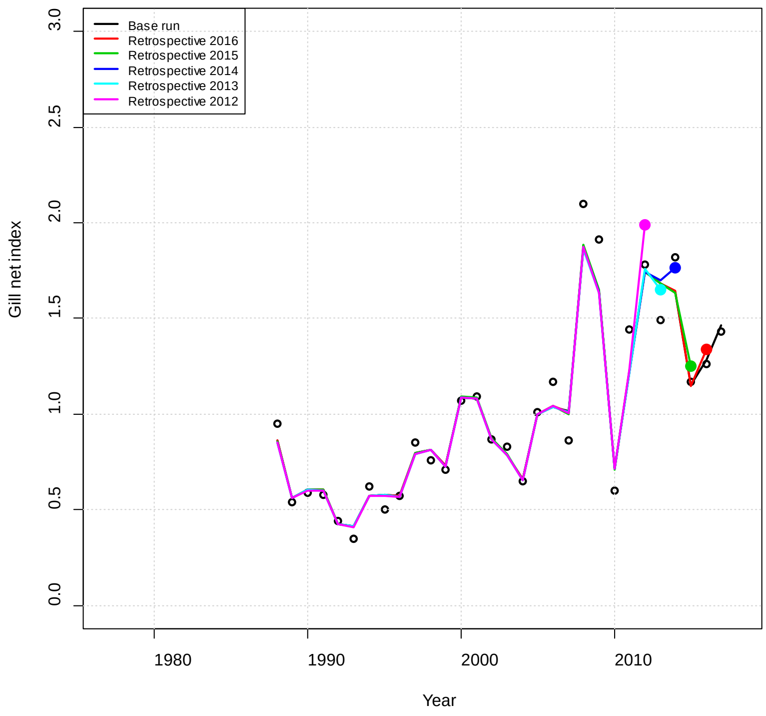


Figure 7.30 Fit to the gill net index for the retrospective analysis.

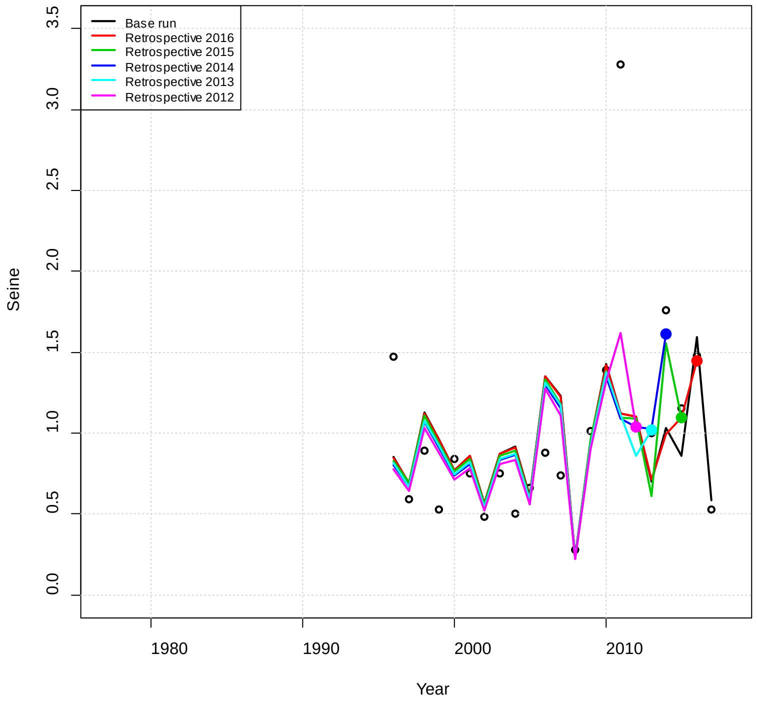


Figure 7.31 Fit to the seine index for the retrospective analysis.

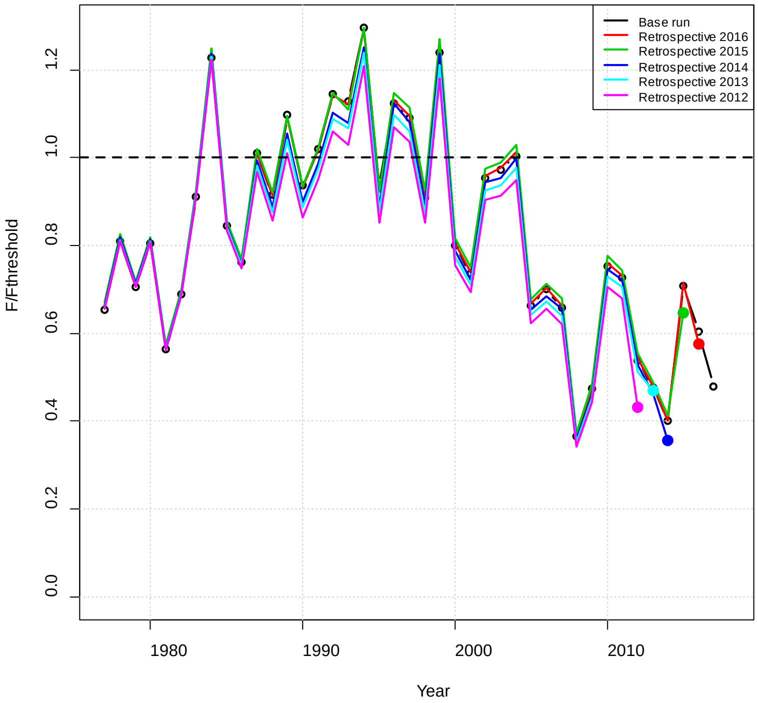


Figure 7.32 Fishing mortality rate over $F_{F=M}$ for the retrospective analysis.

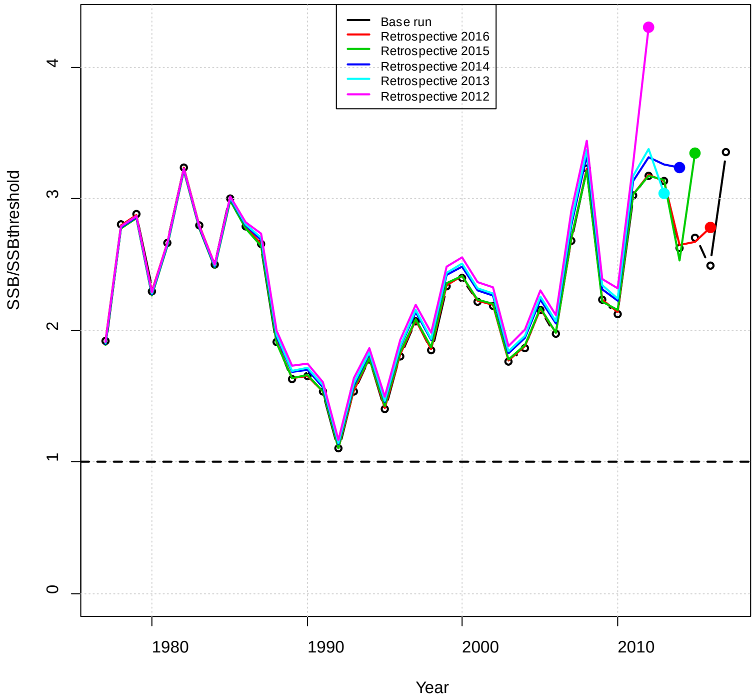


Figure 7.33 Fecundity (*SSB*) over $SSB_{25\%\ at\ F=0}$ for the retrospective analysis.

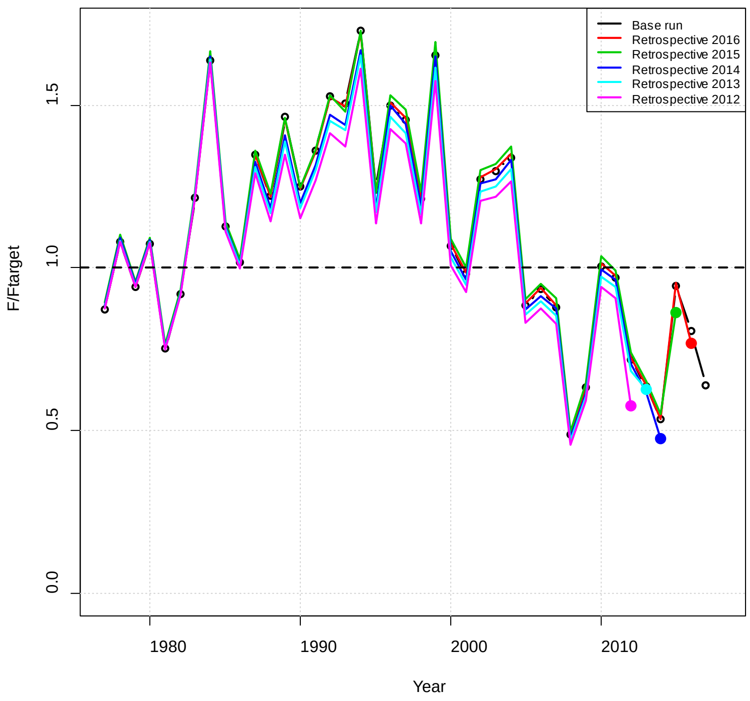


Figure 7.34 Fishing mortality rate over $F_{F=0.75M}$ for the retrospective analysis.

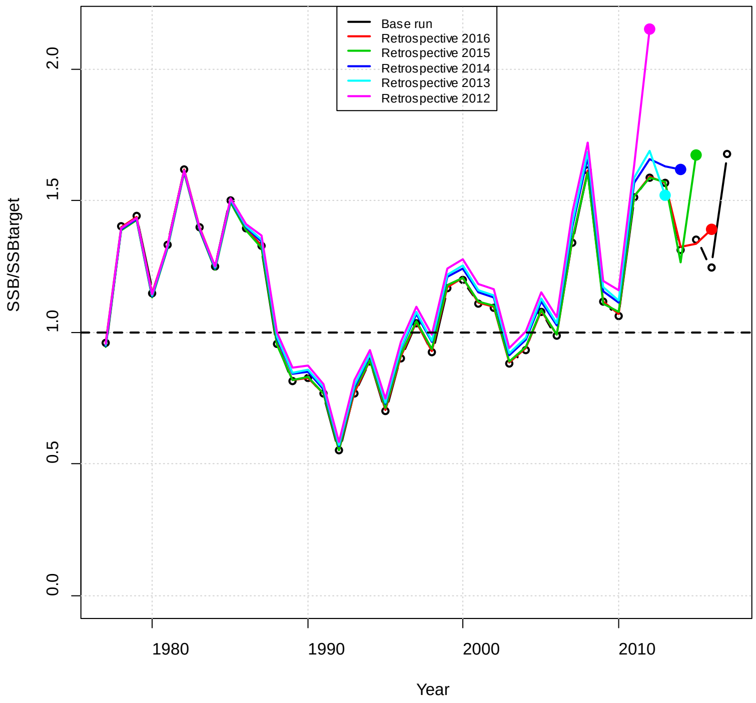


Figure 7.35 Fecundity (SSB) over $SSB_{50\%\ at\ F=0}$ for the retrospective analysis.

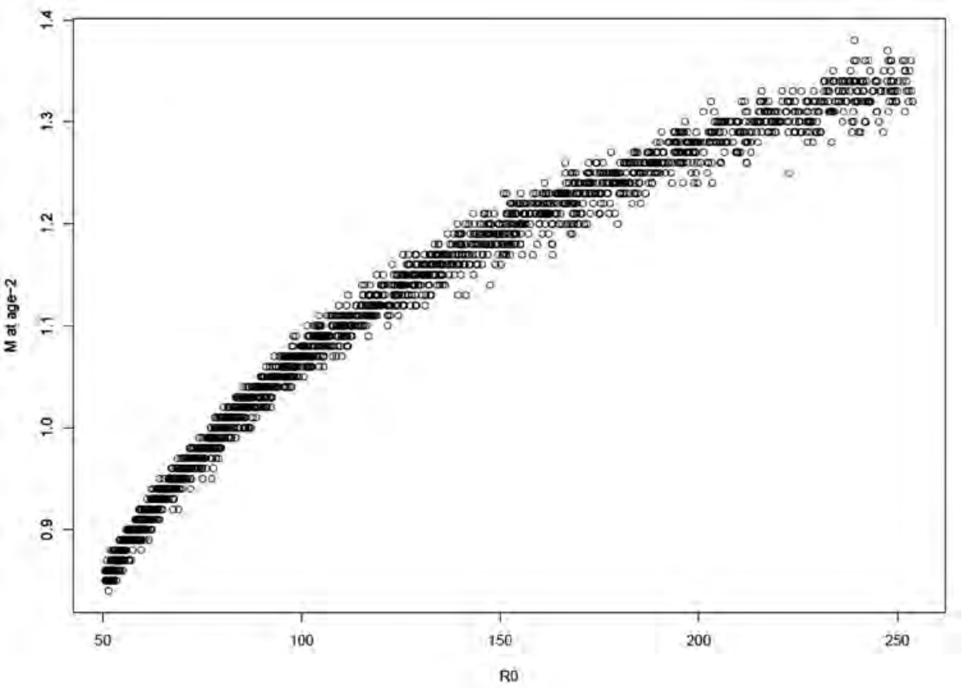


Figure 7.36 Estimated values for R0 versus fixed M at age-2 for the individual MCB runs.

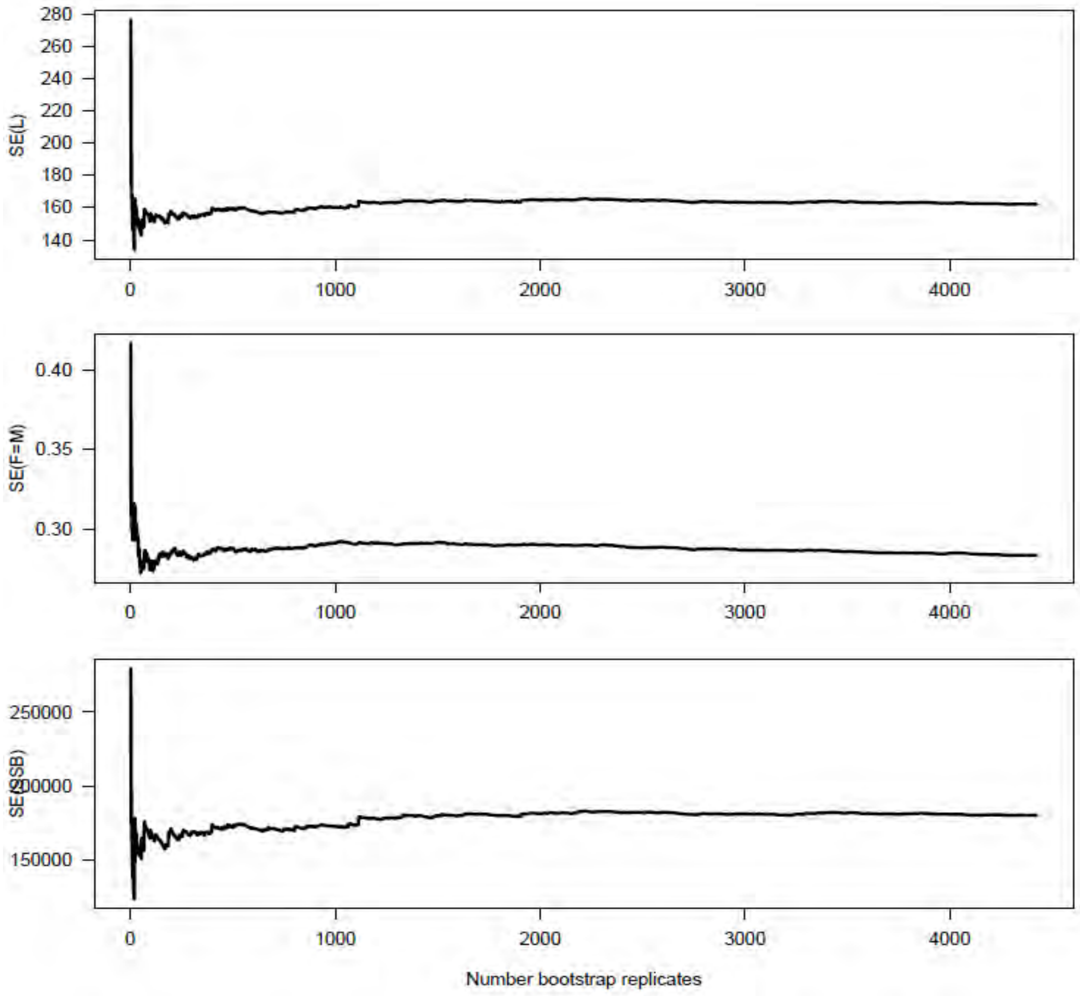


Figure 7.37 Standard error (SE) of landings (L), suggested fishing mortality rate threshold (F=M), and fecundity (SSB) for the MCB runs. Stabilization of the SE indicates that sufficient runs have been completed to approximate the uncertainty and provide a robust estimate of the SE.

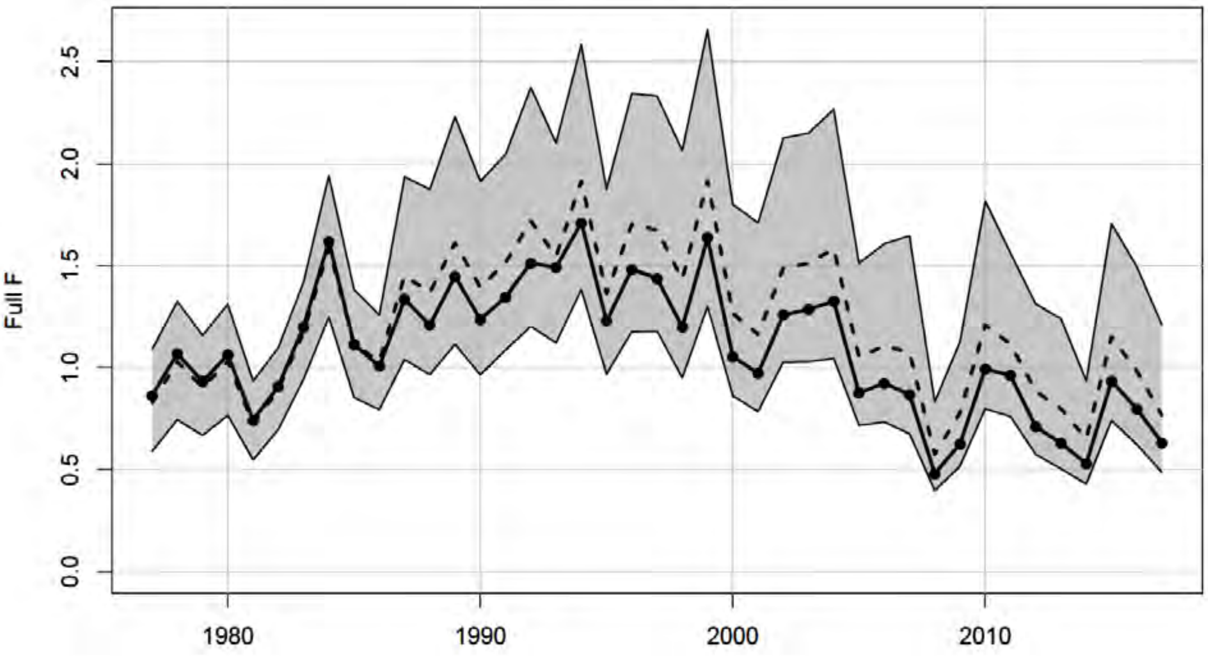


Figure 7.38 Estimated annual full *F* from the base BAM model (connected points) and the median from the MCB runs (dashed line). Shaded area represents the 90% confidence interval of the bootstrap runs after some runs were eliminated.

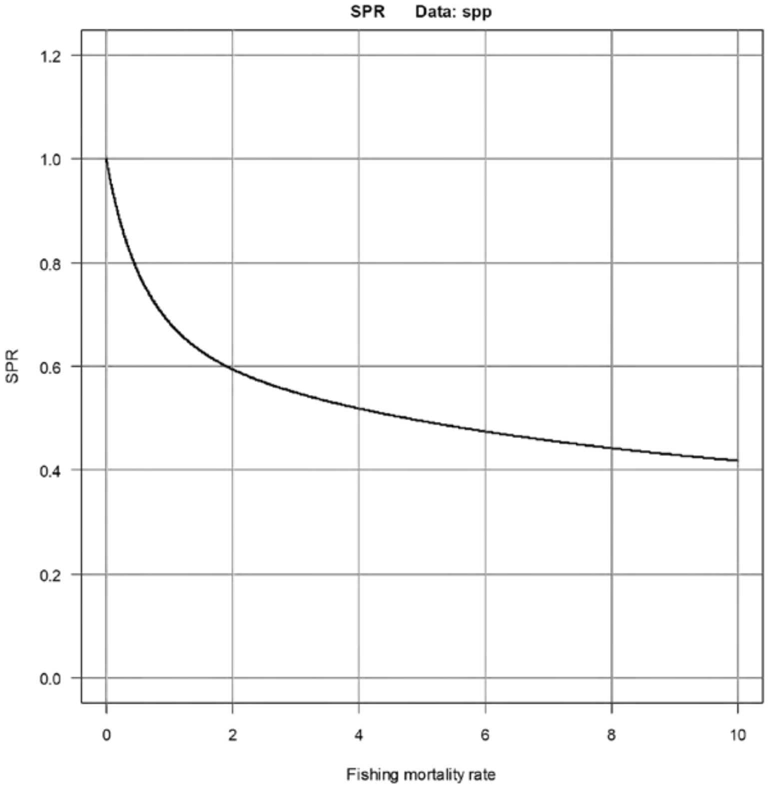


Figure 7.39 Estimates of the proportional (re-scaled to max of 1.0) fecundity-per-recruit as a function of the full fishing mortality rate from the base BAM model.

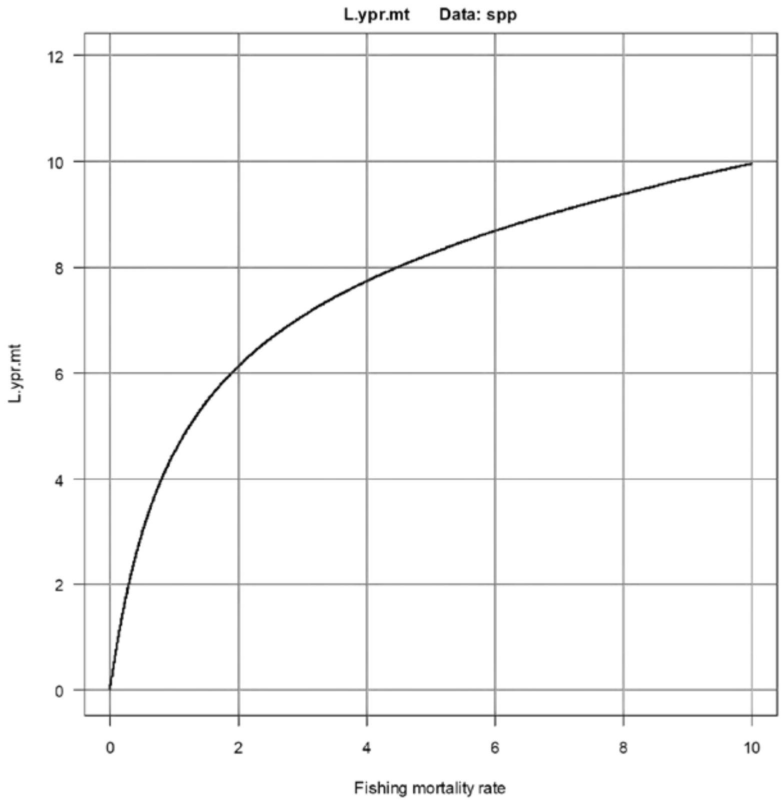


Figure 7.40 Estimates of the yield-per-recruit (mt/million) as a function of the full fishing mortality rate from the base BAM model.

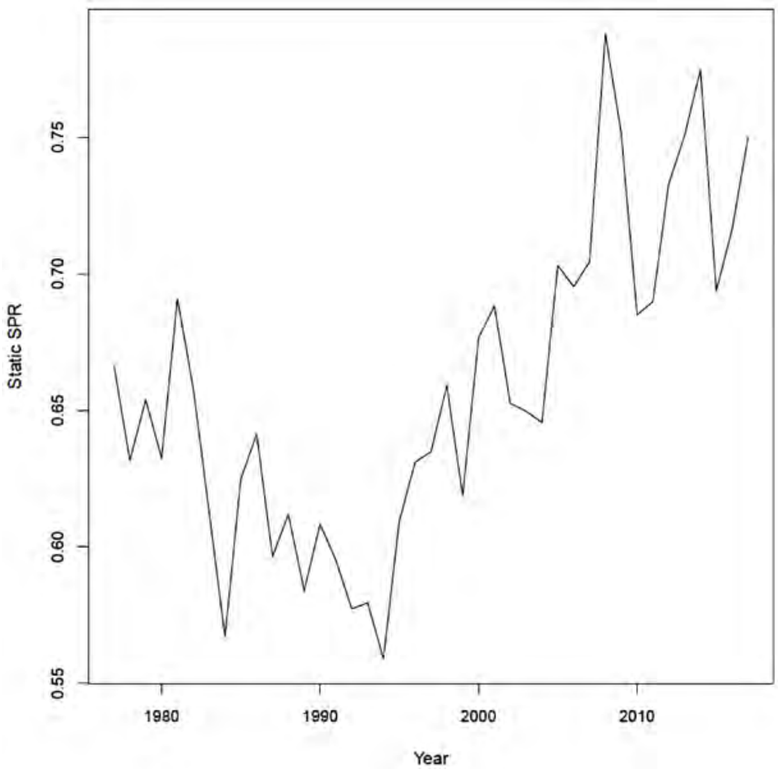


Figure 7.41 Static SPR or the spawner-per-recruit percentage for the respective fishing mortality rate for each year 1977-2017.

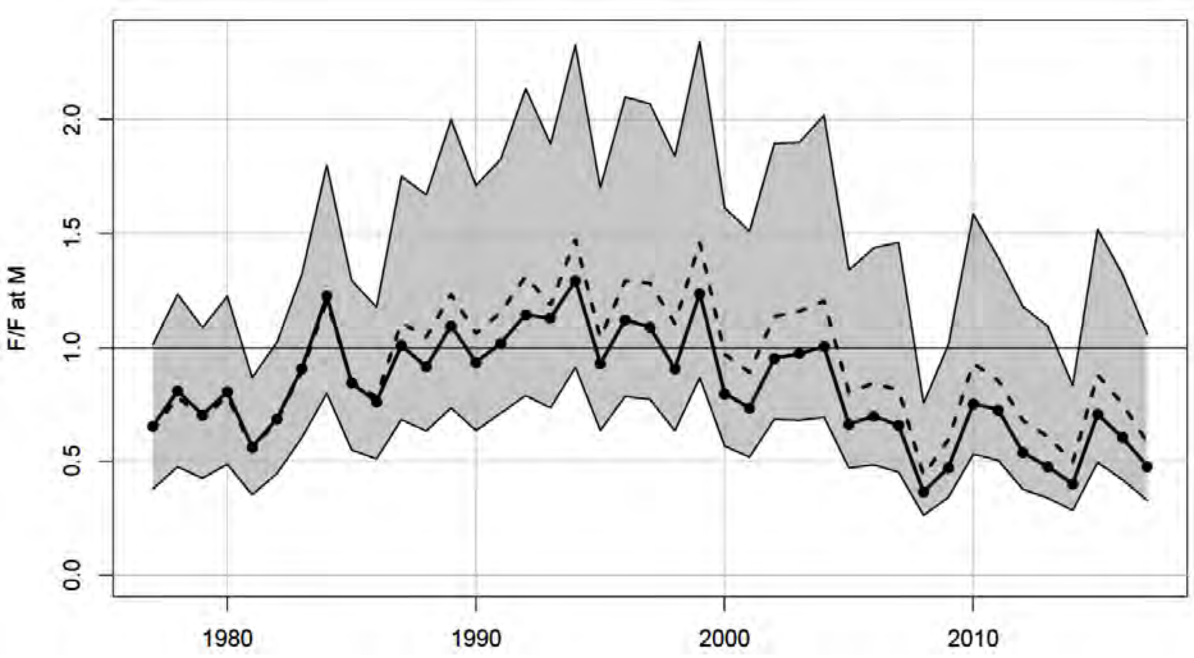


Figure 7.42 Estimates of the full fishing mortality rate relative to $F_{F=M}$ from the base BAM model (connected points) and the median from the MCB runs (dashed line). Shaded area represents the 90% confidence interval of the bootstrap runs.

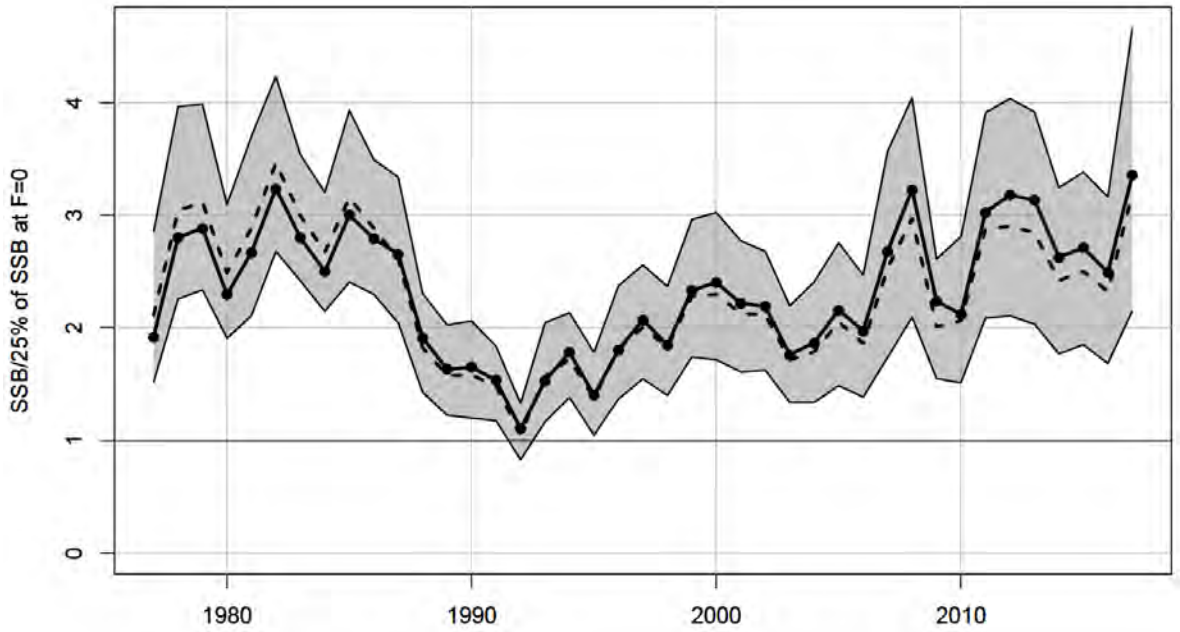


Figure 7.43 Estimates of the population fecundity (*SSB*) relative to $SSB_{25\%\ at\ F=0}$ from the base BAM model (connected points) and the median from the MCB runs (dashed line). Shaded area represents the 90% confidence interval of the bootstrap runs.

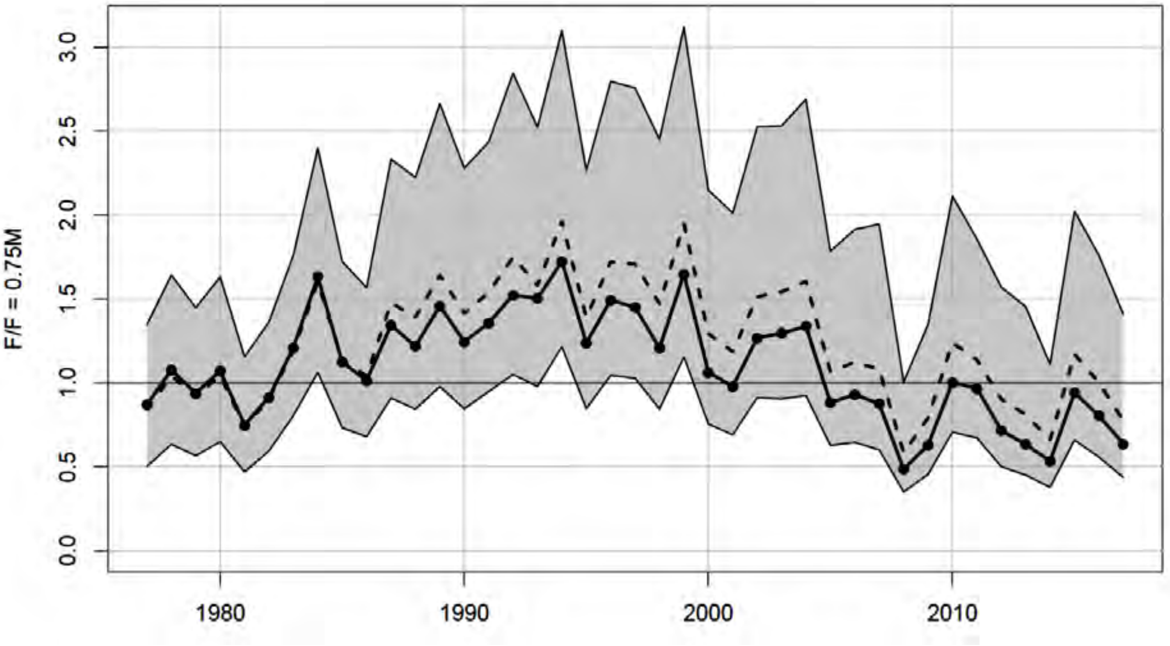


Figure 7.44 Estimates of the full fishing mortality rate relative to $F_{F=0.75M}$ from the base BAM model (connected points) and the median from the MCB runs (dashed line). Shaded area represents the 90% confidence interval of the bootstrap runs.

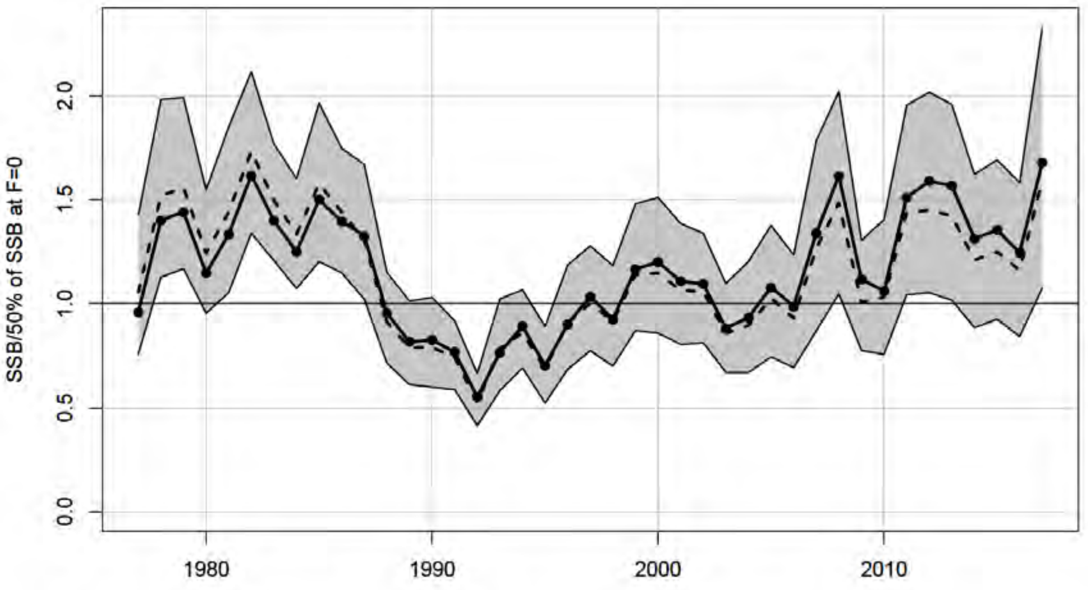


Figure 7.45 Estimates of the population fecundity (SSB) relative to $SSB_{50\%\ at\ F=0}$ from the base BAM model (connected points) and the median from the MCB runs (dashed line). Shaded area represents the 90% confidence interval of the bootstrap runs.

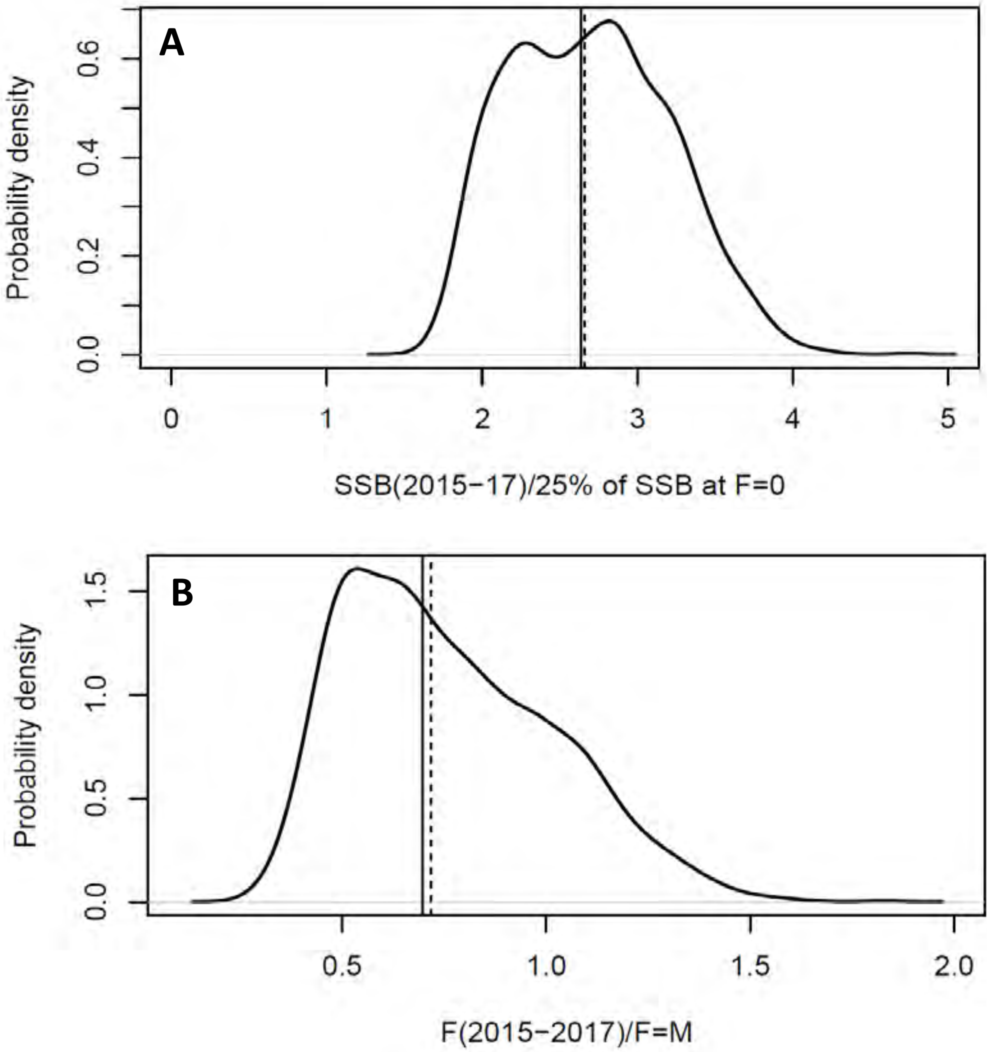


Figure 7.46 Probability density distribution of the geometric mean population fecundity in 2015-2017 relative to *$SSB_{25\%\ at\ F=M}$* from the bootstrap estimates from the base BAM model (Panel A). Probability density distribution of the geometric mean fishing mortality rate in 2015-2017 relative to *$F_{F=M}$* from the bootstrap estimates from the base BAM model (Panel B).

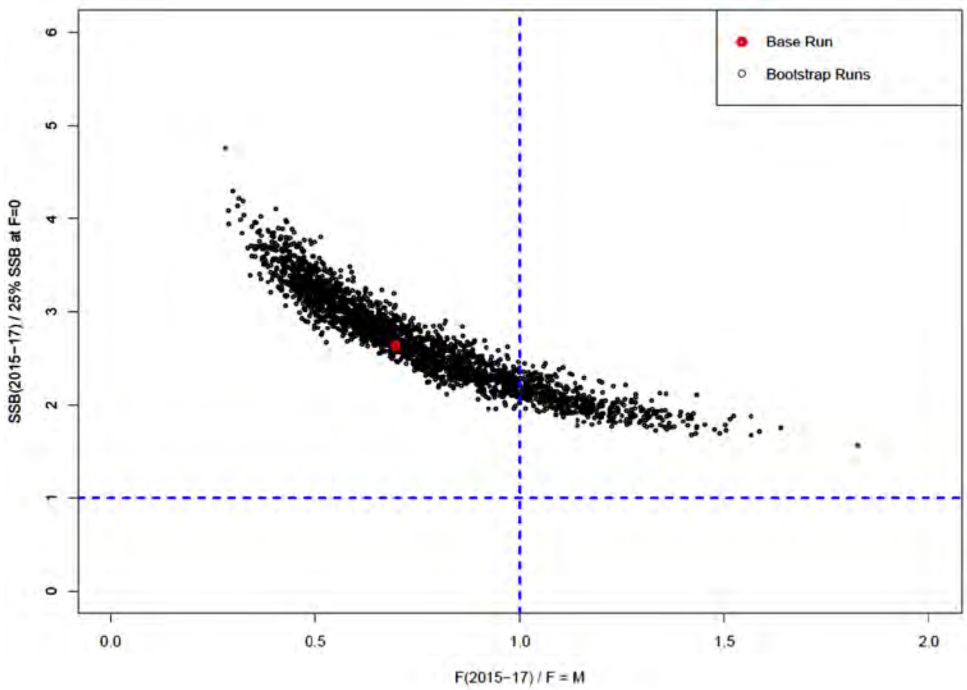


Figure 7.47 Scatter plot of the geometric mean estimates for 2015-2017 relative to $F_{F=M}$ and $SSB_{25\%\ at\ F=0}$ from the 2,557 bootstrap estimates (excluding those that were unable to converge) from the base BAM model. Runs in the overfishing category (19%) all had low natural mortality rate vectors as demonstrated in the histograms of M

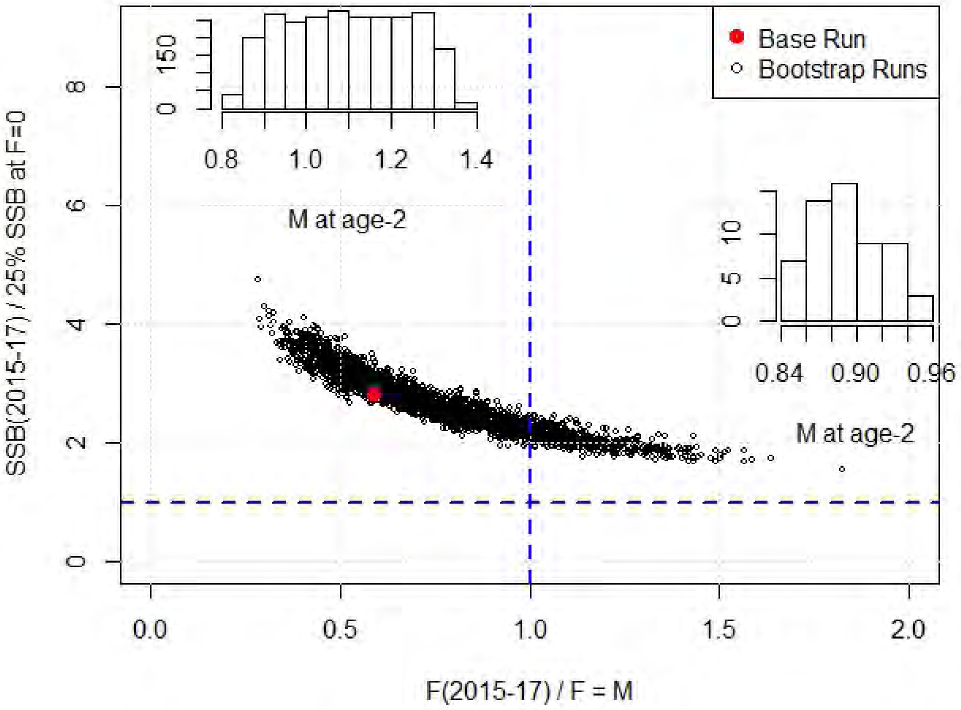


Figure 7.48 Scatter plot of the geometric mean estimates for 2015-2017 relative to $F_{F=M}$ and $SSB_{25\%\ at\ F=0}$ from the 2,557 bootstrap estimates (excluding those that were unable to converge) from the base BAM model. On each panel, a histogram of the natural mortality (*M*) at age-2 is provided.

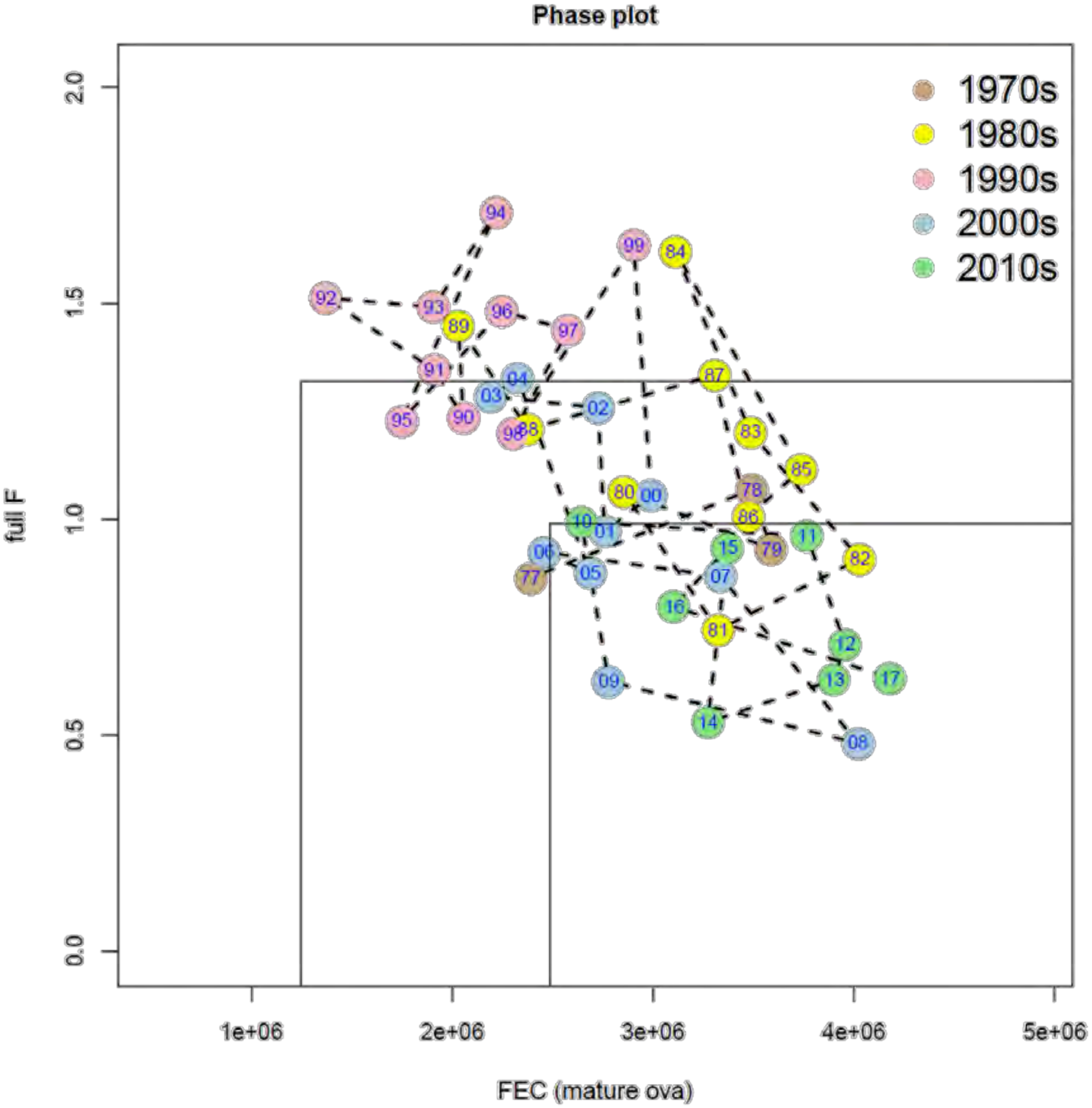


Figure 7.49 Phase plot for fishing years 1977-2017 from the base run with fishing mortality benchmarks of *F=M* (threshold) and *F=0.75M* (target) and with the associated spawning stock biomass (fecundity in billions of eggs) benchmarks of $SSB_{25\% \text{ at } F=0}$ (threshold) and $SSB_{50\% \text{ at } F=0}$ (target).

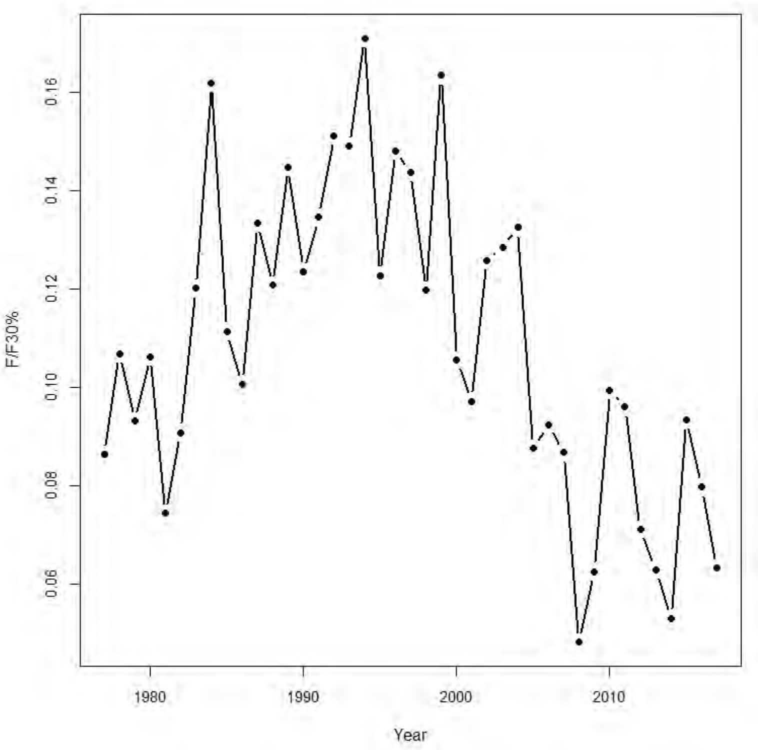


Figure 7.50 Estimates of the full fishing mortality rate relative to $F_{30\%}$ from the base run. **NOTE:** $F_{30\%}$ was considered to be 10 since that is the maximum fishing mortality rate explored for the assessment and calculation of SPR.

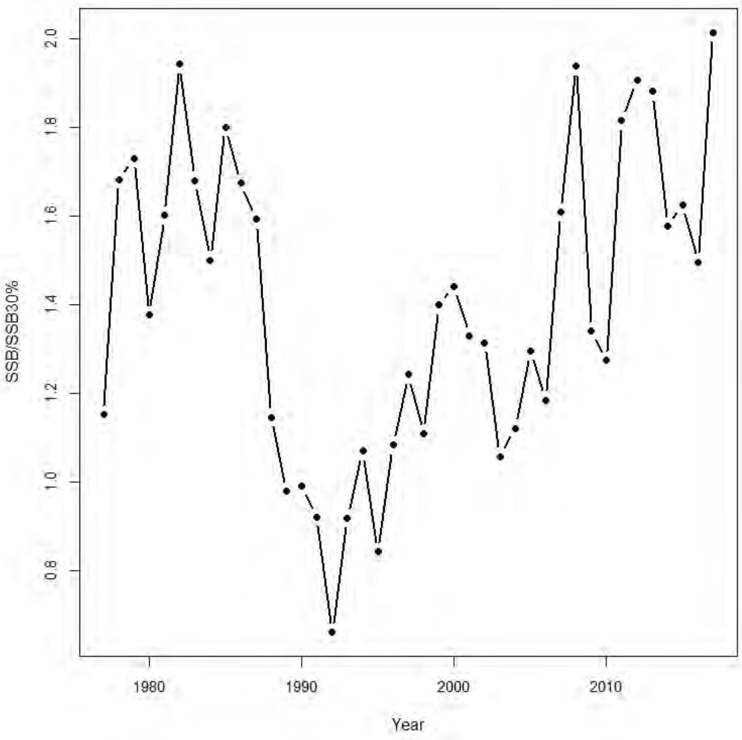


Figure 7.51 Estimates of the *SSB* (fecundity) rate relative to $SSB_{30\%}$ from the base run. **NOTE:** $SSB_{30\%}$ was considered to be 2,074,992 since that is the minimum *SSB* value at an *F*=10 for the SPR analysis.

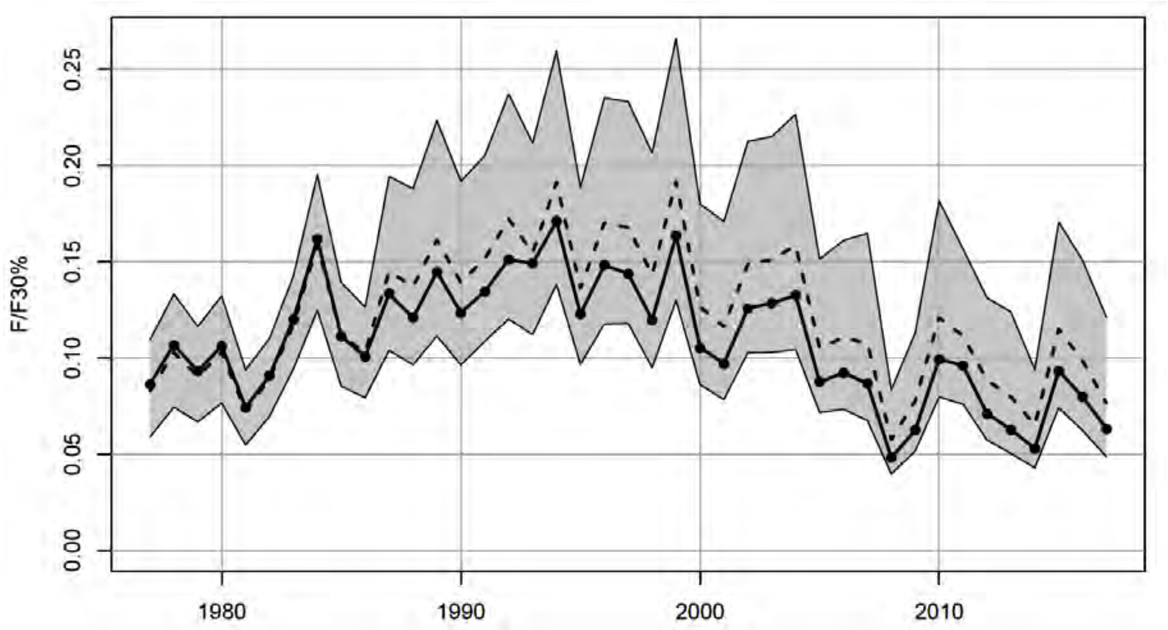


Figure 7.52 Estimates of the full fishing mortality rate relative to $F_{30\%}$ from the base run (connected points) and the median from the MCB runs (dashed line). Shaded area represents the 90% confidence interval of the bootstrap runs. **NOTE:** $F_{30\%}$ was considered to be 10 since that is the maximum fishing mortality rate explored for the assessment and calculation of SPR.

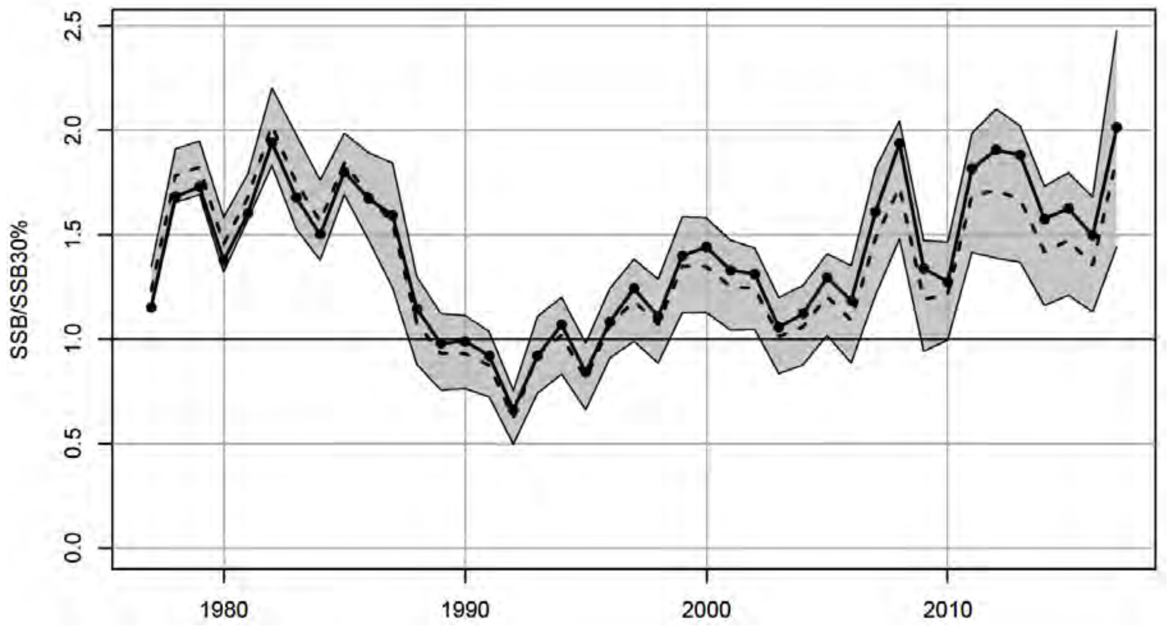


Figure 7.53 Estimates of the *SSB* (fecundity) rate relative to $SSB_{30\%}$ from the base run (connected points) and the median from the MCB runs (dashed line). Shaded area represents the 90% confidence interval of the bootstrap runs. **NOTE:** $SSB_{30\%}$ was considered to be 2,074,992 since that is the minimum *SSB* value at an *F*=10 for the SPR analysis.

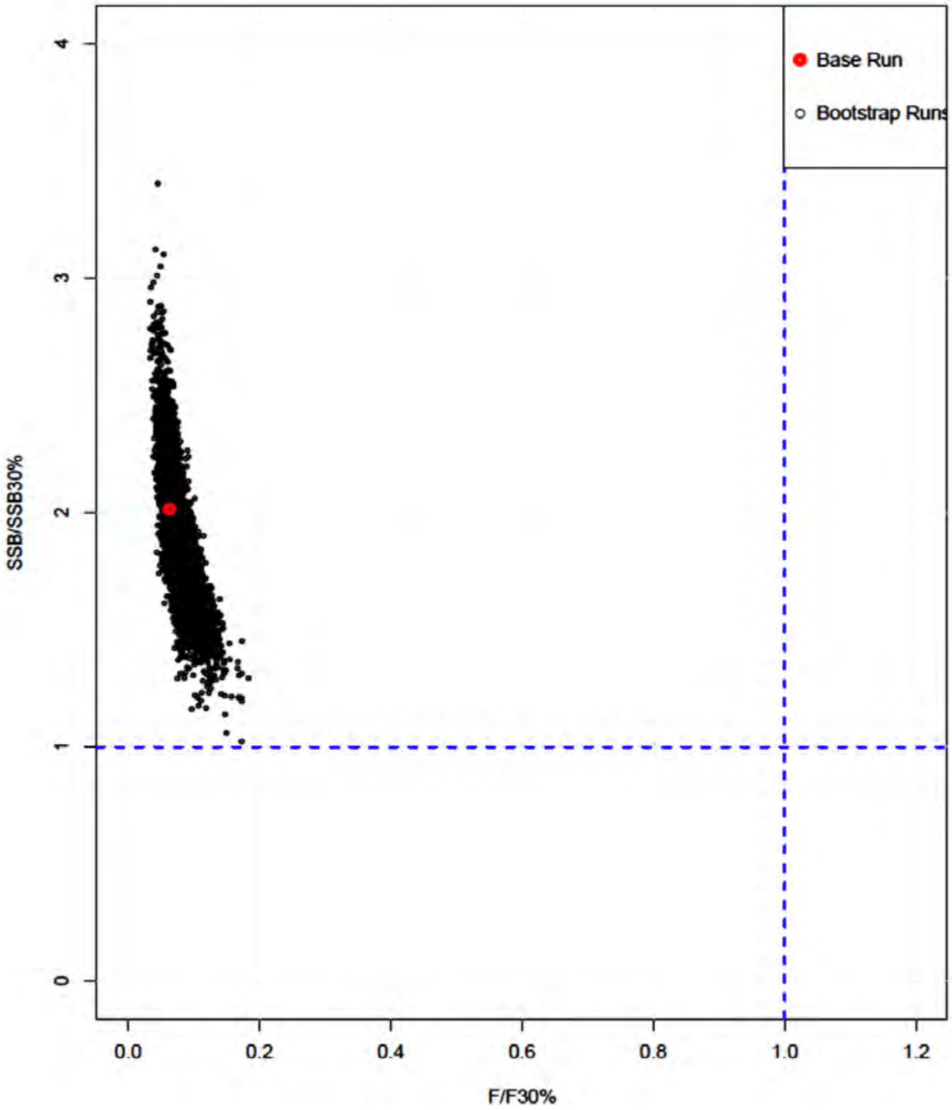


Figure 7.54 Scatter plot of the fishing mortality rate relative to $F_{30\%}$ and spawning stock biomass (fecundity) relative to $SSB_{30\%}$ from the 2,557 bootstrap estimates (excluding those that were unable to converge) from the base BAM model. **NOTE:** $F_{30\%}$ was considered to be 10 since that is the maximum fishing mortality rate explored for the assessment and calculation of SPR. $SSB_{30\%}$ was considered to be 2,074,992 since that is the minimum *SSB* value at an *F*=10 for the SPR analysis.

8.0 Stock Status

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

The Magnuson-Stevens Reauthorization of 1997 (Restrepo et al. 1998) suggests that management measures define both a sustainability limit, as well as a target level for the stock. However, Gulf Menhaden are not a federally managed species. In the current FMP, SPR based benchmarks have been specified for determining stock status, specifically $F_{30\%}$ and $SSB_{30\%}$. However, the fishing mortality rate associated with the benchmarks in the current FMP are defined as functionally infinite (or greater than an *F* of 10) for this stock assessment. Several new data sources for life history and growth were changed for this assessment, which cause the fishing mortality rate scale to change substantially from the last stock assessment. As a consequence, the assessment panel has suggested options provided and described in Section 7 in order to make a statement about the stock status for Gulf Menhaden. The assessment panel recommends that managers work to clearly define the goals for the fishery and to specify measureable objectives for the fishery.

8.1 Current Overfishing, Overfished/Depleted Definitions

Currently, the FMP has in place *SPR* based benchmarks for both the limit and target for Gulf Menhaden (VanderKooy and Smith 2015). Specifically, the fishing mortality rate limit and target are $F_{30\%}$ and $F_{35\%}$, respectively. The *SSB* or fecundity based benchmarks were $SSB_{30\%}$ (limit) and $SSB_{35\%}$ (target). As it currently stands, these thresholds are used to determine the status of the stock with respect to overfishing and overfished. Given fishing mortality rates of greater than $F = 10\ y^{-1}$, the percentage *SPR* was still greater than 40%. Given these target and limit reference points, the Gulf Menhaden stock is not overfished and overfishing is not occurring. Because the benchmarks in the current FMP are providing *F* values that are well above values estimated in the stock assessment, the assessment panel made some further recommendations for benchmarks.

8.2 Discussion of Alternate Reference Points

8.2.1 F_{MSY} Concept

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

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

In the case of Gulf Menhaden, the stock-recruitment relationship was not well defined because of the use of a fixed value of steepness. Because of the fixed steepness for the stock-recruitment curve, the fact that Gulf Menhaden are short-lived, and the infinite value of F_{MSY} as discussed in Section 7.1.6, the panel did not propose using the F_{MSY} based benchmarks for management decisions.

8.2.2 F_{MSY} Proxies

The assessment panel also considered *MSY* proxies based on per recruit analyses (e.g., $F_{35\%}$). The values of $F_{X\%}$ are defined as those F values corresponding to $X\%$ spawning potential ratio, i.e., spawners (population fecundity) per recruit relative to that at the unfished level. These quantities may serve as proxies for F_{MSY}, if the spawner-recruit relationship cannot be estimated reliably. Mace (1994) recommended $F_{40\%}$ as a proxy. However, later studies have found that $F_{40\%}$ is likely too high a fishing rate across many life-history strategies (Williams and Shertzer 2003, Brooks et al. 2009) and can lead to undesirably low levels of biomass and recruitment (Clark 2002).

These are the current benchmarks in the Gulf Menhaden FMP but result in very high values of F, which are greater than 10. Thus, the assessment panel does not recommend the continued to use these benchmarks.

8.2.3 Alternative Benchmarks

The assessment panel considered other candidate options for benchmarks given that *MSY*-based methods and *SPR*-based proxies will not provide adequate benchmarks for the Gulf Menhaden stock. Two options discussed for the fishing mortality rate reference points included historical perspective benchmarks and those based on natural mortality. The assessment panel determined that for fishing mortality, managers should keep the value below which fishing is causing harm, meaning below a value where a population decline can be observed given the fishing mortality rate. The panel determined that the most recent fishing mortality rate was not causing population decline, but suspected that the population biomass may have been in decline at the fishing mortality rates experienced during the late 1980s and 1990s. Therefore, the panel suggested considering the median value of the late 1980s and 1990s as the limit or threshold for the Gulf Menhaden stock. As a target, the panel suggested the median value of the more recent years (2005-2017). These types of benchmarks are based on historical performance of the fishery. Alternatively, the panel also recommended that benchmarks based on natural mortality rate be considered. Specifically, for the threshold, the panel recommended that the fishing mortality rate not exceed the natural mortality rate under the premise that those fish that would die due to natural causes are available to be taken via fishing. This type of benchmark is used in other parts of the world, for example on the category 3 and 4 ICES species (Patterson 1992, Gabriel and Mace 1999, Mace 2001, ICES 2018). The panel suggested using the geometric mean of natural mortality for ages-0 to -2, given that the natural mortality rate was age varying. These ages represent those that are the ages fished the most heavily (age-1 and age-2) and those that will be entering the fishery the next year (age-0). In addition, the panel suggested that the target be 75% of the natural mortality rate. Given these two options, the resultant benchmark values were rather consistent with each other. Thus, the panel recommended using the natural mortality based metric, with support from the historical, observed values.

For the *SSB* based benchmarks (based on fecundity for this stock assessment), the assessment panel recommended using percentages based on equilibrium values when *F*=0. These types of benchmarks are used to determine overfished status for other species in the United States (PFMC 2016). Specifically, the assessment panel recommended using equilibrium based values at *F*=0 to determine the *SSB* associated with a population in equilibrium under no fishing pressure. The panel then recommended that the target be the *SSB* value at 50% of the *SSB* when *F*=0. Theoretically, this would be the level at *MSY* given that when looking at the surplus production curve, *MSY* occurs at half the *SSB* or *B* on the curve (optimum harvest levels are at that point on the curve). Thus, the assessment panel recommended this level as the target because the fishery would be harvested optimally and would be at a place where replacement by recruitment would be optimal to sustain the population. In addition, the assessment panel recommended using 25% of the *SSB* when *F*=0 as the threshold for the population. This threshold is used for groundfish stocks on the West Coast (PFMC 2016) and provides the level below which *SSB* should not drop in order to maintain a sustainable population. The limit reference point of *SSB* value at 25% of the *SSB* when *F*=0 is generally consistent with the equilibrium limit reference point of 0.3 B_0 selected by Fisheries and Oceans Canada for Pacific Herring (*Clupea pallasii*; Sainsbury 2008, DFO 2017).

8.2.4 Ecosytem-Based Reference Points

Reference points are typically defined only for fishery removals that allow for ‘natural’ removals through a separate mortality term. The natural mortality term (*M*) is often constant but is sometimes allowed to vary with age and time when data are sufficient. Reference points based on *MSY* treat this natural mortality term as ‘lost yield’ in that fishing mortality is typically increased in populations with a high *M* and decreased in population with a low *M*. The difficulty with this approach is that it does not consider the value of natural mortality to the ecosystem in the form of prey biomass for other stocks (e.g., large predators). Awareness of the issue of accounting for the role of Gulf Menhaden as a prey resource has increased in recent years due in part to changes in the management of Atlantic Menhaden (SEDAR 2015) and a general increase in both public and regulatory awareness of the importance of ecosystem issues. The assessment panel discussed factors necessary to adequately account for ecosystem value of Gulf Menhaden in defining fishery reference points and concluded that data and techniques are insufficient at present to incorporate them into the assessment. Nonetheless, the panel had some recommendations regarding future efforts to define ecosystem-based reference points for this stock. The primary issue is to separate predatory mortality from ‘lost’ yield in assessments and to consider this mortality source more as a component of the fishery with a more complete accounting of necessary allocation of yield to ecosystem services.

8.3 Stock Status Determination

8.3.1 Overfishing Status

The base BAM model estimates for the benchmarks and the geometric mean of 2015-2017 *F* and *SSB* values are indicated in Table7.10. Based on the benchmarks presented in this section, the results suggest that generally the current stock status is that overfishing is not occurring (Table 7.10).

The entire time series of estimates of full fishing mortality over $F_{F=M}$ is shown in Figure 7.38. Additionally, time series of $F/F_{F=0.75M}$ was shown in Figure 7.44. The history of fishing mortality rates in these figures suggests that overfishing likely occurred in the 1980s and 1990s, but generally, overfishing is unlikely to be occurring in the present (Figure 7.42 and 7.44). We note that the fishery has not been subject historically to management based on target and limit benchmarks suggested here and we caution interpreting retrospectively the overfishing determination because the participants in the fishery were not given an opportunity or indication that reductions in effort may have been warranted. The sensitivity runs agree with the stock status from the base run, while the MCBs demonstrate some uncertainty contingent on the value for natural mortality used (Figures 7.42, 7.44, and 7.46).

8.3.2 Overfished Status

The base BAM model estimates for the benchmarks and the geometric mean of 2015-2017 *F* and *SSB* values are indicated in Table7.10. Based on the benchmarks presented in this section, the results suggest that generally the current stock status is not overfished (Table7.10).

The entire time series of estimates of $SSB/SSB_{25\%\ of\ F=0}$ are shown in Figure 7.43. Additionally, time series of $SSB/SSB_{50\%\ at\ F=0}$ was shown in Figure 7.45. The history of *SSB* in these figures suggests that the population may have been near the overfished level in the past. The results indicate that the geometric mean of fecundity estimates for the terminal three years are well above $SSB_{25\%\ of\ F=0}$, with not a single bootstrap estimate falling below 1.0 (Figure 7.43 and 7.45).

8.3.3 Control Rules

As management goals and objectives have not been clearly defined for the fishery, the phase plot of status variables relative to $F_{F=M}$ based benchmarks is shown for illustrative purposes (Figure 7.57). In the most recent years, full *F* has not exceeded $F_{F=M}$, thus overfishing is not a concern. A phase plot for the terminal year based on 2,557 bootstrapped experiments demonstrates the uncertainty relative to these control rules in the terminal years 2015-2017 (Figure 7.47 and 7.48).

8.3.4 Uncertainty

Uncertainty of the status of the stock relative to the benchmarks was investigated using several approaches in line with the recommendations of the SEDAR Uncertainty Workshop Report (SEDAR 2010b). First sensitivity runs were made to explore the effect on benchmarks from changes in assumptions from the base run (Table 7.10). Next sensitivity of the estimates was investigated based on a bootstrapped analysis within the BAM model. The sensitivity runs resulted in the same stock status as the base run, and generally the MCBs also resulted in the same stock status as the base run.

9.0 Projections

The assessment panel agreed to put together projection methodology and run one example for the stock assessment review. The goal was to have the projections available for review for managers, who will then be able to request specific projections as they continue to work with stakeholders and define the goals and objectives for the fishery on Gulf Menhaden. The specific projection that was run was at the fishing mortality rate at the suggested target or *F=0.75M*, which was a value of 0.99. Each bootstrap run of the projection (realization) has a different target value given that natural mortality was one of the defined uncertainties for the MCB runs.

These projections use the same methods described in the Atlantic Menhaden stock assessments (SEDAR 40) except that fishing mortality rate is being projected rather than a total allowable catch (TAC) being specified. All calculations were done using the latest results from this stock assessment.

9.1 Methods

Data into and output from the Monte Carlo bootstrap (MCB) runs of the base run of the Beaufort Assessment Model (BAM) were used as the basis for the projections within this document (see Section 6 for details on base run and MCB runs). Projections were run for a total of 3 years with constant fishing mortality rate projected (2018-2020). The starting conditions of the projection analysis include initial numbers at age, which were the estimated numbers at age, N_a, for year 2018 from the BAM for each MCB run.

Numbers at age after the initial year were calculated as:

$$N_{a+1,y+1} = N_{a,y} e^{-Z_{a,y}}$$

where Z was age and year specific mortality and equals natural mortality for each age for that year plus the fishing mortality rate times the selectivity at age. The vector for natural mortality for each projection was the vector from each MCB run. Selectivity was a vector from each MCB run and was the vector in the last time period. Fishing mortality was projected as the value of the geometric mean of natural mortality for ages-0 to -2, which is the suggested target. Annual landings were calculated using the Baranov catch equation and weight of landings.

Recruitment was projected without an underlying stock-recruitment function and was based on the median recruitment observed in each MCB run. Recruitment variability was included whereby for each year a deviation in recruitment was selected randomly with replacement from the deviations estimated in each MCB run.

9.2 Projection Methodology Considerations

As usual, projection results should be interpreted in light of the model assumptions and key aspects of the data. Some major considerations are the following:

- Fisheries were assumed to continue fishing at their estimated current selectivity patterns. New management regulations that alter those selectivities would likely affect projection results.

- If future recruitment is characterized by runs of large or small year classes, possibly due to environmental or ecological conditions, stock trajectories may be affected.
- Projections apply the Baranov catch equation to relate *F* and landings using a one-year time step, as in the assessment. The catch equation implicitly assumes that mortality occurs throughout the year. This assumption is violated when seasonal closures are in effect, introducing additional and unquantified uncertainty into the projection results.
- In general, projections of fish stocks are highly uncertain, particularly in the long term (e.g., beyond 5 years).
- Although projections included many major sources of uncertainty, they did not include structural (model) uncertainty. That is, projection results are conditional on one set of functional forms used to describe population dynamics, selectivity, recruitment, etc.

9.3 Projection Results

Projections at the suggested fishing mortality rate target of $F=0.75M$ had a 0% probability of exceeding the threshold of $F=M$ and $SSB25\%_{SSB\ at\ F=0}$. The projections showed that the managing for the suggested target put the spawning stock biomass in fecundity near the suggested target level (Figure 9.1). Recruitment had a high level of uncertainty reflective of the uncertainty observed in the empirical data. Finally, landings changed over time with 2018 having the largest plausible TAC values with a decrease in TAC for 2019 and 2020. The 95% confidence intervals on the landings for 2018 were 455,234 mt to 1,121,728 mt; for 2019 were 320,742 mt to 572,229 mt; and for 2020 were 402,683 mt to 600,859 mt. These values are based on these projections at the specified *F* value, managers need to work to define goals and objectives for the fishery, as well as risk tolerance with respect to a harvest strategy. Once these actions have been taken, managers will have the ability to request projections that suit their needs.

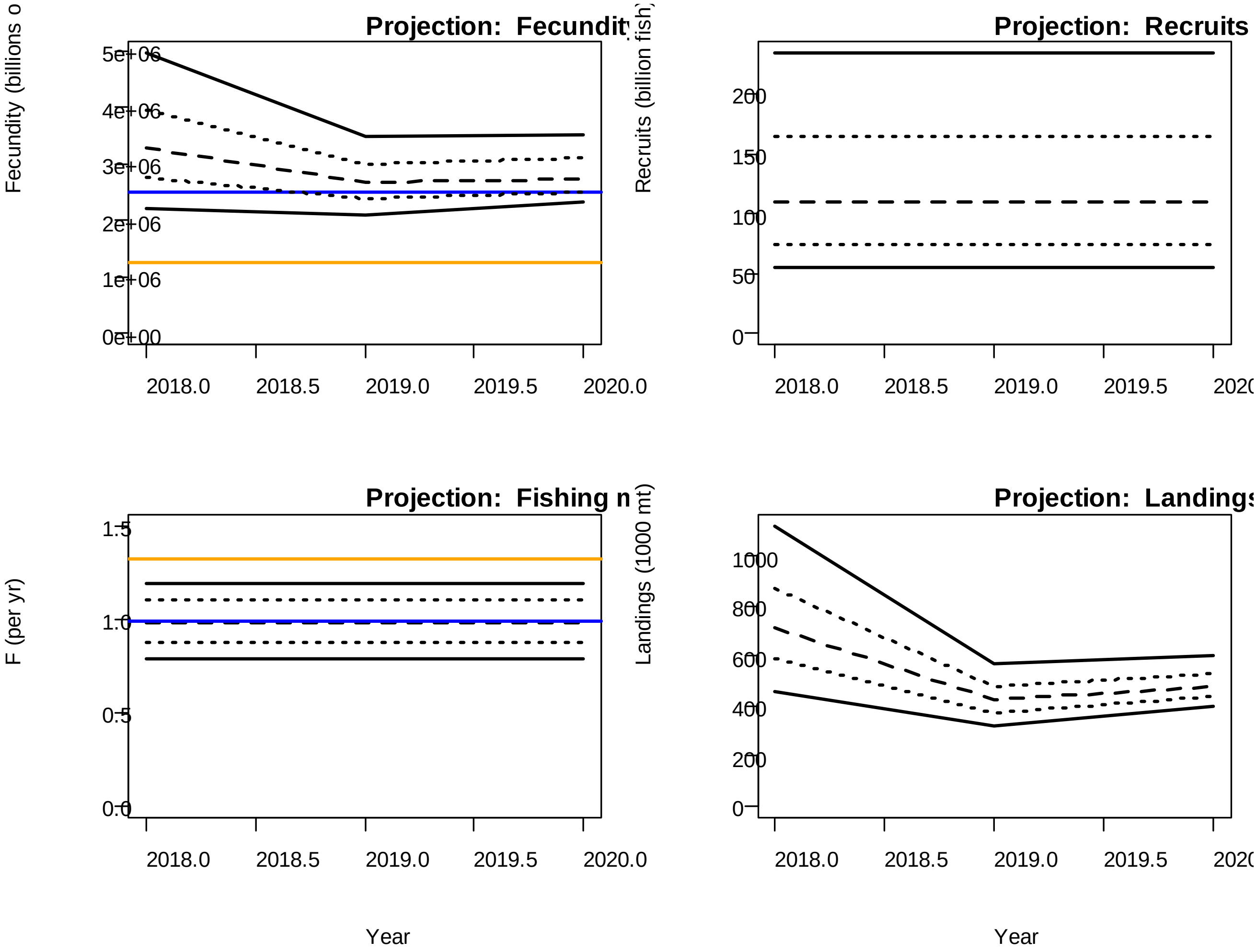


Figure 9.1 Fecundity, recruits, fishing mortality rate, and landings for projections run at *F=0.75M* as defined in Section 7 of this report. The blue lines are the suggested targets, and the orange lines are the suggested thresholds. The dashed line is the median value, the dotted lines are the 25th and 75th percentiles, and the solid lines are the 5th and 95th percentiles.

10.0 Research Recommendations

Throughout the course of the Data Workshop and Assessment Workshop, a number of items were identified as important research topics for future stock assessments. The assessment panel evaluated the various items and developed a consensus priority list.

DATA ELEMENT	RECOMMENDATION	Priority
Genetics And Stock Structure	Improve species identifications at the periphery of the Gulf menhaden's range in Texas and Alabama/Florida waters for juveniles and adults.	High
Tagging Study (New)	Conduct Gulf menhaden tag/recovery study for better estimates of natural mortality, migration, growth, etc. which are inputs for the stock assessment.	High
Fishery-Independent Juvenile Index	Design and implement a survey dedicated to determining menhaden recruitment in the coastal rivers and upper bays of the northern Gulf of Mexico.	Med/High
Genetics And Stock Structure	Identify menhaden-specific nuclear DNA markers (preferably microsatellites or SNPs) using lab-based DNA library screening techniques. Evaluate these markers for use in genetic studies of Gulf menhaden.	Med/High
Fishery-Independent Adult Index	Collect and age Gulf menhaden scales from fishery-independent gears (e.g., gill nets) to determine selectivity. Expand efforts to age menhaden by state agencies.	Med
Stock Status Benchmarks	Research effort should be focused on determining appropriate reference points for the stock to ensure long term sustainability while balancing the desires of stakeholders to effectively exploit the stock.	Med
Modeling	Benchmarks – Develop procedures to establish assessment benchmarks (e.g., F or proxies) that account for the multiple priorities of ecosystem management that could include predation mortality and ecological yield separate from other forms of natural mortality.	Med
Recruitment Evaluation	Understanding the recruitment drivers for Gulf Menhaden that includes a number of environmental parameters.	Med/Low
Environmental Indices	Develop a habitat index to examine the potential shift in the Gulf menhaden population to more inshore waters as marsh converts to open water from coastal land loss.	Med/Low
Legacy Data (Fishery-Dependent Surveys)	Process and analyze samples that address the homogeneity of the catch in the hold of the reduction fishery vessels.	Med/Low
Predator/Prey	Expand understanding of diets of potential Gulf Menhaden predators using a variety of tools including traditional stomach analysis, DNA barcoding, and fatty acid profiles Gulf wide.	Med/Low
Legacy Data (Tagging Study)	Evaluate using current methods the historic archived tag data from Ahrenholz's original work.	Low

DATA ELEMENT	RECOMMENDATION	Priority
Fishery-Independent Adult Survey	Develop and implement an acoustic survey for menhaden populations during winter months to determine spatial distribution and abundance.	Low
Mortality Study	Evaluation of menhaden involved in ‘fish kills’ which can include impingement, red tides, freezes, and jubilees. Quantifying the additional (non-natural) mortality on populations.	Low
Modeling	Conduct additional research into simulation models such as MSVPAs, ECO-SIM, EcoPath, etc.; results could produce better estimates of natural mortality as well as other fishery parameters.	Low

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Appendix A1

```
//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//##
//##  SEDAR 63  Gulf menhaden assessment model, Summer  2018
//##  NMFS, Beaufort Lab, Sustainable Fisheries Branch
//##
//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
DATA_SECTION

!!cout << "Starting Beaufort Assessment Model" << endl;
!!cout << endl;
!!cout << "                BAM!" << endl;
!!cout << endl;

//--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//-- BAM DATA_SECTION: set-up section
//--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>

// Starting and ending year of the model (year data starts)
init_int styr;
init_int endyr;

//Starting year to estimate recruitment deviation from S-R curve
init_int styr_rec_dev;
//Ending year to estimate recruitment deviation from S-R curve
init_int endyr_rec_dev;
//possible 3 phases of constraints on recruitment deviations
init_int endyr_rec_phase1;
init_int endyr_rec_phase2;

// ending years for selectivity blocks
init_int endyr_selex_phase1;
init_int endyr_selex_phase2;

//number assessment years
number nyrs;
number nyrs_rec;

//this section MUST BE INDENTED!!!
 LOCAL_CALCS
   nyrs=endyr-styr+1.;
   nyrs_rec=endyr_rec_dev-styr_rec_dev+1.;
 END_CALCS

//Total number of ages in population model
init_int nages;
// Vector of ages for age bins in population model
init_vector agebins(1,nages);

//Total number of ages used to match age comps: plus group may differ from popn, first age must not
init_int nages_agec;

//Vector of ages for age bins in age comps
init_vector agebins_agec(1,nages_agec);
```

```
//Total number of length bins for each matrix and width of bins)
init_int nlenbins;          //used to match data
init_number lenbins_width;  //width of length bins (mm)

//Vector of lengths for length bins (mm)(midpoint)
init_vector lenbins(1,nlenbins);

//Max F used in spr and msy calcs
init_number max_F_spr_msy;
//Total number of iterations for spr calcs
init_int n_iter_spr;
//Total number of iterations for msy calcs
int n_iter_msy;
 LOCAL_CALCS
                        n_iter_msy=n_iter_spr;
 END_CALCS

//Starting year to compute arithmetic average recruitment for SPR-related values
init_int styr_rec_spr;
//Ending year to compute arithmetic average recruitment for SPR-related values
init_int endyr_rec_spr;
number nyrs_rec_spr;
 LOCAL_CALCS
   nyrs_rec_spr=endyr_rec_spr-styr_rec_spr+1.;
 END_CALCS

//Number years at end of time series over which to average sector F's, for weighted selectivities
init_int selpar_n_yrs_wgted;
//bias correction (set to 1.0 for no bias correction or a negative value to compute from rec variance)
init_number set_BiasCor;

//--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//-- BAM DATA_SECTION: observed data section
//--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>

//###LA gill net index ####################################################
//CPUE
init_int styr_lagn_cpue;
init_int endyr_lagn_cpue;
init_vector obs_lagn_cpue(styr_lagn_cpue,endyr_lagn_cpue);   //Observed CPUE
init_vector lagn_cpue_cv(styr_lagn_cpue,endyr_lagn_cpue);    //CV of cpue

// Length Compositions
init_int nyr_lagn_lenc;
init_ivector yrs_lagn_lenc(1,nyr_lagn_lenc);
init_vector nsamp_lagn_lenc(1,nyr_lagn_lenc);
init_vector nfish_lagn_lenc(1,nyr_lagn_lenc);
init_matrix obs_lagn_lenc(1,nyr_lagn_lenc,1,nlenbins);

//###seine index #############################################################
//CPUE
init_int styr_seine_cpue;
init_int endyr_seine_cpue;
init_vector obs_seine_cpue(styr_seine_cpue,endyr_seine_cpue);   //Observed CPUE
init_vector seine_cpue_cv(styr_seine_cpue,endyr_seine_cpue);    //CV of cpue
```

```
//################Commercial reduction fishery fleet #######################################
// Comm reduction  landings (1000 mt)
init_int styr_cR_L;
init_int endyr_cR_L;
init_vector obs_cR_L(styr_cR_L,endyr_cR_L);
init_vector cR_L_cv(styr_cR_L,endyr_cR_L);

// Comm reduction age compositions
init_int nyr_cR_agec;
init_ivector yrs_cR_agec(1,nyr_cR_agec);
init_vector nsamp_cR_agec(1,nyr_cR_agec);
init_vector nfish_cR_agec(1,nyr_cR_agec);
init_matrix obs_cR_agec(1,nyr_cR_agec,1,nages_agec);


//--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//-- BAM DATA_SECTION: parameter section
//--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//##################Single Parameter values and initial guesses #################################
// von Bert parms in FL mm population
init_vector set_Linf(1,7);
init_vector set_K(1,7);
init_vector set_t0(1,7);
init_vector set_len_cv(1,7);

//Spawner-recruit parameters (Initial guesses or fixed values)
init_vector set_steep(1,7);         //recruitment steepness
init_vector set_log_R0(1,7);        //recruitment R0
init_vector set_R_autocorr(1,7);    //recruitment autocorrelation
init_vector set_rec_sigma(1,7);     //recruitment standard deviation in log space

//Dirichlet-multinomial overdispersion parameters
init_vector set_log_dm_lagn_lc(1,7);    //Dirichlet-multinomial overdispersion parameter-LA gill net
init_vector set_log_dm_cR_ac(1,7);    //Dirichlet-multinomial overdispersion parameter-Comm reduction

//Initial guesses or fixed values of estimated selectivity parameters
init_vector set_selpar_A50_cR1(1,7);     //paramaters for comm reduction double logistic
init_vector set_selpar_slope_cR1(1,7);   //block 1
init_vector set_selpar_A502_cR1(1,7);
init_vector set_selpar_slope2_cR1(1,7);

init_vector set_selpar_A50_cR2(1,7);     //paramaters for comm reduction double logistic
init_vector set_selpar_slope_cR2(1,7);   //block 2
init_vector set_selpar_A502_cR2(1,7);
init_vector set_selpar_slope2_cR2(1,7);

init_vector set_sel_age0_cR(1,7); //input in logit space by age
init_vector set_sel_age1_cR(1,7);
init_vector set_sel_age2_cR(1,7);
init_vector set_sel_age3_cR(1,7);
init_vector set_sel_age4_cR(1,7);

init_vector set_sel_age0_cR2(1,7); //input in logit space by age-period 2
init_vector set_sel_age1_cR2(1,7);
```

```
init_vector set_sel_age2_cR2(1,7);
init_vector set_sel_age3_cR2(1,7);
init_vector set_sel_age4_cR2(1,7);

init_vector set_selpar_A50_lagn(1,7);    //parameters for LA gill net index logistic
init_vector set_selpar_slope_lagn(1,7);

//--index catchability----------------------------------------------------------------------------------
init_vector set_log_q_lagn(1,7);      //catchability coefficient (log) for LA gill net index
init_vector set_log_q_seine(1,7);     //catchability coefficient (log) for seine index

//--mean F's in log space --------------------------------
init_vector set_log_avg_F_cR(1,7);    //commercial reduction fishery

//##################Dev Vector Parameter values (vals) and bounds ################################
//--F vectors---------------------------
init_vector set_log_F_dev_cR(1,3);   //commerical reduction F devs
init_vector set_log_RWq_dev(1,3);    //rand walk on q devs
init_vector set_log_rec_dev(1,3);    //recruitment devs
init_vector set_log_Nage_dev(1,3);   //initial age structure devs

init_vector set_log_F_dev_cR_vals(styr_cR_L,endyr_cR_L);
init_vector set_log_rec_dev_vals(styr_rec_dev,endyr_rec_dev);
init_vector set_log_Nage_dev_vals(2,nages);


//--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//-- BAM DATA_SECTION: likelihood weights section
//--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
init_number set_w_L;           //weight for landings
init_number set_w_I_lagn;       //weight for LA gill net index
init_number set_w_I_seine;      //weight for seine index
init_number set_w_lc_lagn;      //weight for LA gill net len comps
init_number set_w_ac_cR;        //weight for comm reduction age comps
init_number set_w_Nage_init;    //for fitting initial abundance at age (excluding first age)
init_number set_w_rec;          //for fitting S-R curve
init_number set_w_rec_early;    //additional constraint on early years recruitment
init_number set_w_rec_end;      //additional constraint on ending years recruitment
init_number set_w_fullF;        //penalty for any Fapex>3(removed in final phase of optimization)
init_number set_w_Ftune;        //weight applied to tuning F (removed in final phase of optimization)


//--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//-- BAM DATA_SECTION: miscellaneous stuff section
//--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//TL(mm)-weight(whole weight in kg) relationship: W=aL^b
init_number wgtpar_a;
init_number wgtpar_b;

///Maturity and proportion female at age
init_vector maturity_f_obs(1,nages);           //proportion females mature at age
init_vector maturity_m_obs(1,nages);           //proportion males mature at age
init_vector prop_f_obs(1,nages);               //sex ratio; prop female at age
init_vector fecundity(1,nages);                //fecundity at age
init_vector wgt_spawn(1,nages);                //weight at age at spawning
init_vector wgt_middle(1,nages);               //weight at age at middle of year
```

```
init_number spawn_time_frac; //time of year of peak spawning, as a fraction of the year

// Natural mortality
init_vector set_M(1,nages);     //age-dependent: used in model

//Spawner-recruit parameters (Initial guesses or fixed values)
init_int SR_switch;

//rate of increase on q
init_int set_q_rate_phase;  //value sets estimation phase of rate increase, negative value turns it off
init_number set_q_rate;

//density dependence on fishery q's
init_int set_q_DD_phase;      //value sets estimation phase of random walk, negative value turns it off
init_number set_q_DD_beta;    //value of 0.0 is density indepenent
init_number set_q_DD_beta_se;
init_int set_q_DD_stage;      //age to begin counting biomass, should be near full exploitation

//random walk on fishery q's
init_number set_RWq_var;     //assumed variance of RW q

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

//threshold sample sizes for length comps
init_number minSS_lagn_lenc;

//threshold sample sizes for age comps
init_number minSS_cR_agec;

//input for deterministic F-based projections
init_int endyr_proj; //last year of projections, by default, first year is endyr+1
init_int styr_regs;  //apply current F until styr_regs, then the projection F
init_int Fproj_switch; //Value to use for Fproj: 1=current F, 2=Fmsy, 3=F30, 4=F40
init_number Fproj_mult; //multiplier to the Fproj
int styr_proj;
 LOCAL_CALCS
   styr_proj=endyr+1;
 END_CALCS

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

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

number sqrt2pi;
number g2mt;                    //conversion of grams to metric tons
number g2kg;                    //conversion of grams to kg
number g2klb;                   //conversion of grams to 1000 lb
number mt2klb;                  //conversion of metric tons to 1000 lb
number mt2lb;                   //conversion of metric tons to lb
```

```
number dzero;                    //small additive constant to prevent division by zero
number huge_number;              //huge number, to avoid irregular parameter space

init_number end_of_data_file;

//!!cout << "start year of landings" << styr_cR_L << endl;
//!!cout << "fecundity" << fecundity << endl;
//!!cout << "Nage devs settings" << set_log_Nage_dev(1,3) << endl;
//!!cout << "Linf settings" << set_Linf << endl;

//this section MUST BE INDENTED!!!
 LOCAL_CALCS
   if(end_of_data_file!=999)
   {
       cout << "*** WARNING: Data File NOT READ CORRECTLY ****" << endl;
       exit(0);
   }
   else
   {cout << "Data File read correctly" << endl;}
 END_CALCS


PARAMETER_SECTION

 LOCAL_CALCS
  const double Linf_LO=set_Linf(2); const double Linf_HI=set_Linf(3); const double Linf_PH=set_Linf(4);
  const double K_LO=set_K(2); const double K_HI=set_K(3); const double K_PH=set_K(4);
  const double t0_LO=set_t0(2); const double t0_HI=set_t0(3); const double t0_PH=set_t0(4);
  const double len_cv_LO=set_len_cv(2); const double len_cv_HI=set_len_cv(3); const double len_cv_PH=set_len_cv(4);

  const double steep_LO=set_steep(2); const double steep_HI=set_steep(3); const double steep_PH=set_steep(4);
  const double log_R0_LO=set_log_R0(2); const double log_R0_HI=set_log_R0(3); const double log_R0_PH=set_log_R0(4);
  const double R_autocorr_LO=set_R_autocorr(2); const double R_autocorr_HI=set_R_autocorr(3); const double
R_autocorr_PH=set_R_autocorr(4);
  const double rec_sigma_LO=set_rec_sigma(2); const double rec_sigma_HI=set_rec_sigma(3); const double
rec_sigma_PH=set_rec_sigma(4);

  const double log_dm_cR_ac_LO=set_log_dm_cR_ac(2); const double log_dm_cR_ac_HI=set_log_dm_cR_ac(3); const
double log_dm_cR_ac_PH=set_log_dm_cR_ac(4);
  const double log_dm_lagn_lc_LO=set_log_dm_lagn_lc(2); const double log_dm_lagn_lc_HI=set_log_dm_lagn_lc(3); const
double log_dm_lagn_lc_PH=set_log_dm_lagn_lc(4);

  const double selpar_A50_cR1_LO=set_selpar_A50_cR1(2); const double selpar_A50_cR1_HI=set_selpar_A50_cR1(3); const
double selpar_A50_cR1_PH=set_selpar_A50_cR1(4);
  const double selpar_slope_cR1_LO=set_selpar_slope_cR1(2); const double selpar_slope_cR1_HI=set_selpar_slope_cR1(3);
const double selpar_slope_cR1_PH=set_selpar_slope_cR1(4);
  const double selpar_A502_cR1_LO=set_selpar_A502_cR1(2); const double selpar_A502_cR1_HI=set_selpar_A502_cR1(3);
const double selpar_A502_cR1_PH=set_selpar_A502_cR1(4);
  const double selpar_slope2_cR1_LO=set_selpar_slope2_cR1(2); const double
selpar_slope2_cR1_HI=set_selpar_slope2_cR1(3); const double selpar_slope2_cR1_PH=set_selpar_slope2_cR1(4);

  const double selpar_A50_cR2_LO=set_selpar_A50_cR2(2); const double selpar_A50_cR2_HI=set_selpar_A50_cR2(3); const
double selpar_A50_cR2_PH=set_selpar_A50_cR2(4);
  const double selpar_slope_cR2_LO=set_selpar_slope_cR2(2); const double selpar_slope_cR2_HI=set_selpar_slope_cR2(3);
const double selpar_slope_cR2_PH=set_selpar_slope_cR2(4);
```

```
  const double selpar_A502_cR2_LO=set_selpar_A502_cR2(2); const double selpar_A502_cR2_HI=set_selpar_A502_cR2(3);
const double selpar_A502_cR2_PH=set_selpar_A502_cR2(4);
  const double selpar_slope2_cR2_LO=set_selpar_slope2_cR2(2); const double
selpar_slope2_cR2_HI=set_selpar_slope2_cR2(3); const double selpar_slope2_cR2_PH=set_selpar_slope2_cR2(4);

  const double selpar_age0_cR_LO=set_sel_age0_cR(2); const double selpar_age0_cR_HI=set_sel_age0_cR(3); const double
selpar_age0_cR_PH=set_sel_age0_cR(4);
  const double selpar_age1_cR_LO=set_sel_age1_cR(2); const double selpar_age1_cR_HI=set_sel_age1_cR(3); const double
selpar_age1_cR_PH=set_sel_age1_cR(4);
  const double selpar_age2_cR_LO=set_sel_age2_cR(2); const double selpar_age2_cR_HI=set_sel_age2_cR(3); const double
selpar_age2_cR_PH=set_sel_age2_cR(4);
  const double selpar_age3_cR_LO=set_sel_age3_cR(2); const double selpar_age3_cR_HI=set_sel_age3_cR(3); const double
selpar_age3_cR_PH=set_sel_age3_cR(4);
  const double selpar_age4_cR_LO=set_sel_age4_cR(2); const double selpar_age4_cR_HI=set_sel_age4_cR(3); const double
selpar_age4_cR_PH=set_sel_age4_cR(4);

  const double selpar_age0_cR2_LO=set_sel_age0_cR2(2); const double selpar_age0_cR2_HI=set_sel_age0_cR2(3); const
double selpar_age0_cR2_PH=set_sel_age0_cR2(4);
  const double selpar_age1_cR2_LO=set_sel_age1_cR2(2); const double selpar_age1_cR2_HI=set_sel_age1_cR2(3); const
double selpar_age1_cR2_PH=set_sel_age1_cR2(4);
  const double selpar_age2_cR2_LO=set_sel_age2_cR2(2); const double selpar_age2_cR2_HI=set_sel_age2_cR2(3); const
double selpar_age2_cR2_PH=set_sel_age2_cR2(4);
  const double selpar_age3_cR2_LO=set_sel_age3_cR2(2); const double selpar_age3_cR2_HI=set_sel_age3_cR2(3); const
double selpar_age3_cR2_PH=set_sel_age3_cR2(4);
  const double selpar_age4_cR2_LO=set_sel_age4_cR2(2); const double selpar_age4_cR2_HI=set_sel_age4_cR2(3); const
double selpar_age4_cR2_PH=set_sel_age4_cR2(4);

  const double selpar_A50_lagn_LO=set_selpar_A50_lagn(2); const double selpar_A50_lagn_HI=set_selpar_A50_lagn(3);
const double selpar_A50_lagn_PH=set_selpar_A50_lagn(4);
  const double selpar_slope_lagn_LO=set_selpar_slope_lagn(2); const double
selpar_slope_lagn_HI=set_selpar_slope_lagn(3); const double selpar_slope_lagn_PH=set_selpar_slope_lagn(4);

  const double log_q_lagn_LO=set_log_q_lagn(2); const double log_q_lagn_HI=set_log_q_lagn(3); const double
log_q_lagn_PH=set_log_q_lagn(4);
  const double log_q_seine_LO=set_log_q_seine(2); const double log_q_seine_HI=set_log_q_seine(3); const double
log_q_seine_PH=set_log_q_seine(4);

  const double log_avg_F_cR_LO=set_log_avg_F_cR(2); const double log_avg_F_cR_HI=set_log_avg_F_cR(3); const double
log_avg_F_cR_PH=set_log_avg_F_cR(4);

  //-dev vectors-----------------------------------------------------------------------------------------------------------
  const double log_F_dev_cR_LO=set_log_F_dev_cR(1); const double log_F_dev_cR_HI=set_log_F_dev_cR(2); const double
log_F_dev_cR_PH=set_log_F_dev_cR(3);
  const double log_RWq_LO=set_log_RWq_dev(1); const double log_RWq_HI=set_log_RWq_dev(2); const double
log_RWq_PH=set_log_RWq_dev(3);
  const double log_rec_dev_LO=set_log_rec_dev(1); const double log_rec_dev_HI=set_log_rec_dev(2); const double
log_rec_dev_PH=set_log_rec_dev(3);
  const double log_Nage_dev_LO=set_log_Nage_dev(1); const double log_Nage_dev_HI=set_log_Nage_dev(2); const
double log_Nage_dev_PH=set_log_Nage_dev(3);

 END_CALCS

////--------------Growth--------------------------------------------------------------------------
  //Population growth parms and conversions
  init_bounded_number Linf(Linf_LO,Linf_HI,Linf_PH);
  init_bounded_number K(K_LO,K_HI,K_PH);
```

```
  init_bounded_number t0(t0_LO,t0_HI,t0_PH);
  init_bounded_number len_cv_val(len_cv_LO,len_cv_HI,len_cv_PH);
  vector Linf_out(1,8);
  vector K_out(1,8);
  vector t0_out(1,8);
  vector len_cv_val_out(1,8);

  vector meanlen_FL(1,nages);   //mean fork length (mm) at age all fish
  vector wgt_fish_mt(1,nages);
  vector wgt_spawn_mt(1,nages);

  matrix len_cR_mm(styr,endyr,1,nages);         //mean length at age of commercial reduction landings in mm
  matrix wholewgt_cR_mt(styr,endyr,1,nages);    //whole wgt of commercial reduction landings in 1000 mt

  matrix lenprob(1,nages,1,nlenbins);           //distn of size at age (age-length key, 10 mm bins) in population
  number zscore_len;                            //standardized normal values used for computing lenprob
  vector cprob_lenvec(1,nlenbins);              //cumulative probabilities used for computing lenprob
  number zscore_lzero;                          //standardized normal values for length = 0
  number cprob_lzero;                           //length probability mass below zero, used for computing lenprob

  //matrices below are used to match length comps
  matrix lenprob_lagn(1,nages,1,nlenbins);     //distn of size at age in cR

  //init_bounded_dev_vector log_len_cv_dev(1,nages,-2,2,3)
  vector len_sd(1,nages);
  vector len_cv(1,nages); //for fishgraph

//----Predicted length and age compositions
  matrix pred_lagn_lenc(1,nyr_lagn_lenc,1,nlenbins);

  matrix pred_cR_agec(1,nyr_cR_agec,1,nages_agec);
  matrix pred_cR_agec_allages(1,nyr_cR_agec,1,nages);
  matrix ErrorFree_cR_agec(1,nyr_cR_agec,1,nages);

//Sample size (perhaps adjusted herein) used in fitting comp data
  vector nsamp_lagn_lenc_allyr(styr,endyr);
  vector nsamp_cR_agec_allyr(styr,endyr);

//Nfish used in MCB analysis (not used in fitting)
  vector nfish_lagn_lenc_allyr(styr,endyr);
  vector nfish_cR_agec_allyr(styr,endyr);

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

//-----Population-----------------------------------------------------------------------------------
  matrix N(styr,endyr+1,1,nages);          //Population numbers by year and age at start of yr
  matrix N_mdyr(styr,endyr,1,nages);       //Population numbers by year and age at mdpt of yr: used for comps and cpue
  matrix N_spawn(styr,endyr,1,nages);      //Population numbers by year and age at peaking spawning: used for SSB
  init_bounded_vector log_Nage_dev(2,nages,log_Nage_dev_LO,log_Nage_dev_HI,log_Nage_dev_PH);
  vector log_Nage_dev_output(1,nages);     //used in output. equals zero for first age
  matrix B(styr,endyr+1,1,nages);          //Population biomass by year and age at start of yr
  vector totB(styr,endyr+1);               //Total biomass by year
  vector totN(styr,endyr+1);               //Total abundance by year
  vector SSB(styr,endyr+1);                //Total spawning biomass by year (female + male mature biomass)
```

```
  vector rec(styr,endyr+1);               //Recruits by year
  vector prop_f(1,nages);
  vector prop_m(1,nages);
  vector maturity_f(1,nages);
  vector maturity_m(1,nages);
  vector reprod(1,nages);
  matrix SSBatage(styr,endyr,1,nages);

//---Stock-Recruit Function (Beverton-Holt, steepness parameterization)----------
  init_bounded_number log_R0(log_R0_LO,log_R0_HI,log_R0_PH);       //log(virgin Recruitment)
  vector log_R0_out(1,8);
  number R0;                              //virgin recruitment
  init_bounded_number steep(steep_LO,steep_HI,steep_PH); //steepness
  vector steep_out(1,8);
  init_bounded_number rec_sigma(rec_sigma_LO,rec_sigma_HI,rec_sigma_PH);  //sd recruitment residuals
  vector rec_sigma_out(1,8);
  init_bounded_number R_autocorr(R_autocorr_LO,R_autocorr_HI,R_autocorr_PH);  //autocorrelation in SR
  vector R_autocorr_out(1,8);

  number rec_sigma_sq;                    //square of rec_sigma
  number rec_logL_add;                    //additive term in -logL term

  init_bounded_dev_vector log_rec_dev(styr_rec_dev,endyr_rec_dev,log_rec_dev_LO,log_rec_dev_HI,log_rec_dev_PH);
  vector log_rec_dev_output(styr,endyr+1);           //used in t.series output. equals zero except for yrs in log_rec_dev
  vector log_rec_dev_out(styr_rec_dev,endyr_rec_dev);  //used in output for bound checking

  number var_rec_dev;                     //variance of log recruitment deviations, from yrs with unconstrainted S-R(XXXX-
XXXX)
  number sigma_rec_dev;                   //sample SD of log residuals (may not equal rec_sigma
  number BiasCor;                         //Bias correction in equilibrium recruits
  number S0;                              //equal to spr_F0*R0 = virgin SSB
  number B0;                              //equal to bpr_F0*R0 = virgin B
  number R1;                              //Recruits in styr
  number R_virgin;                        //unfished recruitment with bias correction
  vector SdS0(styr,endyr+1);              //Spawners relative to the unfished level

  init_bounded_number log_dm_lagn_lc(log_dm_lagn_lc_LO,log_dm_lagn_lc_HI,log_dm_lagn_lc_PH);
  init_bounded_number log_dm_cR_ac(log_dm_cR_ac_LO,log_dm_cR_ac_HI,log_dm_cR_ac_PH);
  vector log_dm_lagn_lc_out(1,8);
  vector log_dm_cR_ac_out(1,8);


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

//Commercial reduction-------------------------------------------------
  matrix sel_cR(styr,endyr,1,nages);
  vector sel_cR_block1(1,nages);
  vector sel_cR_block2(1,nages);

  //block 1
  init_bounded_number selpar_A50_cR1(selpar_A50_cR1_LO,selpar_A50_cR1_HI,selpar_A50_cR1_PH);
  init_bounded_number selpar_slope_cR1(selpar_slope_cR1_LO,selpar_slope_cR1_HI,selpar_slope_cR1_PH);
  init_bounded_number selpar_A502_cR1(selpar_A502_cR1_LO,selpar_A502_cR1_HI,selpar_A502_cR1_PH);
  init_bounded_number selpar_slope2_cR1(selpar_slope2_cR1_LO,selpar_slope2_cR1_HI,selpar_slope2_cR1_PH);
```

```
  vector selpar_A50_cR1_out(1,8);
  vector selpar_slope_cR1_out(1,8);
  vector selpar_A502_cR1_out(1,8);
  vector selpar_slope2_cR1_out(1,8);

  //block 2
  init_bounded_number selpar_A50_cR2(selpar_A50_cR2_LO,selpar_A50_cR2_HI,selpar_A50_cR2_PH);
  init_bounded_number selpar_slope_cR2(selpar_slope_cR2_LO,selpar_slope_cR2_HI,selpar_slope_cR2_PH);
  init_bounded_number selpar_A502_cR2(selpar_A502_cR2_LO,selpar_A502_cR2_HI,selpar_A502_cR2_PH);
  init_bounded_number selpar_slope2_cR2(selpar_slope2_cR2_LO,selpar_slope2_cR2_HI,selpar_slope2_cR2_PH);

  vector selpar_A50_cR2_out(1,8);
  vector selpar_slope_cR2_out(1,8);
  vector selpar_A502_cR2_out(1,8);
  vector selpar_slope2_cR2_out(1,8);

  //logit based selectivity cR block 1
  init_bounded_number sel_age0_cR_logit(selpar_age0_cR_LO,selpar_age0_cR_HI,selpar_age0_cR_PH);  //cR selectivity at
age in logit space
  init_bounded_number sel_age1_cR_logit(selpar_age1_cR_LO,selpar_age1_cR_HI,selpar_age1_cR_PH);
  init_bounded_number sel_age2_cR_logit(selpar_age2_cR_LO,selpar_age2_cR_HI,selpar_age2_cR_PH);
  init_bounded_number sel_age3_cR_logit(selpar_age3_cR_LO,selpar_age3_cR_HI,selpar_age3_cR_PH);
  init_bounded_number sel_age4_cR_logit(selpar_age4_cR_LO,selpar_age4_cR_HI,selpar_age4_cR_PH);
  vector sel_age_cR_vec(1,nages);
  number selpar_age0_cR;
  number selpar_age1_cR;
  number selpar_age2_cR;
  number selpar_age3_cR;
  number selpar_age4_cR;
  vector selpar_age0_cR_out(1,8);
  vector selpar_age1_cR_out(1,8);
  vector selpar_age2_cR_out(1,8);
  vector selpar_age3_cR_out(1,8);
  vector selpar_age4_cR_out(1,8);

  //logit based selectivity cR block 2
  init_bounded_number sel_age0_cR2_logit(selpar_age0_cR2_LO,selpar_age0_cR2_HI,selpar_age0_cR2_PH);  //cR
selectivity at age in logit space-period 2
  init_bounded_number sel_age1_cR2_logit(selpar_age1_cR2_LO,selpar_age1_cR2_HI,selpar_age1_cR2_PH);
  init_bounded_number sel_age2_cR2_logit(selpar_age2_cR2_LO,selpar_age2_cR2_HI,selpar_age2_cR2_PH);
  init_bounded_number sel_age3_cR2_logit(selpar_age3_cR2_LO,selpar_age3_cR2_HI,selpar_age3_cR2_PH);
  init_bounded_number sel_age4_cR2_logit(selpar_age4_cR2_LO,selpar_age4_cR2_HI,selpar_age4_cR2_PH);
  vector sel_age_cR2_vec(1,nages);
  number selpar_age0_cR2;
  number selpar_age1_cR2;
  number selpar_age2_cR2;
  number selpar_age3_cR2;
  number selpar_age4_cR2;
  vector selpar_age0_cR2_out(1,8);
  vector selpar_age1_cR2_out(1,8);
  vector selpar_age2_cR2_out(1,8);
  vector selpar_age3_cR2_out(1,8);
  vector selpar_age4_cR2_out(1,8);

  //LA gill net index
  matrix sel_lagn(styr_lagn_cpue,endyr_lagn_cpue,1,nages);
```

```
  vector sel_lagn_block1(1,nages);

  init_bounded_number selpar_A50_lagn(selpar_A50_lagn_LO,selpar_A50_lagn_HI,selpar_A50_lagn_PH);
  init_bounded_number selpar_slope_lagn(selpar_slope_lagn_LO,selpar_slope_lagn_HI,selpar_slope_lagn_PH);

  vector selpar_A50_lagn_out(1,8);
  vector selpar_slope_lagn_out(1,8);


//Weighted total selectivity--------------------------------------------
 //effort-weighted, recent selectivities
  vector sel_wgted_L(1,nages);  //toward landings
  vector sel_wgted_tot(1,nages);//toward Z, landings plus deads discards

//-----------------------------------------------------------------------------------------------------------------------------------------------
//-------CPUE Predictions--------------------------------
  vector pred_lagn_cpue(styr_lagn_cpue,endyr_lagn_cpue);    //predicted LA gill net index (number fish per effort)
  matrix N_lagn(styr_lagn_cpue,endyr_lagn_cpue,1,nages);    //used to compute LA gill net index

  vector pred_seine_cpue(styr_seine_cpue,endyr_seine_cpue);  //predicted seine index (number fish per effort)
  matrix N_seine(styr_seine_cpue,endyr_seine_cpue,1,nages);  //used to compute seine index

//---Catchability (CPUE q's)----------------------------------------------------------
  init_bounded_number log_q_lagn(log_q_lagn_LO,log_q_lagn_HI,log_q_lagn_PH);
  init_bounded_number log_q_seine(log_q_seine_LO,log_q_seine_HI,log_q_seine_PH);
  vector log_q_lagn_out(1,8);
  vector log_q_seine_out(1,8);

  number q_rate;
  vector q_rate_fcn_lagn(styr_lagn_cpue,endyr_lagn_cpue);    //increase due to technology creep (saturates in 2003)-
shouldn't really be used since fishery-independent
  vector q_rate_fcn_seine(styr_seine_cpue,endyr_seine_cpue); //increase due to technology creep (saturates in 2003)-
shouldn't really be used since fishery-independent

  //init_bounded_number q_DD_beta(0.1,0.9,set_q_DD_phase);    //not estimated so commented out and declared as
number (below)
  number q_DD_beta;
  vector q_DD_fcn(styr,endyr);    //density dependent function as a multiple of q (scaled a la Katsukawa and Matsuda. 2003)
  number B0_q_DD;               //B0 of ages q_DD_age plus
  vector B_q_DD(styr,endyr);      //annual biomass of ages q_DD_age plus

  //Random walk catchability - not using
  init_bounded_vector q_RW_log_dev_lagn(styr_lagn_cpue,endyr_lagn_cpue-1,log_RWq_LO,log_RWq_HI,log_RWq_PH);
  init_bounded_vector q_RW_log_dev_seine(styr_seine_cpue,endyr_seine_cpue-
1,log_RWq_LO,log_RWq_HI,log_RWq_PH);

  //Fishery independent catchability over time, may be constant
  vector q_lagn(styr_lagn_cpue,endyr_lagn_cpue);
  vector q_seine(styr_seine_cpue,endyr_seine_cpue);

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

```
  matrix L_total_num(styr,endyr,1,nages); //total landings in number at age
  matrix L_total_mt(styr,endyr,1,nages);  //landings in 1000 mt whole wgt at age
  //vector L_total_knum_yr(styr,endyr);     //total landings in 1000 fish by yr summed over ages
  vector L_total_mt_yr(styr,endyr);       //total landings (1000 mt whole wgt) by yr summed over ages


////---MSY calcs----------------------------------------------------------------------------
  number F_cR_prop;       //proportion of F_sum attributable to cR, last X=selpar_n_yrs_wgted yrs
  number F_temp_sum;      //sum of geom mean Fsum's in last X yrs, used to compute F_fishery_prop

  vector F_end(1,nages);
  vector F_end_L(1,nages);
  number F_end_apex;

  number SSB_msy_out;           //SSB (total mature biomass) at msy
  number F_msy_out;             //F at msy
  number msy_mt_out;            //max sustainable yield (1000 mt whole wgt)
  //number msy_knum_out;          //max sustainable yield (1000 fish)
  number B_msy_out;             //total biomass at MSY
  number R_msy_out;             //equilibrium recruitment at F=Fmsy
  number spr_msy_out;           //spr at F=Fmsy

  number F35_dum;                                        //intermediate calculation for F35
  number F30_dum;                                        //intermediate calculation for F30
  number F40_dum;                                        //intermediate calculation for F40
  number F35_out;             //F35
  number F30_out;             //F30
  number F40_out;             //F40
  number SSB_F30_out;
  number B_F30_out;
  number R_F30_out;
  number L_F30_knum_out;
  number L_F30_mt_out;
  number rec_mean;            //arithemetic average recruitment used in SPR-related quantities

  vector N_age_msy(1,nages);          //numbers at age for MSY calculations: beginning of yr
  vector N_age_msy_spawn(1,nages);   //numbers at age for MSY calculations: time of peak spawning
  vector L_age_msy(1,nages);          //landings at age for MSY calculations
  vector Z_age_msy(1,nages);          //total mortality at age for MSY calculations
  vector F_L_age_msy(1,nages);        //fishing mortality landings (not discards) at age for MSY calculations
  vector F_msy(1,n_iter_msy);         //values of full F to be used in equilibrium calculations
  vector spr_msy(1,n_iter_msy);       //reproductive capacity-per-recruit values corresponding to F values in F_msy
  vector R_eq(1,n_iter_msy);          //equilibrium recruitment values corresponding to F values in F_msy
  vector L_eq_mt(1,n_iter_msy);       //equilibrium landings(1000 mt whole wgt) values corresponding to F values in F_msy
  //vector L_eq_knum(1,n_iter_msy);     //equilibrium landings(1000 fish) values corresponding to F values in F_msy
  vector SSB_eq(1,n_iter_msy);        //equilibrium reproductive capacity values corresponding to F values in F_msy
  vector B_eq(1,n_iter_msy);          //equilibrium biomass values corresponding to F values in F_msy

  vector FdF_msy(styr,endyr);
  vector FdF30(styr,endyr);
  vector SdSSB_msy(styr,endyr+1);
  number SdSSB_msy_end;
  number FdF_msy_end;
  number FdF_msy_end_mean;           //geometric mean of last X yrs
  vector SdSSB_F30(styr,endyr+1);
```

```
  number SdSSB_F30_end;
  number FdF30_end_mean;            //geometric mean of last selpar_n_yrs_wgted yrs
  number Fend_mean_temp;               //intermediate calc for geometric mean of last selpar_n_yrs_wgted yrs
  number Fend_mean;                       //geometric mean of last selpar_n_yrs_wgted yrs
  vector L_age_F30(1,nages);        //landings at age for F30 calculations

  vector wgt_wgted_L_mt(1,nages);   //fishery-weighted average weight at age of landings in whole weight
  number wgt_wgted_L_denom;         //used in intermediate calculations

  number iter_inc_msy;             //increments used to compute msy, equals 1/(n_iter_msy-1)

////--------Mortality------------------------------------------------------------------

  vector M(1,nages);                     //age-dependent natural mortality

  matrix F(styr,endyr,1,nages);
  vector Fsum(styr,endyr);                //Full fishing mortality rate by year
  vector Fapex(styr,endyr);                //Max across ages, fishing mortality rate by year (may differ from Fsum bc of dome-
shaped sel
  matrix Z(styr,endyr,1,nages);

  init_bounded_number log_avg_F_cR(log_avg_F_cR_LO,log_avg_F_cR_HI,log_avg_F_cR_PH);
  vector log_avg_F_cR_out(1,8);
  init_bounded_dev_vector log_F_dev_cR(styr_cR_L,endyr_cR_L,log_F_dev_cR_LO,log_F_dev_cR_HI,log_F_dev_cR_PH);
  vector log_F_dev_cR_out(styr_cR_L,endyr_cR_L);
  matrix F_cR(styr,endyr,1,nages);
  vector F_cR_out(styr,endyr);       //used for intermediate calculations in fcn get_mortality
  number log_F_dev_init_cR;
  number log_F_dev_end_cR;


//---Per-recruit stuff-------------------------------------------------------------------------------------
  vector N_age_spr(1,nages);        //numbers at age for SPR calculations: beginning of year
  vector N_age_spr_spawn(1,nages);   //numbers at age for SPR calculations: time of peak spawning
  vector L_age_spr(1,nages);        //catch at age for SPR calculations
  vector Z_age_spr(1,nages);        //total mortality at age for SPR calculations
  vector spr_static(styr,endyr);     //vector of static SPR values by year
  vector F_L_age_spr(1,nages);      //fishing mortality of landings (not discards) at age for SPR calculations
  vector F_spr(1,n_iter_spr);       //values of full F to be used in per-recruit calculations
  vector spr_spr(1,n_iter_spr);      //reproductive capacity-per-recruit values corresponding to F values in F_spr
  vector spr_ratio(1,n_iter_spr);    //reproductive capacity-per-recruit relative to spr_F0 values corresponding to F values in
F_spr
  vector L_spr(1,n_iter_spr);       //landings(lb)-per-recruit (ypr) values corresponding to F values in F_spr

  vector N_spr_F0(1,nages);         //Used to compute spr at F=0: at time of peak spawning
  vector N_bpr_F0(1,nages);         //Used to compute bpr at F=0: at start of year
  vector N_spr_initial(1,nages);     //Initial spawners per recruit at age given initial F
  vector N_initial_eq(1,nages);      //Initial equilibrium abundance at age
  vector F_initial(1,nages);        //initial F at age
  vector Z_initial(1,nages);        //initial Z at age
  number spr_initial;              //initial spawners per recruit
  number spr_F0;                  //Spawning biomass per recruit at F=0
  number bpr_F0;                  //Biomass per recruit at F=0

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

```
////-------SDNR output---------------------------------------------------------------------------

  number sdnr_lc_lagn;

  number sdnr_ac_cR;

  number sdnr_I_lagn;
  number sdnr_I_seine;

////-------Objective function components-----------------------------------------------------------------------------
  number w_L;

  number w_I_lagn;
  number w_I_seine;

  number w_lc_lagn;

  number w_ac_cR;

  number w_Nage_init;
  number w_rec;
  number w_rec_early;
  number w_rec_end;
  number w_fullF;
  number w_Ftune;

  number f_cR_L;

  number f_lagn_cpue;
  number f_seine_cpue;

  number f_lagn_lenc;

  number f_cR_agec;

//  Penalties and constraints. Not all are used.
  number f_Nage_init;             //weight on log devs to estimate initial abundance (excluding first age)
  number f_rec_dev;               //weight on recruitment deviations to fit S-R curve
  number f_rec_dev_early;         //extra weight on deviations in first recruitment stanza
  number f_rec_dev_end;           //extra weight on deviations in ending recruitment stanza
  number f_fullF_constraint;      //penalty for Fapex>X
  number f_Ftune;                 //penalty for tuning F in Ftune yr.  Not applied in final optimization phase.
  number f_priors;                //prior information on parameters

   //init_number xdum;
   objective_function_value fval;
   number fval_data;
   number grad_max;

 //--Dummy variables ----
   number denom;                  //denominator used in some calculations
   number numer;                  //numerator used in some calculations

  //---------- Projection quantities--------------------------------------------------------------
  number F_reg_proj;                                    //value used to define the projections
  vector F_proj(styr_proj,endyr_proj);        //F by yr for projections (=F_reg_proj after regulations start, current F till then)
```

```
  vector L_knum_proj(styr_proj,endyr_proj);    //total landings in 1000 fish for projections
  vector L_mt_proj(styr_proj,endyr_proj);     //total landings in weight (1000 mt) for projections

  vector B_proj(styr_proj,endyr_proj);        //Biomass for projections
  vector SSB_proj(styr_proj,endyr_proj);      //SSB for projections
  vector R_proj(styr_proj,endyr_proj);             //recruits for projections
  vector FL_age_proj(1,nages);                         //F (landings) by age for projections

  matrix N_proj(styr_proj,endyr_proj,1,nages);          //Population numbers by year and age at start of yr
  matrix N_spawn_proj(styr_proj,endyr_proj,1,nages);     //Population numbers by year and age at peaking spawning: used
for SSB in projections
  matrix Z_proj(styr_proj,endyr_proj,1,nages);          //Z by year and age for projections
  matrix L_age_proj(styr_proj,endyr_proj,1,nages);      //Projected landings at age in numbers

//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//INITIALIZATION_SECTION
//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
GLOBALS_SECTION
  #include "admodel.h"          // Include AD class definitions
  #include "admb2r.cpp"         // Include S-compatible output functions (needs preceding)
  #include <time.h>
	time_t start,finish;
	long hour,minute,second;
	double elapsed_time;

//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
RUNTIME_SECTION
 maximum_function_evaluations 1000, 2000,3000, 5000, 10000, 10000, 10000;
 convergence_criteria 1e-2, 1e-2,1e-3, 1e-3, 1e-4, 1e-4, 1e-4;

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

// Set values of fixed parameters or set initial guess of estimated parameters

  //Population
  Linf=set_Linf(1);
  K=set_K(1);
  t0=set_t0(1);
  len_cv_val=set_len_cv(1);

  M=set_M;

  log_R0=set_log_R0(1);
  steep=set_steep(1);
  R_autocorr=set_R_autocorr(1);
  rec_sigma=set_rec_sigma(1);

  log_dm_lagn_lc=set_log_dm_lagn_lc(1);
  log_dm_cR_ac=set_log_dm_cR_ac(1);

  log_q_lagn=set_log_q_lagn(1);
  log_q_seine=set_log_q_seine(1);
```

```
q_rate=set_q_rate;
q_rate_fcn_lagn=1.0;
q_rate_fcn_seine=1.0;
q_DD_beta=set_q_DD_beta;
q_DD_fcn=1.0;
q_RW_log_dev_lagn.initialize();
q_RW_log_dev_seine.initialize();

 if (set_q_rate_phase<0 & q_rate!=0.0)
{
  for (iyear=styr_lagn_cpue; iyear<=endyr_lagn_cpue; iyear++)
    {   if (iyear>styr_lagn_cpue & iyear <=2003)
        {//q_rate_fcn_lagn(iyear)=(1.0+q_rate)*q_rate_fcn_lagn(iyear-1); //compound
           q_rate_fcn_lagn(iyear)=(1.0+(iyear-styr_lagn_cpue)*q_rate)*q_rate_fcn_lagn(styr_lagn_cpue);  //linear
        }
        if (iyear>2003) {q_rate_fcn_lagn(iyear)=q_rate_fcn_lagn(iyear-1);}
    }
  for (iyear=styr_seine_cpue; iyear<=endyr_seine_cpue; iyear++)
    {   if (iyear>styr_seine_cpue & iyear <=2003)
        {//q_rate_fcn_seine(iyear)=(1.0+q_rate)*q_rate_fcn_seine(iyear-1); //compound
           q_rate_fcn_seine(iyear)=(1.0+(iyear-styr_seine_cpue)*q_rate)*q_rate_fcn_seine(styr_seine_cpue);  //linear
        }
        if (iyear>2003) {q_rate_fcn_seine(iyear)=q_rate_fcn_seine(iyear-1);}
    }
} //end q_rate conditional

w_L=set_w_L;

w_I_lagn=set_w_I_lagn;
w_I_seine=set_w_I_seine;

w_lc_lagn=set_w_lc_lagn;

w_ac_cR=set_w_ac_cR;

w_Nage_init=set_w_Nage_init;
w_rec=set_w_rec;
w_rec_early=set_w_rec_early;
w_rec_end=set_w_rec_end;
w_fullF=set_w_fullF;
w_Ftune=set_w_Ftune;

log_avg_F_cR=set_log_avg_F_cR(1);
log_F_dev_cR=set_log_F_dev_cR_vals;

selpar_A50_cR1=set_selpar_A50_cR1(1);
selpar_slope_cR1=set_selpar_slope_cR1(1);
selpar_A502_cR1=set_selpar_A502_cR1(1);
selpar_slope2_cR1=set_selpar_slope2_cR1(1);

selpar_A50_cR2=set_selpar_A50_cR2(1);
selpar_slope_cR2=set_selpar_slope_cR2(1);
selpar_A502_cR2=set_selpar_A502_cR2(1);
selpar_slope2_cR2=set_selpar_slope2_cR2(1);
```

```
  sel_age0_cR_logit=set_sel_age0_cR(1);  //setting cR selectivity at age in logit space
  sel_age1_cR_logit=set_sel_age1_cR(1);
  sel_age2_cR_logit=set_sel_age2_cR(1);
  sel_age3_cR_logit=set_sel_age3_cR(1);
  sel_age4_cR_logit=set_sel_age4_cR(1);

  sel_age0_cR2_logit=set_sel_age0_cR2(1);  //setting cR selectivity at age in logit space
  sel_age1_cR2_logit=set_sel_age1_cR2(1);
  sel_age2_cR2_logit=set_sel_age2_cR2(1);
  sel_age3_cR2_logit=set_sel_age3_cR2(1);
  sel_age4_cR2_logit=set_sel_age4_cR2(1);

  selpar_A50_lagn=set_selpar_A50_lagn(1);
  selpar_slope_lagn=set_selpar_slope_lagn(1);

 sqrt2pi=sqrt(2.*3.14159265);
 g2mt=0.000001;         //conversion of grams to metric tons
 g2kg=0.001;            //conversion of grams to kg
 mt2klb=2.20462;        //conversion of metric tons to 1000 lb
 mt2lb=mt2klb*1000.0;   //conversion of metric tons to lb
 g2klb=g2mt*mt2klb;     //conversion of grams to 1000 lb
 dzero=0.00001;
 huge_number=1.0e+10;

 SSB_msy_out=0.0;

 iter_inc_msy=max_F_spr_msy/(n_iter_msy-1);
 iter_inc_spr=max_F_spr_msy/(n_iter_spr-1);

 maturity_f=maturity_f_obs;
 maturity_m=maturity_m_obs;
 prop_f=prop_f_obs;
 prop_m=1.0-prop_f_obs;

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

     nsamp_lagn_lenc_allyr=missing;
     nsamp_cR_agec_allyr=missing;

     nfish_lagn_lenc_allyr=missing;
     nfish_cR_agec_allyr=missing;

     for (iyear=1; iyear<=nyr_lagn_lenc; iyear++)
       {if (nsamp_lagn_lenc(iyear)>=minSS_lagn_lenc)
         {nsamp_lagn_lenc_allyr(yrs_lagn_lenc(iyear))=nsamp_lagn_lenc(iyear);
          nfish_lagn_lenc_allyr(yrs_lagn_lenc(iyear))=nfish_lagn_lenc(iyear);}}

     for (iyear=1; iyear<=nyr_cR_agec; iyear++)
       {if (nsamp_cR_agec(iyear)>=minSS_cR_agec)
         {nsamp_cR_agec_allyr(yrs_cR_agec(iyear))=nsamp_cR_agec(iyear);
          nfish_cR_agec_allyr(yrs_cR_agec(iyear))=nfish_cR_agec(iyear);}}

  //cout << "nsamp_lagn" << nsamp_lagn_lenc_allyr << endl;

//fill in Fs for msy and per-recruit analyses
```

```
  F_msy(1)=0.0;
  for (ff=2;ff<=n_iter_msy;ff++) {F_msy(ff)=F_msy(ff-1)+iter_inc_msy;}
  F_spr(1)=0.0;
  for (ff=2;ff<=n_iter_spr;ff++) {F_spr(ff)=F_spr(ff-1)+iter_inc_spr;}


//fill in F's, Catch matrices, and log rec dev with zero's
  F_cR.initialize(); L_cR_num.initialize();

  F_cR_out.initialize();

  sel_cR.initialize();
  sel_lagn.initialize();

  sel_cR_block1.initialize();
  sel_cR_block2.initialize();
  sel_lagn_block1.initialize();

  log_rec_dev_output.initialize();
  log_rec_dev=set_log_rec_dev_vals;
  log_Nage_dev_output.initialize();
  log_Nage_dev=set_log_Nage_dev_vals;


//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
//##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
TOP_OF_MAIN_SECTION
  time(&start);
  arrmblsize=20000000;
  gradient_structure::set_MAX_NVAR_OFFSET(1600);
  gradient_structure::set_GRADSTACK_BUFFER_SIZE(2000000);
  gradient_structure::set_CMPDIF_BUFFER_SIZE(2000000);
  gradient_structure::set_NUM_DEPENDENT_VARIABLES(10000);

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

 //cout<<"start"<<endl;

 //get_M_at_age(); //Needed only if M is estimated

  get_length_weight_at_age();
  //cout << "got length, weight, fecundity transitions" <<endl;
  get_reprod();
  //cout << "got reprod" << endl;
  get_length_at_age_dist();
  //cout<< "got predicted length at age distribution"<<endl;
  get_weight_at_age_landings();
  //cout<< "got weight at age of landings"<<endl;
  get_spr_F0();
  //cout << "got F0 spr" << endl;
  get_selectivity();
  //cout << "got selectivity" << endl;
  get_mortality();
  //cout << "got mortalities" << endl;
```

```
 get_bias_corr();
 //cout<< "got recruitment bias correction" << endl;
 get_numbers_at_age();
 //cout << "got numbers at age" << endl;
 get_landings_numbers();
 //cout << "got landings in numbers" << endl;
 get_landings_wgt();
 //cout << "got landings in wgt" << endl;
 get_catchability_fcns();
 //cout << "got catchability_fcns" << endl;
 get_indices();
 //cout << "got indices" << endl;
 get_length_comps();
 //cout<< "got length comps"<< endl;
 get_age_comps();
 //cout<< "got age comps"<< endl;
  evaluate_objective_function();
  //cout << "objective function calculations complete" << endl;


FUNCTION get_length_weight_at_age
        //population fork length in mm
  //compute mean length (mm FL) and weight (whole) at age
  meanlen_FL=Linf*(1.0-mfexp(-K*(agebins-t0)));
  wgt_fish_mt=g2mt*wgt_middle;  //wgt in mt - middle of year
  wgt_spawn_mt=g2mt*wgt_spawn;  //wgt in mt - spawning (Jan 1)

FUNCTION get_reprod

  reprod=elem_prod(elem_prod(prop_f,maturity_f),fecundity);

FUNCTION get_length_at_age_dist
 //compute matrix of length at age, based on the normal distribution
  //population
 for (iage=1;iage<=nages;iage++)
  {
  len_cv(iage)=len_cv_val;
  len_sd(iage)=meanlen_FL(iage)*len_cv(iage);
        zscore_lzero=(0.0-meanlen_FL(iage))/len_sd(iage);
        cprob_lzero=cumd_norm(zscore_lzero);

  //first length bin
        //population
  zscore_len=((lenbins(1)+0.5*lenbins_width)-meanlen_FL(iage)) / len_sd(iage);
  cprob_lenvec(1)=cumd_norm(zscore_len);         //includes any probability mass below zero
  lenprob(iage,1)=cprob_lenvec(1)-cprob_lzero;    //removes any probability mass below zero


  //most other length bins
  //population
  for (ilen=2;ilen<nlenbins;ilen++)
   {
    zscore_len=((lenbins(ilen)+0.5*lenbins_width)-meanlen_FL(iage)) / len_sd(iage);
                cprob_lenvec(ilen)=cumd_norm(zscore_len);
    lenprob(iage,ilen)=cprob_lenvec(ilen)-cprob_lenvec(ilen-1);
   }
```

```
   //last length bin is a plus group
             //population
   zscore_len=((lenbins(nlenbins)-0.5*lenbins_width)-meanlen_FL(iage)) / len_sd(iage);
             lenprob(iage,nlenbins)=1.0-cumd_norm(zscore_len);
    lenprob(iage)=lenprob(iage)/(1.0-cprob_lzero);  //renormalize to account for any prob mass below size=0
  }

 //fleet and survey specific length probs, all assumed here to equal the popn
 lenprob_lagn=lenprob;


FUNCTION get_weight_at_age_landings  ///whole weight in mt

 for (iyear=styr; iyear<=endyr; iyear++)
 {
   wholewgt_cR_mt(iyear)=wgt_fish_mt;
 }


FUNCTION get_spr_F0
 //at mdyr, apply half this yr's mortality, half next yr's
 N_spr_F0(1)=1.0*mfexp(-1.0*M(1)*spawn_time_frac); //at peak spawning time
 N_bpr_F0(1)=1.0;      //at start of year
 for (iage=2; iage<=nages; iage++)
 { N_spr_F0(iage)=N_spr_F0(iage-1)*mfexp(-1.0*(M(iage-1)*(1.0-spawn_time_frac) + M(iage)*spawn_time_frac));
   N_bpr_F0(iage)=N_bpr_F0(iage-1)*mfexp(-1.0*(M(iage-1)));
 }
 N_spr_F0(nages)=N_spr_F0(nages)/(1.0-mfexp(-1.0*M(nages))); //plus group (sum of geometric series)
 N_bpr_F0(nages)=N_bpr_F0(nages)/(1.0-mfexp(-1.0*M(nages)));

 spr_F0=sum(elem_prod(N_spr_F0,reprod));
 bpr_F0=sum(elem_prod(N_bpr_F0,wgt_spawn_mt));



FUNCTION get_selectivity

 //sel_cR_block1=logistic_double(agebins, selpar_A50_cR1, selpar_slope_cR1, selpar_A502_cR1,selpar_slope2_cR1);
 //sel_cR_block2=logistic_double(agebins, selpar_A50_cR2, selpar_slope_cR2, selpar_A502_cR2,selpar_slope2_cR2);
 sel_lagn_block1=logistic(agebins, selpar_A50_lagn, selpar_slope_lagn);

 selpar_age0_cR=1.0/(1.0+mfexp(-sel_age0_cR_logit));
 selpar_age1_cR=1.0/(1.0+mfexp(-sel_age1_cR_logit));
 //selpar_age2_cR=1.0/(1.0+mfexp(-sel_age2_cR_logit));
 selpar_age2_cR=1.0;
 //selpar_age3_cR=1.0/(1.0+mfexp(-sel_age3_cR_logit));
 selpar_age3_cR=0.87;
 //selpar_age4_cR=1.0/(1.0+mfexp(-sel_age4_cR_logit));
 selpar_age4_cR=0.87;
 sel_age_cR_vec(1)=selpar_age0_cR;
 sel_age_cR_vec(2)=selpar_age1_cR;
 sel_age_cR_vec(3)=selpar_age2_cR;
 sel_age_cR_vec(4)=selpar_age3_cR;
 sel_age_cR_vec(5)=selpar_age3_cR;
 sel_cR_block1=sel_age_cR_vec;
```

```
  selpar_age0_cR2=1.0/(1.0+mfexp(-sel_age0_cR2_logit));
  selpar_age1_cR2=1.0/(1.0+mfexp(-sel_age1_cR2_logit));
  //selpar_age2_cR2=1.0/(1.0+mfexp(-sel_age2_cR2_logit));
  selpar_age2_cR2=1.0;
  //selpar_age3_cR2=1.0/(1.0+mfexp(-sel_age3_cR2_logit));
  //selpar_age3_cR2=0.35;
  //selpar_age4_cR2=1.0/(1.0+mfexp(-sel_age4_cR2_logit));
  //selpar_age4_cR2=0.35;
  sel_age_cR2_vec(1)=selpar_age0_cR2;
  sel_age_cR2_vec(2)=selpar_age1_cR2;
  sel_age_cR2_vec(3)=selpar_age2_cR2;
  sel_age_cR2_vec(4)=selpar_age3_cR;
  sel_age_cR2_vec(5)=selpar_age3_cR;
  sel_cR_block2=sel_age_cR2_vec;

  //BLOCK 1 for selex. No size limit
  for (iyear=styr; iyear<=endyr_selex_phase1; iyear++)
   {
    sel_cR(iyear)=sel_cR_block1;
   }

  //BLOCK 2 for selex. same as BLOCK 1, but add in lagn

  for (iyear=(endyr_selex_phase1+1); iyear<=endyr_selex_phase2; iyear++)
   {
    sel_cR(iyear)=sel_cR_block1;
    sel_lagn(iyear)=sel_lagn_block1;
   }

  //BLOCK 3 for selex.  same as block 2, but add time period for cR
   for (iyear=(endyr_selex_phase2+1); iyear<=endyr; iyear++)
   {
    //sel_cR(iyear)=sel_cR_block1;
    sel_cR(iyear)=sel_cR_block2;
    sel_lagn(iyear)=sel_lagn_block1;
   }


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

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

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

```
    Fapex(iyear)=max(F(iyear));
    Z(iyear)=M+F(iyear);

   }  //end iyear

FUNCTION get_bias_corr
  var_rec_dev=norm2(log_rec_dev(styr_rec_dev,endyr_rec_dev)-
            sum(log_rec_dev(styr_rec_dev,endyr_rec_dev))/nyrs_rec)
            /(nyrs_rec-1.0);
  //if (set_BiasCor <= 0.0) {BiasCor=mfexp(var_rec_dev/2.0);}   //bias correction based on empirical residuals
  rec_sigma_sq=square(rec_sigma);
  if (set_BiasCor <= 0.0) {BiasCor=mfexp(rec_sigma_sq/2.0);}   //bias correction based on Rsigma
  else {BiasCor=set_BiasCor;}

FUNCTION get_numbers_at_age
//Initialization
  R0=mfexp(log_R0);
  S0=spr_F0*R0;
  R_virgin=SR_eq_func(R0, steep, spr_F0, spr_F0, BiasCor, SR_switch);

  B0=bpr_F0*R_virgin*1000000;  //virgin biomass
  B0_q_DD=R_virgin*sum(elem_prod(N_bpr_F0(set_q_DD_stage,nages),wgt_spawn_mt(set_q_DD_stage,nages)));

  F_initial=sel_cR(styr)*mfexp(log_avg_F_cR+log_F_dev_init_cR);

  Z_initial=M+F_initial;

//Initial equilibrium age structure
  N_spr_initial(1)=1.0*mfexp(-1.0*Z_initial(1)*spawn_time_frac); //at peak spawning time;
  for (iage=2; iage<=nages; iage++)
    {
      N_spr_initial(iage)=N_spr_initial(iage-1)*
                mfexp(-1.0*(Z_initial(iage-1)*(1.0-spawn_time_frac) + Z_initial(iage)*spawn_time_frac));
    }
  N_spr_initial(nages)=N_spr_initial(nages)/(1.0-mfexp(-1.0*Z_initial(nages))); //plus group
  spr_initial=sum(elem_prod(N_spr_initial,reprod));
  if (styr==styr_rec_dev) {R1=SR_eq_func(R0, steep, spr_F0, spr_initial, 1.0, SR_switch);} //without bias correction (deviation
added later)
  else {R1=SR_eq_func(R0, steep, spr_F0, spr_initial, BiasCor, SR_switch);} //with bias correction
  if(R1<0.0) {R1=1.0;} //Avoid unrealistically low popn sizes during search algorithm

//Compute equilibrium age structure for first year
  N_initial_eq(1)=R1;
  for (iage=2; iage<=nages; iage++)
  {
    N_initial_eq(iage)=N_initial_eq(iage-1)*
        mfexp(-1.0*(Z_initial(iage-1)));
  }
  //plus group calculation
  N_initial_eq(nages)=N_initial_eq(nages)/(1.0-mfexp(-1.0*Z_initial(nages))); //plus group

//Add deviations to initial equilibrium N
  N(styr)(2,nages)=elem_prod(N_initial_eq(2,nages),mfexp(log_Nage_dev));

  if (styr==styr_rec_dev) {N(styr,1)=N_initial_eq(1)*mfexp(log_rec_dev(styr_rec_dev));}
  else {N(styr,1)=N_initial_eq(1);}
```

```
 N_mdyr(styr)(1,nages)=elem_prod(N(styr)(1,nages),(mfexp(-1.*(Z_initial(1,nages))*0.5))); //mid year
 N_spawn(styr)(1,nages)=elem_prod(N(styr)(1,nages),(mfexp(-1.*(Z_initial(1,nages))*spawn_time_frac))); //peak spawning time

 SSB(styr)=sum(elem_prod(N_spawn(styr),reprod));
 B_q_DD(styr)=sum(elem_prod(N(styr)(set_q_DD_stage,nages),wgt_spawn_mt(set_q_DD_stage,nages)));

//Rest of years
 for (iyear=styr; iyear<endyr; iyear++)
 {
  if(iyear<(styr_rec_dev-1)||iyear>(endyr_rec_dev-1)) //recruitment follows S-R curve (with bias correction) exactly
  {
    //N(iyear+1,1)=BiasCor*SR_func(R0, steep, spr_F0, SSB(iyear),SR_switch);
    N(iyear+1)(2,nages)=++elem_prod(N(iyear)(1,nages-1),(mfexp(-1.*Z(iyear)(1,nages-1))));
    N(iyear+1,nages)+=N(iyear,nages)*mfexp(-1.*Z(iyear,nages)); //plus group
    //N_mdyr(iyear+1)(1,nages)=elem_prod(N(iyear+1)(1,nages),(mfexp(-1.*(Z(iyear+1)(1,nages))*0.5))); //mid year
    N_spawn(iyear+1)(1,nages)=elem_prod(N(iyear+1)(1,nages),(mfexp(-1.*(Z(iyear+1)(1,nages))*spawn_time_frac))); //peak spawning time
    SSB(iyear+1)=sum(elem_prod(N_spawn(iyear+1),reprod));
        B_q_DD(iyear+1)=sum(elem_prod(N(iyear+1)(set_q_DD_stage,nages),wgt_spawn_mt(set_q_DD_stage,nages)));

    N(iyear+1,1)=BiasCor*SR_func(R0, steep, spr_F0, SSB(iyear+1),SR_switch);
    N_mdyr(iyear+1)(1,nages)=elem_prod(N(iyear+1)(1,nages),(mfexp(-1.*(Z(iyear+1)(1,nages))*0.5))); //mid year

  }
  else   //recruitment follows S-R curve with lognormal deviation
  {
    //N(iyear+1,1)=SR_func(R0, steep, spr_F0, SSB(iyear),SR_switch)*mfexp(log_rec_dev(iyear+1));
    N(iyear+1)(2,nages)=++elem_prod(N(iyear)(1,nages-1),(mfexp(-1.*Z(iyear)(1,nages-1))));
    N(iyear+1,nages)+=N(iyear,nages)*mfexp(-1.*Z(iyear,nages)); //plus group
    //N_mdyr(iyear+1)(1,nages)=elem_prod(N(iyear+1)(1,nages),(mfexp(-1.*(Z(iyear+1)(1,nages))*0.5))); //mid year
    N_spawn(iyear+1)(1,nages)=elem_prod(N(iyear+1)(1,nages),(mfexp(-1.*(Z(iyear+1)(1,nages))*spawn_time_frac))); //peak spawning time
    SSB(iyear+1)=sum(elem_prod(N_spawn(iyear+1),reprod));
    B_q_DD(iyear+1)=sum(elem_prod(N(iyear+1)(set_q_DD_stage,nages),wgt_spawn_mt(set_q_DD_stage,nages)));

    N(iyear+1,1)=SR_func(R0, steep, spr_F0, SSB(iyear+1),SR_switch)*mfexp(log_rec_dev(iyear+1));
    N_mdyr(iyear+1)(1,nages)=elem_prod(N(iyear+1)(1,nages),(mfexp(-1.*(Z(iyear+1)(1,nages))*0.5))); //mid year

  }
 }

  //last year (projection) has no recruitment variability
 N(endyr+1)(2,nages)=++elem_prod(N(endyr)(1,nages-1),(mfexp(-1.*Z(endyr)(1,nages-1))));
 N(endyr+1,nages)+=N(endyr,nages)*mfexp(-1.*Z(endyr,nages)); //plus group
 SSB(endyr+1)=sum(elem_prod(N(endyr+1),reprod));
 N(endyr+1,1)=BiasCor*SR_func(R0, steep, spr_F0, SSB(endyr+1),SR_switch);

  //Time series of interest
 rec=column(N,1);
 SdS0=SSB/S0;


FUNCTION get_landings_numbers //Baranov catch eqn
 for (iyear=styr; iyear<=endyr; iyear++)
```

```
 {
   for (iage=1; iage<=nages; iage++)
   {
     L_cR_num(iyear,iage)=N(iyear,iage)*F_cR(iyear,iage)*
       (1.-mfexp(-1.*Z(iyear,iage)))/Z(iyear,iage);
   }
   //pred_cR_L_knum(iyear)=sum(L_cR_num(iyear))/1000;//landings already being estimated in 1000s
 }


FUNCTION get_landings_wgt
 for (iyear=styr; iyear<=endyr; iyear++)
 {
   L_cR_mt(iyear)=elem_prod(L_cR_num(iyear),wholewgt_cR_mt(iyear))*1000000; //in 1000 mt whole weight

   pred_cR_L_mt(iyear)=sum(L_cR_mt(iyear));

 }


FUNCTION get_catchability_fcns
 //Get rate increase if estimated, otherwise fixed above
 if (set_q_rate_phase>0.0)
 {
     for (iyear=styr_lagn_cpue; iyear<=endyr_lagn_cpue; iyear++)
     {   if (iyear>styr_lagn_cpue & iyear <=2003)
         {//q_rate_fcn_lagn(iyear)=(1.0+q_rate)*q_rate_fcn_lagn(iyear-1); //compound
            q_rate_fcn_lagn(iyear)=(1.0+(iyear-styr_lagn_cpue)*q_rate)*q_rate_fcn_lagn(styr_lagn_cpue);  //linear
         }
         if (iyear>2003) {q_rate_fcn_lagn(iyear)=q_rate_fcn_lagn(iyear-1);}
     }
     for (iyear=styr_seine_cpue; iyear<=endyr_seine_cpue; iyear++)
     {   if (iyear>styr_seine_cpue & iyear <=2003)
         {//q_rate_fcn_seine(iyear)=(1.0+q_rate)*q_rate_fcn_seine(iyear-1); //compound
            q_rate_fcn_seine(iyear)=(1.0+(iyear-styr_seine_cpue)*q_rate)*q_rate_fcn_seine(styr_seine_cpue);  //linear
         }
         if (iyear>2003) {q_rate_fcn_seine(iyear)=q_rate_fcn_seine(iyear-1);}
     }
 } //end q_rate conditional

 //Get density dependence scalar (=1.0 if density independent model is used)
 if (q_DD_beta>0.0)
 {
   B_q_DD+=dzero;
   for (iyear=styr;iyear<=endyr;iyear++)
       {q_DD_fcn(iyear)=pow(B0_q_DD,q_DD_beta)*pow(B_q_DD(iyear),-q_DD_beta);}
         //{q_DD_fcn(iyear)=1.0+4.0/(1.0+mfexp(0.75*(B_q_DD(iyear)-0.1*B0_q_DD))); }
 }


FUNCTION get_indices
//---Predicted CPUEs------------------------

 //LA gill net  index
 q_lagn(styr_lagn_cpue)=mfexp(log_q_lagn);
 for (iyear=styr_lagn_cpue; iyear<=endyr_lagn_cpue; iyear++)
```

```
 {
    q_lagn(iyear)=q_lagn(styr_lagn_cpue);
    N_lagn(iyear)=elem_prod(N_mdyr(iyear),sel_lagn(iyear));
    pred_lagn_cpue(iyear)=q_lagn(iyear)*sum(N_lagn(iyear));
    //pred_lagn_cpue(iyear)=q_lagn(iyear)*q_rate_fcn_lagn(iyear)*q_DD_fcn(iyear)*sum(N_lagn(iyear));
    //if (iyear<endyr_lagn_cpue){q_lagn(iyear+1)=q_lagn(iyear)*mfexp(q_RW_log_dev_lagn(iyear));}
 }

//Seine index
 q_seine(styr_seine_cpue)=mfexp(log_q_seine);
 for (iyear=styr_seine_cpue; iyear<=endyr_seine_cpue; iyear++)
 {
    q_seine(iyear)=q_seine(styr_seine_cpue);
    N_seine(iyear)=N(iyear,1)*mfexp(-1.*(Z(iyear)(1)*0.25));//matching seine index with April 1 (1/4 of the year completed)
    pred_seine_cpue(iyear)=q_seine(iyear)*N_seine(iyear,1);
    //pred_seine_cpue(iyear)=q_seine(iyear)*q_rate_fcn_seine(iyear)*q_DD_fcn(iyear)*N_seine(iyear,1);
    //if (iyear<endyr_seine_cpue){q_seine(iyear+1)=q_seine(iyear)*mfexp(q_RW_log_dev_seine(iyear));}
 }



FUNCTION get_length_comps

 //LA gill nets
 for (iyear=1;iyear<=nyr_lagn_lenc;iyear++)
 {
   pred_lagn_lenc(iyear)=(N_lagn(yrs_lagn_lenc(iyear))*lenprob_lagn)
                      /sum(N_lagn(yrs_lagn_lenc(iyear)));
 }



FUNCTION get_age_comps

 //Commercial handline
 for (iyear=1;iyear<=nyr_cR_agec;iyear++)
 {
   ErrorFree_cR_agec(iyear)=L_cR_num(yrs_cR_agec(iyear))/sum(L_cR_num(yrs_cR_agec(iyear)));
   pred_cR_agec_allages(iyear)=age_error*(ErrorFree_cR_agec(iyear)/sum(ErrorFree_cR_agec(iyear)));
   for (iage=1; iage<=nages_agec; iage++) {pred_cR_agec(iyear,iage)=pred_cR_agec_allages(iyear,iage);}
   //for (iage=(nages_agec+1); iage<=nages; iage++) {pred_cR_agec(iyear,nages_agec)+=pred_cR_agec_allages(iyear,iage);}
//plus group
 }


////----------------------------------------------------------------------------------------------------------------------------------------------------------
-----------------------------
FUNCTION get_weighted_current
 F_temp_sum=0.0;
 F_temp_sum+=mfexp((selpar_n_yrs_wgted*log_avg_F_cR+
      sum(log_F_dev_cR((endyr-selpar_n_yrs_wgted+1),endyr)))/selpar_n_yrs_wgted);

 F_cR_prop=mfexp((selpar_n_yrs_wgted*log_avg_F_cR+
      sum(log_F_dev_cR((endyr-selpar_n_yrs_wgted+1),endyr)))/selpar_n_yrs_wgted)/F_temp_sum;

 log_F_dev_end_cR=sum(log_F_dev_cR((endyr-selpar_n_yrs_wgted+1),endyr))/selpar_n_yrs_wgted;
```

```
 F_end_L=sel_cR(endyr)*mfexp(log_avg_F_cR+log_F_dev_end_cR);

 F_end=F_end_L;
 F_end_apex=max(F_end);

 sel_wgted_tot=F_end/F_end_apex;
 sel_wgted_L=elem_prod(sel_wgted_tot, elem_div(F_end_L,F_end));

 wgt_wgted_L_denom=F_cR_prop;
 wgt_wgted_L_mt=F_cR_prop/wgt_wgted_L_denom*wholewgt_cR_mt(endyr)*1000; //to scale to 1000s mt


FUNCTION get_msy

 //compute values as functions of F
 for(ff=1; ff<=n_iter_msy; ff++)
 {
   //uses fishery-weighted F's
   Z_age_msy=0.0;
   F_L_age_msy=0.0;

   F_L_age_msy=F_msy(ff)*sel_wgted_L;
   Z_age_msy=M+F_L_age_msy;

   N_age_msy(1)=1.0;
   for (iage=2; iage<=nages; iage++)
     {N_age_msy(iage)=N_age_msy(iage-1)*mfexp(-1.*Z_age_msy(iage-1));}
   N_age_msy(nages)=N_age_msy(nages)/(1.0-mfexp(-1.*Z_age_msy(nages)));
   N_age_msy_spawn(1,(nages-1))=elem_prod(N_age_msy(1,(nages-1)),
                          mfexp((-1.*Z_age_msy(1,(nages-1)))*spawn_time_frac));
   N_age_msy_spawn(nages)=(N_age_msy_spawn(nages-1)*(mfexp(-1.*(Z_age_msy(nages-1)*(1.0-spawn_time_frac) +
                      Z_age_msy(nages)*spawn_time_frac) )))/(1.0-mfexp(-1.*Z_age_msy(nages)));

   spr_msy(ff)=sum(elem_prod(N_age_msy_spawn,reprod));

   R_eq(ff)=SR_eq_func(R0, steep, spr_msy(1), spr_msy(ff), BiasCor, SR_switch);

   if (R_eq(ff)<dzero) {R_eq(ff)=dzero;}
   N_age_msy*=R_eq(ff);
   N_age_msy_spawn*=R_eq(ff);

   for (iage=1; iage<=nages; iage++)
   {
     L_age_msy(iage)=N_age_msy(iage)*(F_L_age_msy(iage)/Z_age_msy(iage))*
               (1.-mfexp(-1.*Z_age_msy(iage)));
   }

   SSB_eq(ff)=sum(elem_prod(N_age_msy_spawn,reprod));
   B_eq(ff)=sum(elem_prod(N_age_msy,wgt_spawn_mt))*1000000; //to scale to 1000s mt and catch in 1000s
   L_eq_mt(ff)=sum(elem_prod(L_age_msy,wgt_wgted_L_mt))*1000; //to scale to catch in 1000s, wgt_wgted_L_mt is
already scaled to 1000s mt
   //L_eq_knum(ff)=sum(L_age_msy)/1000.0;
 }

 msy_mt_out=max(L_eq_mt); //msy in whole weight
```

```
  for(ff=1; ff<=n_iter_msy; ff++)
  {
   if(L_eq_mt(ff) == msy_mt_out)
      {
        SSB_msy_out=SSB_eq(ff);
        B_msy_out=B_eq(ff);
        R_msy_out=R_eq(ff);
        //msy_knum_out=L_eq_knum(ff);
        F_msy_out=F_msy(ff);
        spr_msy_out=spr_msy(ff);
      }
  }

//---------------------------------------------------------------------------------------------------------------------------------------------------------------------------
---------------------------
FUNCTION get_per_recruit_stuff

  //static per-recruit stuff

  for(iyear=styr; iyear<=endyr; iyear++)
  {
    N_age_spr(1)=1.0;
    for(iage=2; iage<=nages; iage++)
     {N_age_spr(iage)=N_age_spr(iage-1)*mfexp(-1.*Z(iyear,iage-1));}
    N_age_spr(nages)=N_age_spr(nages)/(1.0-mfexp(-1.*Z(iyear,nages)));
    N_age_spr_spawn(1,(nages-1))=elem_prod(N_age_spr(1,(nages-1)),
                                 mfexp(-1.*Z(iyear)(1,(nages-1))*spawn_time_frac));
    N_age_spr_spawn(nages)=(N_age_spr_spawn(nages-1)*
                           (mfexp(-1.*(Z(iyear)(nages-1)*(1.0-spawn_time_frac) + Z(iyear)(nages)*spawn_time_frac) )))
                           /(1.0-mfexp(-1.*Z(iyear)(nages)));
    spr_static(iyear)=sum(elem_prod(N_age_spr_spawn,reprod))/spr_F0;
  }

  //compute SSB/R and YPR as functions of F
  for(ff=1; ff<=n_iter_spr; ff++)
  {
    //uses fishery-weighted F's, same as in MSY calculations
    Z_age_spr=0.0;
    F_L_age_spr=0.0;

    F_L_age_spr=F_spr(ff)*sel_wgted_L;
    Z_age_spr=M+F_L_age_spr;

    N_age_spr(1)=1.0;
    for (iage=2; iage<=nages; iage++)
     {N_age_spr(iage)=N_age_spr(iage-1)*mfexp(-1.*Z_age_spr(iage-1));}
    N_age_spr(nages)=N_age_spr(nages)/(1-mfexp(-1.*Z_age_spr(nages)));
    N_age_spr_spawn(1,(nages-1))=elem_prod(N_age_spr(1,(nages-1)),
                                    mfexp((-1.*Z_age_spr(1,(nages-1)))*spawn_time_frac));
    N_age_spr_spawn(nages)=(N_age_spr_spawn(nages-1)*
                           (mfexp(-1.*(Z_age_spr(nages-1)*(1.0-spawn_time_frac) + Z_age_spr(nages)*spawn_time_frac))))
                           /(1.0-mfexp(-1.*Z_age_spr(nages)));
    spr_spr(ff)=sum(elem_prod(N_age_spr_spawn,reprod));
    L_spr(ff)=0.0;
    for (iage=1; iage<=nages; iage++)
```

```
   {
     L_age_spr(iage)=N_age_spr(iage)*(F_L_age_spr(iage)/Z_age_spr(iage))*
                  (1.-mfexp(-1.*Z_age_spr(iage)));
     L_spr(ff)+=L_age_spr(iage)*wgt_wgted_L_mt(iage)*1000.0; //already scaled to 1000s mt, but need to scale to 1000s fish
   }
  }
  spr_ratio=spr_spr/spr_F0;
  F35_dum=min(fabs(spr_ratio-0.35));
  F30_dum=min(fabs(spr_ratio-0.3));
  F40_dum=min(fabs(spr_ratio-0.4));
  for(ff=1; ff<=n_iter_spr; ff++)
  {
     if (fabs(spr_ratio(ff)-0.35)==F35_dum) {F35_out=F_spr(ff);}
              if (fabs(spr_ratio(ff)-0.3)==F30_dum) {F30_out=F_spr(ff);}
              if (fabs(spr_ratio(ff)-0.4)==F40_dum) {F40_out=F_spr(ff);}
  }
  rec=column(N,1);
  rec_mean=sum(rec(styr_rec_spr, endyr_rec_spr))/nyrs_rec_spr;
  R_F30_out=rec_mean;
  F_L_age_spr=F30_out*sel_wgted_L;
  Z_age_spr=M+F_L_age_spr;

  N_age_spr(1)=R_F30_out;
  for (iage=2; iage<=nages; iage++)
    {N_age_spr(iage)=N_age_spr(iage-1)*mfexp(-1.*Z_age_spr(iage-1));}
  N_age_spr(nages)=N_age_spr(nages)/(1-mfexp(-1.*Z_age_spr(nages)));
  N_age_spr_spawn(1,(nages-1))=elem_prod(N_age_spr(1,(nages-1)),
                              mfexp((-1.*Z_age_spr(1,(nages-1)))*spawn_time_frac));
  N_age_spr_spawn(nages)=(N_age_spr_spawn(nages-1)*
                       (mfexp(-1.*(Z_age_spr(nages-1)*(1.0-spawn_time_frac) + Z_age_spr(nages)*spawn_time_frac) )))
                       /(1.0-mfexp(-1.*Z_age_spr(nages)));

  for (iage=1; iage<=nages; iage++)
   {
     L_age_F30(iage)=N_age_spr(iage)*(F_L_age_spr(iage)/Z_age_spr(iage))*
                 (1.-mfexp(-1.*Z_age_spr(iage)));
   }
  SSB_F30_out=sum(elem_prod(N_age_spr_spawn,reprod));
  B_F30_out=sum(elem_prod(N_age_spr,wgt_spawn))*1000000;
  L_F30_mt_out=sum(elem_prod(L_age_F30,wgt_wgted_L_mt))*1000; //in whole weight
  L_F30_knum_out=sum(L_age_F30)/1000.0;


//-------------------------------------------------------------------------------------------------------------------------------------------------------
-------------------------
FUNCTION get_miscellaneous_stuff

//switch here if var_rec_dev <=dzero
  if(var_rec_dev>0.0)
   {sigma_rec_dev=sqrt(var_rec_dev);} //sample SD of predicted residuals (may not equal rec_sigma)
   else{sigma_rec_dev=0.0;}

  len_cv=elem_div(len_sd,meanlen_FL);

  //compute total landings-at-age in 1000 fish and 1000s mt whole weight
  L_total_num.initialize();
```

```
L_total_mt.initialize();
//L_total_knum_yr.initialize();
L_total_mt_yr.initialize();

for(iyear=styr; iyear<=endyr; iyear++)
{
     L_total_mt_yr(iyear)=pred_cR_L_mt(iyear);
     //L_total_knum_yr(iyear)=pred_cR_L_knum(iyear);

     B(iyear)=elem_prod(N(iyear),wgt_spawn_mt)*1000000;  //scale to 1000s mt and 1000s fish landed
     totN(iyear)=sum(N(iyear));   //in 1000s of fish
     totB(iyear)=sum(B(iyear));   //in 1000s of mt
     SSBatage(iyear)=elem_prod(N(iyear),reprod);
}

L_total_num=L_cR_num;   //landings at age in 1000s fish
L_total_mt=L_cR_mt;   //landings at age in 1000s  mt whole weight

//Time series of interest
B(endyr+1)=elem_prod(N(endyr+1),wgt_spawn_mt)*1000000;  //scale to 1000s mt and 1000s fish
totN(endyr+1)=sum(N(endyr+1));  //in 1000s of fish
totB(endyr+1)=sum(B(endyr+1));  //in 1000s of mt
SdS0=SSB/S0;

Fend_mean_temp=1.0;
for (iyear=1; iyear<=selpar_n_yrs_wgted; iyear++) {Fend_mean_temp*=Fapex(endyr-iyear+1);}
Fend_mean=pow(Fend_mean_temp,(1.0/selpar_n_yrs_wgted));
if(F_msy_out>0)
  {
    FdF_msy=Fapex/F_msy_out;
    FdF_msy_end=FdF_msy(endyr);
    FdF_msy_end_mean=Fend_mean/F_msy_out;
  }
if(SSB_msy_out>0)
  {
    SdSSB_msy=SSB/SSB_msy_out;
    SdSSB_msy_end=SdSSB_msy(endyr);
  }

            if(F30_out>0)
  {
              FdF30=Fapex/F30_out;
              FdF30_end_mean=Fend_mean/F30_out;
            }

 if(SSB_F30_out>0)
  {
    SdSSB_F30=SSB/SSB_F30_out;
    SdSSB_F30_end=SdSSB_F30(endyr);
  }
 //fill in log recruitment deviations for yrs they are nonzero
 for(iyear=styr_rec_dev; iyear<=endyr_rec_dev; iyear++)
   {log_rec_dev_output(iyear)=log_rec_dev(iyear);}
 //fill in log Nage deviations for ages they are nonzero (ages2+)
 for(iage=2; iage<=nages; iage++)
   {log_Nage_dev_output(iage)=log_Nage_dev(iage);}
```

```
//------------------------------------------------------------------------------------------------------------------------------------------------------------
-------------------------
FUNCTION get_projection

  switch(Fproj_switch){
    case 1: //F=Fcurrent
      F_reg_proj=Fend_mean;
      break;
    case 2: //F=Fmsy
      F_reg_proj=F_msy_out;
      break;
    case 3: //F=F30
      F_reg_proj=F30_out;
      break;
    case 4: //F=F40
      F_reg_proj=F40_out;
      break;
    default: // no such switch available
      cout << "Error in input: Projection switch Fproj_switch must be set to 1, 2, 3, or 4." << endl;
      cout << "Presently it is set to " << Fproj_switch <<"."<< endl;
      exit(0);
  }

 N_proj(styr_proj)=N(endyr+1); //initial conditions computed previously

 for (iyear=styr_proj; iyear<=endyr_proj; iyear++) //recruitment follows S-R curve (with bias correction) exactly
 {
     if (iyear<styr_regs) {F_proj(iyear)=Fend_mean;}
                     else {F_proj(iyear)=Fproj_mult*F_reg_proj;}

                     FL_age_proj=sel_wgted_L*F_proj(iyear);

     Z_proj(iyear)=M+FL_age_proj;
     N_spawn_proj(iyear)(1,nages)=elem_prod(N_proj(iyear)(1,nages),(mfexp(-
1.*(Z_proj(iyear)(1,nages))*spawn_time_frac))); //peak spawning time
                     SSB_proj(iyear)= sum(elem_prod(N_spawn_proj(iyear),reprod));
     B_proj(iyear)=sum(elem_prod(N_proj(iyear),wgt_spawn_mt))*1000000; //uses spawning weight

                     for (iage=1; iage<=nages; iage++)
                                {
                 L_age_proj(iyear,iage)=N_proj(iyear,iage)*FL_age_proj(iage)*(1.-mfexp(-
1.*Z_proj(iyear,iage)))/Z_proj(iyear,iage);
                                }
     L_knum_proj(iyear)=sum(L_age_proj(iyear))/1000.0;
          L_mt_proj(iyear)=sum(elem_prod(L_age_proj(iyear),wgt_wgted_L_mt));     //in 1000 mt

                     if (iyear<endyr_proj) {
                                N_proj(iyear+1,1)=BiasCor*SR_func(R0, steep, spr_F0, SSB_proj(iyear),SR_switch);
                                N_proj(iyear+1)(2,nages)=++elem_prod(N_proj(iyear)(1,nages-1),(mfexp(-
1.*Z_proj(iyear)(1,nages-1))));
                                N_proj(iyear+1,nages)+=N_proj(iyear,nages)*mfexp(-1.*Z_proj(iyear,nages)); //plus group

                     }
 }
  R_proj=column(N_proj,1);
```

```
//-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------
------------------------------


FUNCTION evaluate_objective_function
  //fval=square(xdum-9.0);

  fval=0.0;
  fval_data=0.0;

//---likelihoods---------------------------

//---Indices-------------------------------

  f_lagn_cpue=0.0;
  f_lagn_cpue=lk_lognormal(pred_lagn_cpue, obs_lagn_cpue, lagn_cpue_cv, w_I_lagn);
  fval+=f_lagn_cpue;
  fval_data+=f_lagn_cpue;

  f_seine_cpue=0.0;
  f_seine_cpue=lk_lognormal(pred_seine_cpue, obs_seine_cpue, seine_cpue_cv, w_I_seine);
  fval+=f_seine_cpue;
  fval_data+=f_seine_cpue;

//---Landings-------------------------------

  //f_cR_L in 1000 mt whole wgt
  f_cR_L=lk_lognormal(pred_cR_L_mt(styr_cR_L,endyr_cR_L), obs_cR_L(styr_cR_L,endyr_cR_L),
                  cR_L_cv(styr_cR_L,endyr_cR_L), w_L);
  fval+=f_cR_L;
  fval_data+=f_cR_L;


//---Length comps-------------------------------

  //f_lagn_lenc
  //f_lagn_lenc=lk_robust_multinomial(nsamp_lagn_lenc, pred_lagn_lenc, obs_lagn_lenc, nyr_lagn_lenc, double(nlenbins),
minSS_lagn_lenc, w_lc_lagn);
  //f_lagn_lenc=lk_logistic_normal(nsamp_lagn_lenc, pred_lagn_lenc, obs_lagn_lenc, nyr_lagn_lenc, double(nlenbins),
minSS_lagn_lenc);
  f_lagn_lenc=lk_dirichlet_multinomial(nsamp_lagn_lenc, pred_lagn_lenc, obs_lagn_lenc, nyr_lagn_lenc, double(nlenbins),
minSS_lagn_lenc, log_dm_lagn_lc);
  fval+=f_lagn_lenc;
  fval_data+=f_lagn_lenc;


//---Age comps-------------------------------

  //f_cR_agec
  //f_cR_agec=lk_robust_multinomial(nsamp_cR_agec, pred_cR_agec, obs_cR_agec, nyr_cR_agec, double(nages_agec),
minSS_cR_agec, w_ac_cR);
  //f_cR_agec=lk_logistic_normal(nsamp_cR_agec, pred_cR_agec, obs_cR_agec, nyr_cR_agec, double(nages_agec),
minSS_cR_agec);
  f_cR_agec=lk_dirichlet_multinomial(nsamp_cR_agec, pred_cR_agec, obs_cR_agec, nyr_cR_agec, double(nages_agec),
minSS_cR_agec, log_dm_cR_ac);
  fval+=f_cR_agec;
```

```
  fval_data+=f_cR_agec;


//-----------Constraints and penalties--------------------------------

  //Light penalty applied to log_Nage_dev for deviation from zero. If not estimated, this penalty equals zero.
  f_Nage_init=norm2(log_Nage_dev);
  fval+=w_Nage_init*f_Nage_init;

  f_rec_dev=0.0;
  //rec_sigma_sq=square(rec_sigma);
  rec_logL_add=nyrs_rec*log(rec_sigma);
  f_rec_dev=(square(log_rec_dev(styr_rec_dev) + rec_sigma_sq/2.0)/(2.0*rec_sigma_sq));
  for(iyear=(styr_rec_dev+1); iyear<=endyr_rec_dev; iyear++)
  {f_rec_dev+=(square(log_rec_dev(iyear)-R_autocorr*log_rec_dev(iyear-1) + rec_sigma_sq/2.0)/
             (2.0*rec_sigma_sq));}
  f_rec_dev+=rec_logL_add;
  fval+=w_rec*f_rec_dev;

  f_rec_dev_early=0.0; //possible extra constraint on early rec deviations
  if (w_rec_early>0.0)
    { if (styr_rec_dev<endyr_rec_phase1)
        {
         for(iyear=styr_rec_dev; iyear<=endyr_rec_phase1; iyear++)
         //{f_rec_dev_early+=(square(log_rec_dev(iyear)-R_autocorr*log_rec_dev(iyear-1) + rec_sigma_sq/2.0)/
         //                (2.0*rec_sigma_sq)) + rec_logL_add;}
         {f_rec_dev_early+=square(log_rec_dev(iyear));}
        }
  fval+=w_rec_early*f_rec_dev_early;
  }

  f_rec_dev_end=0.0; //possible extra constraint on ending rec deviations
  if (w_rec_end>0.0)
  { if (endyr_rec_phase2<endyr_rec_dev)
        {
         for(iyear=(endyr_rec_phase2+1); iyear<=endyr_rec_dev; iyear++)
         //{f_rec_dev_end+=(square(log_rec_dev(iyear)-R_autocorr*log_rec_dev(iyear-1) + rec_sigma_sq/2.0)/
         //               (2.0*rec_sigma_sq)) + rec_logL_add;}
         {f_rec_dev_end+=square(log_rec_dev(iyear));}
        }
     fval+=w_rec_end*f_rec_dev_end;
   }

  //Ftune penalty: does not apply in last phase
  f_Ftune=0.0;
  if (w_Ftune>0.0)
  {if (set_Ftune>0.0 && !last_phase()) {f_Ftune=square(Fapex(set_Ftune_yr)-set_Ftune);}
   fval+=w_Ftune*f_Ftune;
  }

  //Penalty if apical F exceeds 3.0
  f_fullF_constraint=0.0;
  if (w_fullF>0.0)
  {for (iyear=styr; iyear<=endyr; iyear++)
        {if(Fapex(iyear)>3.0) {f_fullF_constraint+=(mfexp(Fapex(iyear)-3.0)-1.0);}}
   fval+=w_fullF*f_fullF_constraint;
```

```
  }

 //Random walk components of fishery dependent indices - we don't have any fishery dependent indices
 //f_cH_RWq_cpue=0.0;
 //for (iyear=styr_cH_cpue; iyear<endyr_cH_cpue; iyear++)
 //    {f_cH_RWq_cpue+=square(q_RW_log_dev_cH(iyear))/(2.0*set_RWq_var);}
 //fval+=f_cH_RWq_cpue;

//---Priors---------------------------------------------------
//neg_log_prior arguments: estimate, prior mean, prior var/-CV, pdf type
//Variance input as a negative value is considered to be CV in arithmetic space (CV=-1 implies loose prior)
//pdf type 1=none, 2=lognormal, 3=normal, 4=beta
  f_priors=0.0;
  f_priors+=neg_log_prior(len_cv_val,set_len_cv(5),set_len_cv(6),set_len_cv(7));

  f_priors+=neg_log_prior(steep,set_steep(5),set_log_R0(6),set_log_R0(7));
  f_priors+=neg_log_prior(log_R0,set_log_R0(5),set_log_R0(6),set_log_R0(7));
  f_priors+=neg_log_prior(R_autocorr,set_R_autocorr(5),set_R_autocorr(6),set_R_autocorr(7));
  f_priors+=neg_log_prior(rec_sigma,set_rec_sigma(5),set_rec_sigma(6),set_rec_sigma(7));

  f_priors+=neg_log_prior(selpar_A50_cR1,set_selpar_A50_cR1(5), set_selpar_A50_cR1(6), set_selpar_A50_cR1(7));
  f_priors+=neg_log_prior(selpar_slope_cR1,set_selpar_slope_cR1(5), set_selpar_slope_cR1(6), set_selpar_slope_cR1(7));
  f_priors+=neg_log_prior(selpar_A502_cR1,set_selpar_A502_cR1(5), set_selpar_A502_cR1(6), set_selpar_A502_cR1(7));
  f_priors+=neg_log_prior(selpar_slope2_cR1,set_selpar_slope2_cR1(5), set_selpar_slope2_cR1(6),
set_selpar_slope2_cR1(7));

  f_priors+=neg_log_prior(selpar_A50_cR2,set_selpar_A50_cR2(5), set_selpar_A50_cR2(6), set_selpar_A50_cR2(7));
  f_priors+=neg_log_prior(selpar_slope_cR2,set_selpar_slope_cR2(5), set_selpar_slope_cR2(6), set_selpar_slope_cR2(7));
  f_priors+=neg_log_prior(selpar_A502_cR2,set_selpar_A502_cR2(5), set_selpar_A502_cR2(6), set_selpar_A502_cR2(7));
  f_priors+=neg_log_prior(selpar_slope2_cR2,set_selpar_slope2_cR2(5), set_selpar_slope2_cR2(6),
set_selpar_slope2_cR2(7));

  f_priors+=neg_log_prior(sel_age0_cR_logit,set_sel_age0_cR(5),set_sel_age0_cR(6), set_sel_age0_cR(7));
  f_priors+=neg_log_prior(sel_age1_cR_logit,set_sel_age1_cR(5),set_sel_age1_cR(6), set_sel_age1_cR(7));
  f_priors+=neg_log_prior(sel_age2_cR_logit,set_sel_age2_cR(5),set_sel_age2_cR(6), set_sel_age2_cR(7));
  f_priors+=neg_log_prior(sel_age3_cR_logit,set_sel_age3_cR(5),set_sel_age3_cR(6), set_sel_age3_cR(7));
  f_priors+=neg_log_prior(sel_age4_cR_logit,set_sel_age4_cR(5),set_sel_age4_cR(6), set_sel_age4_cR(7));

  f_priors+=neg_log_prior(sel_age0_cR_logit,set_sel_age0_cR(5),set_sel_age0_cR(6), set_sel_age0_cR(7));
  f_priors+=neg_log_prior(sel_age1_cR_logit,set_sel_age1_cR(5),set_sel_age1_cR(6), set_sel_age1_cR(7));
  f_priors+=neg_log_prior(sel_age2_cR_logit,set_sel_age2_cR(5),set_sel_age2_cR(6), set_sel_age2_cR(7));
  f_priors+=neg_log_prior(sel_age3_cR_logit,set_sel_age3_cR(5),set_sel_age3_cR(6), set_sel_age3_cR(7));
  f_priors+=neg_log_prior(sel_age4_cR_logit,set_sel_age4_cR(5),set_sel_age4_cR(6), set_sel_age4_cR(7));

  f_priors+=neg_log_prior(selpar_A50_lagn,set_selpar_A50_lagn(5), set_selpar_A50_lagn(6), set_selpar_A50_lagn(7));
  f_priors+=neg_log_prior(selpar_slope_lagn,set_selpar_slope_lagn(5), set_selpar_slope_lagn(6), set_selpar_slope_lagn(7));

  f_priors+=neg_log_prior(log_q_lagn,set_log_q_lagn(5),set_log_q_lagn(6),set_log_q_lagn(7));
  f_priors+=neg_log_prior(log_q_seine,set_log_q_seine(5),set_log_q_seine(6),set_log_q_seine(7));

  f_priors+=neg_log_prior(log_dm_lagn_lc,set_log_dm_lagn_lc(5),set_log_dm_lagn_lc(6),set_log_dm_lagn_lc(7));
  f_priors+=neg_log_prior(log_dm_cR_ac,set_log_dm_cR_ac(5),set_log_dm_cR_ac(6),set_log_dm_cR_ac(7));

  fval+=f_priors;

//----------------------------------------------------------------------------------
```

```
//Logistic function: 2 parameters
FUNCTION dvar_vector logistic(const dvar_vector& ages, const dvariable& A50, const dvariable& slope)
  //ages=vector of ages, A50=age at 50% selectivity, slope=rate of increase
  RETURN_ARRAYS_INCREMENT();
  dvar_vector Sel_Tmp(ages.indexmin(),ages.indexmax());
  Sel_Tmp=1./(1.+mfexp(-1.*slope*(ages-A50))); //logistic;
  RETURN_ARRAYS_DECREMENT();
  return Sel_Tmp;

//----------------------------------------------------------------------------------
//Logistic-exponential: 4 parameters (but 1 is fixed)
FUNCTION dvar_vector logistic_exponential(const dvar_vector& ages, const dvariable& A50, const dvariable& slope, const dvariable& sigma, const dvariable& joint)
  //ages=vector of ages, A50=age at 50% sel (ascending limb), slope=rate of increase, sigma=controls rate of descent (descending)
  //joint=age to join curves
  RETURN_ARRAYS_INCREMENT();
  dvar_vector Sel_Tmp(ages.indexmin(),ages.indexmax());
  Sel_Tmp=1.0;
  for (iage=1; iage<=nages; iage++)
  {
   if (ages(iage)<joint) {Sel_Tmp(iage)=1./(1.+mfexp(-1.*slope*(ages(iage)-A50)));}
   if (ages(iage)>joint){Sel_Tmp(iage)=mfexp(-1.*square((ages(iage)-joint)/sigma));}
  }
  Sel_Tmp=Sel_Tmp/max(Sel_Tmp);
  RETURN_ARRAYS_DECREMENT();
  return Sel_Tmp;

//----------------------------------------------------------------------------------
//Logistic function: 4 parameters
FUNCTION dvar_vector logistic_double(const dvar_vector& ages, const dvariable& A501, const dvariable& slope1, const dvariable& A502, const dvariable& slope2)
  //ages=vector of ages, A50=age at 50% selectivity, slope=rate of increase, A502=age at 50% decrease additive to A501, slope2=slope of decrease
  RETURN_ARRAYS_INCREMENT();
  dvar_vector Sel_Tmp(ages.indexmin(),ages.indexmax());
  Sel_Tmp=elem_prod( (1./(1.+mfexp(-1.*slope1*(ages-A501)))),(1.-(1./(1.+mfexp(-1.*slope2*(ages-(A501+A502)))))) );
  Sel_Tmp=Sel_Tmp/max(Sel_Tmp);
  RETURN_ARRAYS_DECREMENT();
  return Sel_Tmp;

//----------------------------------------------------------------------------------
//Jointed logistic function: 6 parameters (increasing and decreasing logistics joined at peak selectivity)
FUNCTION dvar_vector logistic_joint(const dvar_vector& ages, const dvariable& A501, const dvariable& slope1, const dvariable& A502, const dvariable& slope2, const dvariable& satval, const dvariable& joint)
  //ages=vector of ages, A501=age at 50% sel (ascending limb), slope1=rate of increase,A502=age at 50% sel (descending), slope1=rate of increase (ascending),
  //satval=saturation value of descending limb, joint=location in age vector to join curves (may equal age or age + 1 if age-0 is included)
  RETURN_ARRAYS_INCREMENT();
  dvar_vector Sel_Tmp(ages.indexmin(),ages.indexmax());
  Sel_Tmp=1.0;
  for (iage=1; iage<=nages; iage++)
  {
   if (double(iage)<joint) {Sel_Tmp(iage)=1./(1.+mfexp(-1.*slope1*(ages(iage)-A501)));}
   if (double(iage)>joint){Sel_Tmp(iage)=1.0-(1.0-satval)/(1.+mfexp(-1.*slope2*(ages(iage)-A502)));}
```

```
  }
  Sel_Tmp=Sel_Tmp/max(Sel_Tmp);
  RETURN_ARRAYS_DECREMENT();
  return Sel_Tmp;

//-----------------------------------------------------------------------------------
//Double Gaussian function: 6 parameters (as in SS3)
FUNCTION dvar_vector gaussian_double(const dvar_vector& ages, const dvariable& peak, const dvariable& top, const dvariable& ascwid, const dvariable& deswid, const dvariable& init, const dvariable& final)
  //ages=vector of ages, peak=ascending inflection location (as logistic), top=width of plateau, ascwid=ascent width (as log(width))
  //deswid=descent width (as log(width))
  RETURN_ARRAYS_INCREMENT();
  dvar_vector Sel_Tmp(ages.indexmin(),ages.indexmax());
  dvar_vector sel_step1(ages.indexmin(),ages.indexmax());
  dvar_vector sel_step2(ages.indexmin(),ages.indexmax());
  dvar_vector sel_step3(ages.indexmin(),ages.indexmax());
  dvar_vector sel_step4(ages.indexmin(),ages.indexmax());
  dvar_vector sel_step5(ages.indexmin(),ages.indexmax());
  dvar_vector sel_step6(ages.indexmin(),ages.indexmax());
  dvar_vector pars_tmp(1,6); dvar_vector sel_tmp_iq(1,2);

  pars_tmp(1)=peak;
  pars_tmp(2)=peak+1.0+(0.99*ages(nages)-peak-1.0)/(1.0+mfexp(-top));
  pars_tmp(3)=mfexp(ascwid);
  pars_tmp(4)=mfexp(deswid);
  pars_tmp(5)=1.0/(1.0+mfexp(-init));
  pars_tmp(6)=1.0/(1.0+mfexp(-final));

  sel_tmp_iq(1)=mfexp(-(square(ages(1)-pars_tmp(1))/pars_tmp(3)));
  sel_tmp_iq(2)=mfexp(-(square(ages(nages)-pars_tmp(2))/pars_tmp(4)));

  sel_step1=mfexp(-(square(ages-pars_tmp(1))/pars_tmp(3)));
  sel_step2=pars_tmp(5)+(1.0-pars_tmp(5))*(sel_step1-sel_tmp_iq(1))/(1.0-sel_tmp_iq(1));
  sel_step3=mfexp(-(square(ages-pars_tmp(2))/pars_tmp(4)));
  sel_step4=1.0+(pars_tmp(6)-1.0)*(sel_step3-1.0)/(sel_tmp_iq(2)-1.0);
  sel_step5=1.0/ (1.0+mfexp(-(20.0* elem_div((ages-pars_tmp(1)), (1.0+sfabs(ages-pars_tmp(1)))) )));
  sel_step6=1.0/(1.0+mfexp(-(20.0*elem_div((ages-pars_tmp(2)),(1.0+sfabs(ages-pars_tmp(2)))) )));

  Sel_Tmp=elem_prod(sel_step2,(1.0-sel_step5))+
        elem_prod(sel_step5,((1.0-sel_step6)+ elem_prod(sel_step4,sel_step6)) );

  Sel_Tmp=Sel_Tmp/max(Sel_Tmp);
  RETURN_ARRAYS_DECREMENT();
  return Sel_Tmp;

//-----------------------------------------------------------------------------------
//Spawner-recruit function (Beverton-Holt or Ricker)
FUNCTION dvariable SR_func(const dvariable& R0, const dvariable& h, const dvariable& spr_F0, const dvariable& SSB, int func)
  //R0=virgin recruitment, h=steepness, spr_F0=spawners per recruit @ F=0, SSB=spawning biomass
  //func=1 for Beverton-Holt, 2 for Ricker
  RETURN_ARRAYS_INCREMENT();
  dvariable Recruits_Tmp;
  switch(func) {
   case 1: //Beverton-Holt
```

```
      Recruits_Tmp=((0.8*R0*h*SSB)/(0.2*R0*spr_F0*(1.0-h)+(h-0.2)*SSB));
    break;
    case 2: //Ricker
      Recruits_Tmp=((SSB/spr_F0)*mfexp(h*(1-SSB/(R0*spr_F0))));
    break;
  }
  RETURN_ARRAYS_DECREMENT();
  return Recruits_Tmp;

//--------------------------------------------------------------------------------
//Spawner-recruit equilibrium function (Beverton-Holt or Ricker)
FUNCTION dvariable SR_eq_func(const dvariable& R0, const dvariable& h, const dvariable& spr_F0, const dvariable& spr_F, const dvariable& BC, int func)
  //R0=virgin recruitment, h=steepness, spr_F0=spawners per recruit @ F=0, spr_F=spawners per recruit @ F, BC=bias correction
  //func=1 for Beverton-Holt, 2 for Ricker
  RETURN_ARRAYS_INCREMENT();
  dvariable Recruits_Tmp;
  switch(func) {
    case 1: //Beverton-Holt
      Recruits_Tmp=(R0/((5.0*h-1.0)*spr_F))*(BC*4.0*h*spr_F-spr_F0*(1.0-h));
    break;
    case 2: //Ricker
      Recruits_Tmp=R0/(spr_F/spr_F0)*(1.0+log(BC*spr_F/spr_F0)/h);
    break;
  }
  RETURN_ARRAYS_DECREMENT();
  return Recruits_Tmp;

//--------------------------------------------------------------------------------
//compute multinomial effective sample size for a single yr
FUNCTION dvariable multinom_eff_N(const dvar_vector& pred_comp, const dvar_vector& obs_comp)
  //pred_comp=vector of predicted comps, obscomp=vector of observed comps
  dvariable EffN_Tmp; dvariable numer; dvariable denom;
  RETURN_ARRAYS_INCREMENT();
  numer=sum( elem_prod(pred_comp,(1.0-pred_comp)) );
  denom=sum( square(obs_comp-pred_comp) );
  if (denom>0.0) {EffN_Tmp=numer/denom;}
  else {EffN_Tmp=-missing;}
  RETURN_ARRAYS_DECREMENT();
  return EffN_Tmp;

//--------------------------------------------------------------------------------
//Likelihood contribution: lognormal
FUNCTION dvariable lk_lognormal(const dvar_vector& pred, const dvar_vector& obs, const dvar_vector& cv, const dvariable& wgt_dat)
  //pred=vector of predicted vals, obs=vector of observed vals, cv=vector of CVs in arithmetic space, wgt_dat=constant scaling of CVs
  //small_number is small value to avoid log(0) during search
  RETURN_ARRAYS_INCREMENT();
  dvariable LkvalTmp;
  dvariable small_number=0.0001;
  dvar_vector var(cv.indexmin(),cv.indexmax()); //variance in log space
  var=log(1.0+square(cv/wgt_dat));   // convert cv in arithmetic space to variance in log space
  LkvalTmp=sum(0.5*elem_div(square(log(elem_div((pred+small_number),(obs+small_number)))),var) );
  RETURN_ARRAYS_DECREMENT();
```

```
  return LkvalTmp;

//----------------------------------------------------------------------------------
//Likelihood contribution: multinomial
FUNCTION dvariable lk_multinomial(const dvar_vector& nsamp, const dvar_matrix& pred_comp, const dvar_matrix&
obs_comp, const double& ncomp, const double& minSS, const dvariable& wgt_dat)
  //nsamp=vector of N's, pred_comp=matrix of predicted comps, obs_comp=matrix of observed comps, ncomp = number of
yrs in matrix, minSS=min N threshold, wgt_dat=scaling of N's
  RETURN_ARRAYS_INCREMENT();
  dvariable LkvalTmp;
  dvariable small_number=0.0001;
  LkvalTmp=0.0;
  for (int ii=1; ii<=ncomp; ii++)
  {if (nsamp(ii)>=minSS)
   {LkvalTmp-=wgt_dat*nsamp(ii)*sum(elem_prod((obs_comp(ii)+small_number),
           log(elem_div((pred_comp(ii)+small_number), (obs_comp(ii)+small_number)))));
   }
  }
  RETURN_ARRAYS_DECREMENT();
  return LkvalTmp;

//----------------------------------------------------------------------------------
//Likelihood contribution: robust multinomial
FUNCTION dvariable lk_robust_multinomial(const dvar_vector& nsamp, const dvar_matrix& pred_comp, const
dvar_matrix& obs_comp, const double& ncomp, const dvariable& mbin, const double& minSS, const dvariable& wgt_dat)
  //nsamp=vector of N's, pred_comp=matrix of predicted comps, obs_comp=matrix of observed comps, ncomp = number of
yrs in matrix, mbin=number of bins, minSS=min N threshold, wgt_dat=scaling of N's
  RETURN_ARRAYS_INCREMENT();
  dvariable LkvalTmp;
  dvariable small_number=0.0001;
  LkvalTmp=0.0;
  dvar_matrix Eprime=elem_prod((1.0-obs_comp), obs_comp)+0.1/mbin; //E' of Francis 2011, p.1131
  dvar_vector nsamp_wgt=nsamp*wgt_dat;
  //cout<<nsamp_wgt<<endl;
  for (int ii=1; ii<=ncomp; ii++)
  {if (nsamp(ii)>=minSS)
   {LkvalTmp+= sum(0.5*log(Eprime(ii))-log(small_number+mfexp(elem_div((-square(obs_comp(ii)-pred_comp(ii))) ,
(Eprime(ii)*2.0/nsamp_wgt(ii)) ))) );
   }
  }
  RETURN_ARRAYS_DECREMENT();
  return LkvalTmp;

//----------------------------------------------------------------------------------
//Likelihood contribution: Dirichlet-multinomial
FUNCTION dvariable lk_dirichlet_multinomial(const dvar_vector& nsamp, const dvar_matrix& pred_comp, const
dvar_matrix& obs_comp, const double& ncomp, const dvariable& mbin, const double& minSS, const dvariable&
log_dir_par)
  //nsamp=vector of N's, pred_comp=matrix of predicted comps, obs_comp=matrix of observed comps, ncomp = number of
yrs in matrix, mbin=number of bins, minSS=min N threshold, wgt_dat=scaling of N's
  RETURN_ARRAYS_INCREMENT();
  dvariable LkvalTmp;
  LkvalTmp=0.0;
  dvar_vector nsamp_adjust=nsamp*mfexp(log_dir_par);
  //dvar_vector nsamp_adjust=mfexp(log_dir_par);
  for (int ii=1; ii<=ncomp; ii++)
```

```
 {
            if (nsamp(ii)>=minSS)
   {
                        LkvalTmp-=gammln(nsamp_adjust(ii))-gammln(nsamp(ii)+nsamp_adjust(ii));
                        LkvalTmp-=sum(gammln(nsamp(ii)*obs_comp(ii)+nsamp_adjust(ii)*pred_comp(ii)));
      LkvalTmp+=sum(gammln(nsamp_adjust(ii)*pred_comp(ii)));
   }
 }
 RETURN_ARRAYS_DECREMENT();
 return LkvalTmp;

//----------------------------------------------------------------------------------
//Likelihood contribution: logistic normal (aka multivariate logistic in iSCAM; logistic normal in Francis' terminology)
FUNCTION dvariable lk_logistic_normal(const dvar_vector& nsamp, const dvar_matrix& pred_comp, const dvar_matrix&
obs_comp, const double& ncomp, const dvariable& mbin, const double& minSS)
  //nsamp=vector of N's, pred_comp=matrix of predicted comps, obs_comp=matrix of observed comps, ncomp = number of
yrs in matrix, mbin=number of bins, minSS=min N threshold
 RETURN_ARRAYS_INCREMENT();
 dvariable LkvalTmp;
 dvariable small_number=0.0001;
 LkvalTmp=0.0;
 dvar_matrix nu=pred_comp+0.0;
 dvar_matrix pred_plus=pred_comp+small_number;
 dvar_matrix obs_plus=obs_comp+small_number;

 dvariable nu_mean;
 dvariable nu_sum_sq;
 dvariable tau_hat_sq;
 dvariable year_count; //keeps track of years included in likelihood (i.e., that meet the sample size requirement)

 LkvalTmp=0.0;
 nu_sum_sq=0.0;
 year_count=0.0;
 for (int ii=1; ii<=ncomp; ii++)
 {if (nsamp(ii)>=minSS)
   {
                        year_count+=1.0;
                        nu_mean=sum( log(obs_plus(ii))-log(pred_plus(ii))  )/mbin;     //year-specific mean log residual
                        for (int jj=1; jj<=mbin;jj++)
                        {
                                    nu(ii,jj) = log(obs_plus(ii,jj)) - log(pred_plus(ii,jj)) - nu_mean;
                                    nu_sum_sq += square(nu(ii,jj));
                        }
   }
 }
 if (year_count>0.0)
 {
           tau_hat_sq = nu_sum_sq/((mbin-1.0)*year_count);
           LkvalTmp = (mbin-1.0)*year_count*log(tau_hat_sq);
 }
 RETURN_ARRAYS_DECREMENT();
 return LkvalTmp;

//----------------------------------------------------------------------------------
//----------------------------------------------------------------------------------
//Likelihood contribution: priors
```

```
FUNCTION  dvariable neg_log_prior(dvariable pred, const double& prior, dvariable var, int pdf)
  //prior=prior point estimate, var=variance (if negative, treated as CV in arithmetic space), pred=predicted value, pdf=prior
type (1=none, 2=lognormal, 3=normal, 4=beta)
    dvariable LkvalTmp;
    dvariable alpha, beta, ab_iq;
    dvariable big_number=1e10;
    LkvalTmp=0.0;
    // compute generic pdf's
    switch(pdf) {
      case 1: //option to turn off prior
        LkvalTmp=0.0;
        break;
      case 2: // lognormal
        if(prior<=0.0) cout << "YIKES: Don't use a lognormal distn for a negative prior" << endl;
        else if(pred<=0) LkvalTmp=big_number=1e10;
        else {
          if(var<0.0) var=log(1.0+var*var) ;      // convert cv to variance on log scale
          LkvalTmp= 0.5*( square(log(pred/prior))/var + log(var) );
        }
      break;
      case 3: // normal
        if(var<0.0 && prior!=0.0) var=square(var*prior);       // convert cv to variance on observation scale
        else if(var<0.0 && prior==0.0) var=-var;              // cv not really appropriate if prior value equals zero
        LkvalTmp= 0.5*( square(pred-prior)/var + log(var) );
        break;
      case 4: // beta
        if(var<0.0) var=square(var*prior);          // convert cv to variance on observation scale
        if(prior<=0.0 || prior>=1.0) cout << "YIKES: Don't use a beta distn for a prior outside (0,1)" << endl;
        ab_iq=prior*(1.0-prior)/var - 1.0; alpha=prior*ab_iq; beta=(1.0-prior)*ab_iq;
        if(pred>=0 && pred<=1) LkvalTmp= (1.0-alpha)*log(pred)+(1.0-beta)*log(1.0-pred)-
gammln(alpha+beta)+gammln(alpha)+gammln(beta);
        else LkvalTmp=big_number;
        break;
      default: // no such prior pdf currently available
        cout << "The prior must be either 1(lognormal), 2(normal), or 3(beta)." << endl;
        cout << "Presently it is " << pdf << endl;
        exit(0);
    }
    return LkvalTmp;

//----------------------------------------------------------------------------------
//SDNR: age comp likelihood (assumes fits are done with the robust multinomial function)
FUNCTION dvariable sdnr_multinomial(const double& ncomp, const dvar_vector& ages, const dvar_vector& nsamp,
                                    const dvar_matrix& pred_comp, const dvar_matrix& obs_comp, const dvariable& wgt_dat)
  //ncomp=number of years of data, ages=vector of ages, nsamp=vector of N's,
  //pred_comp=matrix of predicted comps, obs_comp=matrix of observed comps, wgt_dat=likelihood weight for data
source
  RETURN_ARRAYS_INCREMENT();
  dvariable SdnrTmp;
  dvar_vector o(1,ncomp);
  dvar_vector p(1,ncomp);
  dvar_vector ose(1,ncomp);
  dvar_vector res(1,ncomp);
  SdnrTmp=0.0;
  for (int ii=1; ii<=ncomp; ii++)
  {
```

```
    o(ii)=sum(elem_prod(ages,obs_comp(ii)));
    p(ii)=sum(elem_prod(ages,pred_comp(ii)));
    ose(ii)=sqrt((sum(elem_prod(square(ages),pred_comp(ii)))-square(p(ii)))/(nsamp(ii)*wgt_dat));
  }
  res=elem_div((o-p),ose);
  SdnrTmp=sqrt(sum(square(res-(sum(res)/ncomp))/(ncomp-1.0)));
  RETURN_ARRAYS_DECREMENT();
  return SdnrTmp;

//--------------------------------------------------------------------------------------
//SDNR: lognormal likelihood
FUNCTION dvariable sdnr_lognormal(const dvar_vector& pred, const dvar_vector& obs, const dvar_vector& cv, const
dvariable& wgt_dat)
  //nyr=number of years of data, pred=vector of predicted data, obs=vector of observed data, cv=vector of cv's,
wgt_dat=likelihood weight for data source
  RETURN_ARRAYS_INCREMENT();
  dvariable SdnrTmp;
  dvariable small_number=0.00001;
  dvariable n;
  dvar_vector res(cv.indexmin(),cv.indexmax());
  SdnrTmp=0.0;
  res=elem_div(log(elem_div(obs+small_number,pred+small_number)),sqrt(log(1+square(cv/wgt_dat))));
  n=cv.indexmax()-cv.indexmin()+1;
  SdnrTmp=sqrt(sum(square(res-(sum(res)/n))/(n-1.0)));
  RETURN_ARRAYS_DECREMENT();
  return SdnrTmp;

//--------------------------------------------------------------------------------------
REPORT_SECTION

  if (last_phase())
  {
      cout<<"start report"<<endl;
       //cout<<"xdum = "<<xdum<<endl;
      get_weighted_current();
       //cout<<"got weighted"<<endl;
      get_msy();
       //cout<<"got msy"<<endl;
      get_per_recruit_stuff();
       //cout<<"got per recruit"<<endl;
      get_miscellaneous_stuff();
       //cout<<"got misc stuff"<<endl;
      get_projection();
       //cout<<"got projection"<<endl;

      grad_max=objective_function_value::pobjfun->gmax;
      time(&finish);
                  elapsed_time=difftime(finish,start);
                  hour=long(elapsed_time)/3600;
                  minute=long(elapsed_time)%3600/60;
                  second=(long(elapsed_time)%3600)%60;
                  cout<<endl<<endl<<"*********************************************"<<endl;
                  cout<<"--Start time: "<<ctime(&start)<<endl;
                  cout<<"--Finish time: "<<ctime(&finish)<<endl;
                  cout<<"--Runtime: ";
                  cout<<hour<<" hours, "<<minute<<" minutes, "<<second<<" seconds"<<endl;
```

```
        cout << "--TotalLikelihood: " << fval << endl;
    cout<<"--Final gradient: "<<objective_function_value::pobjfun->gmax << endl;
        cout<<"*********************************************"<<endl;

  cout <<endl;
  cout << "><>--><>--><>--><>--><>--><>--><>--><>--><>--><>"  <<endl;
  //cout << "BC Fmsy=" << F_msy_out<< "   BC SSBmsy=" << SSB_msy_out <<endl;
  cout <<"F status="<<FdF_msy_end<<endl;
  cout <<"Pop status="<<SdSSB_msy_end<<endl;
  cout << "h="<<steep<<"   R0="<<R0<<endl;
  //cout << "xdum " << xdum << endl;
  cout << "><>--><>--><>--><>--><>--><>--><>--><>--><>--><>"  <<endl;

  report << "TotalLikelihood " << fval << endl;
  report << "N" << endl;
  report << N<<endl;
  report << "F" << endl;
  report << F <<endl;

  sdnr_lc_lagn=sdnr_multinomial(nyr_lagn_lenc, lenbins, nsamp_lagn_lenc, pred_lagn_lenc, obs_lagn_lenc, w_lc_lagn);

  sdnr_ac_cR=sdnr_multinomial(nyr_cR_agec, agebins_agec, nsamp_cR_agec, pred_cR_agec, obs_cR_agec, w_ac_cR);

  sdnr_I_lagn=sdnr_lognormal(pred_lagn_cpue, obs_lagn_cpue, lagn_cpue_cv, w_I_lagn);
  sdnr_I_seine=sdnr_lognormal(pred_seine_cpue, obs_seine_cpue, seine_cpue_cv, w_I_seine);



//################################################################################################
  //##  Passing parameters to vector for bounds check plotting

//################################################################################################
   Linf_out(8)=Linf; Linf_out(1,7)=set_Linf;
   K_out(8)=K; K_out(1,7)=set_K;
   t0_out(8)=t0; t0_out(1,7)=set_t0;
   len_cv_val_out(8)=len_cv_val; len_cv_val_out(1,7)=set_len_cv;

   log_R0_out(8)=log_R0; log_R0_out(1,7)=set_log_R0;
   steep_out(8)=steep; steep_out(1,7)=set_steep;
   rec_sigma_out(8)=rec_sigma; rec_sigma_out(1,7)=set_rec_sigma;
   R_autocorr_out(8)=R_autocorr; R_autocorr_out(1,7)=set_R_autocorr;

   log_dm_lagn_lc_out(8)=log_dm_lagn_lc; log_dm_lagn_lc_out(1,7)=set_log_dm_lagn_lc;
   log_dm_cR_ac_out(8)=log_dm_cR_ac; log_dm_cR_ac_out(1,7)=set_log_dm_cR_ac;

   selpar_A50_cR1_out(8)=selpar_A50_cR1; selpar_A50_cR1_out(1,7)=set_selpar_A50_cR1;
   selpar_slope_cR1_out(8)=selpar_slope_cR1; selpar_slope_cR1_out(1,7)=set_selpar_slope_cR1;
   selpar_A502_cR1_out(8)=selpar_A502_cR1; selpar_A502_cR1_out(1,7)=set_selpar_A502_cR1;
   selpar_slope2_cR1_out(8)=selpar_slope2_cR1; selpar_slope2_cR1_out(1,7)=set_selpar_slope2_cR1;

   selpar_A50_cR2_out(8)=selpar_A50_cR2; selpar_A50_cR2_out(1,7)=set_selpar_A50_cR2;
   selpar_slope_cR2_out(8)=selpar_slope_cR2; selpar_slope_cR2_out(1,7)=set_selpar_slope_cR2;
   selpar_A502_cR2_out(8)=selpar_A502_cR2; selpar_A502_cR2_out(1,7)=set_selpar_A502_cR2;
   selpar_slope2_cR2_out(8)=selpar_slope2_cR2; selpar_slope2_cR2_out(1,7)=set_selpar_slope2_cR2;

   selpar_age0_cR_out(8)=sel_age0_cR_logit; selpar_age0_cR_out(1,7)=set_sel_age0_cR;
```

```
    selpar_age1_cR_out(8)=sel_age1_cR_logit; selpar_age1_cR_out(1,7)=set_sel_age1_cR;
    selpar_age2_cR_out(8)=sel_age2_cR_logit; selpar_age2_cR_out(1,7)=set_sel_age2_cR;
    selpar_age3_cR_out(8)=sel_age3_cR_logit; selpar_age3_cR_out(1,7)=set_sel_age3_cR;
    selpar_age4_cR_out(8)=sel_age4_cR_logit; selpar_age4_cR_out(1,7)=set_sel_age4_cR;

    selpar_age0_cR2_out(8)=sel_age0_cR2_logit; selpar_age0_cR2_out(1,7)=set_sel_age0_cR2;
    selpar_age1_cR2_out(8)=sel_age1_cR2_logit; selpar_age1_cR2_out(1,7)=set_sel_age1_cR2;
    selpar_age2_cR2_out(8)=sel_age2_cR2_logit; selpar_age2_cR2_out(1,7)=set_sel_age2_cR2;
    selpar_age3_cR2_out(8)=sel_age3_cR2_logit; selpar_age3_cR2_out(1,7)=set_sel_age3_cR2;
    selpar_age4_cR2_out(8)=sel_age4_cR2_logit; selpar_age4_cR2_out(1,7)=set_sel_age4_cR2;

    selpar_A50_lagn_out(8)=selpar_A50_lagn; selpar_A50_lagn_out(1,7)=set_selpar_A50_lagn;
    selpar_slope_lagn_out(8)=selpar_slope_lagn; selpar_slope_lagn_out(1,7)=set_selpar_slope_lagn;

    log_q_lagn_out(8)=log_q_lagn; log_q_lagn_out(1,7)=set_log_q_lagn;
    log_q_seine_out(8)=log_q_seine; log_q_seine_out(1,7)=set_log_q_seine;

    log_avg_F_cR_out(8)=log_avg_F_cR; log_avg_F_cR_out(1,7)=set_log_avg_F_cR;

    log_rec_dev_out(styr_rec_dev, endyr_rec_dev)=log_rec_dev;
    log_F_dev_cR_out(styr_cR_L,endyr_cR_L)=log_F_dev_cR;

 #include "gm_make_Robject5.cxx"   // write the R-compatible report

} //endl last phase loop
```

Appendix A2

```
##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
##
##  Data Input File
##  Gulf menhaden for SEDAR 63
##
##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>

##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
##-- BAM DATA SECTION: set-up section
##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>

#Starting and ending year of model
1977
2017
#Starting year to estimate recruitment deviation from S-R curve
1977
#Ending year to estimate recruitment deviation from S-R curve
2017
#3 phases of constraints on recruitment deviations:
#allows possible heavier constraint (weights defined later) in early and late period, with lighter constraint in the
middle
#ending years of recruitment constraint phases
1978
2015
#3 periods of size regs: place holders for now
#ending years of regulation period
1987
1995

#Number of ages in population model(5 classes are 0,...,N+) //assumes last age is plus group
5
#Vector of agebins, last is a plus group
0.0	1.0		2.0	3.0	4.0
#Number of ages used to match age comps: first age must be same as popn, plus group may differ
5
#Vector of agebins for fitting, last is a plus group
0.0	1.0		2.0	3.0	4.0

#Number length bins used to match length comps and width of bins
22   #number bins
10.0 #width of bins (mm)
#Vector of length bins (mm)(midpoint of bin) used to match length comps and bins used to compute plus group
85	95	105	115	125	135	145	155	165	175	185	195	205	215
225	235	245	255	265	275	285	295
#Max value of F used in spr and msy calculations
10.0
#Number of iterations in spr and msy calculations
10001
```

```
#Starting year to compute arithmetic average recruitment for SPR-related values
1977
#Ending year to compute arithmetic average recruitment for SPR-related values
2017
#Number years at end of time series over which to average sector Fs, for weighted selectivities
3
#Multiplicative bias correction of recruitment (may set to 1.0 for none or negative to compute from recruitment
variance)
-1.0
# ##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
# ##-- BAM DATA SECTION: observed data section
# ##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>

##########################Fishery independent sampling
#####################################################
###LA gill net index
#Starting and ending years of the index
1988
2017
#Observed index (numbers) and CVs
0.95    0.54    0.59    0.58    0.44    0.35    0.62    0.50    0.57    0.85    0.76    0.71    1.07    1.09
        0.87    0.83    0.65    1.01    1.17    0.86    2.10    1.91    0.60    1.44    1.78    1.49    1.82
        1.17    1.26    1.43
0.25    0.25    0.25    0.25    0.25    0.25    0.25    0.25    0.25    0.25    0.25    0.25    0.25    0.25
        0.25    0.25    0.25    0.25    0.25    0.25    0.25    0.25    0.25    0.25    0.25    0.25    0.25
        0.25    0.25    0.25

#Number and vector of years of length composition data
22
1996   1997   1998   1999   2000   2001   2002   2003   2004   2005   2006   2007   2008   2009      2010
        2011    2012    2013    2014    2015   2016   2017
#sample sizes of length comps by year (first row number of trip, second row number of fish)
225     247     276     262     326     279     295     293     256     271     345     298     325     362
        219     421     486     215     211     189     166     188
2529    3566    3299    3184    4736    4343    3566    3661    3000    4069    5142    3870    6708    6554
        2547    6996    8458    3471    3981    2833    2820    3337
#length composition by year (year,lengthbin 3cm)
0.010   0.020   0.010   0.020   0.070   0.160   0.160   0.090   0.110   0.110   0.070   0.050   0.040   0.040
        0.020   0.010   0.000   0.000   0.000   0.000   0.000   0.000
0.000   0.010   0.000   0.020   0.060   0.140   0.140   0.110   0.110   0.120   0.090   0.070   0.060   0.030
        0.020   0.010   0.000   0.000   0.000   0.000   0.000   0.000
0.000   0.010   0.010   0.020   0.070   0.170   0.190   0.120   0.110   0.110   0.070   0.040   0.030   0.020
        0.010   0.010   0.000   0.000   0.000   0.000   0.000   0.000
0.000   0.010   0.010   0.030   0.080   0.160   0.140   0.090   0.110   0.110   0.090   0.060   0.060   0.030
        0.020   0.000   0.000   0.000   0.000   0.000   0.000   0.000
0.000   0.010   0.010   0.020   0.070   0.140   0.110   0.070   0.070   0.120   0.120   0.080   0.080   0.060
        0.030   0.010   0.000   0.000   0.000   0.000   0.000   0.000
0.000   0.010   0.010   0.010   0.060   0.110   0.100   0.080   0.120   0.130   0.090   0.080   0.080   0.060
        0.040   0.020   0.010   0.000   0.000   0.000   0.000   0.000
```

```
0.000   0.010   0.010   0.030   0.060   0.140   0.140   0.080   0.090   0.100   0.090   0.060   0.070   0.060
        0.030   0.010   0.010   0.000   0.000   0.000   0.000   0.000
0.000   0.010   0.010   0.030   0.090   0.190   0.190   0.100   0.090   0.130   0.070   0.020   0.020   0.020
        0.010   0.000   0.000   0.000   0.000   0.000   0.000   0.000
0.000   0.010   0.020   0.040   0.110   0.180   0.170   0.110   0.100   0.080   0.070   0.040   0.040   0.020
        0.010   0.000   0.000   0.000   0.000   0.000   0.000   0.000
0.000   0.010   0.010   0.030   0.060   0.150   0.180   0.120   0.120   0.130   0.080   0.040   0.040   0.020
        0.010   0.000   0.000   0.000   0.000   0.000   0.000   0.000
0.010   0.010   0.010   0.020   0.080   0.160   0.150   0.150   0.100   0.110   0.080   0.050   0.040   0.020
        0.010   0.000   0.000   0.000   0.000   0.000   0.000   0.000
0.010   0.010   0.010   0.010   0.050   0.130   0.170   0.150   0.140   0.130   0.080   0.040   0.030   0.020
        0.010   0.000   0.000   0.000   0.000   0.000   0.000   0.000
0.000   0.010   0.010   0.020   0.040   0.120   0.140   0.100   0.120   0.150   0.110   0.080   0.060   0.030
        0.010   0.010   0.000   0.000   0.000   0.000   0.000   0.000
0.000   0.010   0.010   0.020   0.040   0.090   0.140   0.110   0.110   0.120   0.120   0.080   0.080   0.050
        0.020   0.010   0.000   0.000   0.000   0.000   0.000   0.000
0.000   0.010   0.010   0.030   0.070   0.140   0.120   0.080   0.090   0.110   0.100   0.080   0.060   0.050
        0.020   0.010   0.000   0.000   0.000   0.000   0.000   0.000
0.000   0.010   0.020   0.030   0.080   0.160   0.150   0.080   0.080   0.100   0.100   0.060   0.060   0.040
        0.020   0.000   0.000   0.000   0.000   0.000   0.000   0.000
0.000   0.000   0.010   0.020   0.060   0.160   0.180   0.110   0.110   0.120   0.070   0.050   0.050   0.030
        0.010   0.000   0.000   0.000   0.000   0.000   0.000   0.000
0.000   0.020   0.010   0.020   0.060   0.120   0.140   0.110   0.140   0.130   0.100   0.050   0.060   0.030
        0.010   0.000   0.000   0.000   0.000   0.000   0.000   0.000
0.000   0.000   0.020   0.010   0.040   0.130   0.160   0.090   0.090   0.120   0.130   0.090   0.060   0.040
        0.010   0.000   0.000   0.000   0.000   0.000   0.000   0.000
0.010   0.010   0.010   0.030   0.090   0.180   0.160   0.060   0.060   0.110   0.100   0.070   0.070   0.040
        0.010   0.000   0.000   0.000   0.000   0.000   0.000   0.000
0.000   0.010   0.000   0.020   0.050   0.120   0.200   0.160   0.130   0.110   0.080   0.040   0.040   0.030
        0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000
0.000   0.010   0.010   0.010   0.060   0.170   0.170   0.100   0.110   0.130   0.100   0.050   0.030   0.020
        0.010   0.000   0.000   0.000   0.000   0.000   0.000   0.000

###seine index
#Starting and ending years of the index
1996
2017
#Observed index (numbers) and CVs
1.47    0.59    0.89    0.53    0.84    0.75    0.48    0.75    0.50    0.66    0.88    0.74    0.28    1.01
        1.39    3.28    1.03    1.00    1.76    1.15    1.48    0.53
0.27    0.27    0.27    0.29    0.30    0.26    0.26    0.25    0.27    0.26    0.27    0.27    0.28    0.25
        0.25    0.25    0.25    0.29    0.31    0.22    0.21    0.22


###########################################Commercial reduction fishery
##########################################################
###Starting and ending years for landings time series
1977
2017
##commercial reduction landings vector (1,000s mt; includes rec and bait) and assumed CVs
```

```
447.6   820.6   779.8   702.5   553.7   855.5   925.3   985.1   884.6   830.9   911.7   640.2   583.6   539.5
        552.8   432.7   551.3   774.9   472.0   491.8   623.5   495.7   694.2   590.8   528.6   582.6   524.3
        473.7   438.2   467.7   457.4   425.6   457.7   379.9   614.0   579.8   498.8   400.7   540.3   491.5
        462.5
0.04    0.04    0.04    0.04    0.04    0.04    0.04    0.04    0.04    0.04    0.04    0.04    0.04    0.04
        0.04    0.04    0.04    0.04    0.04    0.04    0.04    0.04    0.04    0.04    0.04    0.04    0.04
        0.04    0.04    0.04    0.04    0.04    0.04    0.04    0.04    0.04    0.04    0.04    0.04    0.04
        0.04

#Number and vector of years of age compositions for commercial handline fleet
41
1977    1978    1979    1980    1981    1982    1983    1984    1985    1986    1987    1988    1989    1990
        1991    1992    1993    1994    1995    1996    1997    1998    1999    2000    2001    2002    2003
        2004    2005    2006    2007    2008    2009    2010    2011    2012    2013    2014    2015    2016
        2017
#Sample size of age comp data (first row observed Nsets, second row Nfish)
1492    1300    1163    1014    1042    1076    1485    1599    1324    1652    1647    1240    1392    1152
        1164    1524    1537    1680    1470    1506    1124    1073    1183    969     740     836     1066
        942     899     594     657     594     748     461     835     1087    852     878     1145    830
        736
14897   12944   11121   9883    10273   10341   14523   15936   13225   16494   16458   12402   13950   11456
        11378   14214   14579   16062   13489   12116   9923    9046    10642   8383    6222    5597    7839
        6644    6206    4698    3989    4663    6193    3678    7254    7692    5801    6077    8677    5713
        5231
##commercial handline age comps
0.000   0.763   0.218   0.018   0.001
0.000   0.708   0.286   0.005   0.001
0.000   0.593   0.363   0.043   0.001
0.009   0.472   0.452   0.060   0.007
0.000   0.763   0.189   0.044   0.005
0.000   0.571   0.366   0.056   0.007
0.000   0.526   0.428   0.043   0.003
0.000   0.697   0.259   0.039   0.004
0.000   0.758   0.218   0.020   0.003
0.000   0.456   0.522   0.019   0.003
0.000   0.603   0.358   0.038   0.001
0.000   0.660   0.319   0.019   0.002
0.000   0.766   0.224   0.009   0.000
0.000   0.668   0.306   0.023   0.002
0.000   0.462   0.487   0.045   0.006
0.000   0.559   0.384   0.050   0.007
0.001   0.666   0.292   0.037   0.004
0.000   0.496   0.437   0.060   0.007
0.000   0.351   0.622   0.026   0.001
0.000   0.391   0.550   0.055   0.004
0.000   0.544   0.403   0.046   0.007
0.000   0.392   0.563   0.041   0.004
0.000   0.544   0.386   0.067   0.003
0.000   0.362   0.564   0.062   0.012
0.000   0.250   0.672   0.074   0.005
```

```
0.000   0.317   0.573   0.107   0.003
0.000   0.362   0.571   0.064   0.003
0.000   0.560   0.353   0.080   0.008
0.019   0.394   0.541   0.043   0.003
0.000   0.459   0.470   0.065   0.006
0.000   0.463   0.510   0.024   0.004
0.000   0.266   0.683   0.044   0.006
0.000   0.126   0.731   0.129   0.013
0.000   0.529   0.404   0.061   0.006
0.007   0.632   0.317   0.037   0.007
0.003   0.309   0.658   0.029   0.001
0.002   0.245   0.727   0.025   0.001
0.006   0.258   0.596   0.134   0.006
0.000   0.625   0.309   0.062   0.005
0.006   0.516   0.411   0.062   0.005
0.010   0.657   0.275   0.056   0.001


###--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
###-- BAM DATA SECTION: parameter section
###--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
#
####################Parameter values and initial
guesses################################################################################
#######################################################
###prior PDF (1=none, 2=lognormal, 3=normal, 4=beta)
#################################################################
##initial # lower # upper #      #  prior  # prior   # prior #
## guess  # bound # bound # phase #  mean   # var/-CV #  PDF  #
##--------#-------#-------#-------#---------#---------#-------#
######Population                                     ###### Biological input #####################################
 236.2     150.0    450.0  -4     248.0    -0.25     1    # VonBert Linf (units in mm FL)
 0.331     0.03     0.9   -4     0.40     -0.25     1    # VonBert K (units in mm FL)
 -1.744    -3.0    -0.01  -4     -0.67    -0.25     1    # VonBert t0 (units in mm FL)
 0.09        0.05    0.3    4              0.09    -0.25   1    # CV of length at age
###### SR parameters ##########################################
0.99      0.21    0.99   -3      0.75    0.021     1    #SR steepness
2.9         2.0     8.0    1      4.9    -0.5      1    # SR log_R0 parameter
0.0       -1.0     1.0    -3      0.0    -0.5      1    # SR recruitment autocorrelation (lag 1)
0.6         0.2     1.2    -4               0.6    0.0225 1    # s.d. of recruitment in log space [SD=0.15=(0.6-0.3)/1.96,
puts closest bound at 95%CI: Mertz & Myers report range of (0.3,1.0)]
##### Dirichlet-multinomial overdispersion parameters
0.0       -5.0      5.0    7      0.0    -1.0      1     # Dirichlet-multinomial overdispersion parameter (log-space): gill
net length comps
0.0       -5.0      5.0    7      0.0    -1.0      1     # Dirichlet-multinomial overdispersion parameter (log-space): cR
age comps

##### Selectivity parameters ##########################
######Commercial reduction
2.0       0.1          10.0   -5      2.0    -0.5          1     #BLOCK 1: comm reduction age at 50% selectivity
```

```
3.0     0.1       10.0   -5        3.0   -0.5    1      #BLOCK 1: comm reduction slope of ascending limb
3.5       0.01    10.0   -5          4.5   -0.5    1    #BLOCK 1: comm reduction age at 50% selectivity
descending limb
3.0       0.1       10.0   -5        3.0   -0.5    1      #BLOCK 1: comm reduction slope of descending limb

1.0     0.1       10.0   -5     2.0   -0.5        1    #BLOCK 2: comm reduction age at 50% selectivity
7.0     0.1       10.0   -5        3.0   -0.5    1      #BLOCK 2: comm reduction slope of ascending limb
6.5       0.01    10.0   -5          4.5   -0.5    1    #BLOCK 2: comm reduction age at 50% selectivity
descending limb
2.0       0.1       10.0   -5        3.0   -0.5    1      #BLOCK 2: comm reduction slope of descending limb

-9.0    -10.0    10.0   -5     -5.0   -0.5    1   #age-0 cR selectivity in logit space
0.0     -10.0    10.0    5      0.0   -0.5    1   #age-1 cR selectivity in logit space
9.0     -10.0    10.0   -5      5.0   -0.5    1   #age-2 cR selectivity in logit space
-0.6    -15.0    0.50   -5      0.0   -0.5    1   #age-3 cR selectivity in logit space
0.0     -10.0    2.75   -5      0.0   -0.5    1   #age-4+ cR selectivity in logit space

-9.0    -10.0    10.0   -5     -5.0   -0.5    1   #age-0 cR selectivity in logit space-period 2
2.0     -10.0    10.0    5      0.0   -0.5    1   #age-1 cR selectivity in logit space-period 2
9.0     -10.0    10.0   -5      5.0   -0.5    1   #age-2 cR selectivity in logit space-period 2
0.0     -15.0    10.0   -5      0.0   -0.5    1   #age-3 cR selectivity in logit space-period 2
0.0     -10.0    10.0   -5      0.0   -0.5    1   #age-4+ cR selectivity in logit space-period 2


######LA gill net index
0.42      0.0      4.0    5           1.42   -0.5    1    #BLOCK 1: la gill net age at 50% selectivity
3.62      0.1      25.0    5     3.62   -0.5        1    #BLOCK 1: la gill net slope

###### Index catchability parameters #######################
-6.0       -9     -0.1    3     -8.0   -0.5    1      #LA gill net index (log q)
-5.377    -9     -1            3         -5.377 -0.5   1    #seine index (log q)
###### Fishing mortality parameters ########################
-3.0      -10.0    1.0    1        -3.0  -0.5        1    #commercial reduction log mean F


##### Dev vectors
#########################################################################################
#########################
# lower # upper #     #
# bound # bound # phase #
#-------#-------#-------#
-5.0    5.0     2   # comm reduction F devs
-3.0      3.0    -4   # Random walk on q
-5.0    5.0     2   # recruitment devs
-15.0   15.0     3   # Nage devs

# commercial reduction F dev initial guesses (1977-2017)
0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
        0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
```

```
          0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0
          0.0
# rec devs  (1977-2017)
0.0       0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0
          0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0
          0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0
          0.0
# initial N age devs, all ages but the first one (1 to 4+)
0.0       0.0      0.0      0.0


##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
##-- BAM DATA SECTION: likelihood weights section
##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
###################Likelihood Component
Weighting#####################################################################################
1.0    #landings

4.0    #LA gill net index
1.0    #seine index

1.0    #LA gill net len comps

1.0    #cR age comps

1.0    #log N.age.dev residuals (initial abundance)
1.0    #S-R residuals
0.0    #constraint on early recruitment deviations
0.0    #constraint on ending recruitment deviations
0.0    #penalty if F exceeds 3.0 (reduced by factor of 10 each phase, not applied in final phase of optimization)
fULL F summed over fisheries
0.0    #weight on tuning F (penalty not applied in final phase of optimization)


##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
##-- BAM DATA SECTION: miscellaneous stuff section
##--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>--><>
#length-weight (FL-whole wgt) coefficients a and b, W=aL^b, (W in g, FL in mm)--sexes combined
9.60E-06
3.14

#vector of maturity-at-age for females (ages 0-4+)
0.0       0.8      1.0      1.0      1.0

#vector of maturity-at-age for males (ages 0-4+)
0.0       0.8      1.0      1.0      1.0

#Proportion female by age
0.5       0.5      0.5      0.5      0.5
```

```
#time-invariant fecundity at age (number of maturing ova per individual)
0   164106   404404   744264   1149697

#time-invariant weight (in grams) at age at spawning
0.0     53.4         97.5      146.7    196.4

#time-invariant weight (in grams) at age at start of fishing year
35.9      89.3      140.4    179.9    207.6

#time of year (as fraction) for spawning: Jan 1=0d/365d
0.000

#age-dependent natural mortality at age (ages 0-4+)
1.67      1.26      1.10      1.02      0.98

#Spawner-recruit parameters
# SR function switch (integer 1=Beverton-Holt, 2=Ricker)
1
#switch for rate increase in q: Integer value (choose estimation phase, negative value turns it off)
-1
#annual positive rate of increase on all fishery dependent q's due to technology creep
0.0
# DD q switch: Integer value (choose estimation phase, negative value turns it off)
-1
#density dependent catchability exponent, value of zero is density independent, est range is (0.1,0.9)
0.0
#SE of density dependent catchability exponent (0.128 provides 95% CI in range 0.5)
0.128
#Age to begin counting D-D q (should be age near full exploitation)
2.0
#Variance (sd^2) of fishery dependent random walk catchabilities (0.03 is near the sd=0.17 of Wilberg and
Bence)
0.03
#Tuning F (not applied in last phase of optimization, or not applied at all if penalty weight=0)
0.35
#Year for tuning F
2008

#threshold sample sizes ntrips (>=)for length comps (set to 99999.0 if sel is fixed):
1.0    #LA gill net len comps

#threshold sample sizes ntrips (>=) for age comps (set to 99999.0 if sel is fixed)
1.0    #cR age comps

# Projection input
2022 #Projection end year, must be later than assessment endyr
2018 #New management start year, must be later than assessment endyr
3    #Switching indicating value to use for defining projection F: 1=Fcurrent, 2=Fmsy, 3=F30, 4=F40
1.0  #Multiplier "c" applied to compute projection F, for example Fproj=cFmsy
```

```
#Ageing error matrix (columns are true age 0-4+, rows are ages as read for age comps: columns should sum to one)
1.0	0.0	0.0	0.0	0.0
0.0	1.0	0.0	0.0	0.0
0.0	0.0	1.0	0.0	0.0
0.0	0.0	0.0	1.0	0.0
0.0	0.0	0.0	0.0	1.0

999 #end of data file flag
```

Appendix A3

```
// Create a file with an R object from AD Model Builder

// open the file using the default AD Model Builder file name, and
// 6 digits of precision
open_r_file(adprogram_name + ".rdat", 6);

// Example of an INFO object
open_r_info_list("info", true);
        wrt_r_item("title", "SEDAR 63 Assessment");
        wrt_r_item("species", "Gulf menhaden");
        wrt_r_item("model", "Statistical Catch at Age");
        if(SR_switch==1)
          {wrt_r_item("rec.model", "BH-steep");}
    if(SR_switch==2)
          {wrt_r_item("rec.model", "Ricker-steep");}
        wrt_r_item("base.run", "gm001.tpl");
        wrt_r_item("units.length", "mm");
        wrt_r_item("units.weight", "1000s mt");
        wrt_r_item("units.biomass", "1000s mt");
        wrt_r_item("units.ssb", "billions of eggs");
        wrt_r_item("units.ypr", "1000s mt");
        wrt_r_item("units.landings", "1000s mt");
        wrt_r_item("units.numbers", "billion fish");
    wrt_r_item("units.naa", "billion fish");
        wrt_r_item("units.rec", "billion fish");
close_r_info_list();


// VECTOR object of parameters and estimated quantities
open_r_info_list("parms", false);
        wrt_r_item("styr", styr);
        wrt_r_item("endyr", endyr);
        wrt_r_item("styrR", styr_rec_dev);
        wrt_r_item("Linf", Linf);
        wrt_r_item("K", K);
        wrt_r_item("t0", t0);
        wrt_r_item("len_cv_val",len_cv_val);
        wrt_r_item("wgt.a", wgtpar_a);
        wrt_r_item("wgt.b", wgtpar_b);
    wrt_r_item("spawn.time", spawn_time_frac);
        wrt_r_item("q.lagn", mfexp(log_q_lagn));
        wrt_r_item("q.seine", mfexp(log_q_seine));

    wrt_r_item("q.rate",q_rate);
        wrt_r_item("q.beta",q_DD_beta);
        wrt_r_item("q.DD.B0.exploitable", B0_q_DD);
        wrt_r_item("F.prop.cR", F_cR_prop);
        wrt_r_item("Fend.mean", Fend_mean);

        wrt_r_item("B0", B0);
        wrt_r_item("Bstyr.B0", totB(styr)/B0);
        wrt_r_item("SSB0", S0);
        wrt_r_item("SSBstyr.SSB0", SSB(styr)/S0);
```

```
            wrt_r_item("Rstyr.R0", rec(styr)/R0);
            if(SR_switch==1)
            {
   wrt_r_item("BH.biascorr",BiasCor);
             wrt_r_item("BH.Phi0", spr_F0);
             wrt_r_item("BH.R0", R0);
             wrt_r_item("BH.steep", steep);
  }
  if(SR_switch==2)
            {
   wrt_r_item("Ricker.biascorr",BiasCor);
             wrt_r_item("Ricker.Phi0", spr_F0);
             wrt_r_item("Ricker.R0", R0);
             wrt_r_item("Ricker.steep", steep);
  }
            wrt_r_item("R.sigma.logdevs", sigma_rec_dev);
            wrt_r_item("R.sigma.par",rec_sigma);
            wrt_r_item("R.autocorr",R_autocorr);
            wrt_r_item("R0", R0); //same as BH.R0, but used in BSR.time.plots
            wrt_r_item("R.virgin.bc", R_virgin); //bias-corrected virgin recruitment
            wrt_r_item("rec.lag", 1.0);
            wrt_r_item("msy.mt", msy_mt_out);
            //wrt_r_item("msy.knum", msy_knum_out);
            wrt_r_item("Fmsy", F_msy_out);
            wrt_r_item("SSBmsy", SSB_msy_out);
            wrt_r_item("Bmsy", B_msy_out);
            wrt_r_item("Rmsy", R_msy_out);
            wrt_r_item("sprmsy",spr_msy_out);
            wrt_r_item("Fend.Fmsy", FdF_msy_end);
            wrt_r_item("Fend.Fmsy.mean", FdF_msy_end_mean);
            wrt_r_item("SSBend.SSBmsy", SdSSB_msy_end);
            wrt_r_item("F30", F30_out); //For FishGraph
            wrt_r_item("SSB.F30", SSB_F30_out); //For FishGraph
            wrt_r_item("B.F30", B_F30_out);
            wrt_r_item("R.F30", R_F30_out);
    wrt_r_item("L.F30.knum", L_F30_knum_out);
    wrt_r_item("L.F30.mt", L_F30_mt_out);
 close_r_info_list();

 // VECTOR object of parameters and estimated quantities
open_r_info_list("spr.brps", false);
            wrt_r_item("F35", F35_out);
            wrt_r_item("F30", F30_out);
            wrt_r_item("F40", F40_out);
            wrt_r_item("SSB.F30", SSB_F30_out);
    wrt_r_item("B.F30", B_F30_out);
            wrt_r_item("R.F30", R_F30_out);
    wrt_r_item("L.F30.knum", L_F30_knum_out);
    wrt_r_item("L.F30.mt", L_F30_mt_out);
            wrt_r_item("Fend.F30.mean", FdF30_end_mean);
    wrt_r_item("SSBend.SSBF30", SdSSB_F30_end);
close_r_info_list();

// MATRIX object of parameter constraints
open_r_df("parm.cons",1,8,2);
  wrt_r_namevector(1,8);
```

```
   wrt_r_df_col("Linf",Linf_out);
   wrt_r_df_col("K",K_out);
   wrt_r_df_col("t0",t0_out);
   wrt_r_df_col("len_cv_val",len_cv_val_out);
   wrt_r_df_col("log_R0",log_R0_out);
   wrt_r_df_col("steep",steep_out);
   wrt_r_df_col("rec_sigma",rec_sigma_out);
   wrt_r_df_col("R_autocorr",R_autocorr_out);
   wrt_r_df_col("log_dm_lagn_lc",log_dm_lagn_lc_out);
   wrt_r_df_col("log_dm_cR_ac",log_dm_cR_ac_out);

   wrt_r_df_col("selpar_A50_cR1",selpar_A50_cR1_out);
   wrt_r_df_col("selpar_slope_cR1",selpar_slope_cR1_out);
   wrt_r_df_col("selpar_A502_cR1",selpar_A502_cR1_out);
   wrt_r_df_col("selpar_slope2_cR1",selpar_slope2_cR1_out);

   wrt_r_df_col("selpar_A50_cR2",selpar_A50_cR2_out);
   wrt_r_df_col("selpar_slope_cR2",selpar_slope_cR2_out);
   wrt_r_df_col("selpar_A502_cR2",selpar_A502_cR2_out);
   wrt_r_df_col("selpar_slope2_cR2",selpar_slope2_cR2_out);

   wrt_r_df_col("selpar_age0_cR_logit",selpar_age0_cR_out);
   wrt_r_df_col("selpar_age1_cR_logit",selpar_age1_cR_out);
   wrt_r_df_col("selpar_age2_cR_logit",selpar_age2_cR_out);
   wrt_r_df_col("selpar_age3_cR_logit",selpar_age3_cR_out);
   wrt_r_df_col("selpar_age4_cR_logit",selpar_age4_cR_out);

   wrt_r_df_col("selpar_age0_cR2_logit",selpar_age0_cR2_out);
   wrt_r_df_col("selpar_age1_cR2_logit",selpar_age1_cR2_out);
   wrt_r_df_col("selpar_age2_cR2_logit",selpar_age2_cR2_out);
   wrt_r_df_col("selpar_age3_cR2_logit",selpar_age3_cR2_out);
   wrt_r_df_col("selpar_age4_cR2_logit",selpar_age4_cR2_out);

   wrt_r_df_col("selpar_A50_lagn",selpar_A50_lagn_out);
   wrt_r_df_col("selpar_slope_lagn",selpar_slope_lagn_out);

   wrt_r_df_col("log_q_lagn",log_q_lagn_out);
   wrt_r_df_col("log_q_seine",log_q_seine_out);

   wrt_r_df_col("log_avg_F_cR",log_avg_F_cR_out);
   //wrt_r_df_col("F_init",F_init_out);
close_r_df();

// DATA FRAME of time series deviation vector estimates
// names used in this object must match the names used in the "parm.tvec.cons" object
open_r_df("parm.tvec", styr, endyr, 2);
            wrt_r_namevector(styr,endyr);
            wrt_r_df_col("year", styr,endyr);
      wrt_r_df_col("log.rec.dev", log_rec_dev_out);
      wrt_r_df_col("log.F.dev.cR", log_F_dev_cR_out);
            wrt_r_df_col("log.q.dev.lagn.RWq", q_RW_log_dev_lagn);
            wrt_r_df_col("log.q.dev.seine.RWq", q_RW_log_dev_seine);

close_r_df();

// MATRIX object of deviation vector constraints
```

```
// names used in this object must match the names used in the "parm.tvec" object
open_r_df("parm.tvec.cons",1,3,2);
        wrt_r_namevector(1,3);
        wrt_r_df_col("log.rec.dev",set_log_rec_dev);
        wrt_r_df_col("log.F.dev.cR",set_log_F_dev_cR);
                wrt_r_df_col("log.q.dev.lagn.RWq", set_log_RWq_dev);
                wrt_r_df_col("log.q.dev.seine.RWq", set_log_RWq_dev);
close_r_df();

// DATA FRAME of age vector deviation estimates
// names used in this object must match the names used in the "parm.avec.cons" object
open_r_df("parm.avec", 1, nages, 2);
                wrt_r_namevector(1,nages);
                wrt_r_df_col("age", agebins); //deviations for first age not estimated
        wrt_r_df_col("log.Nage.dev", log_Nage_dev_output);
close_r_df();

// MATRIX object of age vector deviation constraints
// names used in this object must match the names used in the "parm.avec" object
open_r_df("parm.avec.cons",1,3,2);
    wrt_r_namevector(1,3);
    wrt_r_df_col("log.Nage.dev",set_log_Nage_dev);
close_r_df();

// VECTOR object of SDNR calculations
open_r_vector("sdnr");
    wrt_r_item("sdnr.U.lagn", sdnr_I_lagn);
    wrt_r_item("sdnr.U.seine", sdnr_I_seine);

    wrt_r_item("sdnr.lc.lagn", sdnr_lc_lagn);

    wrt_r_item("sdnr.ac.cR", sdnr_ac_cR);

 close_r_vector();

// VECTOR object of likelihood contributions
open_r_vector("like");
    wrt_r_item("lk.total", fval); //weighted likelihood
    wrt_r_item("lk.unwgt.data", fval_data);  //likelihood of just data components

    wrt_r_item("lk.L.cR", f_cR_L);

    wrt_r_item("lk.U.lagn", f_lagn_cpue);
    wrt_r_item("lk.U.seine", f_seine_cpue);

    wrt_r_item("lk.lenc.lagn", f_lagn_lenc);

    wrt_r_item("lk.agec.cR", f_cR_agec);

    wrt_r_item("lk.Nage.init", f_Nage_init);
    wrt_r_item("lk.SRfit", f_rec_dev);
    wrt_r_item("lk.SRearly", f_rec_dev_early);
    wrt_r_item("lk.SRend", f_rec_dev_end);
    wrt_r_item("lk.fullF", f_fullF_constraint);
    wrt_r_item("lk.Ftune", f_Ftune);
    wrt_r_item("lk.priors",f_priors);
```

```
  wrt_r_item("gradient.max",grad_max);

  wrt_r_item("w.L", w_L);

  wrt_r_item("w.U.lagn", w_I_lagn);
  wrt_r_item("w.U.seine", w_I_seine);

  wrt_r_item("w.lc.lagn", w_lc_lagn);

  wrt_r_item("w.ac.cR", w_ac_cR);

  wrt_r_item("w.Nage.init", w_Nage_init);
  wrt_r_item("w.R", w_rec);
  wrt_r_item("w.R.init", w_rec_early);
  wrt_r_item("w.R.end", w_rec_end);
  wrt_r_item("w.F.early.phases", w_fullF);
  wrt_r_item("w.Ftune.early.phases", w_Ftune);
  wrt_r_item("var.RWq", set_RWq_var);

close_r_vector();

  open_r_matrix("N.age");
  wrt_r_matrix(N, 2, 2);
  wrt_r_namevector(styr, (endyr+1));
  wrt_r_namevector(agebins);
  close_r_matrix();

  open_r_matrix("N.age.mdyr");
  wrt_r_matrix(N_mdyr, 2, 2);
  wrt_r_namevector(styr, endyr);
  wrt_r_namevector(agebins);
  close_r_matrix();

  open_r_matrix("N.age.spawn");
  wrt_r_matrix(N_spawn, 2, 2);
  wrt_r_namevector(styr, endyr);
  wrt_r_namevector(agebins);
  close_r_matrix();

  open_r_matrix("B.age");
  wrt_r_matrix(B, 2, 2);
  wrt_r_namevector(styr, (endyr+1));
  wrt_r_namevector(agebins);
  close_r_matrix();

  open_r_matrix("F.age");
  wrt_r_matrix(F, 2, 2);
  wrt_r_namevector(styr,endyr);
  wrt_r_namevector(agebins);
  close_r_matrix();

  open_r_matrix("Z.age");
  wrt_r_matrix(Z, 2, 2);
  wrt_r_namevector(styr,endyr);
  wrt_r_namevector(agebins);
  close_r_matrix();
```

```
   open_r_matrix("L.age.pred.knum");
   wrt_r_matrix(L_total_num, 2, 2);
   wrt_r_namevector(styr,endyr);
   wrt_r_namevector(agebins);
   close_r_matrix();

   open_r_matrix("L.age.pred.mt");
   wrt_r_matrix(L_total_mt, 2, 2);
   wrt_r_namevector(styr,endyr);
   wrt_r_namevector(agebins);
   close_r_matrix();

   open_r_matrix("SSB.age.pred");
   wrt_r_matrix(SSBatage, 2, 2);
   wrt_r_namevector(styr,endyr);
   wrt_r_namevector(agebins);
   close_r_matrix();



// LIST object with annual selectivity at age by fishery

open_r_list("size.age.fishery");

   open_r_matrix("len.cR.mm");
   wrt_r_matrix(len_cR_mm, 2, 2);
   wrt_r_namevector(styr,endyr);
   wrt_r_namevector(agebins);
   close_r_matrix();

   open_r_matrix("wholewgt.cR.mt");
   wrt_r_matrix(wholewgt_cR_mt*1000.0, 2, 2);
   wrt_r_namevector(styr,endyr);
   wrt_r_namevector(agebins);
   close_r_matrix();

close_r_list();

open_r_list("sel.age");

   wrt_r_complete_vector("sel.v.wgted.L",sel_wgted_L, agebins);
   wrt_r_complete_vector("sel.v.wgted.tot",sel_wgted_tot, agebins);

   open_r_matrix("sel.m.cR");
   wrt_r_matrix(sel_cR, 2, 2);
   wrt_r_namevector(styr,endyr);
   wrt_r_namevector(agebins);
   close_r_matrix();

   open_r_matrix("sel.m.lagn");
   wrt_r_matrix(sel_lagn, 2, 2);
   wrt_r_namevector(styr_lagn_cpue,endyr_lagn_cpue);
   wrt_r_namevector(agebins);
   close_r_matrix();
```

```
 close_r_list();


//LIST object with predicted and observed composition data
open_r_list("comp.mats");

   open_r_matrix("lcomp.lagn.ob");
   wrt_r_matrix(obs_lagn_lenc, 2, 2);
   wrt_r_namevector(yrs_lagn_lenc);
   wrt_r_namevector(lenbins);
   close_r_matrix();

   open_r_matrix("lcomp.lagn.pr");
   wrt_r_matrix(pred_lagn_lenc, 2, 2);
   wrt_r_namevector(yrs_lagn_lenc);
   wrt_r_namevector(lenbins);
   close_r_matrix();

   open_r_matrix("acomp.cR.ob");
   wrt_r_matrix(obs_cR_agec, 2, 2);
   wrt_r_namevector(yrs_cR_agec);
   wrt_r_namevector(agebins_agec);
   close_r_matrix();

   open_r_matrix("acomp.cR.pr");
   wrt_r_matrix(pred_cR_agec, 2, 2);
   wrt_r_namevector(yrs_cR_agec);
   wrt_r_namevector(agebins_agec);
   close_r_matrix();

 close_r_list();

// DATA FRAME of time series
open_r_df("t.series", styr, (endyr+1), 2);
   wrt_r_namevector(styr,(endyr+1));
   wrt_r_df_col("year", styr,(endyr+1));
   wrt_r_df_col("F.Fmsy", FdF_msy);
   wrt_r_df_col("F.F30.ratio", FdF30);          //*.ratio extension is for FishGraph
   wrt_r_df_col("F.full", Fapex);
   wrt_r_df_col("F.cR", F_cR_out);
   wrt_r_df_col("Fsum", Fsum);
   wrt_r_df_col("N", totN); //abundance at start of year
   wrt_r_df_col("recruits", rec);
   wrt_r_df_col("logR.dev", log_rec_dev_output); //places zeros in yrs deviations not estimated  //KWS
   wrt_r_df_col("SSB", SSB);
   wrt_r_df_col("SSB.SSBmsy", SdSSB_msy);
   wrt_r_df_col("SSB.SSBF30", SdSSB_F30);
   wrt_r_df_col("B", totB);
   wrt_r_df_col("B.B0", totB/B0);
   wrt_r_df_col("SPR.static", spr_static);

   wrt_r_df_col("total.L.mt", L_total_mt_yr);
   //wrt_r_df_col("total.L.knum", L_total_knum_yr);

   wrt_r_df_col("U.lagn.ob", obs_lagn_cpue);
   wrt_r_df_col("U.lagn.pr", pred_lagn_cpue);
```

```
   wrt_r_df_col("cv.U.lagn", lagn_cpue_cv/w_I_lagn);  //applied CV after weighting
   wrt_r_df_col("cv.unwgted.U.lagn", lagn_cpue_cv); //CV before weighting

   wrt_r_df_col("U.seine.ob", obs_seine_cpue);
   wrt_r_df_col("U.seine.pr", pred_seine_cpue);
   wrt_r_df_col("cv.U.seine", seine_cpue_cv/w_I_seine);
   wrt_r_df_col("cv.unwgted.U.seine", seine_cpue_cv);

   wrt_r_df_col("q.lagn", q_lagn);
   wrt_r_df_col("q.lagn.rate.mult",q_rate_fcn_lagn);
   wrt_r_df_col("q.lagn.RW.log.dev",q_RW_log_dev_lagn);

   wrt_r_df_col("q.seine", q_seine);
   wrt_r_df_col("q.seine.rate.mult",q_rate_fcn_seine);
   wrt_r_df_col("q.seine.RW.log.dev",q_RW_log_dev_seine);

   wrt_r_df_col("q.DD.mult", q_DD_fcn);
   wrt_r_df_col("q.DD.B.exploitable", B_q_DD);

   wrt_r_df_col("L.cR.ob", obs_cR_L);
   wrt_r_df_col("L.cR.pr", pred_cR_L_mt);
   wrt_r_df_col("cv.L.cR", cR_L_cv);

   //comp sample sizes
         wrt_r_df_col("lcomp.lagn.n", nsamp_lagn_lenc_allyr);

     wrt_r_df_col("acomp.cR.n", nsamp_cR_agec_allyr);

         wrt_r_df_col("lcomp.lagn.nfish", nfish_lagn_lenc_allyr);

     wrt_r_df_col("acomp.cR.nfish", nfish_cR_agec_allyr);

         wrt_r_df_col("lcomp.lagn.neff",
(1+nsamp_lagn_lenc_allyr*exp(log_dm_lagn_lc_out(8)))/(1+exp(log_dm_lagn_lc_out(8))));

     wrt_r_df_col("acomp.cR.neff", (1+nsamp_cR_agec_allyr*exp(log_dm_cR_ac_out(8)))/(1+exp(log_dm_cR_ac_out(8))));

 close_r_df();

// DATA FRAME of L and D time series by fishery
open_r_df("LD.pr.tseries", styr, endyr, 2);
         wrt_r_namevector(styr,endyr);
         wrt_r_df_col("year", styr, endyr);

     wrt_r_df_col("L.cR.mt", pred_cR_L_mt);
     //wrt_r_df_col("L.cR.knum", pred_cR_L_knum);

close_r_df();

 open_r_df("a.series", 1, nages, 2);
         wrt_r_namevector(1,nages);
         wrt_r_df_col("age", agebins);
         wrt_r_df_col("length", meanlen_FL);
         wrt_r_df_col("length.cv", len_cv);
         wrt_r_df_col("length.sd", len_sd);
         wrt_r_df_col("weight.middle", wgt_fish_mt);     //for FishGraph
```

```
        wrt_r_df_col("weight.spawn", wgt_spawn_mt);
            wrt_r_df_col("wholewgt.wgted.L.mt", wgt_wgted_L_mt);
            wrt_r_df_col("prop.female", prop_f);
        wrt_r_df_col("prop.male", prop_m);
            wrt_r_df_col("mat.female", maturity_f);
            wrt_r_df_col("mat.male", maturity_m);
            wrt_r_df_col("reprod", reprod);
            wrt_r_df_col("fecundity", fecundity);

            wrt_r_df_col("M", M);
            wrt_r_df_col("F.initial", F_initial);
            wrt_r_df_col("Z.initial", Z_initial);
            wrt_r_df_col("Nage.eq.init",N_initial_eq);
            wrt_r_df_col("log.Nage.init.dev",log_Nage_dev_output);
    close_r_df();


    open_r_df("eq.series", 1, n_iter_msy, 2);
            wrt_r_namevector(1,n_iter_msy);
            wrt_r_df_col("F.eq", F_msy);
            wrt_r_df_col("spr.eq", spr_msy);
            wrt_r_df_col("R.eq", R_eq);
            wrt_r_df_col("SSB.eq", SSB_eq);
            wrt_r_df_col("B.eq", B_eq);
            wrt_r_df_col("L.eq.mt", L_eq_mt);
            //wrt_r_df_col("L.eq.knum", L_eq_knum);
    close_r_df();

    open_r_df("pr.series", 1, n_iter_spr, 2);
            wrt_r_namevector(1,n_iter_spr);
            wrt_r_df_col("F.spr", F_spr);
            wrt_r_df_col("spr", spr_spr);
            wrt_r_df_col("SPR", spr_ratio);
            wrt_r_df_col("L.ypr.mt", L_spr); //whole weight
    close_r_df();


    open_r_list("CLD.est.mats");

      open_r_matrix("Lw.cH");
        wrt_r_matrix(L_cR_mt, 1,1);
      close_r_matrix();

      open_r_matrix("Lw.total");
        wrt_r_matrix(L_total_mt, 1,1);
      close_r_matrix();

      open_r_matrix("Ln.cR");
        wrt_r_matrix(L_cR_num, 1,1);
      close_r_matrix();

      open_r_matrix("Ln.total");
        wrt_r_matrix(L_total_num, 1,1);
      close_r_matrix();

    close_r_list();
```

```
  //LIST object of age error matrix
open_r_list("age.error");

    open_r_matrix("error.mat");
    wrt_r_matrix(age_error, 2, 2);
    wrt_r_namevector(agebins);
    wrt_r_namevector(agebins);
    close_r_matrix();

close_r_list();

// DATA FRAME of projection time series
open_r_df("projection", styr_proj, endyr_proj, 2);
    wrt_r_namevector(styr_proj,endyr_proj);
    wrt_r_df_col("year", styr_proj,endyr_proj);
    wrt_r_df_col("F.proj", F_proj);
    wrt_r_df_col("SSB.proj", SSB_proj);
    wrt_r_df_col("B.proj", B_proj);
    wrt_r_df_col("R.proj", R_proj);
    wrt_r_df_col("L.knum.proj", L_knum_proj);
    wrt_r_df_col("L.mt.proj", L_mt_proj);

 close_r_df();

close_r_file();
```

SEDAR

Southeast Data, Assessment, and Review

SEDAR 63

Gulf Menhaden

SECTION II: Review Workshop Report

December 2018

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

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1. Introduction

1.1 Workshop Time and Place

The SEDAR 63 Review Workshop for Gulf Menhaden was held November 6-7, 2018 in New Orleans, LA.

1.2 Terms of Reference

1) Evaluate the data used in the assessment, addressing the following:
    a) Are data decisions made by the Data and Assessment Workshop sound and robust?
    b) Are data uncertainties acknowledged, reported, and within normal or expected levels?
    c) Are data applied properly within the assessment model?
    d) Are input data series reliable and sufficient to support the assessment approach and findings?

2) Evaluate the methods used to assess the stock, taking into account the available data.
    a) Are methods scientifically sound and robust?
    b) Are assessment models configured properly and used consistent with standard practices?
    c) Are the methods appropriate for the available data?

3) Evaluate the assessment findings with respect to the following:
    a) Are abundance, exploitation, and biomass estimates reliable, consistent with input data and population biological characteristics, and useful to support status inferences?
    b) Is the stock overfished? What information helps you reach this conclusion?
    c) Is the stock undergoing overfishing? What information helps you reach this conclusion?
    d) Is there an informative stock recruitment relationship? Is the stock recruitment curve reliable and useful for evaluation of productivity and future stock conditions?
    e) Are the quantitative estimates of the status determination criteria for this stock appropriate for management use? If not, are there other indicators that may be used to inform managers about stock trends and conditions?

4) Consider how uncertainties in the assessment, and their potential consequences, are addressed.
    a) Comment on the degree to which methods used to evaluate uncertainty reflect and capture the significant sources of uncertainty in the population, data sources, and assessment methods
    b) Ensure that the implications of uncertainty in technical conclusions are clearly stated.

5) Consider the research recommendations provided by the Data and Assessment workshop and make any additional recommendations or prioritizations warranted.
    a) Clearly denote research and monitoring that could improve the reliability of, and information provided by, future assessments.
    b) Provide recommendations on possible ways to improve the SEDAR process.

6) Provide guidance on key improvements in data or modeling approaches which should be considered when scheduling the next assessment.

7) Prepare a Peer Review Summary summarizing the Panel's evaluation of the stock assessment and addressing each Term of Reference. Develop a list of tasks to be completed following the workshop. Complete and submit the Peer Review Summary Report in accordance with the project guidelines.

The panel shall ensure that corrected estimates are provided by addenda to the assessment report in the event corrections are made in the assessment, alternative model configurations are recommended, or additional analyses are prepared as a result of review panel findings regarding the TORs above.

1.3 List of Participants

REVIEW PANEL

Will Patterson	Review Panel Chair	GSMFC Appointee
Joe Powers	Reviewer	GSMFC Appointee
Matt Cieri	CIE Reviewer	CIE
Anders Nielsen	CIE Reviewer	CIE
Kevin Stokes	CIE Reviewer	CIE

ANALYTICAL REPRESENTATIVES

Amy Schueller	Lead analyst	SEFSC Beaufort
Robert Leaf	Assessment Team	GCRL
Ray Mroch	Assessment team	SEFSC Beaufort

COUNCIL AND AGENCY STAFF

Julia Byrd	Coordinator	SEDAR
Kimberly Cole	Admin	SEDAR/SAFMC
Steve VanderKooy	GSFMC	GSMFC

Review Workshop Attendees

Mike Prager, NOAA retired
Scott Herbert, Daybrook Fisheries
Peter Himchak, Omega Protein

1.4 List of Background Documents

Gulf Menhaden document list.

Document #	Title	Authors
Final Assessment Report		
SEDAR63-SAR1	Assessment of Gulf Menhaden	To be prepared by SEDAR 63
Reference Documents		
SEDAR63-RD01	Genetic Population structure of the Gulf Menhaden (*Brevoortia patronus*) Presentation from SFFMC Menhaden Advisory Committee & GSMFC Spring Meeting	Anderson 2016
SEDAR63-RD02	The Selection and Role of Limit Reference Points for Pacific Herring (*Clupea pallasii*) in British Columbia, Canada	Canadian Science Advisory Secretariat 2017
SEDAR63-RD03	Data weighting in statistical fisheries stock assessment models	Francis 2011
SEDAR63-RD04	A Review of Biological Reference Points in the Context of the Precautionary Approach	Gabriel and Mace 1999
SEDAR63-RD05	A new role for MSY in single-species and ecosystem approaches to fisheries stock assessment and management	Mace 2001
SEDAR63-RD06	NPFMC Groundfish Species Profiles 2015	NPFMC 2015
SEDAR63-RD07	Fisheries for small pelagic species: an empirical approach to management targets	Patterson 1992
SEDAR63-RD08	Status of the Pacific Coast Groundfish Fishery: Stock Assessment and Fishery Evaluation	PFMC 2016
SEDAR63-RD09	A spatial model for fishery age-selection at the population level	Sampson & Scott 2011
SEDAR63-RD10	GDAR 02: Gulf Menhaden Stock Assessment - 2016 Update	Schueller 2016
SEDAR63-RD11	Model-based estimates of effective sample size in stock assessment models using the Dirichlet-multinomial distribution	Thorson et al. 2017
SEDAR63-RD12	The Gulf Menhaden Fishery of the Gulf of Mexico: A Regional Management Plan, 2015 Revision	VanderKooy and Smith 2015
SEDAR63-RD13	Technical documentation of the Beaufort Assessment Model (BAM)	Williams and Shertzer 2015
SEDAR63-RD14	Fishery Models	Shertzer et al. 2014

SEDAR63-RD15	Gulf menhaden (*Brevoortia patronus*) fishery-independent catch-rate trends for Louisiana	West and Zhang 2018
SEDAR63-RD16	Mortality and Movement of Adult Atlantic Menhaden During 1966-1969 Estimated from Mark-Recapture Models	Liljestrand 2017
SEDAR63-RD17	Multi-state dead recovery mark-recovery model performance for estimating movement and mortality rates	Liljestrand et al. 2018
SEDAR63-RD18	Estimation of movement and mortality of Atlantic menhaden during 1966-1969 using a Bayesian multi-state mark-recovery model	Liljestrand et al. 2018

2. Review Panel Report

Executive Summary

The SEDAR 63 Review Panel met in New Orleans, Louisiana for two days in November 2018 to review the Gulf menhaden stock assessment. The analytical team presented the history of the fishery, aspects of Gulf menhaden life history and ecology, landings and fishery-independent data, parameterization of the Gulf menhaden Beaufort Assessment Model, results from the base model run, and model diagnostics, including various sensitivity analyses. Discussions centered on several key aspects of the assessment, including the appropriateness of the estimated natural mortality (M) function, the gillnet fishery-dependent abundance index and model sensitivity to it, choices made with respect to the type of and fitting (fixing steepness) the stock-recruitment function, appropriate proxies for biological reference points (i.e., stock status benchmarks), and methods for capturing uncertainty in estimates of spawning stock biomass (SSB) and fishery mortality (F). Panel discussions led in some cases to assessment scientists reviewing model code and attempting to implement panel suggestions for further sensitivity or diagnostics exploration. Overall, the Panel was satisfied with the level of scrutiny applied to the assessment and deemed its results sufficient to evaluate stock status, although several recommendations were passed along to the assessment scientists with respect to model parameterization and presentation of model diagnostics for future assessments. Given steepness was fixed in the stock-recruitment function, biological reference points (e.g., F_{MSY}, B_{MSY}) could not be estimated directly. The Panel felt equating F_{MSY} to M was a poor approach given uncertainty in estimated M. Based on an MSY proxy of 30% spawning potential ratio (SPR), the Panel concluded it was not likely the Gulf menhaden stock was overfished or had undergone overfishing in recent years. A series of research and assessment recommendations were made to help improve future assessments, including robust exploration of stock status criteria for Gulf menhaden via management strategy evaluation. However, given model-derived estimates relative to an MSY proxy of 30%SPR, recent fishery effort and landings trends, and the life history of the species, the Panel felt there was little danger the stock was currently overfished or undergoing overfishing.

2.1 Statements Addressing Each ToR

Term of Reference 1: Data Inputs

The Data and Assessment Workshops considered and included biological, fishery, and fishery independent data. Decisions made are sound and robust, uncertainties are acknowledged, reported, and within expected levels. Data are applied properly within the assessment model (see ToR 2) and as used and uncertainties explored (see ToR 4), the data series are reliable and sufficient to support the assessment approach and findings.

Biological data decisions that were made include: i) consideration of Gulf menhaden as a single stock for assessment purposes, consistent with past practice and well supported by information; ii) use of age-varying but time invariant natural mortality, M, with well-justified and explained (continued) use of the Lorenzen (1996)-type age estimates, scaled for the base case run and for sensitivity runs on estimates from Ahrenholz (1981); iii) use of growth and weight-at-age at mid-year for the fishery but start-of-year for spawning stock biomass (actually fecundity); and, iv) continued use of fecundity as the measure of spawning stock biomass, as estimated with updated annual egg production-at-age estimates (Brown-Peterson et al. 2017). Among data inputs, M was clearly identified as the source of greatest uncertainty in the assessment.

Fishery removals data are good for Gulf menhaden due to lack of multiple fleets and sectors and the presence of a long-term, high-quality logbook system. The reduction fishery is well-sampled and the lack of composition data for the very small bait and recreational catches is not of concern. The reduction fishery sampling system was well reported and discussed at the Review Workshop and Review Panel members see no areas of concern. Fishery-dependent data considerations and decisions include exploration of alternative measures of nominal fishing effort. The continued use of vessel-ton-weeks (VTW) was well explained during the Review process. A key issue in the fishery data is ageing and consequent uncertainty. Ageing error was explored at the Data and Assessment Workshops through development of ageing error matrices based on i) re-reading of 6,000 scale samples read/re-read over multiple years by the one long-term reader; and ii) between-reader comparisons of age readings for two newer readers for recent years, with a much smaller sample size.

Two fishery independent indices are utilized in the stock assessment, a juvenile seine net index using LA, MS and AL (but not TX and FL) data, and an adult LA-only gillnet survey index, with associated length, but not age, composition. The Data and Assessment Workshops considered in detail the multiple, potential indices (seine, inshore trawl, and gillnet) from all states and clearly explained reasoning for final selection for inclusion in the base case assessment and sensitivity testing. The gill net index in particular is influential in the assessment (intentionally) but seemingly conflicts with other fishery and fishery-independent data. Uncertainty was acknowledged by the Data and Assessment Workshops and was considered during review (see

ToR 4) by considering a run with a non-standardised index. There are no corresponding age compositions for the gill net survey (though samples exist for reading)

Term of Reference 2: Assessment Methods

The Gulf menhaden assessment model is scientifically sound and robust. The model is the Beaufort Assessment Model (BAM), which is a standard model that has been used for many accepted SEDAR assessments (e.g., Atlantic Menhaden, Spanish Mackerel, and Red Grouper). The core model is a statistical catch-at-age model, but it also allows matching to length composition observations. Statistical catch-at-age models are commonly used to assess fish stocks world wide (e.g., SS3, SCAA, ASAP), and menhaden BAM model details are well-documented (SEDAR63-RD13).

The specific configuration for Gulf menhaden is clearly documented in the assessment report. It was clear from the review meeting that the model is not a black box to the assessment scientists. They were able to answer questions and modify the model beyond changing simple configurations, including modifying the code. The panel concluded the model is configured properly and consistent with standard practices.

Many model parameters are input as fixed values (partial selectivity, growth, steepness, recruitment deviation variance, natural mortality, and uncertainty parameters). However, the model fits all data sources (i.e., landings, indices, and age and length compositions) reasonably well, so the assigned values appear reasonable. Uncertainty parameters are not estimated directly and jointly within the model, but input as fixed values. The values are fixed at levels that are either coming from sample sizes (with subsequent Francis adjustment) or from external evaluation of the uncertainties of the input data sources in isolation.

The model is appropriate to fit the data on the annual time scale currently utilized, but data with even finer-scaled temporal resolution are available. It would be of interest to evaluate the effect of the timing of the fishing season relative to mortality from other sources (natural mortality). Catch data appear to be available weekly, so it should also be possible to utilize quarterly or even weekly timesteps.

There is some indication of conflict between the gillnet index and the remaining data sources. The sensitivity runs indicated a somewhat different trend when this index was removed, and the retrospective pattern shows that recruitment events that are large in the terminal year (when they are only based on the recruitment index) are adjusted downwards in subsequent years (when they have to match all the data). Additional runs were performed to isolate the cause of the conflict and it appeared not to be caused by the standardization. This conflict may be resolved if age composition were available to accompany the gillnet index. Additionally, model validation could be improved. The Panel suggests residuals be presented on log-scale when a log-normal distribution is assumed, and to de-correlate the residuals consistent with the model assumptions.

Additional support for the assessment model's main results was provided by a surplus production model (ASPIC) run presented at the review meeting. After ASPIC had been suitably configured, it showed the same overall trends as the BAM assessment.

Term of Reference 3: Assessment Findings

The BAM assessment model utilized to assess the Gulf menhaden stock is an accepted modeling approach using standard population equations and statistical fitting procedures. As with all assessment models, it relies on indices of abundance, catch and size data and biological knowledge of growth rates, fecundity and natural mortality rates. The statistical fitting allowed the estimation of fishery selectivity parameters, recruitment deviances and unfished abundance and recruitment measures. The model was consistent with the data and provided useful estimates of biomass, spawning biomass (fecundity) and fishing rates.

As expected, major uncertainties (discussed under Uncertainty section) were with the appropriateness of the indices, with the shape of the stock-recruitment (S-R) function, and estimated M. The natural mortality rate was specified as a decreasing scale from ages 0 to 4 years, with age-2 fixed at $M=1.0\ y^{-1}$. This was based on independent estimates from limited tagging data from the 1980s. Nevertheless, it is consistent with general knowledge of biology and ecology of Gulf menhaden.

The base case assessment assumed a Beverton-Holt (B-H) model in which steepness was fixed at 0.99. This procedure is not really assuming that the slope at origin is 0.99, but rather that over the range of biomass that occurred, there was no observed trend in recruitment. In other words, the underlying recruitment was effectively constant with variations around it (sigmaR=0.6). This approach is acceptable over the range of biomass that the model is depicting. However, it is not helpful for determining status criteria related to the shape of the S-R function. For those reasons, the assessment (as with many assessments) employed spawning potential ratio (SPR) measures as proxy stock status criteria. Additionally, at the review meeting a BAM run was made with a Ricker function as the underlying S-R relationship (Fig. 1). Approximate replacement lines have been superimposed on both the base case (B-H) and Ricker S-R functions relating to no fishing (SPR=100%) and a fishing at a rate of $F_{25\%SPR}$ (Fig. 1).

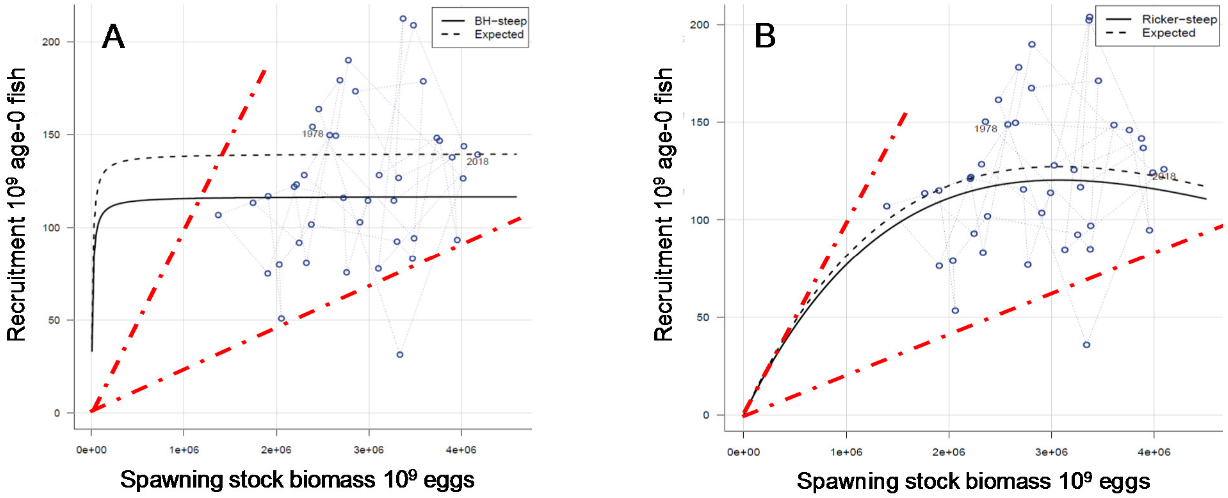

Figure 1. Stock-Recruit data fit with A) a Beverton-Holt function (base case) with steepness fixed at 0.99 and B) a Ricker function. The red diagonals are approximate replacement lines with no fishing (diagonal with smaller slope) and the replacement line at 25% SPR (larger slope).

The base case S-R function provides no information to define MSY-related status criteria (Fig. 1). The Ricker curve provides an estimate of the biomass that would maximize recruitment, but this is not directly related to B_{MSY}. Additionally, the implication of the Ricker fit is that an SPR of 25% is not sustainable, which is not consistent with the known life-history and ecology of Gulf menhaden.

Hockey-stick and non-parametric S-R models were suggested as possible approaches for future research. Fitting such functions may help in providing pragmatic approaches to approximate B_{MSY}. However, the basic problem is that we are trying to define the dynamics at lower biomass levels than have ever been observed.

The stock assessment suggested that M could serve as an approximation of F_{MSY}. However, the uncertainty in M makes this problematic. Before it might be accepted, simulation evaluation, perhaps in the context of Management Strategy Evaluation (MSE), would be needed. Indeed, pragmatic definition of targets and thresholds will likely require MSE-like exploration through simulation.

Therefore, alternatives to defining status were explored. An ASPIC run was compared to the BAM run and their results were generally consistent. The status measures from ASPIC were $F_{2017}/F_{MSY} = 0.31$ and $B_{2018}/B_{MSY}=1.53$. Additionally, the S-R observations provide some insight into the dynamics of the Gulf menhaden population. The assessment indicates that SPR of less than 25% has never been observed; thus, $F_{25\%SPR}$ is certainly sustainable. The lowest SSB observed was in 1992 and the population quickly increased as fishing effort declined thereafter, thus indicating it was unlikely that recruitment overfishing had occurred. This evidence indicates that while the exact status criteria cannot be determined, accepted scientific understanding of

Gulf menhaden biology and population dynamics strongly support the conclusion that the Gulf menhaden stock is not overfished and is not undergoing overfishing.

Based on the above discussion, the Panel's specific findings are presented below.

> 1) The model is consistent with the data and Gulf menhaden population characteristics, and model-derived estimates are useful to infer stock status.
>
> 2) There is no evidence the Gulf menhaden stock is overfished or undergoing overfishing.
>
> 3) The S-R function is not informative for estimating stock status criteria. However, the S-R data, themselves, provide some guidance for projecting future productivity, as well as for fishery management.
>
> 4) The quantitative estimates of status determination criteria are of sufficient reliability to support the overfishing/overfished conclusions. Stock indicators, such as estimated SSB trends and recruitment dynamics, the response from low observed SSB, and the known dynamics of growth and variability in Gulf menhaden life history and ecology, support the status conclusions of no overfishing occurring and the stock not being overfished. More refined management determinations related to pragmatic targets and thresholds will likely require further evaluation through simulation.

Term of Reference 4: Uncertainty

In the ideal scenario, a model is formulated such that all important model parameters are estimated from observations. Then, observation noise is propagated into correct uncertainty estimates of estimated model parameters and derived quantities of interest (e.g., SSB and F). This is uncommon for fish stock assessment models because it is often necessary to fix at least some model parameters (e.g., M).

The assessment team has put a lot of effort into exploring uncertainty in parameter estimates. They have clearly stated what has been done and have illustrated the effect on main model results. The assessment panel correctly identified that simply supplying the standard uncertainties from the model estimation procedure (derived from the inverse Hessian matrix of the objective function at its minimum) is not realistically representing the uncertainty in Gulf menhaden SSB and F estimates. The assessment panel went on to derive a Monte Carlo bootstrap procedure, where observations were simulated along with values of the fixed model parameters. As such, for each new set of observations the model provided new estimates and thereby the distribution of these new estimates provided a new quantification of uncertainty (e.g., confidence intervals).

The derived procedure does larger confidence bounds around parameter estimates, but the interpretation of these uncertainty estimates is not straight forward. However, there are a few technical caveats. The data are simulated assuming the subjectively assigned level of uncertainty from the base run. Natural mortality and the selection parameters are simulated from a joint uniform distribution, which basically assumes that all values are equally likely. Non-converging runs are removed, but it seems unlikely that convergence problems should occur at random. The range of uncertainty in M and selection parameters is taken from the profile likelihood in the base run, which means the ranges are consequences of the observation noise, the bootstrap procedure is, strictly speaking including the same uncertainty twice. Some fixed parameters (for growth and likelihood weighting) are not bootstrapped over. Issues listed here may lead to larger uncertainties or smaller confidence limits around parameter estimates, hence the interpretation of whether uncertainty is fully accounted for is problematic. The most positive interpretation is that this method is an *ad hoc* combination of sensitivity runs and uncertainty.

In addition to the Monte Carlo bootstrap method mentioned above, the assessment team presented a range of sensitivities and supplemented with additional reviewer requested runs. These clearly illustrated the range of uncertainty, and which parts of the model is sensitive to which inputs. The relative results appeared to be fairly robust to different fixed inputs, and the absolute values changed as could be expected with regard to direction and range. The one exception was the gillnet index, which appeared to be in conflict with other data sources, as mentioned previously. Uncertainty with regard to age estimation is explored by double-reading studies (both within and among readers) and the ranges of errors are used to define sensitivity runs. This gives a clear illustration of the effect of age reading on the main results of the model.

Overall, the Panel feels the assessment team adequately and sincerely addressed uncertainty via methods described above.

Term of Reference 5: Research Recommendations

The Review Panel discussed the research recommendation from the Assessment Panel in detail. As stated above the main sources of uncertainty including 1) the sensitivity of the model to inclusion of the adult gillnet survey and associated length structure, 2) natural mortality, 3) lack of reference points or management benchmarks. Considering the main sources of uncertainty in this assessment, the Review Panel re-prioritized the Assessment Panels list and made a few additions, as outlined below.

Table 1. Research recommendations reviewed or offered by the Review Panel, including the Panel's indication of priority for implementation prior to the next Gulf menhaden assessment.

DATA ELEMENT	RECOMMENDATION	Priority
Tagging Analysis	Reevaluation of tag based natural mortality estimates including evaluation of tag data from Ahrenholz's original work	High
Stock Status Benchmarks	Use simulations of potential stock recruitment relationships, coupled with MSE, to examine single species reference points or management approaches	High
Modeling	Further explore alternative models, particularly ASPIC, and compare with the current model.	High
Modeling	Exploring finer time resolution (e.g. quarterly) on the model	High
Ageing	Continue to explore the effects of ageing error and ageing bias in the model	High
Ageing	In cooperation with state agencies, implement aging of fish caught in independent sampling to allow for use of ages in modeling	High
Genetics and Stock Structure	Improve species identifications at the periphery of the Gulf menhaden's range in Texas and Alabama/Florida waters for juveniles and adults.	Med
Tagging Study	Conduct Gulf menhaden tag/recovery study for better estimates of natural mortality, migration, growth, etc. which are inputs for the stock assessment. After achieve data analyzed	Med
Modeling	Explore further diagnostics and presentation of model uncertainty	Med
Predator/Prey	Expand understanding of diets of potential Gulf Menhaden predators using a variety of tools including traditional stomach analysis, DNA barcoding, and fatty acid profiles Gulf wide.	Med
Fishery-Independent Adult Index	Collect and age Gulf menhaden scales from fishery-independent gears (e.g., gill nets) to determine selectivity. Expand efforts to age menhaden by state agencies.	Med
Predator/Prey	Expand understanding of diets of potential Gulf Menhaden predators using a variety of tools including traditional stomach analysis, DNA barcoding, and fatty acid profiles Gulf wide.	Med
Fishery-Independent Juvenile Index	Design and implement a survey dedicated to determining menhaden recruitment in the coastal rivers and upper bays of the northern Gulf of Mexico.	Low
Genetics and Stock Structure	Identify menhaden-specific nuclear DNA markers (preferably microsatellites or SNPs) using lab-based DNA library screening techniques. Evaluate these markers for use in genetic studies of Gulf menhaden.	Low
Legacy Data (Fishery-Dependent Surveys)	Process and analyze samples that address the homogeneity of the catch in the hold of the reduction fishery vessels.	Low

While the Panel did not make detailed recommendations as to what should be improved in the SEDAR process, it is likely that the individual CIE review reports may contain some information in that respect. The Panel did agree that the recommendation to improve model diagnostics and presentation would be useful for this assessment, and a standardization presentation of that type of information would like improve the review of other SEDAR assessments.

Term of Reference 6: Future Considerations

Research recommendations evaluated to have high priority should be considered and at least explored prior to commencing the next assessment. These recommendations are specifically targeted at the main areas of uncertainty, including; the adult gillnet survey and associated length structure, natural mortality, and lack of reference points or management benchmarks. The Review Panel agreed that progress on these would be important prior to the next benchmark.

2.2 Summary Results of Analytical Requests

Analytical requests made during the meeting were discussed throughout Section 2.1.