Stock Assessment of Striped Mullet (*Mugil cephalus*) in North Carolina Waters

2018

Prepared by

North Carolina Division of Marine Fisheries
Striped Mullet Plan Development Team

July 2018

NCDMF SAP-SAR-2018-03

This document may be cited as:

NCDMF (North Carolina Division of Marine Fisheries). 2018. Stock assessment of striped mullet (*Mugil cephalus*) in North Carolina waters, 2018. North Carolina Division of Marine Fisheries, NCDMF SAP-SAR-2018-03, Morehead City, North Carolina. 117 p.

ACKNOWLEDGEMENTS

This report was prepared by the North Carolina Division of Marine Fisheries (NCDMF) Striped Mullet Plan Development Team. The members are Dan Zapf (co-lead), Tracey Bauer (co-lead), Jason Rock (mentor), Alan Bianchi, Marc Hamric, Casey Knight, Laura Lee (lead analyst), Forrest Nelson, Lee Paramore, John Perry, Adam Stemle, and Amanda Tong.

We would also like to thank Kathy Rawls, Catherine Blum, and Katy West for their contributions to the stock assessment.

EXECUTIVE SUMMARY

The North Carolina Fisheries Reform Act requires that fishery management plans be developed for the state's commercially and recreationally important species to achieve sustainable levels of harvest. Stock assessments are the primary tools used by managers to assist in determining the status of stocks and developing appropriate management measures to ensure the long-term viability of stocks.

In April 2006, the North Carolina Division of Marine Fisheries adopted a Fishery Management Plan for the striped mullet resource. In 2013, a benchmark (i.e., peer reviewed) stock assessment was conducted in support of the development of Amendment 1 to the original Striped Mullet Fishery Management Plan (FMP) and deemed acceptable as a basis for management. Note that the North Carolina Division of Marine Fisheries (NCDMF) makes the final decision as to whether a stock assessment is acceptable for management based on input from the peer reviewers. This stock assessment is an update of the benchmark completed in 2013.

A population assessment of the North Carolina striped mullet stock was conducted using the Stock Synthesis model, which incorporated data from commercial fisheries and three fishery-independent surveys from 1994 to 2017. The most recent trends observed in adult relative abundance suggest a decline in the adult stock in the last two years of the assessment time series. The model results show a decline in recruitment (small increase in 2017) and spawning stock biomass in recent years. Estimates of fishing mortality have been steady from 2003 through 2016 and an increase in fishing mortality was predicted for 2017.

Amendment 1 to the NCDMF FMP for striped mullet adopted a fishing mortality threshold of $F_{25\%}$ and a fishing mortality target of $F_{35\%}$. Stock Synthesis computed a value of 0.57 for $F_{25\%}$ and a value of 0.40 for $F_{35\%}$. These estimates represent numbers-weighted values for ages 1–5. Predicted F in 2017 was 0.13. As such, overfishing is currently not occurring in the striped mullet stock ($F_{2017} < F_{25\%}$). Due to the poor stock-recruitment relationship, estimates of a biomass-based reference point were considered unreliable. Therefore, status in relation to the overfished condition is considered unknown.

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1 INTRODUCTION

1.1 The Resource

Striped mullet (*Mugil cephalus*) occur in fresh, brackish, and marine waters in tropical and subtropical latitudes worldwide. Their widespread distribution results in them being known by many names: jumping mullet, black mullet, grey mullet, popeye mullet, whirligig mullet, common mullet, molly, callifavor, menille, liza, and lisa (Ibáñez-Aguirre et al. 1995; Leard et al. 1995). The striped mullet resource is an important food source, supporting commercial and recreational fisheries worldwide. In North Carolina, striped mullet are harvested recreationally and commercially and are typically targeted for bait and roe.

Three Mugilid species exist in North Carolina: the striped mullet, white mullet (*Mugil curema*), and mountain mullet (*Agonostomus monticola*). Striped mullet and white mullet sometimes overlap spatially but can be distinguished by the presence of longitudinal stripes in striped mullet, anal fin ray counts, or pectoral fin measurements (Collins 1985a, 1985b).

In 2013, a benchmark (i.e., peer reviewed) stock assessment was conducted in support of the development of Amendment 1 to the Striped Mullet Fishery Management Plan (FMP; NCDMF 2013, 2015) and deemed acceptable as a basis for management. Note that the North Carolina Division of Marine Fisheries (NCDMF) makes the final decision as to whether a stock assessment is acceptable for management based on input from the peer reviewers. This stock assessment is an update of the benchmark completed in 2013.

1.2 Life History

1.2.1 Stock Definitions

The unit stock is defined as all striped mullet inhabiting North Carolina coastal and inland waters. Tagging studies in North Carolina indicate a residential adult stock (Wong 2001; Bacheler et al. 2005) since most (98.2%) striped mullet dart-tagged in North Carolina (n = 14,987) between 1997 and 2001 were recovered in state (Wong 2001). Striped mullet tagging studies, in general, reveal a small mark-recapture distance and a typical southward spawning migration along the South Atlantic Bight (SAB; Mahmoudi et al. 2001; McDonough 2001; Wong 2001). An observed northward movement pattern during and after its spawning period suggests that adults continue to colonize North Carolina estuarine habitats after its southward spawning migration (Bacheler et al. 2005). In conjunction with the southward (and offshore) spawning migration by adults, the northward advection of eggs and larvae via the Gulf Stream likely provides some measure of self-replenishment of the North Carolina stock. However, the influx of eggs and larvae into North Carolina from stocks residing in South Carolina to Florida is uncertain, as is the northward loss of North Carolina-born eggs and larvae into the mid-Atlantic Bight. Although these larval recruitment processes that occur on a coast-wide scale would suggest a genetically homogenous striped mullet population in the SAB, the assumption of a distinct North Carolina stock was necessary for this assessment. As a reference, the Gulf States Marine Fisheries Commission considers all striped mullet occurring in the United States Gulf of Mexico as one population because of widespread larval mixing but also recognizes that state-specific or regional management programs (including assessments) are appropriate because of the limited movement patterns observed by juveniles and adults (Leard et al. 1995).

1.2.2 Movements & Migration

Striped mullet larvae are found during winter and spring months over a range of offshore depths (9 to 914 m) in the SAB (Collins and Stender 1989). The greatest abundance of larvae occurs at <25°C (mean = 23°C) and >34 ppt in the Gulf of Mexico (Ditty and Shaw 1996) and along the 180-m contour off the SAB (Powles 1981). Larval size is negatively related to distance from shore, indicating an inshore migration with growth (Powles 1981; Collins and Stender 1989). Larvae exhibit a strong association with surface waters and show no indication of diel vertical migration (Powles 1981; Collins and Stender 1989). The shoreward migration in the SAB is likely facilitated by onshore, wind-driven (Ekman) drift, characteristic of southeast U.S. winter wind patterns (Powles 1981).

Larval and young-of-year (YOY) striped mullet are absent in offshore waters by April in the Gulf of Mexico and by early March in the SAB (Anderson 1958; Ditty and Shaw 1996). Pre-juvenile striped mullet are 20 to 25 mm when they appear on outer beaches, reported as early as November in Georgia (Gunter 1945; Anderson 1958; Ditty and Shaw 1996). Pre-juveniles enter estuarine areas from December through March in North Carolina, at approximately 22 mm (Higgins 1927; NOAA, unpublished data). YOY overwinter in estuarine marsh areas and apparently scatter among a range of habitat types during summer and fall months (Anderson 1958). Collins (1985a) noted YOY and juveniles move into deeper waters with the adult migration in the fall.

Adults occupy shallow waters during a ‘trophic’ (feeding) phase from spring to summer/early fall between migration (spawning) periods (Martin and Drewry 1978) and generally do not move extensively during this period (Leard et al. 1995). Most adult movement occurs during a pronounced spawning migration that occurs in fall and winter months in the southeast U.S. and Gulf of Mexico (Leard et al. 1995; Collins 1985a; Bichy 2000). Onset of migration is marked by increased schooling aggregations and downstream movement towards marine waters (Jacot 1920; Martin and Drewry 1978). Increased migratory movements have been associated with north/northwest winds and cold fronts (Jacot 1920; Apekin and Vilenskaya 1979; Mahmoudi et al. 1990; NCDMF, unpublished data). Hurricanes and unseasonably warm fall water temperatures may delay or disrupt spawning migrations (Thompson et al. 1991). Patterns of movement unrelated to spawning are otherwise difficult to generalize, as all age groups can be found from freshwater to lower estuarine waters at all times of the year (Thomson 1955).

Most tagging studies show limited distances between tagging and recapture locations for adults (Idyll and Sutton 1951; Broadhead and Mefford 1956; Collins 1985a; Mahmoudi et al. 2001; McDonough 2001; Wong 2001). Ninety percent of recaptures occurred within 32 km of the tagging location in Florida (Idyll and Sutton 1951; Broadhead and Mefford 1956), while 91% of recaptures were found within 83 km of the release site in North Carolina (Wong 2001). Most of the movements observed in tagging studies are associated with the spawning migration. The spawning migration along the southeast U.S. coast occurs in a general southward direction (Jacot 1920; Broadhead and Mefford 1956; Martin and Drewry 1978; Wong 2001). The vast majority of tagged fish recaptured during spring months (presumably after spawning) in North Carolina were found south of the original tagging location (Wong 2001). Northern movement has been reported in the fall, lagging behind the southward migration by about 2 months but on a smaller scale (Bacheler et al. 2005). However, egg and larval transport occurs in a northward direction with the Florida current (Gulf Stream) along the southeastern U.S. (Able and Fahay 1998). The overall direction of recapture in tagging studies in North Carolina and South Carolina was to the south (McDonough 2001; Wong 2001). Almost every out-of-state recapture was found in more southern states. Low percentages of out-of-state recaptures in North Carolina and South Carolina (1.8% and 9%) suggest striped mullet stocks are residential to native states. Mahmoudi et al. (2001) noted the majority of adults in Florida were recaptured in the same system in which they were tagged.

1.2.3 Age & Size

Striped mullet are approximately 11 mm at the end of the larval stage (24 to 28 days; Martin and Drewry 1978). Martin and Drewry (1978) recognize a pre-juvenile stage from 11 to 52 mm total length (TL), with an approximate age of 30 to 90 days at its conclusion (Thomson 1966).

The juvenile stage encompasses a size range from 52 to 248 mm TL (Martin and Drewry 1978). Striped mullet reach 50 mm TL by 5 months (by their first March–May; Futch 1966). Males and females are at similar lengths at early ages (<age 2), after which, females grow larger and live longer (Mahmoudi et al. 1990; NCDMF, unpublished data). Large variability in size at early ages is seen in North Carolina, South Carolina, and Georgia stocks (Foster 2001; McDonough 2001; Carmichael and Gregory 2001). North Carolina striped mullet appear to achieve larger mean lengths at earlier ages than more southern U.S. states (Bichy 2000; Carmichael and Gregory 2001). For example, mean length for age 1 striped mullet (both sexes) in South Carolina was 257 mm TL, substantially smaller than that observed for males (325 mm TL) and females (350 mm TL) in North Carolina (McDonough 2001; NCDMF, unpublished data). On average, age-2 males and females in South Carolina were 310 mm compared to 348 mm TL and 390 mm TL in North Carolina, respectively (McDonough 2001; NCDMF, unpublished data). Since birth date is standardized as January 1 for ageing convention along the U.S. east coast, earlier spawning times and true birth dates in North Carolina may contribute to slightly larger mean lengths at young ages. The maximum age for striped mullet has been reported as 13 years (Thomson 1963); however, male and female maximum ages of 14 and 13 years were recorded in North Carolina research (NCDMF, unpublished data). Maximum reported sizes ranged from 771 mm TL in North Carolina to a 914 mm TL specimen from India (Gopalakrishnan 1971; NCDMF, unpublished data).

1.2.4 Growth

1.2.4.1 Larvae

Beginning at an average size of 2.65 mm, larvae grow quickly at first (Pattillo et al. 1999; Martin and Drewry 1978) before slowing down during the time they retain their yolk sac (4–5 days; Kuo et al. 1973; Martin and Drewry 1978). Once feeding begins, between 5 and 8 days after hatching, the larvae grow more quickly. Striped mullet are approximately 11 mm at the end of the larval stage (24 to 28 days; Martin and Drewry 1978).

1.2.4.2 Juveniles

The juvenile stage occurs when striped mullet are between 52 and 248 mm TL, the intervening size (11–52 mm TL) is considered the pre-juvenile stage (Martin and Drewry 1978). Striped mullet have been observed arriving to North Carolina waters during this stage by mid-January (Higgins 1927). Growth is slow or nonexistent until water temperature reaches around 20°C in April. Striped mullet grow approximately 20 mm per month from May to October. Anderson (1958) estimated 5 mm growth per month for Georgia YOY (~18 to 19 mm standard length) from November until January, followed by no growth during the coldest winter months. About 10 mm growth occurred between February and March during rising water temperatures, followed by a growth rate of 17 mm per month through October. Anderson (1958) suggested that the longer period of delayed

YOY growth observed by Higgins in North Carolina was due to the extended time with temperatures <20 °C.

1.2.4.3 Adults

Adults grow at a rate of 38 mm to 64 mm per year (Broadhead 1953; Wong 2001). Spring and summer growth is twice as fast as fall and winter growth (Broadhead 1953; Rivas 1980). Adults grew 7 mm in each of the first and fourth quarters of the year and averaged 16 and 19 mm growth in the second and third quarters of the year in a Florida tagging study (Broadhead 1958). Thompson et al. (1991) indicated that energy required for somatic growth was reallocated for reproduction and post-spawning recovery (during the fall and winter, November–March). Summer growth depression in striped mullet (age 1+) was observed in Texas, associated with prolonged elevation of water temperatures and potential shifts in food types (Moore 1973; Cech and Wohlschlag 1975). A similar cessation in otolith marginal incremental growth was observed for older striped mullet in August and September in North Carolina (Carmichael and Gregory 2001).

1.2.4.4 Models

Available otolith-based annual age data were fit with a von Bertalanffy age-length model to estimate growth parameters for both female and male striped mullet. Inverse weighting was applied due to the low sample sizes at the oldest ages. As was done in the 2013 stock assessment, unsexed age-0 fish were included in the fits for both the males and females (NCDMF 2013). The predicted growth curves appeared to fit the observations well for females (Figure 1.1) and males (Figure 1.2); however, the results of the current study suggest males grow larger and at a slower rate than females (Table 1.1). This contradicts the observed data and the results of previous studies, which provide evidence that females grow larger and at slower rates than males. For this reason, the estimates used in the 2013 NCDMF stock assessment were assumed instead.

Parameters of the allometric length-weight relationship were also estimated in this study. The relation of fork length in centimeters to weight in kilograms was modeled for males and females separately. Fish of unknown sex were included in the fits of both males and females. The estimated parameters from this and previous studies are presented in Table 1.2. Plots of the observed and predicted values from this study are shown in Figures 1.3 (females) and 1.4 (males).

1.2.5 Reproduction

Striped mullet are gonochoristic and their sex is genetically determined (McDonough et al. 2005). Due to the plasticity of their gonad development, striped mullet retain some characteristics of the opposite sex during the initial stages of differentiation. Undifferentiated gonads appear to have male morphological characteristics. Previous studies have suggested the possibility of hermaphrodism in striped mullet (Stenger 1959; Moe 1966). Yet, there is only one documented example of a simultaneous hermaphroditic striped mullet (Franks et al. 1998). It has been shown that most immature mullet were sexually differentiated by the time of their first annular increment deposition (15–19 months; McDonough et al. 2005) or at 175 mm to 225 mm (Stenger 1959; Bichy 2000).

The majority of striped mullet reach sexual maturity at 300 mm (male range = 250 mm to 325 mm, female range = 290 mm to 430 mm) and at age 2 (McDonough et al. 2005). However, striped mullet in North Carolina appear to mature at a younger age and larger size than other striped mullet populations, with an estimated age of maturity of age 1 for both males and females and at 285 mm and 335 mm for males and females, respectively (Bichy 2000). Striped mullet can mature in a range of salinities; however, the best production is reached when their gonads develop in salinities of 13 to 35 ppt (McDonough et al. 2005). Reported estimates of fecundity in North Carolina ranged from 4.8×10^5 to 4.2×10^6 eggs per female (Bichy 2000).

Immature and inactive males and females have been collected during every month of the year. The presence of ripe males from October through February and developing females from August through March support the idea of an extended spawning season from October through March. In striped mullet, it is unknown what initiates gametogenesis, but generally, it is accepted that changes in temperature and photoperiod help regulate the seasonal reproductive cycle (McDonough et al. 2005). Bichy (2000) found the proportion of males to females varied by fish length with fish over 300 mm being predominately female. Below 300 mm, males dominated, but the sex ratio was closer to 1:1.

In North Carolina, peak spawning occurs from October through early December when estuarine water temperatures are often below 15°C, suggesting striped mullet spawn when estuarine water temperatures are between 13°C and 22°C (Bichy 2000). Striped mullet are considered isochronal spawning fishes (Greeley et al. 1987; Render et al. 1995). The spawning location of striped mullet is largely based in theory and indirect evidence of larval size, but it has been suggested that striped mullet spawn offshore in and around the edge of the continental shelf, often referred to as the SAB (Collins and Stender 1989).

Maturity of female striped mullet was estimated using data collected from various NCDMF fisheries-dependent and -independent programs. Maturity at length (M_l) was modeled as:

$$M_l = \frac{1}{1 + e^{\alpha(l-\beta)}}$$

where l is length, α is the slope, and β is the inflection point.

The parameters α and β were estimated via logistic regression. The estimated value for α was -0.450 and the estimated value for β was 30.2 cm (Figure 1.5).

1.2.6 Natural Mortality

Natural mortality (M) is one of the most important, and often most uncertain, parameters used in stock assessments. Several approaches have been developed to provide indirect estimates of M at age (Peterson and Wroblewski 1984; Boudreau and Dickie 1989; Lorenzen 1996, 2005). In the 2013 NCDMF assessment of striped mullet (NCDMF 2013), age-specific M values were calculated for males and females using the method of Lorenzen (1996), which is based on the relationship of body weight to natural mortality. Lorenzen's (1996) approach requires estimates of parameters from the von Bertalanffy age-length growth function, estimates of parameters from the allometric length-weight relationship, and the range of ages over which M will be estimated.

Because this stock assessment assumes the same values for the von Bertalanffy parameters as the 2013 stock assessment (section 1.2.4.4), the estimates of M used in the 2013 NCDMF stock assessment, which were based on Lorenzen's (1996) approach, were also assumed here (Table 1.3).

1.2.7 Food & Feeding Habits

The striped mullet is recognized as an important ecological bridge among a wide range of trophic levels. It connects base food chain items such as detritus and diatomaceous microalgae, phytoplankton and zooplankton, and marine snow (Odum 1968; Moore 1974; Collins 1985a; Larson and Shanks 1996; Torras et al. 2000) with top-level predators, such as birds, fishes, sharks, and bottlenose dolphins (Breuer 1957; Thomson 1963; Collins 1985a; Barros and Odell 1995; Fertl and Wilson 1997). Carnivorous feeding (on copepods, mosquito larvae, and microcrustaceans) is common in striped mullet larvae and small juveniles (Harrington and Harrington 1961; De Silva 1980), followed by a stronger dependence on benthic (bottom) detritus and sediment with increasing body size (De Silva and Wijeyaratne 1977).

Adult striped mullet are well-documented herbivorous detritivores (Odum 1970; Collins 1985a). Adults are commonly described as 'interface feeders' (feed on water surface, water bottom, or surface of objects). Adults consume epiphytic (attached to the surface of a plant) and benthic microalgae (*viz*. unicellular green algae, filamentous blue-green algae, diatoms), bacteria, Protozoa, and other microorganisms associated with the top layers of fine sediments, detritus, and submerged surfaces such as rocks, eelgrass (*Zostera marina*), and turtle grass (*Thalassia* spp.) blades (Odum 1970; Moore 1974). Adults also feed on surface water 'scum' composed of accumulations of microalgae (Odum 1970). Ingested sediment particles are known to function as a grinding substrate in the degradation of plant cell walls in a gizzard-like pyloric stomach of the striped mullet (Thomson 1966). Anecdotal reports of feeding behaviors on mid-water polychaetes, *Nereis succinea*, and live bait of anglers also indicate opportunistic, carnivorous feeding by adults in non-interface areas (Bishop and Miglarese 1978). Collins (1981) reported that feeding activity was restricted to daylight hours.

1.3 Habitat

Striped mullet habitat use varies greatly based on life history stages, seasons, and location (Able and Fahay 1998; Pattillo et al. 1999; Cardona 2000; Whitfield et al. 2012). Salinity seems to play a major role on habitat use and distribution of both adult and juvenile mullet (Cardona 2000). They are a highly euryhaline fish and live in a wide range of salinities, based on size and maturity (Pattillo et al. 1999; Cardona 2000; McDonough and Wenner 2003; Górski et al. 2015). The availability of suitable food may also influence habitat use by striped mullet (Moore 1974). They are found in almost all shallow marine and estuarine habitats including beaches, tidal flats, lagoons, bays, rivers, channels, marshes and grassbeds (Moore 1974; Pattillo et al. 1999; Nordlie 2000). They can be found in depths ranging from a few centimeters to over 1,000 m but are mostly collected within 40 m of the surface. Once in estuarine waters, striped mullet prefer depths of 3 m or less.

1.3.1 Spawning Habitat

As discussed in section **Error! Reference source not found.**, the spawning location of striped m ullet is thought to be offshore, in and around the edge of the continental shelf (Collins and Stender 1989), from the 20-fathom line to the Gulf Stream in North Carolina to lower Florida (Anderson 1958). Striped mullet spawning migrations are cued by environmental conditions, including northeasterly winds and strong cold fronts with dropping barometric pressure (Thompson et al. 1991; Mahmoudi 1993). These cues may vary due to unseasonably warm temperatures or hurricanes. Larval striped mullet will then pass through inlets into the estuarine nursery areas (Hettler et al. 1997).

1.3.2 Nursery & Juvenile Habitat

Juvenile striped mullet spend a majority of their time in estuarine rivers and marshes, with abundance highest in May and lowest in September (Bretsch and Allen 2006; McDonough and Wenner 2003). These juvenile striped mullet use wetlands for foraging and refuge from predators. Within these marshes, striped mullet have been observed in the interior and on the edge of the marsh depending on flows and water levels (Kneib and Wagner 1994; Peterson and Turner 1994; Allen et al. 2007). Larval and juvenile striped mullet are also found in lesser numbers in the surf zone (Modde and Ross 1981; Strydom and d'Hotman 2005; Able et al. 2013; Park et al. 2015).

1.3.3 Adult Habitat

As striped mullet mature, they are more commonly found in polyhaline estuarine and marine waters and may avoid freshwater areas (Cardona 2000; Chang et al. 2004; Górski et al. 2015). Adult striped mullet are found in almost all shallow marine and estuarine habitats including beaches, tidal flats, lagoons, bays, rivers, channels, marshes and grassbeds (Moore 1974; Pattillo et al. 1999; Nordlie 2000), as their high mobility allows them to utilize a wide range of habitats (Baker et al. 2013). Generally, when adult striped mullet are in the estuaries they are found over soft bottom in the vicinity of freshwater wetlands. As the wetland plant matter dies, it settles on the soft bottom where striped mullet spend most of their time foraging on detritus and benthic invertebrates. Striped mullet will also spend time feeding on epiphytes found in beds of submerged aquatic vegetation (SAV). Once striped mullet are ready to spawn they will move offshore to their spawning grounds.

1.3.4 Habitat Issues & Concerns

Suitable and adequate habitat is a critical element in the ecology and productivity of estuarine systems. Degradation or improvement in one aspect of habitat may have a corresponding impact on water quality. Maintenance and improvement of suitable estuarine habitat and water quality are probably one of the most important factors in providing sustainable striped mullet stocks. All of the habitats used by striped mullet are threatened in some way. Water quality degradation through stormwater runoff, discharges, toxic chemicals, sedimentation, and turbidity all have been documented as threats to striped mullet and their habitat. Due to the importance of inlets to striped mullet estuarine immigration, terminal groins may act as a threat to striped mullet stocks. Wetlands are threatened by human activities, including dredging for marinas and channels, filling for development, ditching and draining for agriculture, silviculture, and development, channelization, and shoreline stabilization. Dredging also threatens soft bottom habitat affecting striped mullet food sources and water quality.

1.4 Description of Fisheries

1.4.1 Commercial Fishery

Historically, the striped mullet fishery had a prominent role in the early development of the North Carolina commercial fishing industry. Smith (1907) ranked striped mullet as the most abundant and important saltwater fish of North Carolina in the early 1900s. Woodward (1956) referred to mullet (white and striped combined) as the most important food finfish in North Carolina. The striped mullet fishery operated at over 1,300 metric tons (mt) annually during the late 1800s (Figure 1.6). Peak landings of over 3,000 mt and 2,200 mt were harvested in 1902 and 1908 (Chestnut and Davis 1975). The fishery was highly seasonal and occurred primarily during the fall spawning migration, but landings occurred throughout the year (Taylor 1951; Woodward 1956). Enormous catches—greater than 450 mt (1 million pounds) of mullet landings in a single day—were common during these fall migrations (Smith 1907). These massive pulses were larger than the market's distribution and holding capacity well into the 1950s (Taylor 1951; Woodward 1956). Commercial landings reached their lowest levels from 1964 to 1971, averaging around 515 mt annually (Chestnut and Davis 1975). Strong demand from Asia for striped mullet roe and competing roe-exporting companies combined to create a highly profitable roe fishery in North Carolina in 1988. In 1988, landings exceeded 1,300 mt for the first time in 28 years. More recently, commercial landings reached low levels from 2015 to 2017 averaging around 540 mt annually and commercial landings in 2016 were 437 mt.

Seines and gill nets are the primary gear used to harvest striped mullet in North Carolina. From 1887 to 1978, 60% of the commercial harvest was from seines and 39% from gill nets (Chestnut and Davis 1975; NCDMF, unpublished data). Since 1979, gill nets (runaround, set, and drift) have replaced seines as the dominant gear type in the fishery. Gill nets have been the dominant gear from 1994 through 2017 (Figure 1.7). From 1994 to 2002, 92% of striped mullet landings were attributed to gill nets and 48% of all landings were attributed to runaround gill nets. Since then gill nets have continued to be the dominant gear type, accounting for 93% of the landings from 2003 to 2011. Runaround gill nets accounted for 64% of striped mullet landings during this period. Since 2011, gill nets have accounted for 90% of commercial landings and seines have accounted for four percent. Runaround gill nets have continued to be the dominant gear type in the striped mullet commercial fishery accounting for 68% of the landings from 2012 through 2017. The use of cast nets in the striped mullet commercial has been increasing since 2003. From 1994 to 2002, cast nets accounted for one percent of commercial landings and from 2003 to 2011, cast nets accounted for three percent of commercial landings. Despite fluctuations in recent years, including large landings declines in 2016 and 2017, cast nets accounted for five percent of commercial landings from 2012 to 2017.

1.4.2 Recreational Fishery

Striped mullet are not typically targeted by anglers using hook and line. Although, striped mullet and white mullet are commonly used as bait fish by recreational anglers targeting a wide variety of inshore and offshore species (Nickerson 1984). YOY mullets, commonly referred to as finger mullet, caught by cast net are primarily used for bait by recreational anglers. The drying of mullet and their roe for later consumption is also popular with some coastal North Carolina residents. Finger mullet are generally available in the summer and fall with the majority caught in September and October. The fall harvest coincides with the southward migration of YOY striped and white mullet (NCDMF, unpublished data).

1.5 Fisheries Management

1.5.1 Management Authority

The NCDMF is responsible for the management of estuarine and marine resources occurring in all state coastal fishing waters extending to three miles offshore (Figure 1.8). There are no federal or interstate FMPs that apply specifically to the striped mullet fishery in North Carolina.

1.5.2 Management Unit Definition

The management unit includes the striped mullet and its fisheries in all of North Carolina's coastal fishing waters.

1.5.3 Regulatory History

In 2006, the North Carolina Marine Fisheries Commission adopted the FMP for striped mullet in joint and coastal waters of North Carolina. The major goal of the FMP was to conserve and protect the striped mullet resource to ensure ecological stability while providing for sustainable fisheries. All management authority for North Carolina's striped mullet fishery is vested in the State of North Carolina.

Very few regulations exist that pertain directly to striped mullet. Many of the regulations that can be applied to the striped mullet fishery relate to fishing gear and bait fish in general. Statutes that have been applied to the striped mullet fishery include:

- Recreational fishery limit of two hundred per person per day for striped and white mullets combined
- It is unlawful to fish in the ocean from vessels or with a net within 750 feet of a properly licensed and marked fishing pier.
- It is unlawful to engage in trash or scrap fishing (the taking of young of edible fish before they are of sufficient size to be of value as individual food fish) for commercial disposition as bait, for sale to any dehydrating or nonfood processing plant, or for sale or commercial disposition in any manner. The MFC's rules may authorize the disposition of the young of edible fish taken in connection with the legitimate commercial fishing operations, provided it is a limited quantity and does not encourage "scrap fishing".
- It is unlawful for any person without the authority of the owner of the equipment to take fish from nets, traps, pots, and other devices to catch fish, which have been lawfully placed in the open waters of the State.
- It is unlawful for any vessel in the navigable waters of the State to willfully, wantonly, and unnecessarily do injury to any seine, net, or pot.
- It is unlawful for any person to willfully destroy or injure any buoys, markers, stakes, nets, pots, or other devices or property lawfully set out in the open waters of the State in connection with any fishing or fishery.
- It is unlawful to use spotter planes in an operation that takes food fish.
- It shall be unlawful to possess, sell, or purchase fish under four inches in length except:

1. For use as bait in the crab pot fishery in North Carolina with the following provision: such crab pot bait shall not be transported west of U.S. Interstate 95 and when transported, shall be accompanied by documentation showing the name and address of the shipper, the name and address of the consignee, and the total weight of the shipment
2. For use as bait in the finfish fishery with the following provisions:
    - It shall be unlawful to possess more than 200 pounds of live fish or 100 pounds of dead fish.
    - Such finfish bait may not be transported outside the State of North Carolina.

- It is unlawful to possess aboard a vessel or while engaged in fishing any species of finfish that is subject to a size of harvest restriction without having head and tail attached, except:
    1. Mullet when used for bait;
    2. Hickory shad when used for bait provided that not more than two hickory shad per vessel or fishing operation may be cut for bait at any one time; and
    3. Tuna possessed in a commercial fishing operation as provided in 15A NCAC 03M .0520.

Bait dealers who possess valid finfish dealers license from the NCDMF are exempt from sub-items 2(a) and (b) of this Rule. Tolerance of not more than five percent shall be allowed. Menhaden, herring, gizzard shad, pinfish, and live fish in aquaria other than those for which a minimum size exists are exempt from this Rule.

1.5.4 Current Regulations

Detailed information regarding North Carolina's current commercial and recreational fishery regulations is available on the NCDMF website (http://portal.ncdenr.org/web/mf/rules-and-regulations).

1.5.4.1 Commercial Fishery

The Standard Commercial Fishing License (SCFL) and Retired Standard Commercial Fishing License are annual licenses issued to commercial fishermen who harvest and sell fish, shrimp, or crab. The number of SCFL licenses is currently capped at 8,896. A Commercial Fishing Vessel Registration is also required for fishermen who use boats to harvest seafood.

The stop net fishery has operated under fixed seasons and net and area restrictions since 1993. Annually, a proclamation is issued by the director of the NCDMF to establish the season, specify net restrictions, and define areas in which stop nets can be used during the beach seine striped mullet fishery. Annually, the season for stop nets is from October 1 through November 30; however, the stop net season was extended to include December 3 to December 17 in 2015 (Proclamation M-28-2015). Net restrictions include: a maximum of four stop nets can be used between Beaufort Inlet and Bogue Inlet at any one time, a combined fishing operation cannot use more than two stop nets at any one time, stop nets cannot exceed 400 yards in length (the inshore 100-yard portion and the offshore 50-yard portion must be constructed of webbing a minimum of 8 inches stretched mesh and the remaining section of the net must be constructed of webbing a minimum of 6 inches stretched mesh), and stop nets are not allowed within 880 yards of an existing stop net. The areas where stop nets are allowed include: Atlantic Ocean on Bogue Banks, Carteret

County, and between Beaufort Inlet and Bogue Inlet with stop nets prohibited in specified areas on Bogue Banks.

1.5.4.2 Recreational Fishery

Prior to 1999, no recreational fishing license was required unless a vessel was used. After July 1, 1999, the Recreational Commercial Gear License (RCGL) was required when using certain allowable commercial gear to harvest finfish and crustaceans for personal consumption. No license is required for the following non-commercial equipment: collapsible crab traps, cast nets, dip nets, and seines less than 30 feet.

There are currently no size restrictions on striped mullet in North Carolina. As of July 1, 2006, there has been a 200-mullet (white and striped aggregate) daily possession limit per person in the recreational fishery and the mutilated finfish rule was modified to exempt mullet (white and striped) used as bait. However, the NCDMF director may, by proclamation, impose any or all of the following restrictions on the taking of mullet: specify season, specify area, specify quantity, specify means/methods, and specify size.

1.6 Previous Assessment (benchmark)

The most recent assessment of the striped mullet stock in North Carolina waters for management purposes was performed in association with the development of Amendment 1 to the Striped Mullet FMP (NCDMF 2013, 2015). The assessment applied a sex-specific, forward-projecting statistical catch-at-age model to estimate population size, fishing mortality rates, and reference points. The model incorporated data from commercial fisheries and three fisheries-independent surveys based on the 1994 to 2011 time period. The results of that assessment suggested the stock was not undergoing overfishing in 2011 (Figure 1.9). A poor stock-recruit relationship resulting in unreliable biomass-based reference points prevented determination of the overfished status.

The previous NCDMF stock assessment underwent a desk-type peer review. As of 2017, NCDMF stock assessments are reviewed through an in-person process. The reviewers of the 2013 stock assessment ultimately recommended that the stock assessment could be used for management purposes, which the NCDMF agreed.

2 DATA

2.1 Fisheries-Dependent

2.1.1 Commercial Fishery Monitoring

Prior to 1978, North Carolina's commercial landings data were collected by the National Marine Fisheries Service (NMFS). In 1978, the NCDMF entered into a cooperative program with the NMFS to maintain and expand the monthly surveys of North Carolina's major commercial seafood dealers. Beginning in 1994, the NCDMF instituted a mandatory trip-ticket system to track commercial landings.

2.1.1.1 Survey Design & Methods

On January 1, 1994, the NCDMF initiated a Trip Ticket Program (TTP) to obtain more complete and accurate trip-level commercial landings statistics (Lupton and Phalen 1996). Trip ticket forms are used by state-licensed fish dealers to document all transfers of fish sold from coastal waters from the fishermen to the dealer. The data reported on these forms include transaction date, area fished, gear used, and landed species as well as fishermen and dealer information.

The majority of trips reported to the NCDMF TTP only record one gear per trip; however, as many as three gears can be reported on a trip ticket and are entered by the program's data clerks in no particular order. When multiple gears are listed on a trip ticket, the first gear may not be the gear used to catch a specific species if multiple species were listed on the same ticket but caught with different gears. In 2004, electronic reporting of trip tickets became available to commercial dealers and made it possible to associate a specific gear for each species reported. This increased the accuracy of reporting by documenting the correct relationship between gear and species.

2.1.1.2 Sampling Intensity

North Carolina dealers are required to record the transaction at the time of the transactions and report trip-level data to the NCDMF on a monthly basis.

2.1.1.3 Biological Sampling

In 1982, the NCDMF initiated a statewide sampling program for the dominant commercial finfish fisheries. The objective was to obtain biological data on economically important fishes for use in management evaluations. Biological data were collected from fish houses for the ocean gill-net, long haul seine, pound net (sciaenid and flounder), beach seine/stop net, estuarine gill-net (began 1990), and cast net (began 2002) commercial fisheries. Similar methods are used across these programs to sample commercial catches. Information gathered from this sampling includes catch composition, poundage landed (from Trip Ticket), area fished, soak time, gear characteristics as well as length, weight, age, and sex information for target species.

2.1.1.4 Potential Biases & Uncertainties

Because trip tickets are only submitted when fish are transferred from fishermen to dealers, records of unsuccessful fishing trips are not available. As such, there is no direct information regarding trips where a species was targeted but not caught. Information on these unsuccessful trips is necessary for calculating a reliable index of relative abundance for use in stock assessments.

Another potential bias relates to the reporting of multiple gears on a single trip ticket. It is not always possible to identify the gear used to catch a particular species on a trip ticket that lists multiple gears and species.

Commercial landings do not differentiate between striped mullet and white mullet; however, the proportion of white mullet that occur in North Carolina's commercial landings is considered very small.

2.1.1.5 Development of Estimates

Commercial landings were summarized by year using the NCDMF TTP data. Biological data collected from the NCDMF's Estuarine Gill-Net, Beach Seine, Ocean Gill-Net, Cast Net, Long Haul Seine, Sciaenid Pound Net, and Flounder Pound Net commercial fishery sampling programs were used to compute annual length and age compositions, average body weights, and average lengths at age. The length and age compositions and average lengths at age were computed by sex.

2.1.1.6 Estimates of Commercial Fishery Statistics

The NCDMF TTP is considered a census of North Carolina commercial landings. Annual commercial landings of striped mullet ranged from a low of 438 mt in 2016 to a high of 1,283 mt in 2000 (Table 2.1; Figure 2.1).

Length-frequency distributions of striped mullet from the commercial fishery expanded in the early part of the time series but began to truncate in more recent years (Figure 2.2). The commercial landings are dominated by age-2 striped mullet and there is some evidence the age distribution of the landings has truncated in recent years (Figure 2.3). Average body weight of striped mullet from the commercial fishery increased from 1998 through 2005 before declining in 2007 (Figure 2.4). Average body weight has remained relatively constant at less than 1.0 kg since 2007. Average length at age has remained relatively constant throughout the time series though there is some evidence that length at age for younger stiped mullet has increased toward the end of the time series (Table 2.2).

2.1.2 Recreational Fishery Monitoring

The available statistics for North Carolina's recreational fishery for striped mullet are considered very uncertain and were not included in the 2013 NCDMF stock assessment (NCDMF 2013). As this is an update of the 2013 assessment, recreational fisheries data are not included in the current assessment.

The federal Marine Recreational Information Program (MRIP) is primarily designed to sample anglers who use rod and reel as the mode of capture. Since most striped mullet are caught with cast nets for bait, striped mullet recreational harvest data are imprecise. Angler misidentification between striped mullet and white mullet is also common (NCDMF 2006). Bait mullet are usually released by anglers before visual verification by creel clerks and therefore are not identified to the species level in the MRIP data (Type B catch).

Recreational catch data from the NCDMF Recreational Commercial Gear License (RCGL) survey were collected from 2002 to 2008. The program was discontinued in 2009 due to lack of funding and the minimal contributions from RCGL to overall harvest. In October 2011, the NCDMF began a mail survey to develop catch and effort estimates for recreational cast net and seine use. The mail survey was established as a direct response to a lack of precision in the MRIP estimates for difficult to sample or overlooked recreational fisheries and activities. The survey does not distinguish between striped and white mullet and all data should be interpreted with caution because the ratio of striped mullet to white mullet in the recreational catch will differ between seasons and areas of the state (note: most common county and waterbody of cast net/seine effort is asked as part of the survey but estimates are not developed by county).

2.2 Fisheries-Independent

2.2.1 Striped Mullet Electroshock Survey (Program 146)

2.2.1.1 Survey Design & Methods

The NCDMF Striped Mullet Electroshock Survey, also known as Program 146 (P146), was initiated in 2003 to produce a fisheries-independent index of relative abundance of striped mullet in the central district of North Carolina. Twelve sampling stations were established among four sites (three per site) in the Neuse River and its tributaries (Figure 2.5). The Neuse River area is an important year-round habitat and a major migration path for striped mullet in North Carolina.

Electroshock sampling is conducted over a fixed 500-m stretch of shoreline in linear transects at each station. Electric current is generated from a 16-hp Briggs and Straton generator (model number 7.5GPP—Smith Root). Sampling is conducted by boat with two netters. Dip-net mesh sizes are ⅛ and ¾ inches, respectively.

2.2.1.2 Sampling Intensity

Samples were collected monthly from 2003 to 2008. As of 2009, sampling has been reduced to January through April and October through December; each station is sampled once per month.

2.2.1.3 Biological Sampling

All species that are netted are identified to the lowest possible taxon and counted. Individual length measurements are recorded for commercially and recreationally important marine species. All netted fish are held in a holding tub and enumerated and/or measured after the 500-m transect has been sampled.

2.2.1.4 Potential Biases & Uncertainties

Program 146 is the only index the NCDMF has designed to target striped mullet. Currently this program has a relatively short time period and covers a small geographic area located within the Neuse River. Electrofishing gear can have biases in species composition, size distribution, and abundance (Reynolds 1983; McInerny and Cross 1996).

Indices based on fixed-station surveys such as Program 146 may not accurately reflect changes in population abundance (Warren 1994, 1995). Accuracy of estimates is tied to the degree of spatial persistence in catch data of the species. An evaluation of the striped mullet data collected from Program 146 indicated the presence of spatial persistence for striped mullet, suggesting the derived index is reflective of changes in relative abundance (Lee and Rock 2018).

2.2.1.5 Development of Estimates

To provide the most relevant index, data were limited to those collected during January through April, when the majority of striped mullet occurred in the Neuse River. Since the survey primarily catches adult striped mullet, juveniles were excluded from the calculations. A generalized linear model (GLM) framework was used to model the relative abundance of adult striped mullet in Program 146. Potential covariates were evaluated for collinearity by calculating variance inflation factors. Collinearity exists when there is correlation between covariates and its presence causes inflated *p*-values.

The Poisson distribution is commonly used for modeling count data; however, the Poisson distribution assumes equidispersion; that is, the variance is equal to the mean. Count data are more often characterized by a variance larger than the mean, known as overdispersion. Some causes of overdispersion include missing covariates, missing interactions, outliers, modeling non-linear effects as linear, ignoring hierarchical data structure, ignoring temporal or spatial correlation, excessive number of zeros, and noisy data (Zuur et al. 2009, 2012). A less common situation is underdispersion in which the variance is less than the mean. Underdispersion may be due to the model fitting several outliers too well or inclusion of too many covariates or interactions (Zuur et al. 2009).

Data were first fit with a standard Poisson GLM and the degree of dispersion was then evaluated. If over- or underdispersion was detected, an attempt was made to identify and eliminate the cause of the over- or underdispersion (to the extent allowed by the data) before considering alternative models, as suggested by Zuur et al. (2012). In the case of overdispersion, a negative binomial distribution can be used as it allows for overdispersion relative to the Poisson distribution. Alternatively, one can use a quasi-GLM model to correct the standard errors for overdispersion. If the overdispersion results from an excessive number of zeros (more than expected for a Poisson or negative binomial), then a model designed to account for these excess zeros can be applied. There are two types of models that are commonly used for count data that contain excess zeros. Those models are zero-altered (two-part or hurdle models) and zero-inflated (mixture) models (see Minami et al. 2007 and Zuur et al. 2009 for detailed information regarding the differences of these models). Minami et al. (2007) suggests that zero-inflated models may be more appropriate for catches of rarely encountered species; therefore, zero-inflated models were considered here when appropriate.

All available covariates were included in the initial model and assessed for significance using the appropriate statistical test. Non-significant covariates were removed using backwards selection to find the best-fitting predictive model.

Annual length and age compositions, average body weights, and average lengths at age were computed based on the same reference data used to calculate the index. The length and age compositions and average lengths at age were computed by sex.

2.2.1.6 Estimates of Survey Statistics

Available covariates were year, area, depth, water temperature, salinity, and dissolved oxygen. Year and area were treated as categorical variables in the models. Since effort was constant across sampling events, the modeled response variable was counts of striped mullet. The final, best-fitting model was a quasi-Poisson model and included year, area, depth, and dissolved oxygen as significant covariates. The index was variable and no discernable trend was apparent except for a persistent decline from 2015 to 2017 (Figure 2.6).

The length-frequency distributions of adult striped mullet collected by Program 146 suggest a slight expansion to larger size classes in the early part of the time series before contracting in more recent years to a narrower range of sizes (Figure 2.7). The catch of male and female striped mullet has been dominated by age-1 and age-2 fish (Figure 2.8). The age-frequency distribution has contracted in recent years to be almost exclusively age-2 fish. Average weight of striped mullet from Program 146 has varied little and in most years is near 0.5 kg (Figure 2.9). Average length at age has varied little throughout the time series for males and females (Table 2.3).

2.2.2 Striped Bass Independent Gill-Net Survey (Program 135)

2.2.2.1 Survey Design & Methods

In October 1990, the NCDMF initiated the Striped Bass Independent Gill-Net Survey, also known as Program 135 (P135). The survey was designed to monitor the striped bass population in the Albemarle Sound and Roanoke River.

The survey follows a random stratified design, stratified by geographic area. This survey divides the water bodies comprising the Albemarle region into six sample zones that are further subdivided into one-mile square quadrants with an average of 22 quadrants per zone (Figure 2.10). The survey gear is a multi-mesh monofilament gill net. Four gangs of twelve meshes (2.5-, 3-, 3.5-, 4-, 4.5-, 5-, 5.5-, 6-, 6.5-, 7-, 8-, 10-inch stretch) of gill nets are set in each quadrant by the fishing crew, one two-gang set is weighted to fish at the bottom (sink net), and the other is floating unless the area is unsuitable for gill-net sampling (marked waterways and areas with excessive submerged obstructions). Alternate zones and quadrants are randomly selected in the event that the primary selection cannot be fished. A fishing day is defined as the two crews fishing the described full complement of nets for that segment for one day. One unit of effort is defined as each 40-yard net fished for 24 hours.

2.2.2.2 Sampling Intensity

The sampling year is divided into three segments: fall-winter, spring, and summer. Summer sampling was discontinued in 1993. The areas fished, sampling frequency, and sampling effort are altered seasonally to sample the various segments of the striped bass population.

2.2.2.3 Biological Sampling

All striped bass are measured and additional data are recorded while other species collected are counted and sub-sampled for length, age, and sex information.

2.2.2.4 Potential Biases & Uncertainties

Program 135 is specifically designed to target striped bass; however, striped mullet are counted and sub-sampled for length (mm) when collected. Gill nets are the only gear used in this program, which could exclude some smaller species/individuals and species that evade the nets.

2.2.2.5 Development of Estimates

To provide the most relevant index, data were limited to those collected from mesh sizes 2.5” to 5.5” during November through February, when and where the majority of striped mullet occurred. Data were also limited to those collected from nets fished in less than 10 feet of water to only include nets fishing the entire water column. Since the survey primarily catches adult striped mullet, juveniles were excluded from the calculations. The GLM method used to model the relative abundance of adult striped mullet in Program 146 (see section 2.2.1.5) was also used to model the relative abundance of adult striped mullet in Program 135.

Annual length and age compositions, average body weights, and average lengths at age were computed based on the same reference data used to calculate the index. The length and age compositions and average lengths at age were computed by sex.

2.2.2.6 Estimates of Survey Statistics

Available covariates were year, quad, depth, water temperature, weather, wind direction, and wind speed. Year, quad, weather, and wind direction were treated as categorical variables in the models. Since effort was constant across sampling events, the modeled response variable was counts of striped mullet. The final, best-fitting model was a quasi-Poisson model and included year, quad, depth, and weather as significant covariates. The index varied little from 1994 through 2013 before peaking in 2014 and 2015 (Figure 2.11). Relative abundance declined to zero in 2016 and 2017.

Trends in the length-frequency distributions are difficult to discern due to varying sample sizes (Figure 2.12); however, there does appear to be some truncation of lengths in the last few years of the time series. The striped mullet catch in Program 135 is dominated by age-1 and age-2 fish

(Figure 2.13). Because of small sample sizes trends in age-frequency distribution are difficult to discern, though there does seem to be some truncation of ages in the latter part of the time series. Average weight has varied little over time usually ranging from 0.5 to 1.0 kg (Figure 2.14). Length at age has varied little over time but trends are difficult to discern due to low sample sizes (Table 2.4).

2.2.3 Fisheries Independent Gill-Net Survey (Program 915)

2.2.3.1 Survey Design & Methods

The Fisheries-Independent Gill-Net Survey, also known as Program 915 (P915), began on March 1, 2001 and includes Hyde and Dare counties (Figure 2.15). In July 2003, sampling was expanded to include the Neuse, Pamlico, and Pungo rivers (Figures 2.16, 2.17). Additional areas in the Southern District were added in April 2008.

Floating gill nets are used to sample shallow strata while sink gill nets are fished in deep strata. Each net gang consists of 30-yard segments of 3-, 3.5-, 4-, 4.5-, 5-, 5.5-, 6-, and 6.5-inch stretched mesh, for a total of 240 yards of nets combined. Catches from an array of gill nets comprise a single sample; two samples (one shallow, one deep)—totaling 480 yards of gill net—are completed each trip. Gill nets are typically deployed within an hour of sunset and fished the following morning. Efforts are made to keep all soak times within 12 hours. All gill nets are constructed with a hanging ratio of 2:1. Nets constructed for shallow strata have a vertical height between 6 and 7 feet. Prior to 2005, nets constructed for deep and shallow strata were made with the same configurations. Beginning in 2005, all deepwater nets were constructed with a vertical height of approximately 10 feet. With this configuration, all gill nets were floating and fished the entire water column.

A stratified random sampling design is used, based on area and water depth. Each region is overlaid with a one-minute by one-minute grid system (equivalent to one square nautical mile) and delineated into shallow (<6 feet) and deep (>6 feet) strata using bathymetric data from NOAA navigational charts and field observations. Beginning in 2005, deep sets have been made along the 6-ft contour. Sampling is divided into two regions: Region 1, which includes areas of eastern Pamlico Sound adjacent to the Outer Banks from southern Roanoke Island to the northern end of Portsmouth Island; and Region 2, which includes Hyde County bays from Stumpy Point Bay to Abel's Bay and adjacent areas of western Pamlico Sound. Each of the two regions is further segregated into four similar sized areas to ensure that samples are evenly distributed throughout each region. These are denoted by either Hyde or Dare and numbers 1 through 4. The Hyde areas are numbered east to west, while the Dare areas are numbered north to south. The rivers are divided into four areas in the Neuse River (Upper, Upper-Middle, Lower-Middle, and Lower), three areas in the Pamlico River (Upper, Middle, and Lower), and only one area for the Pungo River. The upper Neuse area was reduced to avoid damage to gear from obstructions, and the lower Neuse was expanded to increase coverage in the downstream area. The Pungo area was expanded to include a greater number of upstream sites where a more representative catch of striped bass may be acquired.

2.2.3.2 Sampling Intensity

Initially, sampling occurred during all 12 months of the year. In 2002, sampling during December 15 to February 14 was eliminated due to extremely low catches and unsafe working conditions. Sampling delays were extensive in 2003, so this year was excluded from analysis because of the lack of temporal completeness. Each of the sampling areas within each region is sampled twice a month. Within a month, a total of 32 samples are completed (eight areas × twice a month × two samples) in the river systems.

2.2.3.3 Biological Sampling

All fish are sorted by species. A count and a total weight to the nearest 0.01 kg, including damaged (partially eaten or decayed) specimens, are recorded. Length, age, and reproductive samples are taken from selected target species, including striped mullet. Samples are processed according to the ageing project protocols.

2.2.3.4 Potential Biases & Uncertainties

Although striped mullet are a target species, this program was not designed to specifically target striped mullet. The sampling effort is designed to gather data on fishes using the estuarine habitats but does not take into account nearshore ocean and offshore ocean populations. Also, the range of gill-net mesh sizes used in this survey will exclude the smallest individuals. This survey does not sample the many shallow creeks and tributaries off the main river stems, habitats that are frequently used by striped mullet (NCDMF, unpublished data).

2.2.3.5 Development of Estimates

To provide the most relevant index, data were limited to those collected from shallow river (Pamlico/Pungo and Neuse rivers) areas during October and November, when and where the majority of striped mullet occurred. Since the survey primarily catches adult striped mullet, juveniles were excluded from the calculations. The GLM method used to model the relative abundance of adult striped mullet in Programs 146 and 135 (see section 2.2.1.5) was also used to model the relative abundance of adult striped mullet in Program 915.

Annual length and age compositions, average body weights, and average lengths at age were computed based on the same reference data used to calculate the index. The length and age compositions and average lengths at age were computed by sex.

2.2.3.6 Estimates of Survey Statistics

Available covariates were year, stratum, water depth, water temperature, salinity, and dissolved oxygen. Year and stratum were treated as categorical variables in the models. Since effort was constant across sampling events, the modeled response variable was counts of striped mullet. The final, best-fitting model assumed a negative binomial distribution and included year, water depth, and salinity as significant covariates. The index increased from 2006 to 2011 before gradually declining from 2011 to 2014 (Figure 2.18). Relative abundance declined sharply in 2015 and remained near time series lows through 2017.

Length-frequency distributions of adult striped mullet suggest a slight expansion into larger sizes during the early part of the time series before the length-frequency distributions began to truncate in the latter portion of the time series (Figure 2.19). The trend in age-frequency distributions is difficult to interpret due to low sample sizes that occurred in the earlier years of the time series but the catch is predominantly composed of age-1 and age-2 fish with few fish over age-3 in any year (Figure 2.20). There is little trend in average body weight with values usually falling between 0.5 and 1.0 kg in every year (Figure 2.21). Male and female length at age have varied little throughout the time series (Table 2.5).

3 ASSESSMENT

3.1 Method

3.1.1 Description

This is an update of the benchmark NCDMF stock assessment completed in 2013 (NCDMF 2013). As such, all assumptions and model decisions made in the 2013 assessment are repeated here to the extent possible. Any exceptions have been noted.

This assessment is based on a forward-projecting, length-based, age-structured model. A two-sex model is assumed. The stock was modeled using Stock Synthesis (SS) text version 3.24f software (Methot 2000, 2012; Methot and Wetzel 2013). Stock Synthesis is an integrated statistical catch-at-age model that is widely used for stock assessments throughout the world. SS was also used to estimate values for established reference points. All SS model input files are available upon request.

3.1.2 Dimensions

The assessment model was applied to data collected from within the range of the assumed biological unit stock (North Carolina coastal and inland waters; section 1.2.1). The time period modeled was 1994 to 2017 using an annual time step based on the calendar year.

3.1.3 Structure / Configuration

3.1.3.1 Catch

The model incorporated commercial landings of striped mullet in North Carolina as reported in the NCDMF TTP. No commercial discards were included in the model as they are considered minimal. The available statistics for North Carolina's recreational fishery for striped mullet are considered very uncertain and recreational catch of striped mullet is thought to be minimal (section 2.1.2). As such, recreational fishery statistics were not included in the assessment model.

3.1.3.2 Survey Indices

The model incorporated annual indices of relative abundance (and associated standard errors) derived from Programs 135, 915, and 146. As described in detail in section 2.2.1.5, the fisheries-independent indices were standardized using a GLM approach to attempt to remove some of the factors other than changes in abundance that can influence the observed changes over time (Maunder and Punt 2004).

Catchability was assumed to be time-invariant for each survey. All survey indices were assumed to have a nonlinear relation to abundance, requiring an additional parameter to be estimated for each survey (survey "power"). The model also estimated a parameter that contained an additive constant to be added to the input standard deviation of the survey variability for each index. Following a recommendation by the model developer, the power and extra standard deviation parameters were assigned prior values (R. Methot, NOAA Fisheries, personal communication). The power parameters were assigned a prior value of 0 and assumed to follow a normal distribution. The extra standard deviation parameters were assigned a prior value of 0.05 and assumed to follow a symmetric beta distribution.

3.1.3.3 Average Body Weight

The annual average body weight (sexes pooled) and associated coefficients of variation (CV) were input for the commercial fishery landings and each survey. Average body weights for the surveys were calculated using the same reference (subset) data used to develop the indices.

3.1.3.4 Length Composition

Annual sex-specific length frequencies were input for the commercial fishery landings and each survey. As with the average body weight data, the survey length frequencies were calculated using the same reference data used to develop the indices.

3.1.3.5 Age Data

Annual sex-specific age compositions were input for the commercial fishery and each survey. The age data were input as raw age-at-length data, rather than age compositions generated from applying age-length keys to the catch-at-length compositions. The input compositions are therefore the distribution of ages obtained from samples in each length bin (conditional age-at-length). This is considered a superior approach because it avoids the double use of fish for both age and size information since the age information is considered conditional on the length information, it contains more detailed information about the age-length relationship, and can directly match the protocols of the sampling program when age data are collected using a length-stratified approach (Methot 2012).

As with the average body weight data and length frequencies, the survey age compositions were calculated using the same reference data used to develop the indices. Age 7 was treated as a plus group that included ages 7 through 14. Ages were assumed to be associated with small bias and negligible imprecision.

3.1.3.6 Average Length at Age

Annual sex-specific average lengths at age and associated sample sizes were input for the commercial fishery and each survey. As with the other biological data, the survey average lengths at age were calculated using the same reference data used to develop the indices.

3.1.3.7 Biological Parameters

Natural Mortality

The Stock Synthesis model allows for several options regarding natural mortality. For the current assessment, the Lorenzen option was selected. Natural mortality is specified for a given reference age and calculated for other ages based on Lorenzen's (1996) method. The selected reference age was age 2. Based on Lorenzen's (1996) approach, M at age 2 for females was assumed equal to 0.464 (see section 1.2.6). The model was allowed to estimate M at age 2 for males.

Growth

Growth (age-length) was assumed to be sex specific and was modeled using the Schnute (1981) parameterization of the von Bertalanffy growth curve in which the growth parameters are defined in terms of length at two reference ages, L1 and L2. In the SS model, when fish recruit at the real age of 0.0, their length is set equal to the lower edge of the first population length bin (here, 10 cm; Methot 2012). Fish then grow linearly until they reach a real age equal to the user-specified value for A1 and have a length equal to L1. As the fish continue to age, they grow according to the von Bertalanffy growth equation. The growth curve is calibrated to go through the length L2 when they reach the user-specified value for A2. The value for A1 was set at 2 and the value for A2 was set at 999, which tells the model that L2 represents L_∞.

The von Bertalanffy parameters were fixed in the model at the values used in the benchmark (NCDMF 2013) as the values estimated using data through 2017 were considered biologically unrealistic (see section 1.2.4.4; Table 1.1).

Parameters of the allometric length-weight relationship were fixed for both males and females. The assumed values were those estimated in this report as described in section 1.2.4.4 (Table 1.2).

Maturity & Reproduction

The length logistic maturity option was selected for defining female maturity. The maturity parameters were fixed in the model at the values estimated in section 1.2.5.

Reproduction was assumed to occur on January 1 each year.

Fecundity

The SS model allows several options for relating fecundity to body size (length or weight). Empirical parameter values describing a linear or non-linear relationship to length or weight can be entered. Alternatively, the user can specify that either eggs or fecundity is equivalent to spawning biomass. Here, the selected fecundity option was that which causes eggs to be equivalent to spawning biomass.

3.1.3.8 Stock-Recruitment

A Beverton-Holt stock-recruitment relationship was assumed. Recruitment varied log-normally about the curve. The steepness parameter (*h*) was fixed at 0.9 because there was not enough contrast in the time series to estimate this value reliably (R. Methot, NOAA Fisheries, personal communication). Virgin recruitment (R_0) was estimated by the model and the standard deviation of log(recruitment), σ_R, was fixed at 0.6. Recruitment deviations were estimated from 1980 to 2017. The deviations are assumed to sum to 0 over this time period. Setting the first year in which to estimate recruitment deviations (1980) earlier than the model start year (1994) allows for a non-equilibrium age structure at the start of the assessment time series (Methot 2012). The expected recruitments require a bias adjustment so that the recruitment level is mean unbiased because SS estimates recruitment on a log scale. Methot and Taylor (2011) recommend that the full bias adjustment be applied to data-rich years. The SS_plots function within the r4ss package (Taylor et al. 2018) can be used to obtain a recommendation for the time period for which to apply the full bias adjustment. An initial model was run and the SS_plots function was applied through the R software (version 3.5.0; R Core Team 2018) to obtain the recommended start and end years (1995 and 2015), which were implemented in the base model run.

3.1.3.9 Fishing Mortality

SS allows several options for reporting fishing mortality (*F*). Based on a recommendation from the model developer (R. Methot, NOAA Fisheries, personal communication), the *F* values reported here represent a real annual *F* calculated as a numbers-weighted *F* (see Methot 2012) for ages 1–5, the age range that comprises the majority of the commercial landings. Note that last NCDMF stock assessment for striped mullet reported *F* values as a numbers-weighted *F* for ages 2–5 and so are not comparable to the results of this assessment (NCDMF 2013).

The model estimates fishing mortality for the initial equilibrium catch for each fleet. Here, it is estimated for the commercial fleet. Following the recommendation of Methot (2012), a normal prior with a value of 0 was assumed for the commercial fleet's initial fishing mortality.

3.1.3.10 Selectivity

Selectivity can be cast as length and/or age specific in the SS model. As the length data were considered more reliable, the length-specific option was chosen for the commercial fleet and the fisheries-independent surveys. The recommended double normal selectivity pattern was assumed for the commercial fishery and for the fishery-independent surveys. The commercial fishery was assumed to have a dome-shaped pattern due to the dominance of the runaround gill net in the fishery. Runaround gill nets tend to exclude the smallest striped mullet and the largest individuals don't get gilled by the gear. Selectivity parameters defining the initial and final selectivity values were fixed for the commercial fleet to guide the model towards a dome shape. The selectivity patterns for Programs 135 and 915 were assumed to have an asymptotic shape so the parameters defining the top, descending width, and initial and final selectivity values were fixed. Parameters defining the peak and ascending width were estimated by the model. All selectivity parameters for Program 146 were freely estimated.

3.1.4 Optimization & Weighting

SS assumes an error distribution for each data component and assigns a variance to each observation. The commercial landings were fit in the model assuming a lognormal error structure. Commercial landings were assumed well known and assigned a minimal observation error (standard error, SE = 0.05).

Survey indices were fit assuming a lognormal error distribution with variance estimated from the GLM standardization. Due to the lognormal assumption, the observed values of 0 in 2016 and 2017 for the Program 135 survey (section 2.2.2.6) were assigned a value of 0.1 for input into the model as values of 0 would not be allowed. The variance associated with these two data points was assumed equal to the minimum variance observed for the survey over the time series (CV = 0.324).

Composition information was fit assuming a multinomial error structure with variance described by the effective sample size. For the commercial fleet and each survey, the effective sample size was the number of sampled trips, assuming a maximum of 200, for each year.

Priors were assumed for the power parameters and extra standard deviation parameters for the fisheries-independent surveys (section 3.1.3.2) and the initial fishing mortality for the commercial fleet landings (section 3.1.3.9). Bounds (minimum and maximum values) were established on all estimated parameters to prevent estimation of unrealistic parameter values and convergence problems (Table 3.1).

The objective function for the base model included likelihood contributions from the commercial landings, survey indices, average body weight, length compositions, age data, average length at age, initial equilibrium catch, and recruitment deviations. The total likelihood is the weighted sum of the individual components. All likelihood components were assigned a lambda weight equal to 1.0 in the base run.

3.1.5 Diagnostics

Several approaches were used to assess model convergence. The first diagnostic was to check whether the Hessian matrix (i.e., matrix of second derivatives of the likelihood with respect to the parameters) inverted. Next, the model convergence level was compared to the convergence criterion (0.0001, common default value). Ideally, the model convergence level will be less than the criterion. Model stability was further evaluated using a "jitter" analysis. This analysis is a built-in feature of SS in which the initial parameter values are varied by a user-specified fraction. This allows evaluation of varying input parameter values on model results to ensure the model has converged on a global minimum. A model that is well behaved should converge on a global solution across a reasonable range of initial parameter estimates (Cass-Calay et al. 2014). Initial parameters were randomly jittered by 10% and 25% for a series of 50 random trials each.

Additional diagnostics included evaluation of fits to commercial landings, survey indices, average body weights, and length compositions and comparison of predicted male natural mortality at age 2 to the empirically-derived value. The evaluation of fits to the various data components included a visual comparison of observed and predicted values and calculation of standardized residuals for the fits to the fisheries-independent survey indices and length composition data. The standardized residuals were first visually inspected to evaluate whether any obvious patterns were present. If most of the residuals are within one standard deviation of the observed value, there is evidence of under-dispersion. This is indicative of a good predictive model for the data. That is, the model is fitting the data much better than expected, given the assumed sample size.

In a model that is fit well, there should be no apparent pattern in the standardized residuals over time. This can be confirmed via the runs test, which was applied to the standardized residuals of the fits to the fisheries-independent survey indices. The runs test was applied using the RunsTest function in the DescTools package (Signorell 2018) in R (R Core Team 2018). In a perfectly fit model, the standardized residuals have a normal distribution with mean equal to 0 and standard deviation equal to 1. The Shapiro-Wilk distribution test was applied to determine whether the standardized residuals of the fits to the fisheries-independent survey indices were normally distributed ($\alpha = 0.05$). This test was conducted using the shapiro.test function within the stats package in R (R Core Team 2018). An alpha level of 0.05 was used for both the runs test and Shapiro-Wilk distribution test to determine significance.

3.1.6 Uncertainty & Sensitivity Analyses

3.1.6.1 Retrospective Analysis

A retrospective analysis was run to examine the consistency of estimates over time (Mohn 1999). This type of analysis gives an indication of how much recent data have changed our perspective of the past (Harley and Maunder 2003). The analysis is run by removing one year of data from the end of the time series, evaluating results, removing two years of data from the end of the time series, evaluating results, and so on. Ideally, retrospective patterns are random and do not show a clear bias in any direction. The degree of retrospectivity for a given variable can be described by the Mohn's ρ metric (Mohn 1999). Here, a modified Mohn's ρ (Hurtado-Ferro et al. 2015) was calculated for estimated female spawning stock biomass (SSB) and F. Based on the results of simulation studies, Hurtado-Ferro et al. (2015) suggested that values of the modified Mohn's ρ lower than -0.22 or higher than 0.30 for shorter-lived species are indicators of retrospective patterns and should be cause for concern. The results of their work also suggested that positive values of Mohn's ρ for biomass and negative values for fishing mortality imply consistent overestimation of biomass and the highest risk for overfishing. The retrospective analysis was run by removing up to six years of data.

3.1.6.2 Contribution of Data Sources

Uncertainty can also be explored by assessing the contribution of each source of information (Methot 1990). The contribution of a data source can be manipulated by changing the weight, or emphasis, of the associated likelihood component.

The contribution of Program 135 was examined in one sensitivity run by reducing the emphasis (assigned a lambda weight of 0.0) of all inputs (index, average body weight, length compositions, age compositions, length at age) derived from this survey. Similar sensitivity runs were performed for Program 915 and Program 146. In another sensitivity run, all data associated with all the fishery-independent surveys (indices, biological data) were removed by reducing the associated lambda weights to 0.0. The contribution of the biological data (length compositions and age data) collected from all sources was evaluated by essentially removing these data (assigning a lambda weight of 0.0) in two additional runs. Annual estimates of female SSB and *F* were compared to the base run results for these analyses.

3.1.6.3 Alternate Commercial Fleet Selectivity

A dome shape was assumed for the selectivity pattern of the commercial fleet due to the dominance of the runaround gill net (section 3.1.3.10); however, other gears (e.g., beach seines/stop nets, cast nets, gigs, haul seines, pound nets) are also used to commercially harvest striped mullet. These other gears may have a different selectivity pattern than that of runaround gill nets. The sensitivity of predicted female SSB and *F* to the assumed shape of the selectivity pattern for the commercial fleet was investigated by performing a run in which the selectivity pattern for the commercial fleet was assumed to have an asymptotic shape. As in the base run, the commercial fleet selectivity was modeled using the double normal function. Parameters defining the initial and final values of the selectivity function were fixed such that an asymptotic pattern was fit.

3.1.7 Results

3.1.7.1 Diagnostics

A summary of the input data used in the base run of the striped mullet stock assessment model is shown in Figure 3.1. The final base run resulted in an inverted Hessian matrix, but the model's final convergence level was 0.000333824. This value is higher than the convergence criterion, which was set at 0.0001. It is not unusual for models with large numbers of parameters to produce higher convergence levels and so values less than 1.0 for such models are typically deemed acceptable (R. Methot, NOAA Fisheries, personal communication). None of the 64 estimated parameters were estimated near their bounds (Table 3.2).

Two of the 50 runs that jittered initial values by 10% did not successfully converge (Table 3.3). The remaining runs resulted in inverted Hessian matrices and small (<1.0) convergence values. Forty-five of the successful runs returned the same or similar values for the objective function (negative log likelihood; Table 3.3; Figure 3.2). The predicted estimates of female SSB and *F* were identical or very similar to the estimates from the base run in the majority of the jitter trials (Figure 3.3). One of the 50 runs (run 27) suggested that female SSB has had a lower magnitude over the time series than the female SSB estimates from the base run (Figure 3.3a); however, the temporal trend is similar. This same run (run 27) predicted that *F* values were of a greater magnitude and different trend over time than the base run (Figure 3.3b). Note that this run did not result in a better (i.e., smaller) objective function.

The jitter analysis was also run using a jitter of 25% for 50 trial runs to expand the region of the likelihood surface explored and to see if a better objective function could be identified. Four of the jitter trials at 25% did not converge successfully. Of the jitter trials that converged successfully, none resulted in a smaller value for the objective function lending support to the identification of a global minimum in the base run (Figure 3.4).

The results of the base model show good agreement between observed and predicted landings for the commercial fleet (Figure 3.5). This is not unexpected given the small amount of error (SE = 0.05) assumed for these data. Fits to the fisheries-independent survey indices were not as good. The fit to the Program 135 survey index captures the general trend in the observed values but fails to predict the peak values observed in 2014 and 2015 (Figure 3.6a). Most (14 of 24) of the Program 135 survey index standardized residuals are within one standard deviation of the observed values, suggesting a good fit (Figure 3.6b); however, the runs test indicates the presence of a pattern in the residuals while the Shapiro-Wilk distribution test found the standardized residuals to be non-normally distributed (Table 3.4). The predicted trend for the Program 915 survey index does a poor job of capturing the observed pattern over time (Figure 3.7a). The standardized residuals for the Program 915 survey index are large and most (12 of 14) of these residuals have absolute values greater than one, suggesting poor prediction (Figure 3.7b). The runs test did not detect a temporal trend in the standardized residuals for the Program 915 survey index, but the residuals are not normally distributed (Table 3.4). The fit to the Program 146 survey index is consistent with the observed trend, but does not capture the observed inter-annual variability (Figure 3.8a). Half (7 of 14) of the standardized residuals for the Program 146 survey index fall within one standard deviation of the observed values, suggesting a moderate fit (Figure 3.8b). No temporal trend was detected in the Program 146 survey index standardized residuals and these residuals are normally distributed (Table 3.4).

The fits to the average body weights were within the observed variability for the commercial fleet (Figure 3.9) and the fisheries-independent surveys (Figures 3.10–3.12); however, the predicted fits fail to capture the inter-annual variability observed in each of the data sources and predict a relatively flat trend over the time series with a potentially small increase in the last year.

The fits to the length compositions aggregated across time provide fair fits to the observed length compositions for the commercial fleet and the fisheries-independent surveys (Figure 3.13). The fits to the lengths from the commercial fleet landings tended to overestimate the proportion of females at smaller lengths while underestimating the proportion of males at smaller lengths and overestimating the proportion of males at larger lengths (Figures 3.14 and 3.15). Initial examination of the residuals was difficult due to the presence of extremely large residuals for both females (Figure 3.16) and males (Figure 3.17) in 2002 and 2003. These residuals were replotted excluding any residuals with absolute values greater than 10. The patterns observed in the comparison of observed and predicted length compositions for the commercial fleet landings are also seen in the updated residual plots (Figures 3.18 and 3.19). The predicted length compositions for the Program 135 survey provide a poor fit to the observed length compositions for females and males (Figures 3.20 and 3.21). Note that the input observed effective samples sizes for most (12 of 17) of the Program 135 survey length compositions are small (<30). The standardized residuals of the fits to the Program 135 length compositions indicate overestimation at the smallest and largest sizes and underestimation at mid-range sizes for females (Figure 3.22). Consistent patterns in the residuals for males observed in the Program 135 survey are not as obvious (Figure 3.23). The model results suggest underestimation of the smaller lengths and overestimation of the larger lengths for both females and males observed in the Program 915 survey (Figure 3.24). These same patterns are reflected in the associated residuals (Figures 3.25 and 3.26). The predicted length compositions for females observed in the Program 146 survey are narrower than the observed length compositions (Figure 3.27). In most years, the model overestimates the proportions of males at length for the Program 146 survey over most of the size range. The standardized residuals for the female length compositions from the Program 146 survey suggest underestimation for the mid-range of lengths and overestimation at the tails (Figure 3.28). Residuals from the fit of the Program 146 survey length compositions for males show the opposite trend: overestimation for the mid-range of lengths and underestimation at the tails (Figure 3.29).

The empirically-derived estimate of male *M* at age 2 was 0.51 (section 1.2.6; Table 1.3). The base run of the SS model predicted a value (0.58) very similar to this estimate (Table 3.2).

3.1.7.2 Selectivity & Population Estimates

The predicted selectivity curves were consistent with the assumptions made about their shapes for the commercial fleet and Programs 135 and 915 (section 3.1.3.10; Figure 3.30). The predicted selectivity curves suggest that Program 135 selects for smaller fish than the commercial fleet or either of the other surveys. All selectivity parameters for the Program 146 survey were freely estimated. The model predicted a narrow, dome-shaped curve for this survey that selects fish from approximately 24 cm to 32 cm. This is narrower than the size range observed for this survey (Figure 2.7).

Annual predicted recruitment is variable among years and demonstrates a general decrease from the late 2000s through 2016 (Table 3.5; Figure 3.31). There is a slight increase in recruitment in 2017. Most of the recruitment deviations are positive from 1994 through 2013. There is a sharp decline through 2016 and recruitment deviations are negative from 2014 forward. Recall that the model forces the average recruitment deviations to sum to zero during the main deviation period (section 3.1.3.8). If there are a number of years in which recruitment deviations are predicted to be low, the model will compensate by predicting high values in other years (I.G. Taylor, NOAA Fisheries, personal communication). Female SSB shows an increasing trend from the beginning of the time series through the mid- to late 2000s followed by a decline through the terminal year (Figure 3.32). Predicted stock numbers at age for striped mullet indicate the stock has been dominated by age-0 fish over time (Table 3.6; Figure 3.33). A relatively weak year class was predicted in 2016.

The predictions of commercial landings at age demonstrate that fish age 1 and 2 dominate the commercial landings (Table 3.7; Figure 3.34). Fish at ages 1 through 5 make up the majority (>93%) of the commercial landings. Estimates of fishing mortality (numbers-weighted, ages 1–5) are variable from 1994 through 2002 followed by a period of little variation through 2016 (Table 3.8; Figure 3.35). An increase in *F* is predicted in 2017.

3.1.7.3 Retrospective Analysis

The results of the retrospective analysis indicate an underestimation of female SSB and an overestimation of *F* in the terminal year (Figure 3.36). The calculated values of the modified

Mohn's ρ for female SSB (-0.50) and F (2.0) are outside the "acceptable" range (-0.22 to 0.30) for shorter-lived species and provide further evidence of a retrospective bias in both of these estimates.

3.1.7.4 Contribution of Data Sources

The influence of the different surveys on the model results was evaluated by effectively removing (lambda = 0.0) all fisheries-independent inputs (index, average body weight, length compositions, age compositions, length at age) from a particular survey and then from all surveys. Removing the individual surveys and all surveys resulted in generally lower estimates of female SSB in most instances (Figure 3.37a). Removing the individual surveys and all surveys resulted in higher estimates of fishing mortality (Figure 3.37b). When the Program 135 survey index and associated data were removed, estimates of F in the terminal year were an order of magnitude higher than the base run in the terminal year.

Removing the length composition data resulted in biologically unrealistic estimates of female SSB ($>1\times10^{9}$) and F ($<1\times10^{-7}$) and so figures were not created. Removing the conditional age-at-length data predicted that female SSB has been an order of magnitude lower than the values estimated in the base run (Figure 3.38a). Estimates of F from the run in which the conditional age-at-length data were removed were an order of magnitude higher than the estimates in the base run (Figure 3.38b).

3.1.7.5 Alternate Commercial Fleet Selectivity

Assuming an asymptotic pattern for the commercial fleet selectivity showed nearly identical selectivity for fish that are 30 cm or less in length (Figure 3.39). The assumption of an asymptotic selectivity pattern for the commercial fleet did not have a substantial impact on estimates of female SSB or F (Figure 3.40). Trends were similar over time for both female SSB and F though estimates of female SSB were lower and estimates of F were higher when asymptotic selectivity was assumed.

3.2 Discussion of Results

The striped mullet resource in North Carolina has been fished since at least the late 1800s and has historically supported catches larger than those observed in recent years. The most recent trends observed in adult relative abundance suggest a decline in the adult stock in the last two years of the assessment time series. No adult striped mullet were observed in the Program 135 survey during November through February of 2016 and 2017 (in nets fished in less than 10 feet of water using 2.5" to 5.5" mesh). Also, the observed values in 2016 and 2017 for the Program 915 and Program 146 surveys were among the lowest on record for each of those individual time series.

The model results show a decline in recruitment (small increase in 2017) and spawning stock biomass in recent years. Estimates of fishing mortality have been steady from 2003 through 2016 and an increase in fishing mortality was predicted for 2017.

The reliability of the model results is tied to the reliability of the input data and model performance. A major concern with this assessment that was also noted in the benchmark (NCDMF 2013) is the lack of contrast and high variances associated with the survey indices and lack of contrast in the commercial landings data. Models require variation in stock size and fishing effort to reliably estimate parameters (Hilborn and Walters 1992). Lack of such contrast leads to parameter uncertainty.

Preliminary model runs suggested lack of contrast in spawning stock biomass and recruitment, so the steepness parameter was fixed. Steepness strongly influences maximum sustainable yield (MSY)-based reference points (Brooks et al. 2010) and fixing steepness limits the way the data can inform the reference point (Mangel et al. 2013). For this reason, estimated biomass-based reference points were considered unreliable.

In addition to lack of contrast associated with the input data, the model produced poor fits to the survey indices and length composition data. The standardized residuals from the fits to the survey indices suggested some potential issues with temporal patterns and non-normality. Poor fits to the length compositions may suggest predicted trends in recruitment are not reliable.

The lack of contrast, high variances, and low sample sizes associated with different parts of the input data along with the poor fits to the observed indices, average body weights, and annual length compositions are cause for concern. The poor fits to the indices can be explained, in part, by the model's assumption that all input indices are measuring the same population trend and trying to fit similar trends to the different indices while taking into account the different errors associated with each survey index.

The population trends predicted from the current assessment are generally consistent with those from the benchmark assessment completed in 2013 (NCDMF 2013). Temporal trends in predicted female spawning stock biomass (Figure 3.41) and recruitment (Figure 3.42) were similar to the 2013 assessment results but the current estimates are two to 14 times larger than those in the earlier assessment, depending on the years being compared. While estimates of fishing mortality are not directly comparable between the two assessments (section 3.1.3.9), trends are similar except for during the earliest years. The addition of new data to the model provides a refined perspective on population trends and can cause the observed differences. The retrospective analyses in both assessments suggested a tendency to underestimate female spawning stock biomass and overestimate fishing mortality in the terminal year.

In the 2013 benchmark and current assessment, all data components were weighted equally (lambdas = 1.0) in the base run of the model (section 3.1.4). Stock assessment model results are dependent, sometimes highly, on the weighting of each data set (Francis 2011). Francis (2011) points out that there is wide agreement on the importance of weighting, but there is lack of consensus as to how it should be addressed. In integrated models such as the one used here that use multiple data sets, it is not uncommon for the composition data to drive the estimation of absolute abundance when inappropriate data weightings are applied or the selectivity process is miss-specified (Lee et al. 2014). Francis (2011) argues that abundance information should primarily come from indices of abundance and not from composition data. Future stock assessments of striped mullet should explore alternative weighting schemes that consider recommendations consistent with the current literature.

4 STATUS DETERMINATION CRITERIA

The General Statutes of North Carolina define overfished as "the condition of a fishery that occurs when the spawning stock biomass of the fishery is below the level that is adequate for the recruitment class of a fishery to replace the spawning class of the fishery" (NCGS § 113-129). The General Statues define overfishing as "fishing that causes a level of mortality that prevents a fishery from producing a sustainable harvest."

Amendment 1 to the NCDMF FMP for striped mullet adopted a fishing mortality threshold of $F_{25\%}$ and a fishing mortality target of $F_{35\%}$ (NCDMF 2015). Stock Synthesis computed a value of 0.57 for $F_{25\%}$ and a value of 0.40 for $F_{35\%}$. These estimates are numbers-weighted values for ages 1–5 and so are consistent with the reported F values. Predicted F in 2017 was 0.13. As such, overfishing is currently not occurring in the striped mullet stock ($F_{2017} < F_{25\%}$; Figure 4.1).

Due to the poor stock-recruitment relationship, estimates of a biomass-based reference point were considered unreliable (see section 3.2). Therefore, status in relation to the overfished condition is considered unknown.

5 RESEARCH RECOMMENDATIONS

The following research recommendations are offered (in no particular order) to improve the next assessment of the North Carolina striped mullet stock:

- Improved recreational fisheries statistics provided by the MRIP or some other program to reliably characterize the magnitude and length and age structure of recreational fisheries losses
- Development of a reliable fisheries-independent index of juvenile abundance
- Increase the number of age samples from both fisheries-dependent and fisheries-independent sources
- Investigate how catchability of striped mullet by Program 146 is affected by variations in salinity and conductivity
- Initiate an adult striped mullet survey in the Core and Bogue sound areas where approximately 20% of the striped mullet harvest occurs
- Explore the NOAA Bridge Net Survey as a possible larval/juvenile abundance index for striped mullet
- Consider sex-specific selectivity curves in future modeling work
- Consider a tagging program, using PIT tags similar to the ongoing PIT-tagging program for striped bass; such a program would provide estimates of stock size, F, and M that are not dependent on assumptions about steepness; the estimates of M would be based on field data for this species in this state, rather than generic Ms for fish of this size based on a meta-analysis

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7 TABLES

Table 1.1. Estimated parameter values of the von Bertalanffy age-length model fit to striped mulled data from this and previous studies, where length is measured as fork length in centimeters. FI = fishery-independent; FD = fishery-dependent.

Location	Collection Period	Gear	Type	n	Sex	L_∞	K	t_0	Reference
North Carolina	Oct–Nov	Various	FI & FD	934	Female	35.4	1.07	0	Bichy 2004
North Carolina	Oct–Nov	Various	FI & FD	641	Male	29.6	1.74	0.01	Bichy 2004
North Carolina	1997–2002	Various	FI & FD	2,480	Female	50.4	0.43	-0.11	Wong 2006
North Carolina	1997–2002	Various	FI & FD	1,200	Male	40.3	0.50	-0.38	Wong 2006
North Carolina	1996–2011	Various	FI & FD	6,831	Female	45.2	0.503	-1.06	NCDMF 2013
North Carolina	1996–2011	Various	FI & FD	2,820	Male	33.6	1.11	-0.703	NCDMF 2013
North Carolina	1996–2017	Various	FI & FD	10,096	Female	45.2	0.496	-1.14	current study
North Carolina	1996–2017	Various	FI & FD	4,782	Male	50.7	0.195	-2.73	current study

Table 1.2. Estimated parameter values of the allometric length-weight function fit to striped mulled data from this and previous studies, where length is measured as fork length in centimeters and weight is measured in kilograms. FI = fishery-independent; FD = fishery-dependent.

Location	Collection Period	Gear	Type	n	Sex	*a*	*b*	Reference
North Carolina	May 1997–Apr 1999	Various	FI & FD	447	Female	1.42E-05	3.00	Bichy 2000
North Carolina	May 1997–Apr 1999	Various	FI & FD	210	Male	1.14E-05	3.08	Bichy 2000
North Carolina	Jul 1996–Apr 2000	Various	FI & FD	2,238	Female	1.61E-05	2.98	Bichy 2004
North Carolina	Jul 1996–Apr 2000	Various	FI & FD	1,144	Male	1.43E-05	3.01	Bichy 2004
North Carolina	1996–2011	Various	FI & FD	6,482	Female	1.63E-05	2.97	NCDMF 2013
North Carolina	1996–2011	Various	FI & FD	2,465	Male	1.92E-05	2.92	NCDMF 2013
North Carolina	1996–2017	Various	FI & FD	13,937	Female	1.83E-05	2.94	current study
North Carolina	1996–2017	Various	FI & FD	7,338	Male	1.71E-05	2.95	current study

Table 1.3. Sex-specific estimates of age-specific, instantaneous natural mortality for striped mullet calculated using the method of Lorenzen (1996).

Age	Male	Female
0	0.807	0.802
1	0.559	0.549
2	0.509	0.464
3	0.495	0.425
4	0.490	0.405
5	0.489	0.393
6	0.488	0.387
7	0.488	0.383
8	0.488	0.381
9	0.488	0.379
10	0.488	0.379
11	0.488	0.378
12	0.488	0.378
13	0.488	0.378
14	0.488	

Table 2.1. Annual commercial landings (metric tons) of striped mullet in North Carolina, 1994–2017.

Year	Commercial Landings (mt)
1994	783
1995	1,043
1996	797
1997	1,108
1998	1,006
1999	663
2000	1,283
2001	1,051
2002	1,178
2003	739
2004	725
2005	735
2006	784
2007	757
2008	760
2009	765
2010	945
2011	738
2012	843
2013	703
2014	829
2015	566
2016	438
2017	618

Table 2.2. Average length (centimeters) at age of striped mullet sampled from North Carolina commercial fisheries' landings by sex, 1998–2017.

Sex	Year	0	1	2	3	4	5	6	7+
Female	**1998**	24.3	28.3	36.1	39.8	45.1	45.8	49.3	49.0
	1999		33.4	37.2	40.6	45.4	50.2	52.6	57.8
	2000		37.5	34.1	42.1	44.9	47.2	46.4	57.2
	2001		36.4	40.6	40.9	43.7	48.5		
	2002		35.5	38.3	46.8	49.2	50.1	49.5	
	2003		32.0	38.3	41.8	44.4	45.3	36.0	
	2004		30.6	38.5	46.4	50.3	51.2	46.5	55.2
	2005		39.6	46.6	46.7	50.1	51.6		58.6
	2006		36.8	40.2	44.3	48.2	46.5	54.5	
	2007		30.2	40.0	38.5	38.7	69.8		
	2010		28.2	35.4	39.6				
	2011			36.5	34.9		54.0		
	2013		35.9	37.6	40.5	41.6			
	2014		38.9	34.8					
	2015	28.7	32.4	38.8	40.2	33.0			
	2016		36.0	40.2	48.5	46.0	52.3		62.0
	2017		36.6	40.5	43.3		47.0		
Male	**1998**	24.8	29.1	32.5	36.9				
	1999	22.2	31.8	34.7	33.1	41.3			
	2000		32.4	31.4		37.8			
	2001		31.8	34.7	35.6				
	2002			34.0					
	2003		30.0	33.0	32.8	41.3	30.0		
	2004		32.5	35.3					
	2005		31.1	34.2					
	2006		35.3	35.9					
	2007			36.0					
	2010			31.2	36.9				
	2011			33.2	33.4				
	2013		33.7	33.6					
	2014								
	2015	28.9	33.2	35.9	37.2	39.6			
	2016						47.0		
	2017			38.0					

Table 2.3. Average length (centimeters) at age of striped mullet collected by the NCDMF Program 146 during January through April by sex, 2004–2017.

Sex	Year	0	1	2	3	4	5	6	7+
Female	**2004**			31.1	36.1	39.5	39.9	44.1	43.9
	2005		38.7	34.3	38.7	37.5	45.3		
	2006		28.8	32.4	38.8	42.2	41.0		
	2007			31.2	40.3	43.3	44.5	48.2	55.2
	2008			33.1	35.9	41.9	43.2	39.6	
	2009			30.8	37.3	42.3	44.2	44.7	46.6
	2010			32.5	37.1	42.3		49.1	
	2014			30.5	35.9				
	2016			33.9	36.8	38.4			39.0
	2017			31.6	38.1		43.1		50.9
Male	**2004**		23.1	27.4					44.6
	2005		31.6	30.7	39.0				
	2006		27.7	28.5	30.4				51.5
	2007			30.7		38.2			
	2008			30.8	32.5				
	2009			30.1	33.4	34.7			
	2010			30.4					
	2014			30.3					
	2016			30.0					
	2017			29.1					

Table 2.4. Average length (centimeters) at age of striped mullet collected by the NCDMF Program 135 during November through February by sex, 1998–2016.

Sex	Year	0	1	2	3	4	5	6	7+
Female	**1998**		24.0	33.7	37.0				
	1999		35.3	34.7	39.1				
	2000								
	2001			39.1	34.7				
	2003		34.4	36.9	37.2				52.0
	2004	24.2	26.9	28.7	35.5				
	2005		22.9	33.2	36.4	44.5			
	2006		31.0	38.0	38.0	37.6			
	2007	25.0	33.4	33.8	39.8	43.1	44.2		
	2008		31.6			44.8	48.3		
	2009	25.0	30.8	37.1	33.9		53.7	46.0	
	2010		29.6	34.5	38.9	45.3	44.9		
	2011		28.1	29.3	39.7	45.5			
	2012		33.2	36.1	43.9				
	2013		32.6	35.4		43.7			
	2014		28.3						
	2015		31.9	31.6	42.0				
	2016			33.0	37.0	39.0			
Male	**1998**		26.2	29.4					
	1999	25.2	30.2	32.8					
	2000		31.2						
	2001				32.8				
	2003		29.0	32.3					
	2004		25.6	25.9	35.6				
	2005		29.2	30.2	33.6				
	2006	24.1	26.9	37.2					
	2007	23.6	28.5	32.1	38.7				
	2008		30.9	37.1					
	2009	24.2	29.7	34.0	33.3				
	2010	24.9	26.5	29.5					
	2011		27.9	27.9	33.0				
	2012		31.7	33.2	38.3				
	2013	23.1							
	2014		28.7						
	2015			31.6					
	2016			32.6					

Table 2.5. Average length (centimeters) at age of striped mullet collected by the NCDMF Program 915 during October and November by sex, 2004–2017.

Sex	Year	0	1	2	3	4	5	6	7+
Female	**2004**		32.6	39.6	44.0	48.7			
	2005		34.4	39.4	43.5	41.7			
	2006		30.3	36.4	37.1				
	2007		34.2	40.3	40.4		39.7		
	2008	29.9	32.3	36.5	39.9	42.9			44.5
	2009		33.6	38.2	40.9	44.4	54.6	47.5	
	2010		31.6	38.9	40.8	43.6	43.8	47.5	
	2011	28.5	34.5	38.0	41.8	45.3	48.2	47.7	45.5
	2012	29.7	32.5	36.6	39.4	40.9	41.5	46.7	
	2013	33.5	31.6	36.0	40.9	40.9	41.4	38.0	
	2014	34.2	33.0	37.1	38.9	42.2	41.8		
	2015	37.2	32.5	38.2	38.9	38.1	37.0		
	2016	29.9	34.3	36.6	37.7	41.3	36.3	35.4	40.2
	2017		34.0	38.8	40.2	42.5	39.9		
Male	**2004**		30.5	35.2					
	2005		30.9	33.0	37.4				
	2006		30.6						
	2007	30.5	32.0	31.7					
	2008		30.6	34.3	35.4	38.2			
	2009	27.8	32.2	30.6	34.6				
	2010		30.0	33.2	37.3	36.4			
	2011		31.7	33.3	38.4				
	2012	29.3	30.1	33.1	34.1				
	2013	30.3	30.7	32.1	29.5				
	2014	31.6	29.9	32.2	34.6	37.8			
	2015		31.2	34.3	38.1	34.0			
	2016	27.1	31.8	34.6	29.5	34.5			
	2017	28.4	30.6	30.2					

Table 3.1. Initial values, bounds (min and max), and prior types assumed for parameters in the base run of the stock assessment model.

ID	Label	Initial	Min	Max	Prior Type
1	NatM_p_1_Fem_GP_1	0.464	0.01	0.8	na
2	L_at_Amin_Fem_GP_1	35.5	10	50	na
3	L_at_Amax_Fem_GP_1	45.2	25	68	na
4	VonBert_K_Fem_GP_1	0.503	0.01	2	na
5	CV_young_Fem_GP_1	0.136	0.01	0.5	na
6	CV_old_Fem_GP_1	0.13	0.01	0.5	na
7	NatM_p_1_Mal_GP_1	0.583	0.01	1.5	na
8	L_at_Amin_Mal_GP_1	31.9	10	50	na
9	L_at_Amax_Mal_GP_1	33.6	25	68	na
10	VonBert_K_Mal_GP_1	1.11	0.01	2	na
11	CV_young_Mal_GP_1	0.116	0.01	0.5	na
12	CV_old_Mal_GP_1	0.02	0.01	0.5	na
13	Wtlen_1_Fem	1.83E-05	-3	3	na
14	Wtlen_2_Fem	2.94	2.5	3.5	na
15	Mat50%_Fem	30.2	10	50	na
16	Mat_slope_Fem	-0.45	-3	3	na
17	Eggs/kg_inter_Fem	1	-3	3	na
18	Eggs/kg_slope_wt_Fem	0	-3	4	na
19	Wtlen_1_Mal	1.71E-05	-3	3	na
20	Wtlen_2_Mal	2.95	2.5	3.5	na
21	RecrDist_GP_1	0	-4	4	na
22	RecrDist_Area_1	0	-4	4	na
23	RecrDist_Seas_1	0	-4	4	na
24	CohortGrowDev	0	-4	4	na
25	SR_LN(R0)	10.2	3	31	na
26	SR_BH_steep	0.9	0.2	1	na
27	SR_sigmaR	0.6	0	2	na
28	SR_envlink	0.1	-5	5	na
29	SR_R1_offset	0	-5	5	na
30	SR_autocorr	0	0	0	na
31	Main_InitAge_14				na

Table 3.1. (*continued*) Initial values, bounds (min and max), and prior types assumed for parameters in the base run of the stock assessment model.

ID	Label	Initial	Min	Max	Prior Type
32	Main_InitAge_13				na
33	Main_InitAge_12				na
34	Main_InitAge_11				na
35	Main_InitAge_10				na
36	Main_InitAge_9				na
37	Main_InitAge_8				na
38	Main_InitAge_7				na
39	Main_InitAge_6				na
40	Main_InitAge_5				na
41	Main_InitAge_4				na
42	Main_InitAge_3				na
43	Main_InitAge_2				na
44	Main_InitAge_1				na
45	Main_RecrDev_1994				na
46	Main_RecrDev_1995				na
47	Main_RecrDev_1996				na
48	Main_RecrDev_1997				na
49	Main_RecrDev_1998				na
50	Main_RecrDev_1999				na
51	Main_RecrDev_2000				na
52	Main_RecrDev_2001				na
53	Main_RecrDev_2002				na
54	Main_RecrDev_2003				na
55	Main_RecrDev_2004				na
56	Main_RecrDev_2005				na
57	Main_RecrDev_2006				na
58	Main_RecrDev_2007				na
59	Main_RecrDev_2008				na
60	Main_RecrDev_2009				na
61	Main_RecrDev_2010				na
62	Main_RecrDev_2011				na

Table 3.1. (*continued*) Initial values, bounds (min and max), and prior types assumed for parameters in the base run of the stock assessment model.

ID	Label	Initial	Min	Max	Prior Type
63	Main_RecrDev_2012				na
64	Main_RecrDev_2013				na
65	Main_RecrDev_2014				na
66	Main_RecrDev_2015				na
67	Main_RecrDev_2016				na
68	Main_RecrDev_2017				na
69	InitF_1Comm	0.01	0	1	Normal
70	Q_power_2_P135	2.2	-25	25	Normal
71	Q_power_3_P915	0.18	-25	25	Normal
72	Q_power_4_P146	-0.14	-25	25	Normal
73	Q_extraSD_2_P135	0.8	0	10	Sym_Beta
74	Q_extraSD_3_P915	0.32	0	10	Sym_Beta
75	Q_extraSD_4_P146	0.17	0	10	Sym_Beta
76	Q_base_2_P135	-30.8	-50	25	na
77	Q_base_3_P915	-9.3	-25	25	na
78	Q_base_4_P146	-2.4	-25	25	na
79	SizeSel_1P_1_Comm	30.5	15	60	na
80	SizeSel_1P_2_Comm	-9	-10	5	na
81	SizeSel_1P_3_Comm	3.6	-9	9	na
82	SizeSel_1P_4_Comm	5.6	-9	9	na
83	SizeSel_1P_5_Comm	-999	-1000	15	na
84	SizeSel_1P_6_Comm	-999	-1000	15	na
85	SizeSel_2P_1_P135	21.7	15	60	na
86	SizeSel_2P_2_P135	-3	-10	5	na
87	SizeSel_2P_3_P135	-1.9	-9	9	na
88	SizeSel_2P_4_P135	5	-9	9	na
89	SizeSel_2P_5_P135	-999	-1000	15	na
90	SizeSel_2P_6_P135	15	-1000	15	na
91	SizeSel_3P_1_P915	27	15	60	na
92	SizeSel_3P_2_P915	-3	-10	5	na
93	SizeSel_3P_3_P915	2.6	-9	9	na

Table 3.1. (*continued*) Initial values, bounds (min and max), and prior types assumed for parameters in the base run of the stock assessment model.

ID	Label	Initial	Min	Max	Prior Type
94	SizeSel_3P_4_P915	8	-9	9	na
95	SizeSel_3P_5_P915	-999	-1000	15	na
96	SizeSel_3P_6_P915	15	-15	15	na
97	SizeSel_4P_1_P146	28.1	15	60	na
98	SizeSel_4P_2_P146	-3.7	-10	5	na
99	SizeSel_4P_3_P146	1.8	-9	9	na
100	SizeSel_4P_4_P146	-6.3	-9	9	na
101	SizeSel_4P_5_P146	-9.3	-1000	15	na
102	SizeSel_4P_6_P146	-3.1	-15	15	na

Table 3.2. Values, standard deviations (if estimated), status, and phase of estimation for parameters in the base run of the stock assessment model. A negative phase indicates the parameter value was fixed in the model.

ID	Label	Value	SD[Value]	Status	Phase
1	NatM_p_1_Fem_GP_1	0.464		fixed	-3
2	L_at_Amin_Fem_GP_1	35.5		fixed	-2
3	L_at_Amax_Fem_GP_1	45.2		fixed	-2
4	VonBert_K_Fem_GP_1	0.503		fixed	-2
5	CV_young_Fem_GP_1	0.136		fixed	-3
6	CV_old_Fem_GP_1	0.13		fixed	-5
7	NatM_p_1_Mal_GP_1	0.578	0.00827	estimated	6
8	L_at_Amin_Mal_GP_1	31.9		fixed	-2
9	L_at_Amax_Mal_GP_1	33.6		fixed	-2
10	VonBert_K_Mal_GP_1	1.11		fixed	-2
11	CV_young_Mal_GP_1	0.116		fixed	-3
12	CV_old_Mal_GP_1	0.02		fixed	-5
13	Wtlen_1_Fem	1.83E-05		fixed	-3
14	Wtlen_2_Fem	2.94		fixed	-3
15	Mat50%_Fem	30.2		fixed	-3
16	Mat_slope_Fem	-0.45		fixed	-3
17	Eggs/kg_inter_Fem	1		fixed	-3
18	Eggs/kg_slope_wt_Fem	0		fixed	-3
19	Wtlen_1_Mal	1.71E-05		fixed	-3
20	Wtlen_2_Mal	2.95		fixed	-3
21	RecrDist_GP_1	0		fixed	-4
22	RecrDist_Area_1	0		fixed	-4
23	RecrDist_Seas_1	0		fixed	-4
24	CohortGrowDev	0		fixed	-4
25	SR_LN(R0)	10.1	0.166	estimated	1
26	SR_BH_steep	0.9		fixed	-4
27	SR_sigmaR	0.6		fixed	-4
28	SR_envlink	0.1		fixed	-3
29	SR_R1_offset	0		fixed	-4
30	SR_autocorr	0		fixed	-99
31	Main_InitAge_14	-0.0468	0.587	estimated	

Table 3.2. (*continued*) Values, standard deviations (if estimated), status, and phase of estimation for parameters in the base run of the stock assessment model. A negative phase indicates the parameter value was fixed in the model.

ID	Label	Value	SD[Value]	Status	Phase
32	Main_InitAge_13	-0.0406	0.589	estimated	
33	Main_InitAge_12	-0.0467	0.587	estimated	
34	Main_InitAge_11	-0.0566	0.584	estimated	
35	Main_InitAge_10	-0.0722	0.579	estimated	
36	Main_InitAge_9	-0.0967	0.572	estimated	
37	Main_InitAge_8	-0.133	0.562	estimated	
38	Main_InitAge_7	-0.188	0.547	estimated	
39	Main_InitAge_6	-0.267	0.528	estimated	
40	Main_InitAge_5	-0.377	0.505	estimated	
41	Main_InitAge_4	-0.527	0.477	estimated	
42	Main_InitAge_3	-0.334	0.399	estimated	
43	Main_InitAge_2	-0.485	0.350	estimated	
44	Main_InitAge_1	-0.403	0.277	estimated	
45	Main_RecrDev_1994	0.385	0.175	estimated	
46	Main_RecrDev_1995	0.945	0.127	estimated	
47	Main_RecrDev_1996	0.0686	0.140	estimated	
48	Main_RecrDev_1997	-0.0103	0.140	estimated	
49	Main_RecrDev_1998	-0.475	0.177	estimated	
50	Main_RecrDev_1999	0.605	0.116	estimated	
51	Main_RecrDev_2000	0.220	0.121	estimated	
52	Main_RecrDev_2001	0.732	0.102	estimated	
53	Main_RecrDev_2002	0.588	0.105	estimated	
54	Main_RecrDev_2003	0.445	0.106	estimated	
55	Main_RecrDev_2004	0.726	0.0975	estimated	
56	Main_RecrDev_2005	0.540	0.101	estimated	
57	Main_RecrDev_2006	0.271	0.106	estimated	
58	Main_RecrDev_2007	0.666	0.0952	estimated	
59	Main_RecrDev_2008	0.0612	0.109	estimated	
60	Main_RecrDev_2009	0.445	0.101	estimated	
61	Main_RecrDev_2010	0.467	0.105	estimated	
62	Main_RecrDev_2011	0.337	0.110	estimated	

Table 3.2. (*continued*) Values, standard deviations (if estimated), status, and phase of estimation for parameters in the base run of the stock assessment model. A negative phase indicates the parameter value was fixed in the model.

ID	Label	Value	SD[Value]	Status	Phase
63	Main_RecrDev_2012	-0.00946	0.122	estimated	
64	Main_RecrDev_2013	0.0659	0.130	estimated	
65	Main_RecrDev_2014	-0.177	0.148	estimated	
66	Main_RecrDev_2015	-0.754	0.176	estimated	
67	Main_RecrDev_2016	-2.29	0.285	estimated	
68	Main_RecrDev_2017	-0.784	0.446	estimated	
69	InitF_1Comm	0.126	0.0275	estimated	1
70	Q_power_2_P135	2.11	0.904	estimated	4
71	Q_power_3_P915	0.139	0.495	estimated	4
72	Q_power_4_P146	-0.117	0.301	estimated	4
73	Q_extraSD_2_P135	0.803	0.185	estimated	4
74	Q_extraSD_3_P915	0.324	0.106	estimated	4
75	Q_extraSD_4_P146	0.150	0.0947	estimated	4
76	Q_base_2_P135	-29.5	9.16	estimated	1
77	Q_base_3_P915	-8.72	4.78	estimated	1
78	Q_base_4_P146	-2.51	2.69	estimated	1
79	SizeSel_1P_1_Comm	30.6	0.300	estimated	2
80	SizeSel_1P_2_Comm	-9.83	5.01	estimated	3
81	SizeSel_1P_3_Comm	3.70	0.0831	estimated	3
82	SizeSel_1P_4_Comm	5.66	0.0860	estimated	3
83	SizeSel_1P_5_Comm	-999		fixed	-2
84	SizeSel_1P_6_Comm	-999		fixed	-2
85	SizeSel_2P_1_P135	21.7	26.4	estimated	4
86	SizeSel_2P_2_P135	-3		fixed	-3
87	SizeSel_2P_3_P135	-1.89	76.1	estimated	5
88	SizeSel_2P_4_P135	5		fixed	-4
89	SizeSel_2P_5_P135	-999		fixed	-2
90	SizeSel_2P_6_P135	15		fixed	-2
91	SizeSel_3P_1_P915	27.0	0.184	estimated	4
92	SizeSel_3P_2_P915	-3		fixed	-3
93	SizeSel_3P_3_P915	1.62	0.314	estimated	4

Table 3.2. (*continued*) Values, standard deviations (if estimated), status, and phase of estimation for parameters in the base run of the stock assessment model. A negative phase indicates the parameter value was fixed in the model.

ID	Label	Value	SD[Value]	Status	Phase
94	SizeSel_3P_4_P915	8		fixed	-4
95	SizeSel_3P_5_P915	-999		fixed	-2
96	SizeSel_3P_6_P915	15		fixed	-3
97	SizeSel_4P_1_P146	28.2	0.595	estimated	4
98	SizeSel_4P_2_P146	-3.80	1.22	estimated	4
99	SizeSel_4P_3_P146	1.84	0.404	estimated	5
100	SizeSel_4P_4_P146	-7.14	25.4	estimated	5
101	SizeSel_4P_5_P146	-9.32	5.16	estimated	3
102	SizeSel_4P_6_P146	-3.04	0.122	estimated	4

Table 3.3. Convergence level, negative log likelihood (Total LL), terminal year fishing mortality (F_{2017}), and threshold fishing mortality ($F_{25\%}$) from the base run and 50 jitter trials in which initial parameter values were jittered by 10%.

Run	Convergence	Total LL	F_{2017}	$F_{25\%}$
Base	0.00033	10,540	0.13	0.57
1	0.0014	10,540	0.13	0.57
2	0.0006	10,540	0.13	0.57
3	0.0044	10,540	0.13	0.57
4	0.00025	10,540	0.13	0.57
5	0.00029	10,540	0.13	0.57
6	0.008	10,545	0.11	0.57
7	0.00064	10,540	0.13	0.57
8	0.015	10,540	0.13	0.57
9	0.0057	10,544	0.13	0.57
10	*did not converge*			
11	0.0089	10,544	0.13	0.57
12	0.00017	10,540	0.13	0.57
13	0.014	10,547	0.13	0.57
14	0.0013	10,540	0.13	0.57
15	0.0047	10,551	0.11	0.57
16	0.00034	10,540	0.13	0.57
17	*did not converge*			
18	0.00037	10,545	0.11	0.57
19	0.0041	10,540	0.13	0.57
20	0.0032	10,545	0.11	0.57
21	0.0097	10,540	0.13	0.57
22	0.0011	10,540	0.13	0.57
23	0.0036	10,544	0.13	0.57
24	0.0034	10,549	0.11	0.57
25	0.00029	10,544	0.13	0.57

Table 3.3. (*continued*) Convergence level, negative log likelihood (Total LL), terminal year fishing mortality (F_{2017}), and threshold fishing mortality ($F_{25\%}$) from the base run and 50 jitter trials in which initial parameter values were jittered by 10%.

Run	Convergence	Total LL	F_{2017}	$F_{25\%}$
26	0.0026	10,540	0.13	0.57
27	0.029	11,381	0.82	0.56
28	0.016	10,906	0.14	0.56
29	0.0049	10,909	0.14	0.56
30	4.3E-05	10,546	0.12	0.57
31	0.0013	10,540	0.13	0.57
32	0.00033	10,540	0.13	0.57
33	0.11	10,540	0.13	0.57
34	0.067	11,120	0.15	0.56
35	0.00095	10,544	0.13	0.57
36	0.00048	10,544	0.13	0.57
37	0.0034	10,964	0.14	0.56
38	4.7E-05	10,545	0.11	0.57
39	0.012	10,543	0.13	0.57
40	0.00038	10,544	0.13	0.57
41	0.0020	10,540	0.13	0.57
42	0.0005	10,545	0.11	0.57
43	0.0058	10,540	0.13	0.57
44	0.0072	10,543	0.13	0.57
45	0.0008	10,540	0.13	0.57
46	0.00012	10,540	0.13	0.57
47	0.0014	10,540	0.13	0.57
48	0.0072	10,540	0.13	0.57
49	0.00039	10,544	0.13	0.57
50	6.8E-05	10,540	0.13	0.57

Table 3.4. Results of the runs tests and the Shapiro-Wilk test for normality applied to the standardized residuals of the fits to the survey indices from the base run of the stock assessment model.

	Runs Test	Shapiro-Wilk test	
Survey	**p-value**	**W**	**p-value**
Program 135	0.019	0.73	2.5E-05
Program 915	0.16	0.84	0.015
Program 146	0.42	0.96	0.68

Table 3.5. Annual estimates of recruitment (thousands of fish) and female spawning stock biomass (metric tons) and associated standard deviations from the base run of the stock assessment model, 1994–2017.

	Recruits (000s of fish)		SSB (metric tons)	
Year	**Value**	**SD**	**Value**	**SD**
1994	29,162	5,395	3,706	889
1995	50,007	7,698	3,512	795
1996	21,073	3,686	4,401	859
1997	19,819	3,572	6,803	1,135
1998	12,445	2,641	6,645	1,139
1999	36,553	5,746	6,114	1,094
2000	24,745	4,290	5,382	979
2001	41,448	6,991	6,019	1,095
2002	35,932	6,497	6,146	1,144
2003	31,321	5,730	7,272	1,377
2004	41,619	7,540	8,161	1,549
2005	34,591	6,430	8,522	1,630
2006	26,495	5,099	9,416	1,804
2007	39,366	7,484	9,607	1,867
2008	21,468	4,355	9,145	1,814
2009	31,538	6,385	9,518	1,915
2010	32,160	6,808	8,673	1,803
2011	28,240	6,197	8,456	1,832
2012	19,968	4,673	8,540	1,904
2013	21,511	5,284	8,262	1,923
2014	16,821	4,424	7,505	1,826
2015	9,422	2,695	6,836	1,771
2016	2,148	794	6,132	1,663
2017	10,149	5,095	5,076	1,442

Table 3.6. Predicted stock numbers (thousands of fish) at age from the base run of the stock assessment model, 1994–2017.

Year	Age 0	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11	Age 12	Age 13	Age 14
1994	48,252	10,099	4,775	3,029	1,399	929	604	386	243	152	93	57	35	21	33
1995	69,097	16,628	4,844	2,682	1,509	827	550	357	229	144	90	55	34	21	33
1996	82,739	21,110	4,881	2,426	1,586	750	508	336	217	138	87	54	33	20	32
1997	53,805	30,040	7,958	2,444	1,398	805	451	304	201	130	83	52	32	20	32
1998	34,875	36,735	10,330	2,503	1,283	859	414	285	191	125	80	51	32	20	31
1999	33,621	24,349	15,334	4,326	1,358	792	465	263	180	120	78	50	32	20	32
2000	32,798	15,434	18,934	5,663	1,408	737	502	245	171	115	76	49	31	20	32
2001	25,424	14,893	12,515	8,254	2,390	769	457	272	156	107	72	47	31	19	32
2002	20,595	14,497	7,816	10,163	3,120	793	422	292	144	101	69	46	30	19	32
2003	44,702	11,334	7,527	6,720	4,529	1,338	439	265	159	92	64	43	29	19	31
2004	60,493	9,138	7,354	4,197	5,607	1,757	454	245	171	86	61	42	28	18	31
2005	48,684	19,482	5,829	4,098	3,755	2,583	775	258	157	96	56	39	27	18	31
2006	40,943	26,558	4,639	3,970	2,327	3,173	1,010	265	145	102	51	37	25	17	30
2007	57,646	21,483	9,479	3,045	2,192	2,072	1,432	436	148	91	56	33	23	16	29
2008	68,587	18,069	13,027	2,393	2,109	1,265	1,758	567	151	83	59	30	22	15	28
2009	63,072	25,236	10,734	4,997	1,649	1,214	1,166	820	253	86	54	33	20	14	27
2010	59,461	30,304	9,078	6,921	1,308	1,177	719	1,014	331	89	50	36	18	13	26
2011	54,850	27,940	12,663	5,725	2,731	924	692	674	479	149	51	32	20	12	25
2012	51,838	26,502	15,444	4,894	3,832	740	677	419	598	197	53	30	22	11	24
2013	62,137	24,534	14,595	7,049	3,257	1,592	544	413	406	293	92	32	20	13	23
2014	68,883	23,130	13,970	8,686	2,820	2,248	441	408	255	368	122	33	19	14	23
2015	61,855	27,550	12,968	8,227	4,064	1,914	947	329	252	250	181	57	20	13	23
2016	57,252	30,757	12,229	7,886	5,019	1,659	1,341	266	249	157	228	76	21	12	23
2017	49,155	27,741	14,555	7,339	4,765	2,393	1,144	572	201	155	155	113	36	13	23

Table 3.7. Predicted commercial landings (thousands of fish) at age from the base run of the stock assessment model, 1994–2017.

Year	Age 0	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11	Age 12	Age 13	Age 14
1994	45	549	335	202	88	56	35	21	13	8.0	4.8	2.9	1.7	1.0	1.6
1995	82	1,221	364	172	106	48	31	20	12	7.7	4.8	2.9	1.8	1.1	1.7
1996	17	1,038	378	87	42	27	12	8.2	5.3	3.4	2.1	1.3	0.82	0.50	0.79
1997	20	568	902	257	60	30	20	9.2	6.2	4.1	2.6	1.7	1.1	0.65	1.0
1998	13	560	390	483	140	34	17	11	5.5	3.8	2.5	1.6	1.1	0.67	1.1
1999	31	282	294	159	201	60	15	7.7	5.2	2.5	1.8	1.2	0.78	0.51	0.85
2000	37	1,395	315	256	142	184	56	14	7.5	5.2	2.6	1.8	1.2	0.81	1.4
2001	47	736	687	120	100	57	76	24	6.1	3.3	2.3	1.1	0.81	0.55	1.0
2002	39	1,188	460	334	60	51	30	41	13	3.4	1.8	1.3	0.65	0.46	0.92
2003	19	580	438	132	98	18	16	9.4	13	4.2	1.1	0.61	0.43	0.22	0.47
2004	24	481	377	223	68	52	10	8.7	5.3	7.4	2.4	0.64	0.36	0.26	0.41
2005	19	599	309	190	114	36	28	5.3	4.8	3.0	4.2	1.4	0.37	0.21	0.40
2006	15	512	424	171	107	66	21	17	3.3	3.0	1.9	2.7	0.88	0.24	0.39
2007	23	405	363	235	97	62	39	13	10	2.0	1.9	1.2	1.7	0.56	0.41
2008	12	592	273	192	126	53	35	22	7.4	6.0	1.2	1.1	0.72	1.0	0.60
2009	19	349	438	158	113	76	33	22	14	4.8	3.9	0.80	0.75	0.48	1.1
2010	26	663	308	303	111	82	56	25	17	11	3.8	3.1	0.63	0.60	1.3
2011	17	523	345	125	125	47	35	25	11	7.6	5.1	1.7	1.5	0.30	0.91
2012	14	530	412	213	78	81	31	24	17	7.7	5.3	3.6	1.2	1.0	0.87
2013	14	348	333	202	106	40	42	17	13	9.3	4.3	3.0	2.0	0.70	1.1
2014	14	488	307	230	142	77	30	32	13	10	7.3	3.4	2.4	1.6	1.5
2015	6.2	294	251	124	94	60	33	13	14	5.7	4.6	3.4	1.6	1.1	1.5
2016	1.3	156	189	126	63	50	32	18	7.2	8.0	3.3	2.6	1.9	0.91	1.5
2017	13	71	211	201	137	70	56	37	21	8.7	9.7	4.0	3.2	2.4	3.0

Table 3.8. Annual estimates of fishing mortality (numbers-weighted, ages 1–5) and associated standard deviations from the base run of the stock assessment model, 1994–2017.

	Fishing Mortality	
Year	**Value**	**SD**
1994	0.14	0.030
1995	0.15	0.026
1996	0.071	0.011
1997	0.10	0.016
1998	0.10	0.017
1999	0.082	0.014
2000	0.13	0.022
2001	0.11	0.018
2002	0.10	0.017
2003	0.057	0.010
2004	0.055	0.0098
2005	0.050	0.0091
2006	0.053	0.0096
2007	0.055	0.010
2008	0.052	0.0099
2009	0.059	0.012
2010	0.074	0.015
2011	0.057	0.012
2012	0.067	0.015
2013	0.063	0.015
2014	0.081	0.020
2015	0.063	0.016
2016	0.060	0.016
2017	0.13	0.037

8 FIGURES

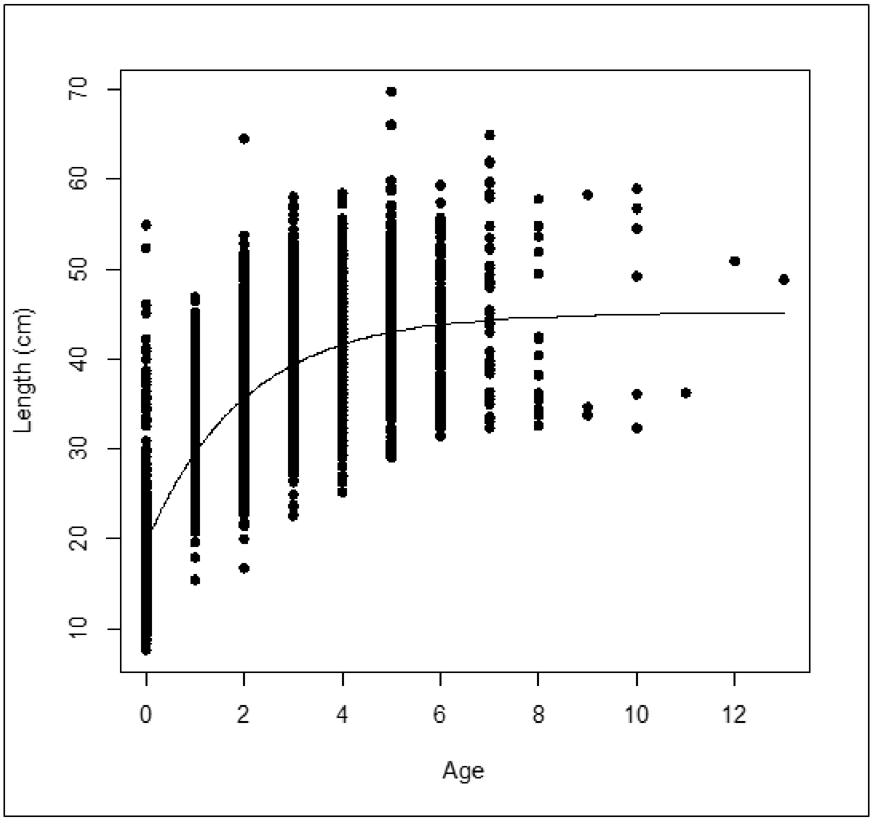

Figure 1.1. Fit of the von Bertalanffy age-length model to available biological data for female striped mullet.

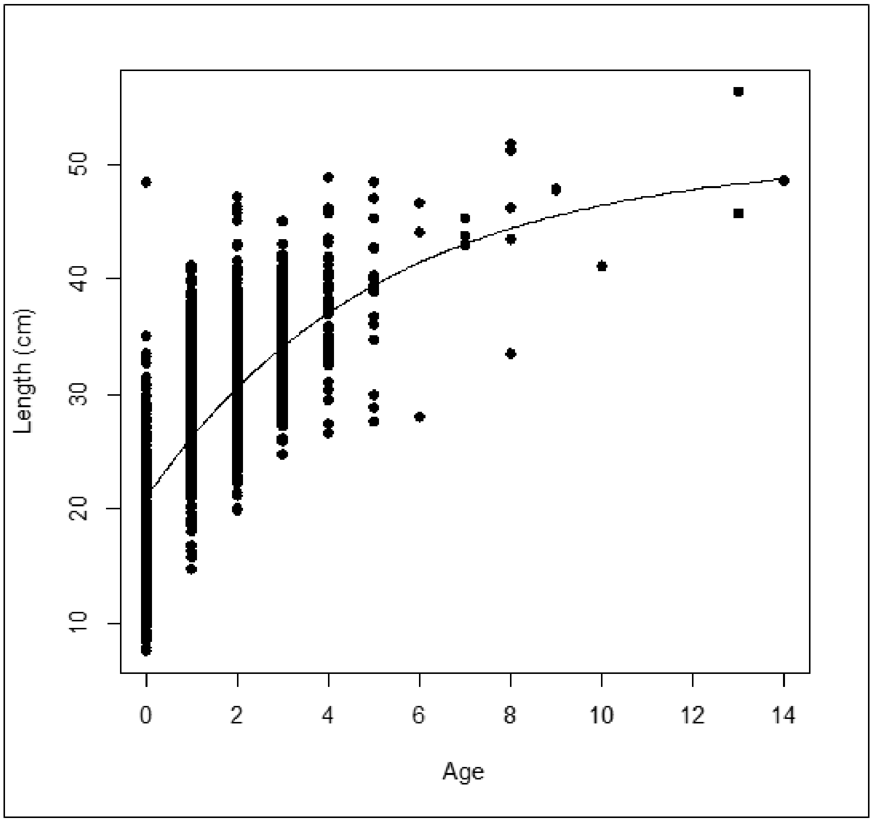

Figure 1.2. Fit of the von Bertalanffy age-length model to available biological data for male striped mullet.

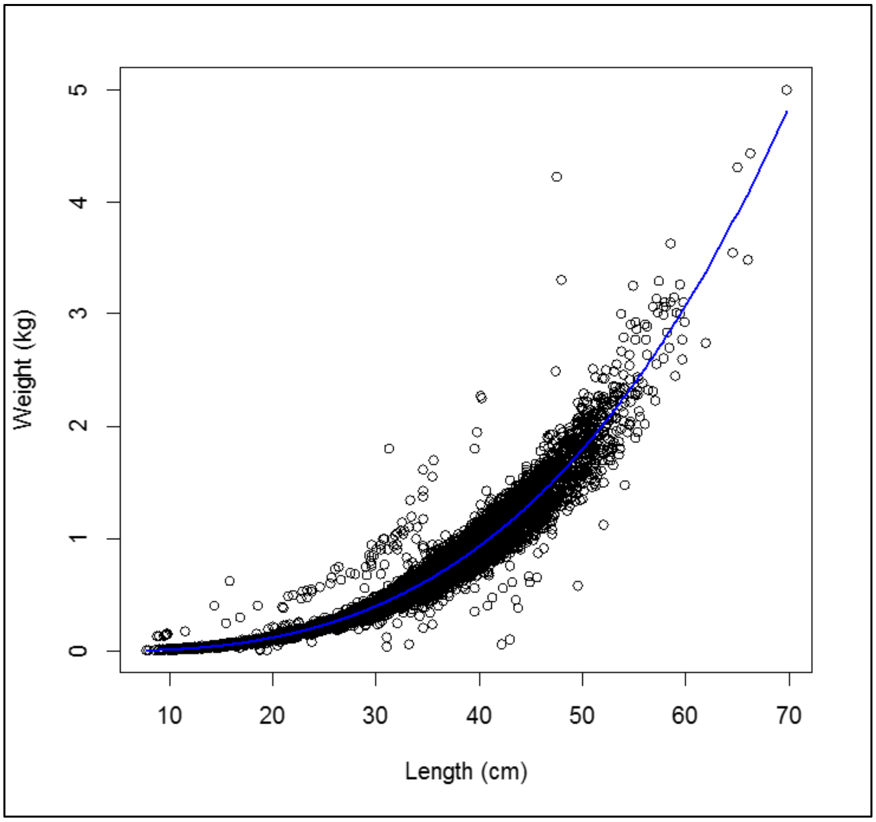

Figure 1.3. Fit of allometric length-weight model to female striped mullet data collected in North Carolina.

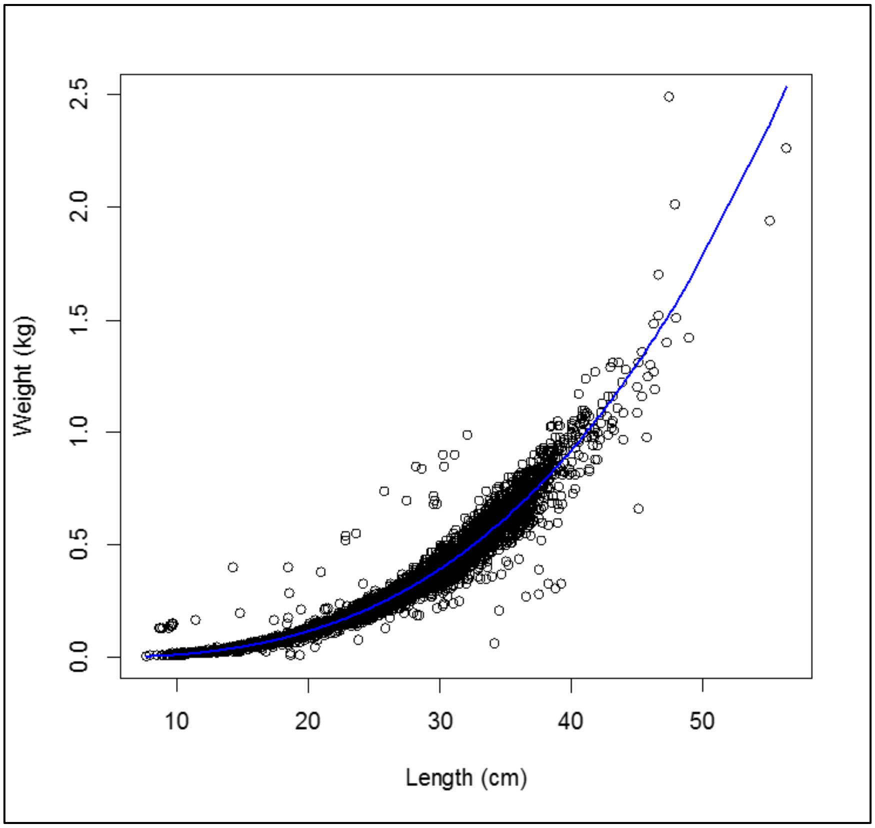

Figure 1.4. Fit of allometric length-weight model to male striped mullet data collected in North Carolina.

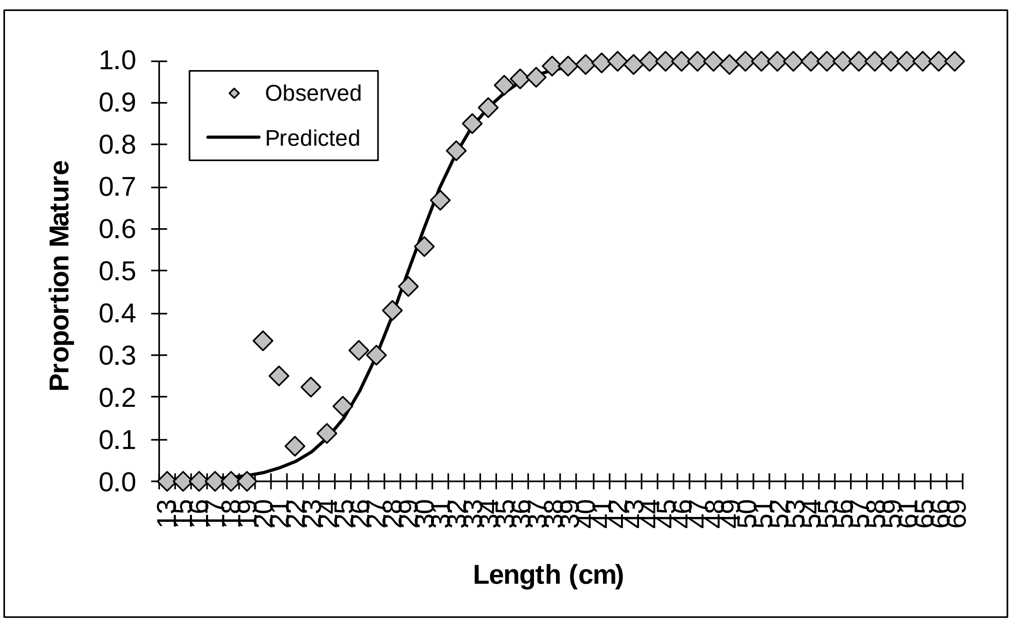

Figure 1.5. Fit of maturity curve to female striped mullet data collected in North Carolina.

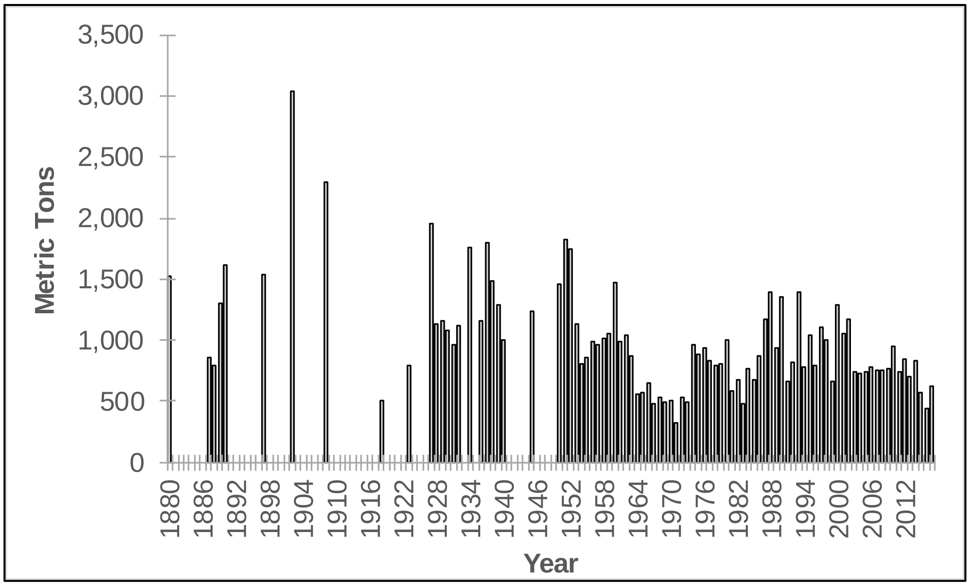

Figure 1.6. Annual commercial landings of striped mullet in North Carolina, 1880–2017. Note that commercial landings data were not available for all years.

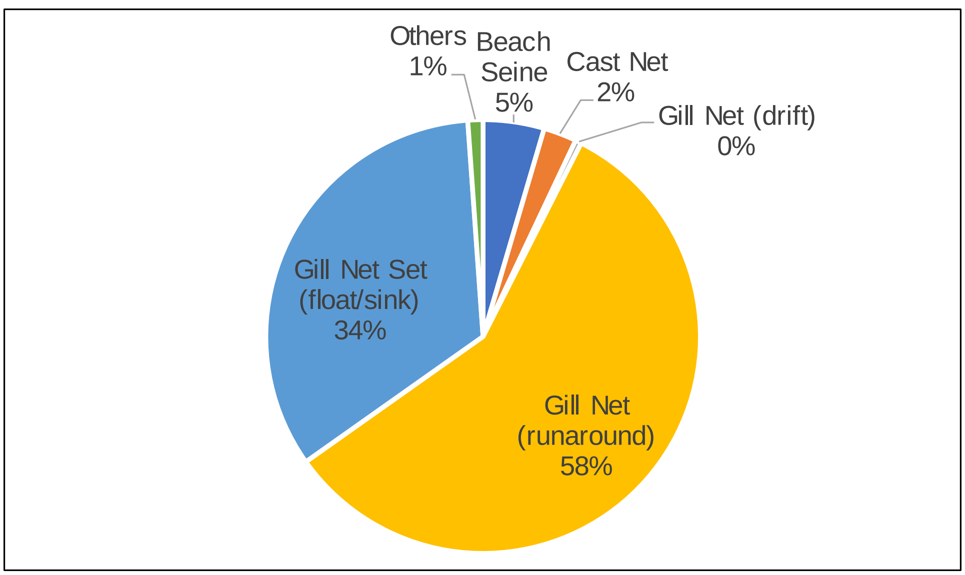

Figure 1.7. Percentages of North Carolina's commercial landings of striped mullet attributed to major gear types, 1994–2017.

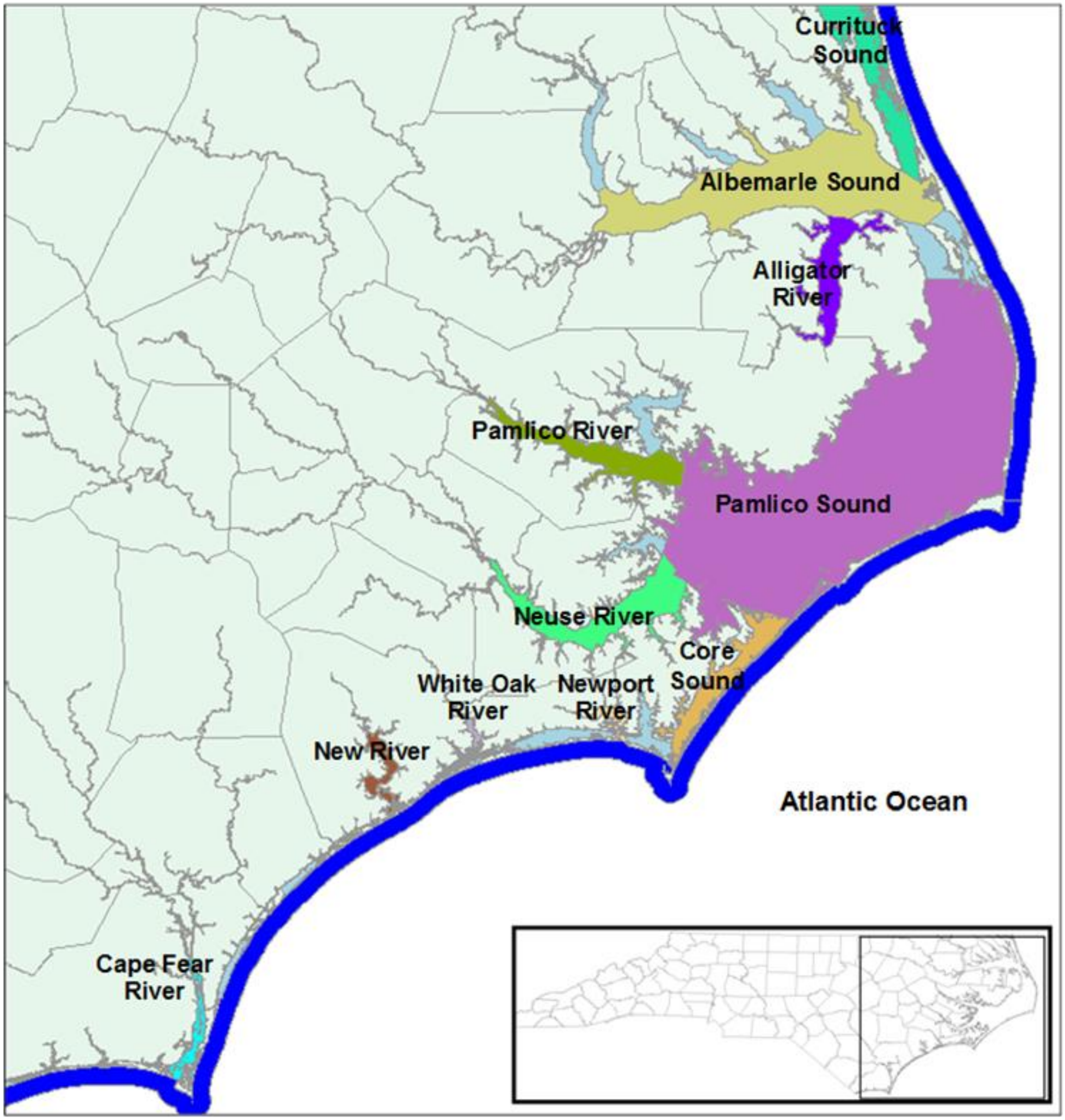

Figure 1.8. Major water bodies within and around North Carolina. The dark blue area represents the extent of the state's coastal fishing waters, which extend to three miles offshore.

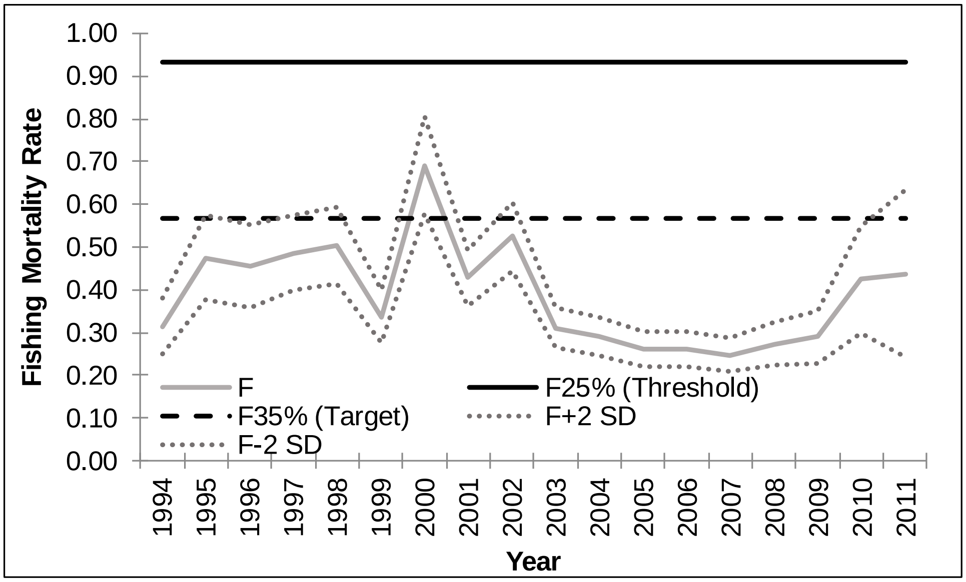

Figure 1.9. Estimates of annual estimates of fishing mortality (numbers weighted, ages 2–5) compared to estimates of the fishing mortality target ($F_{35\%}$) and threshold ($F_{25\%}$) from the 2013 NCDMF stock assessment of striped mullet.

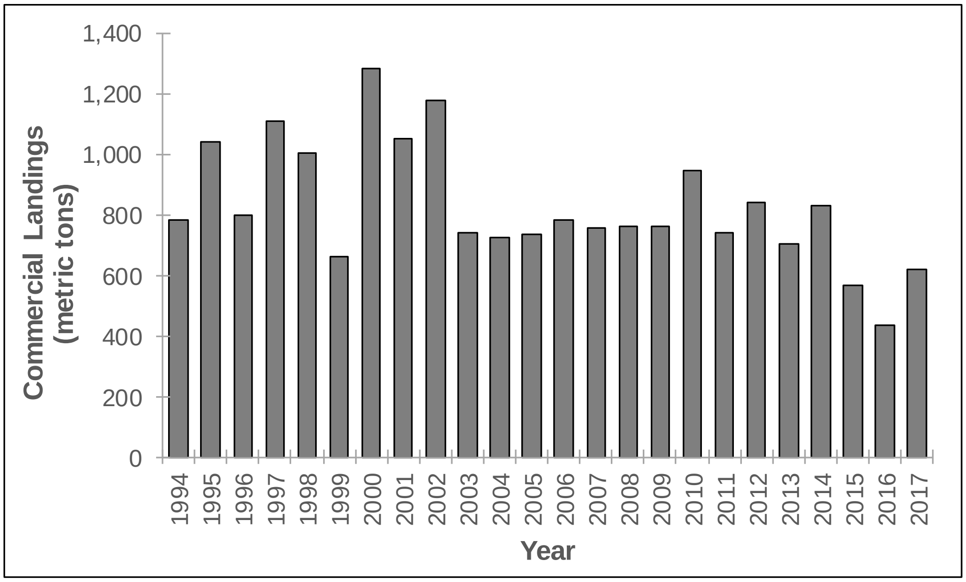

Figure 2.1. Annual commercial landings of striped mullet in North Carolina, 1994–2017.

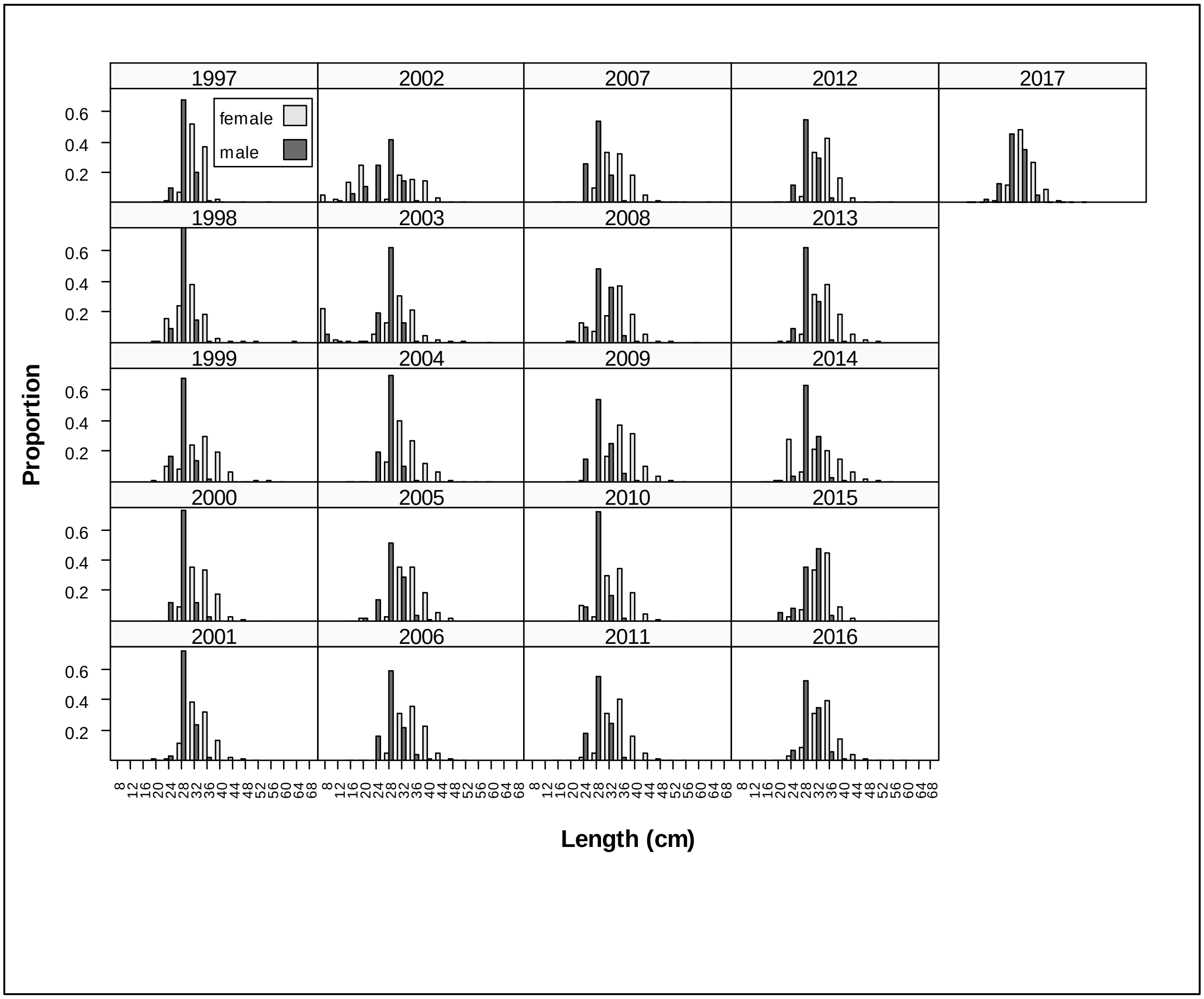

Figure 2.2. Annual length-frequency distributions of striped mullet sampled from North Carolina commercial fisheries' landings by sex, 1997–2017.

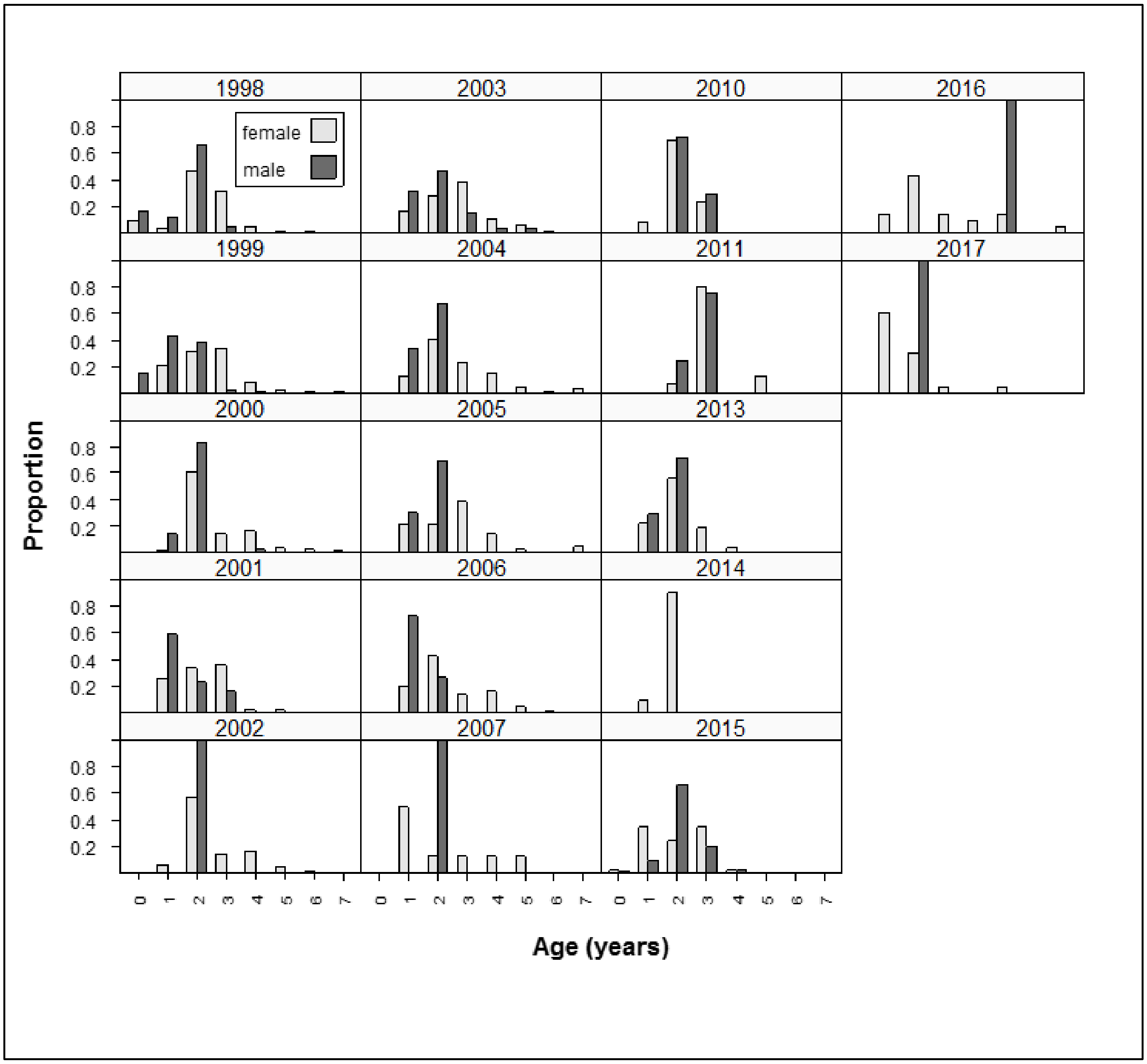

Figure 2.3. Annual age-frequency distributions of striped mullet sampled from North Carolina commercial fisheries' landings by sex, 1998–2017.

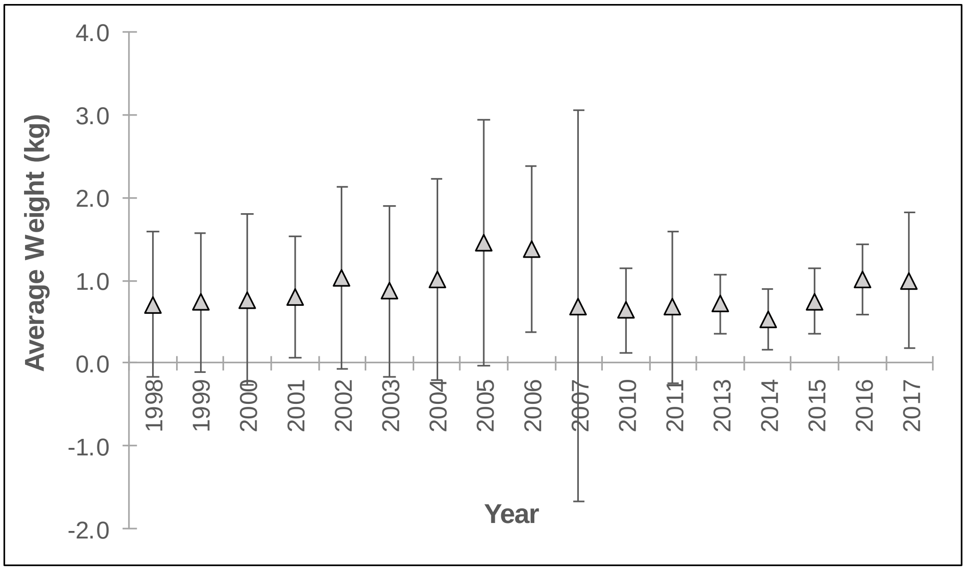

Figure 2.4. Annual average body weight of striped mullet (sexes pooled) sampled from North Carolina commercial fisheries' landings, 1998–2017.

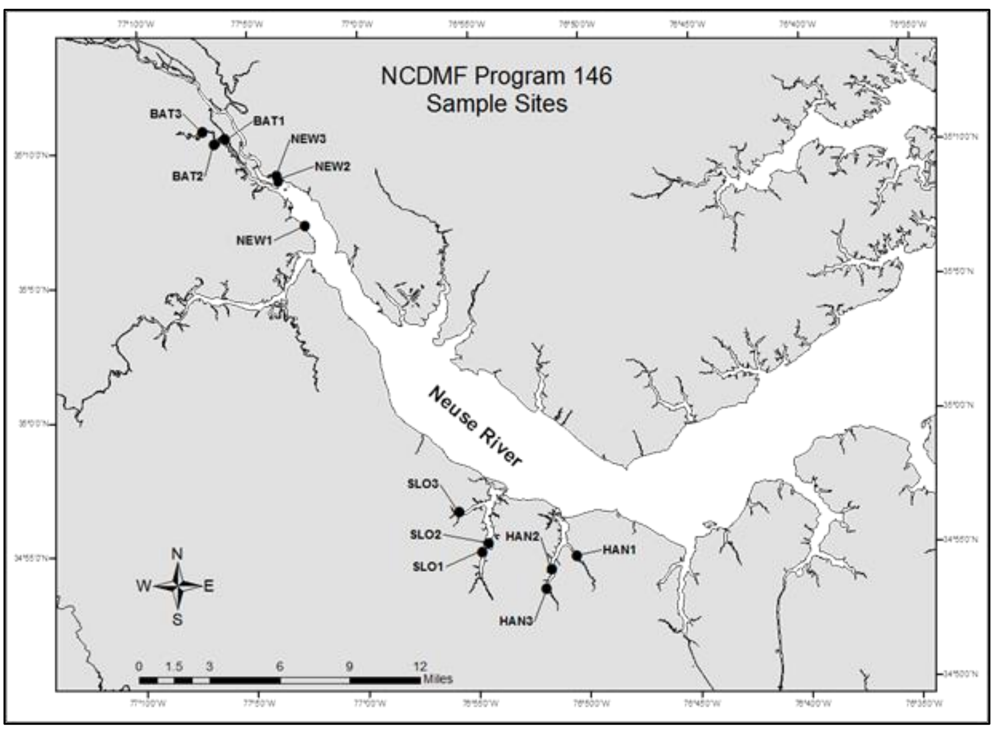

Figure 2.5. Map of sampling locations for NCDMF Program 146.

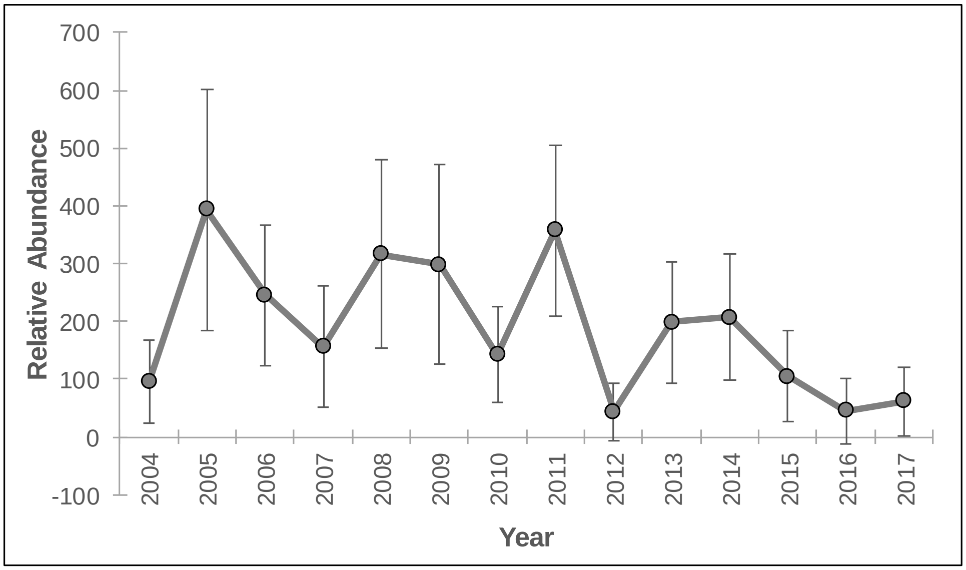

Figure 2.6. GLM-standardized index of relative abundance for adult striped mullet collected from Program 146 during January through April, 2004–2017. Error bars represent ± 2 standard errors.

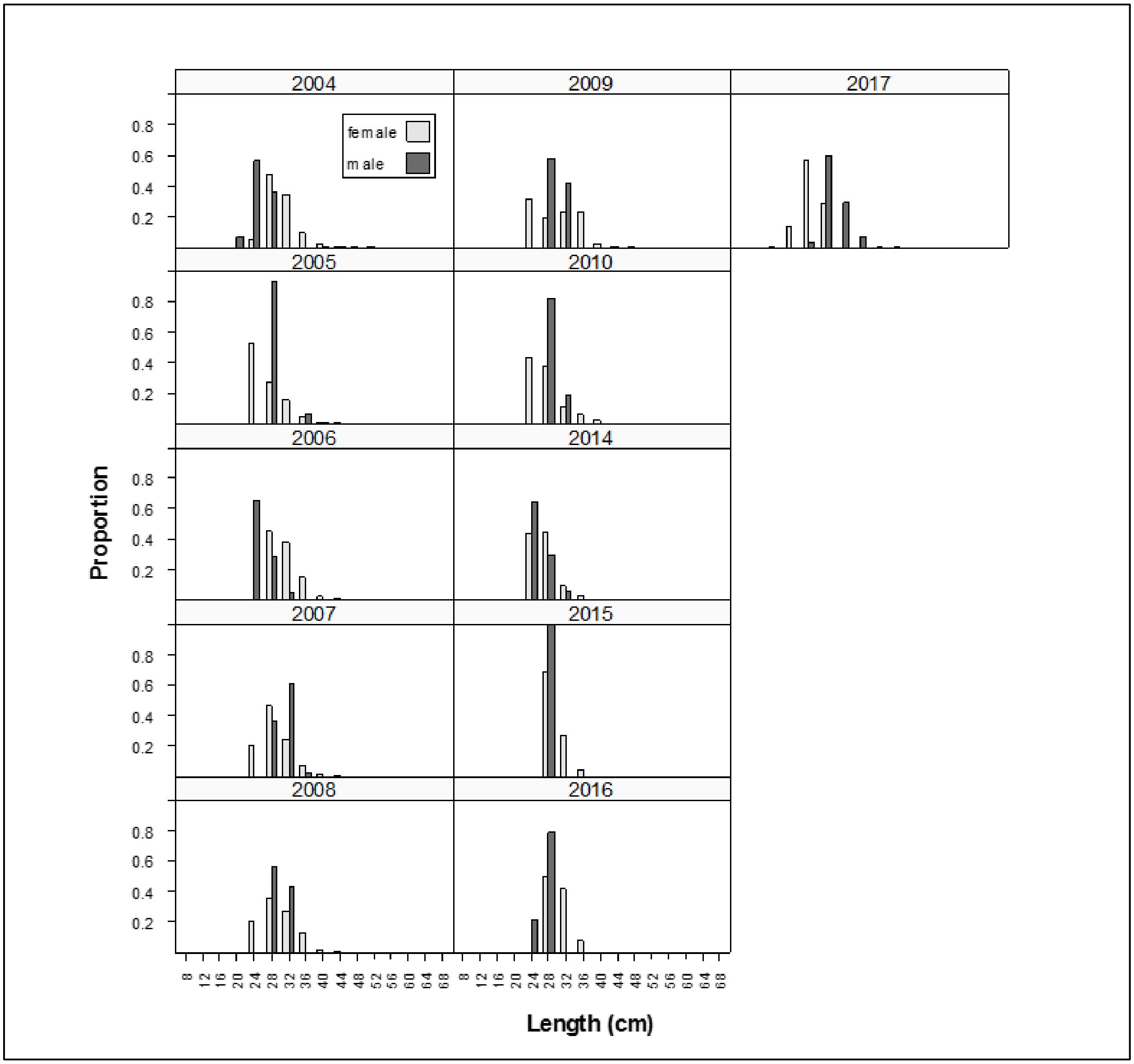

Figure 2.7. Annual length-frequency distributions of adult striped mullet collected by the NCDMF Program 146 during January through April by sex, 2004–2017.

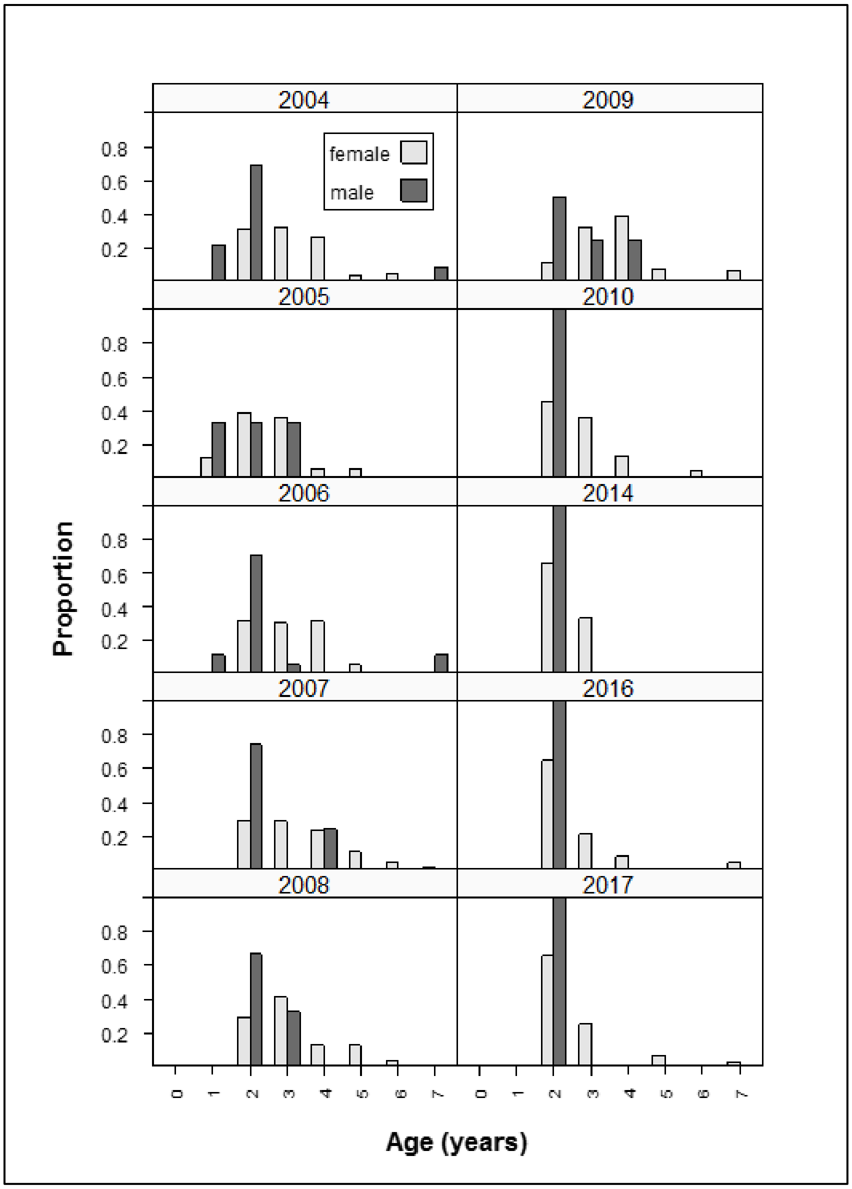

Figure 2.8. Annual age-frequency distributions of adult striped mullet collected by the NCDMF Program 146 during January through April by sex, 2004–2017.

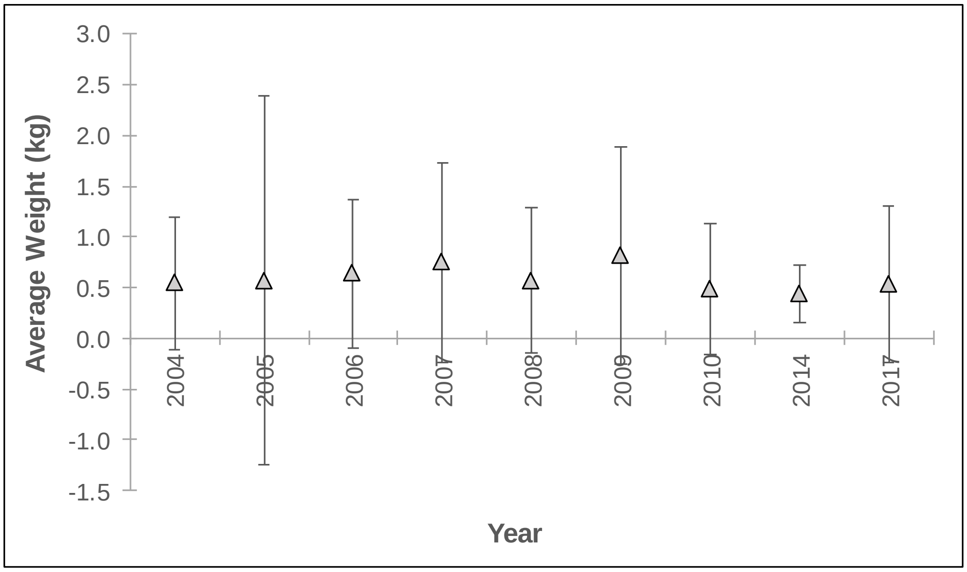

Figure 2.9. Annual average body weight of striped mullet (sexes pooled) collected by the NCDMF Program 146 during January through April, 2004–2017.

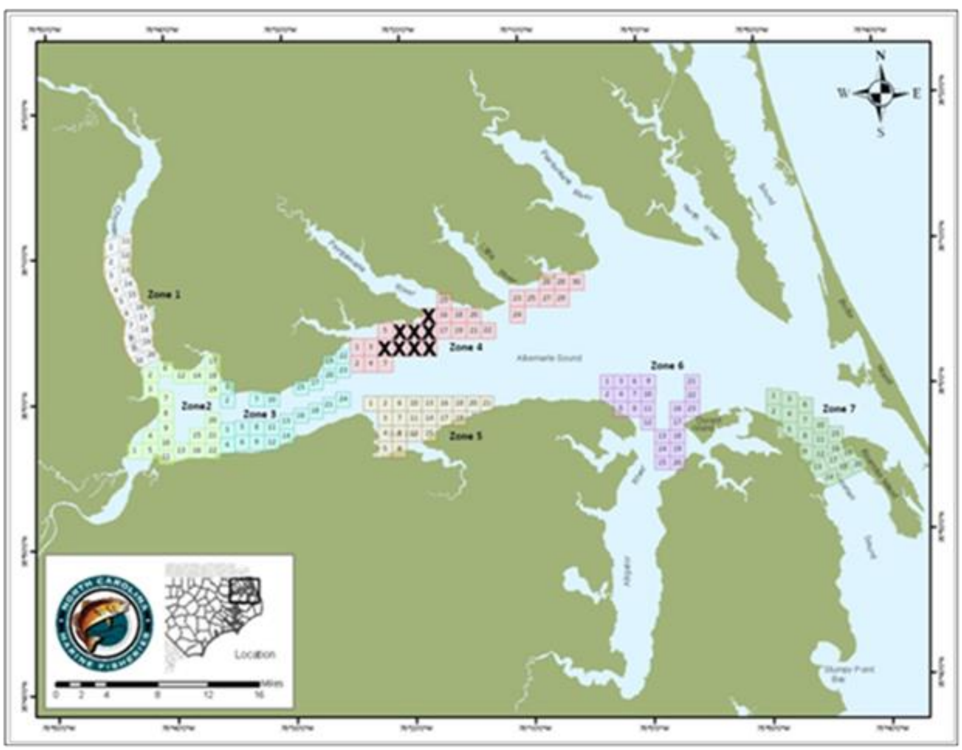

Figure 2.10. Locations of sampling zones and quadrants in Albemarle Sound sampled by NCDMF Program 135.

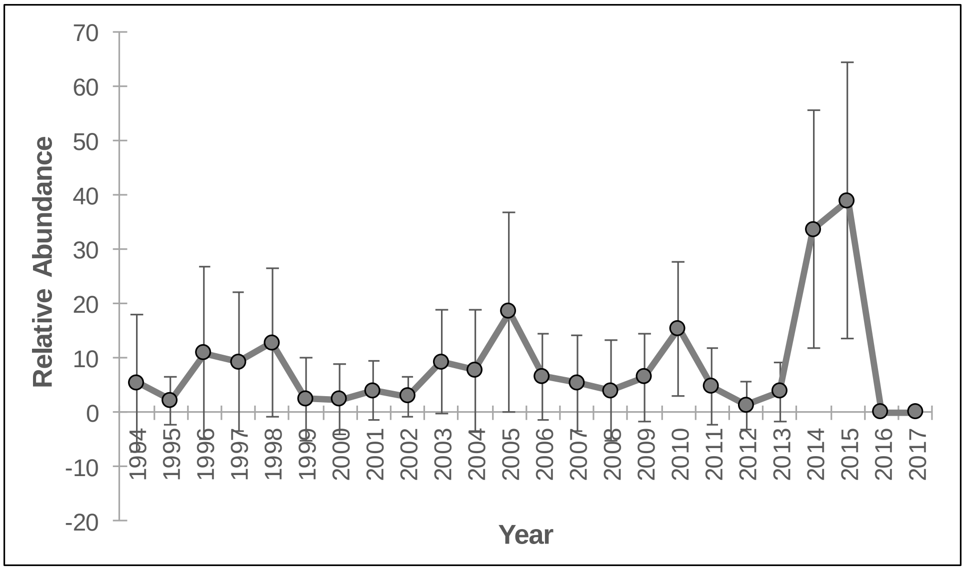

Figure 2.11. GLM-standardized index of relative abundance for adult striped mullet collected from Program 135 during November through February, 1994–2017. Error bars represent ± 2 standard errors.

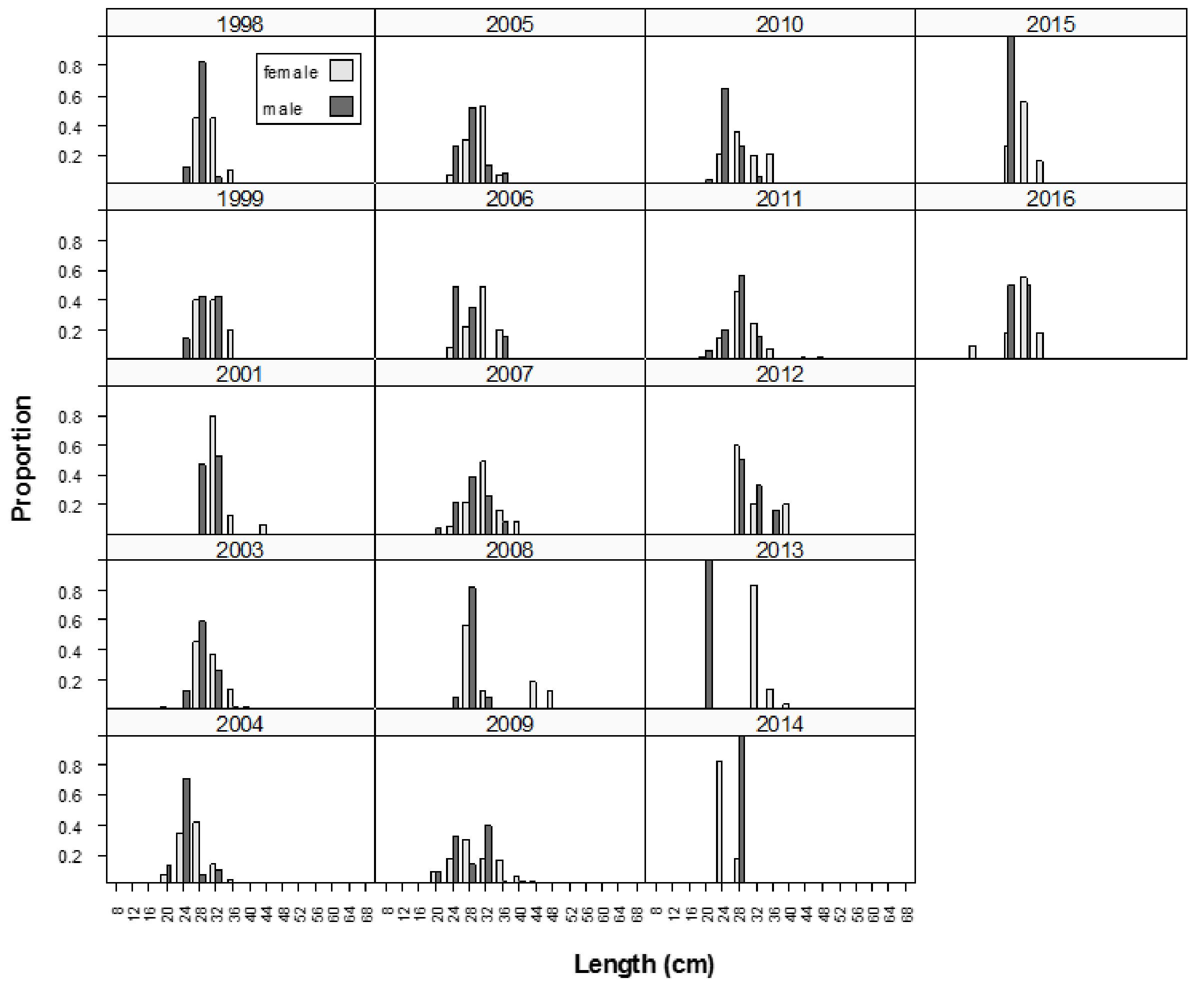

Figure 2.12. Annual length-frequency distributions of adult striped mullet collected by the NCDMF Program 135 during November through February by sex, 1998–2016.

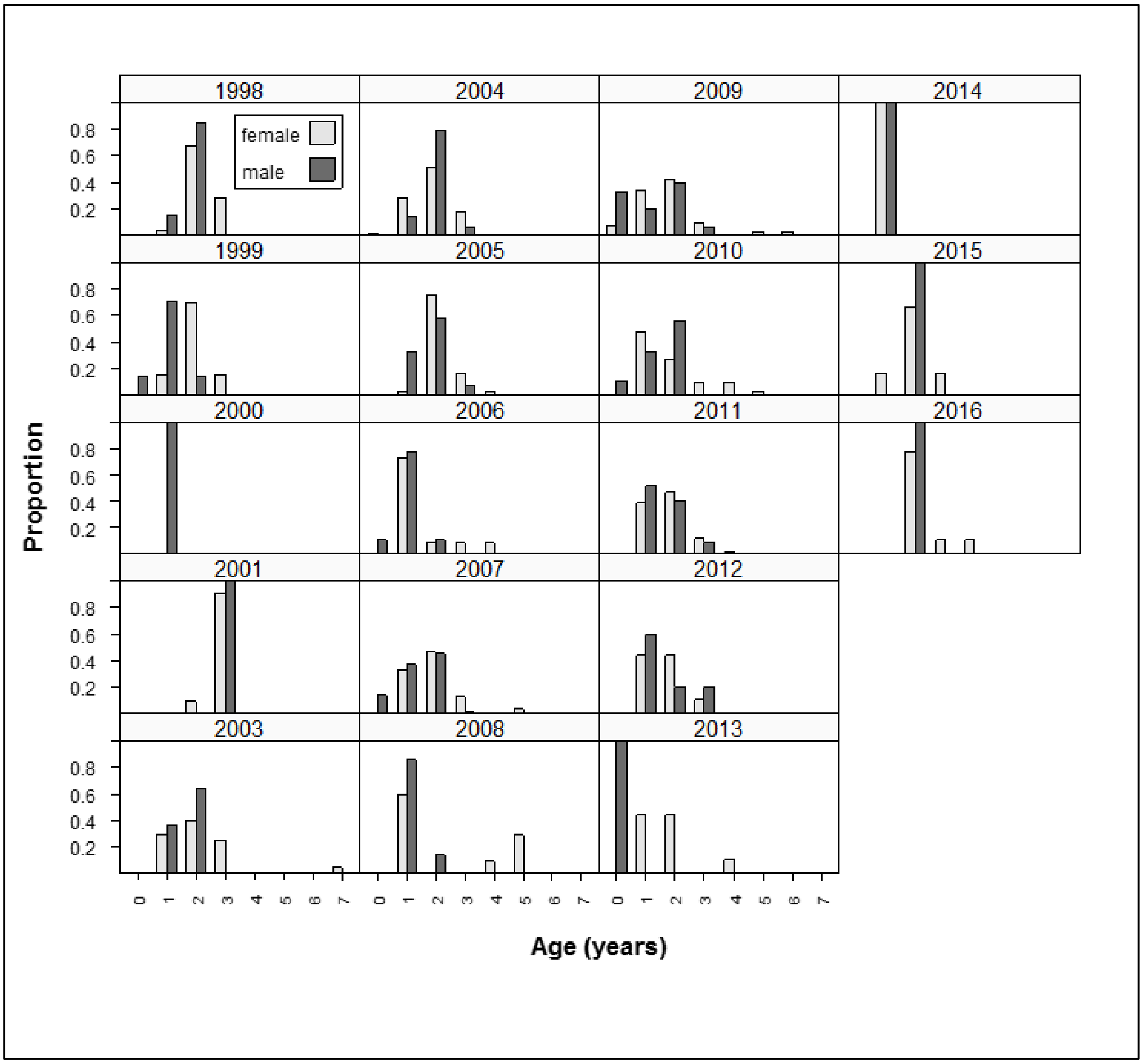

Figure 2.13. Annual age-frequency distributions of adult striped mullet collected by the NCDMF Program 135 during November through February by sex, 1998–2016.

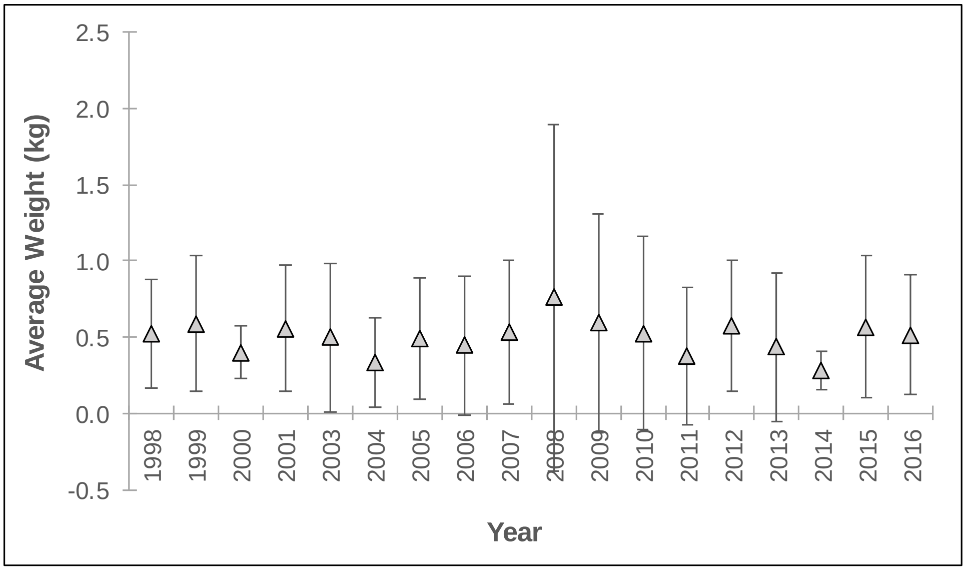

Figure 2.14. Annual average body weight of striped mullet (sexes pooled) collected by the NCDMF Program 135 during November through February, 1998–2016.

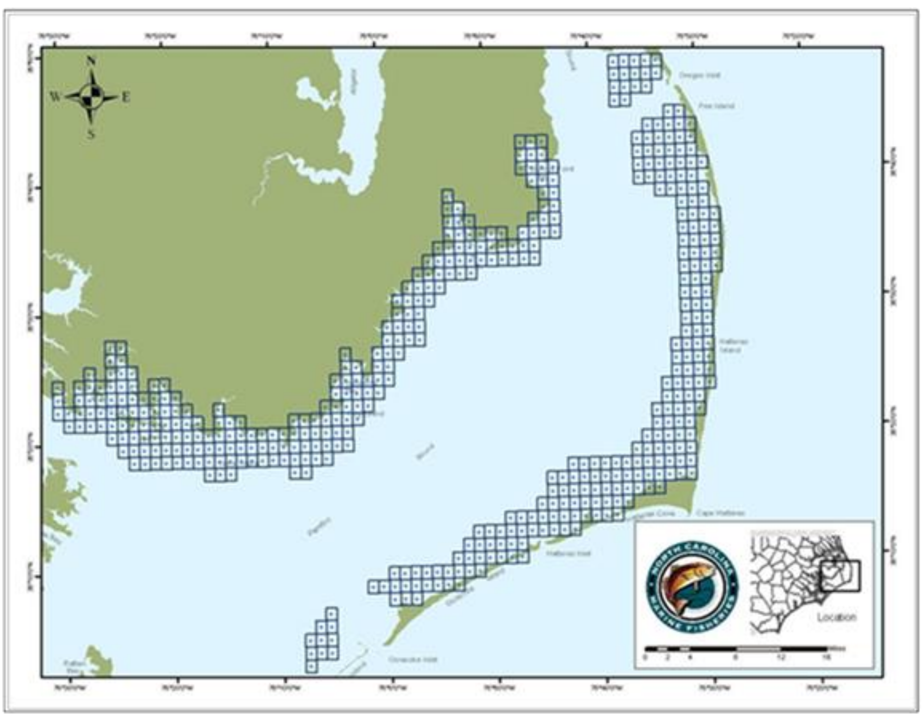

Figure 2.15. The sample regions and grid system for the Pamlico Sound portion of NCDMF Program 915.

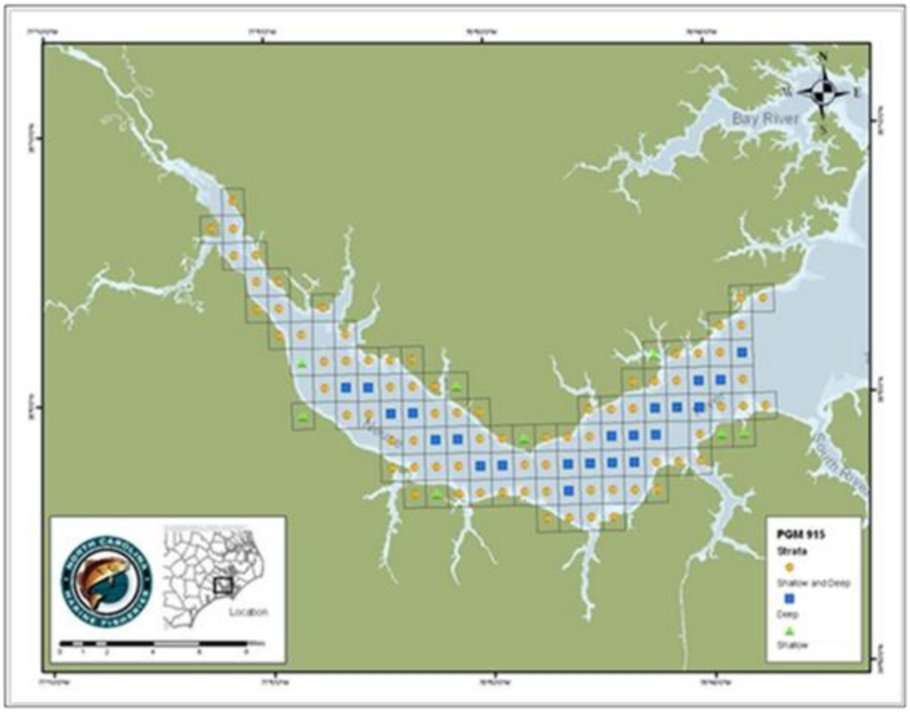

Figure 2.16. The sample regions and grid system for the Neuse River portion of NCDMF Program 915.

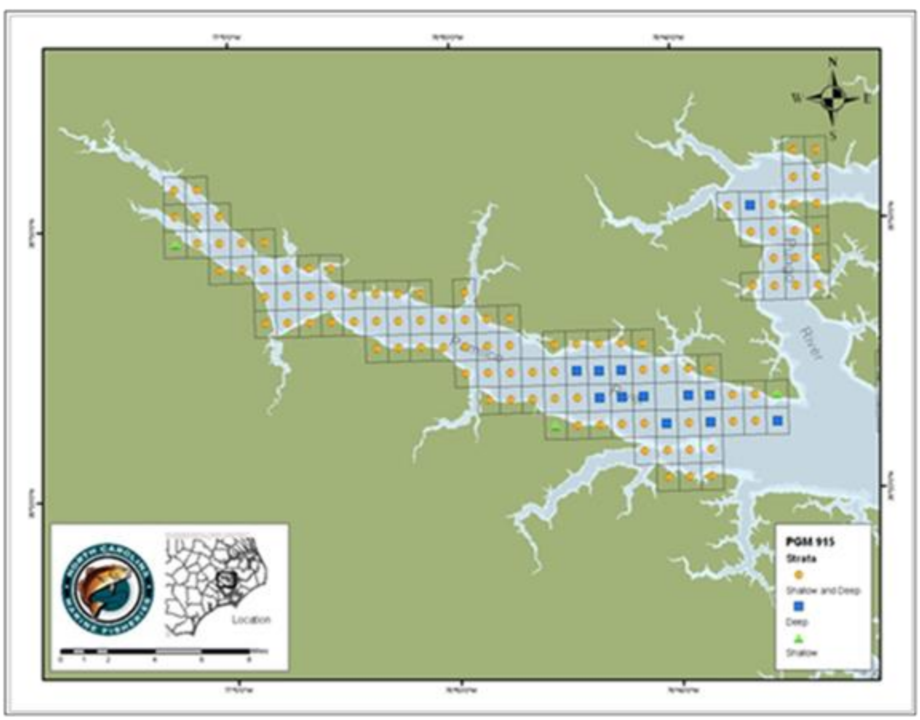

Figure 2.17. The sample regions and grid system for the Pamlico and Pungo river portions of NCDMF Program 915.

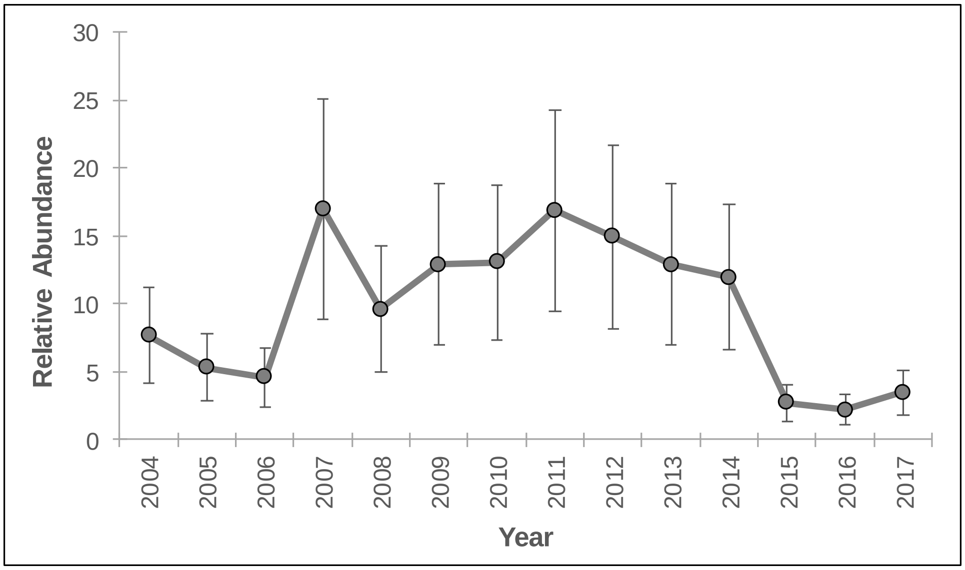

Figure 2.18. GLM-standardized index of relative abundance for adult striped mullet collected from Program 915 during October and November, 2004–2017. Error bars represent ± 2 standard errors.

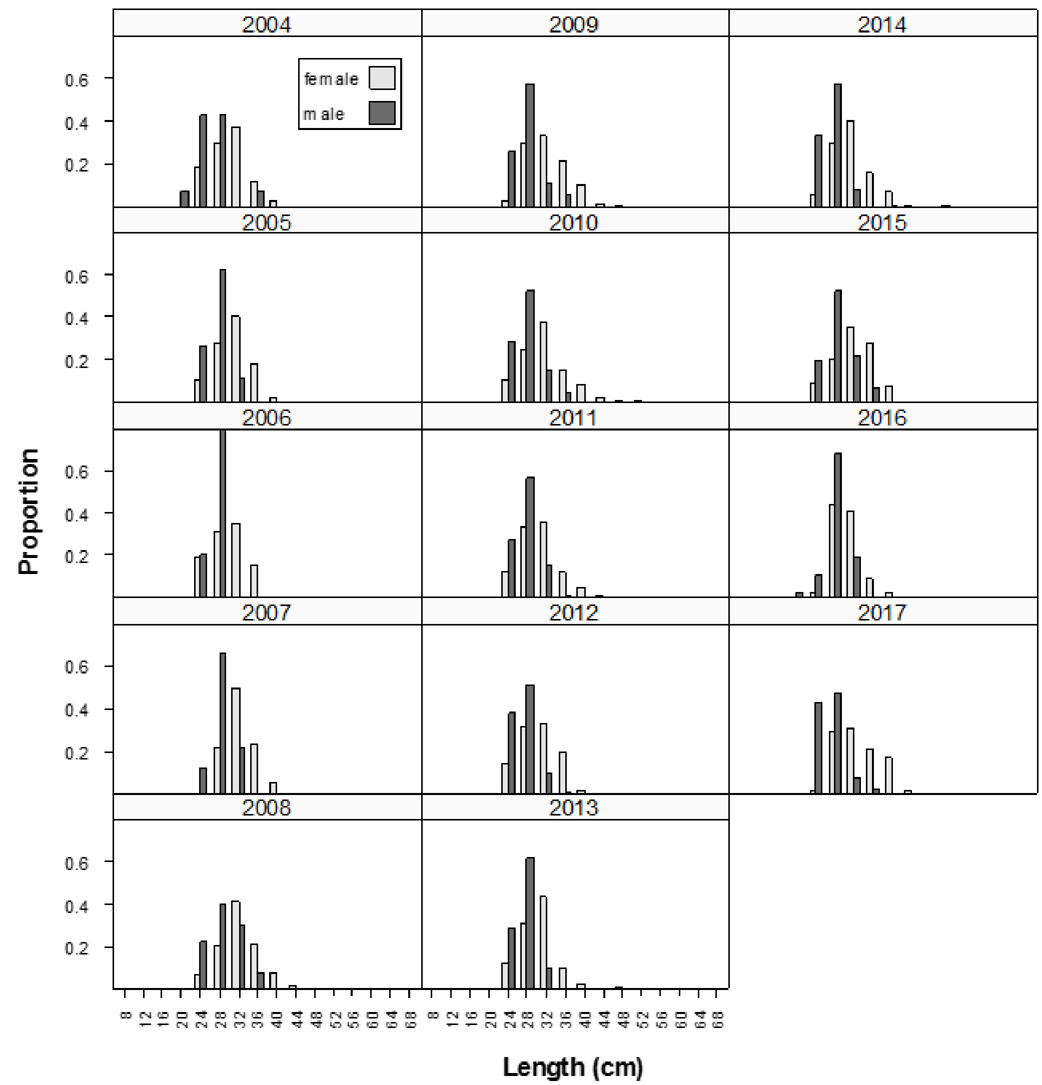

Figure 2.19. Annual length-frequency distributions of adult striped mullet collected by the NCDMF Program 915 during October and November by sex, 2004–2017.

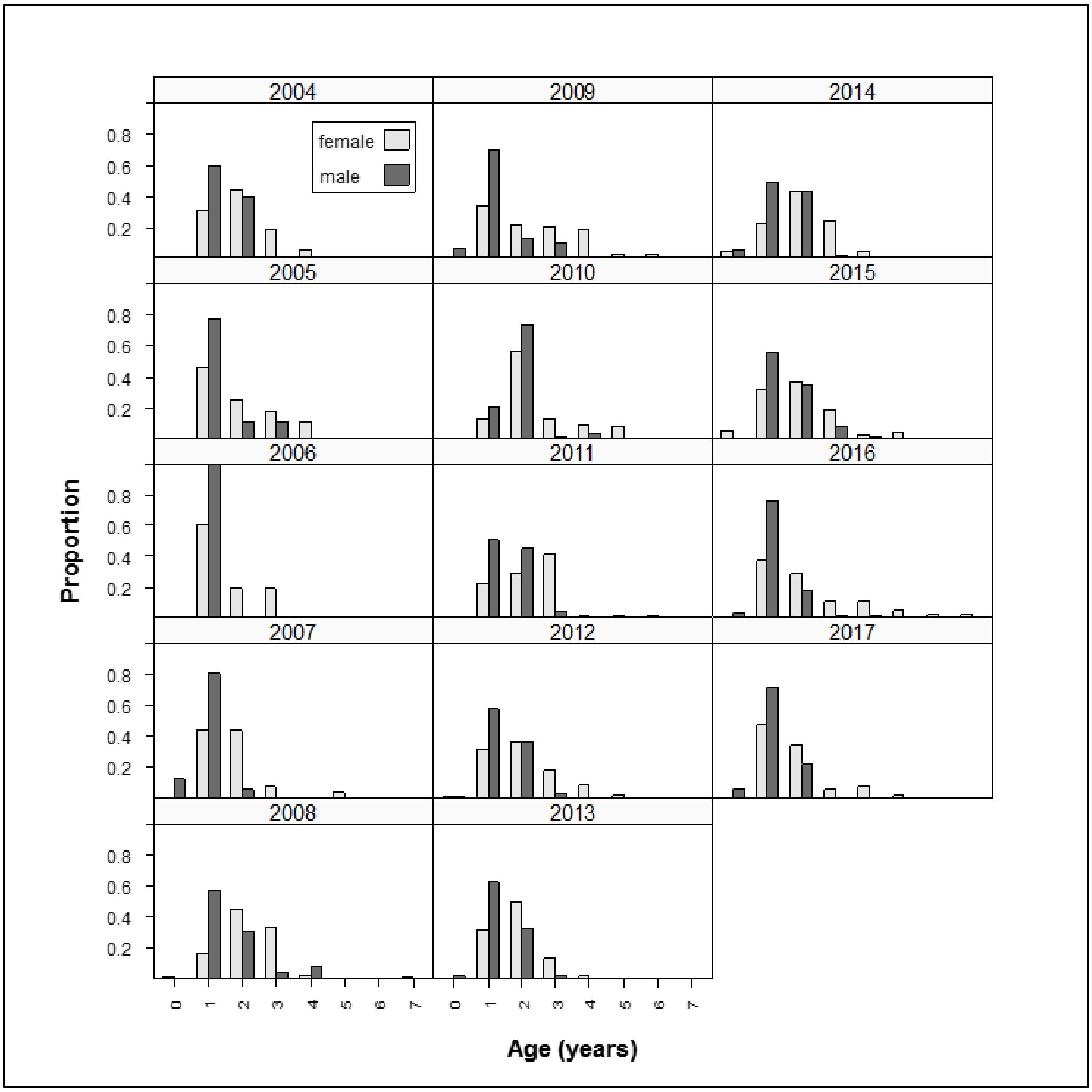

Figure 2.20. Annual age-frequency distributions of adult striped mullet collected by the NCDMF Program 915 during October and November by sex, 2004–2017.

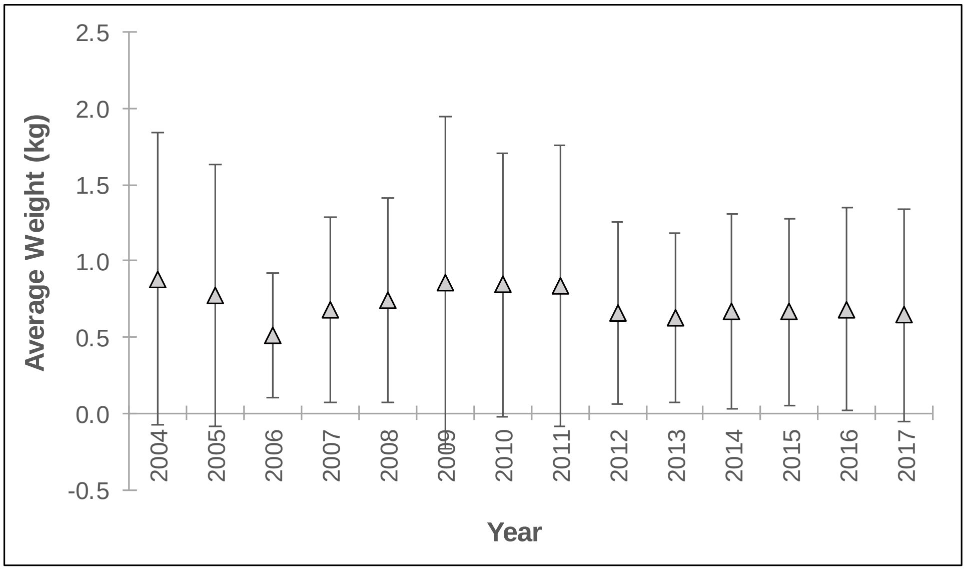

Figure 2.21. Annual average body weight of striped mullet (sexes pooled) collected by the NCDMF Program 915 during October and November, 2004–2017.

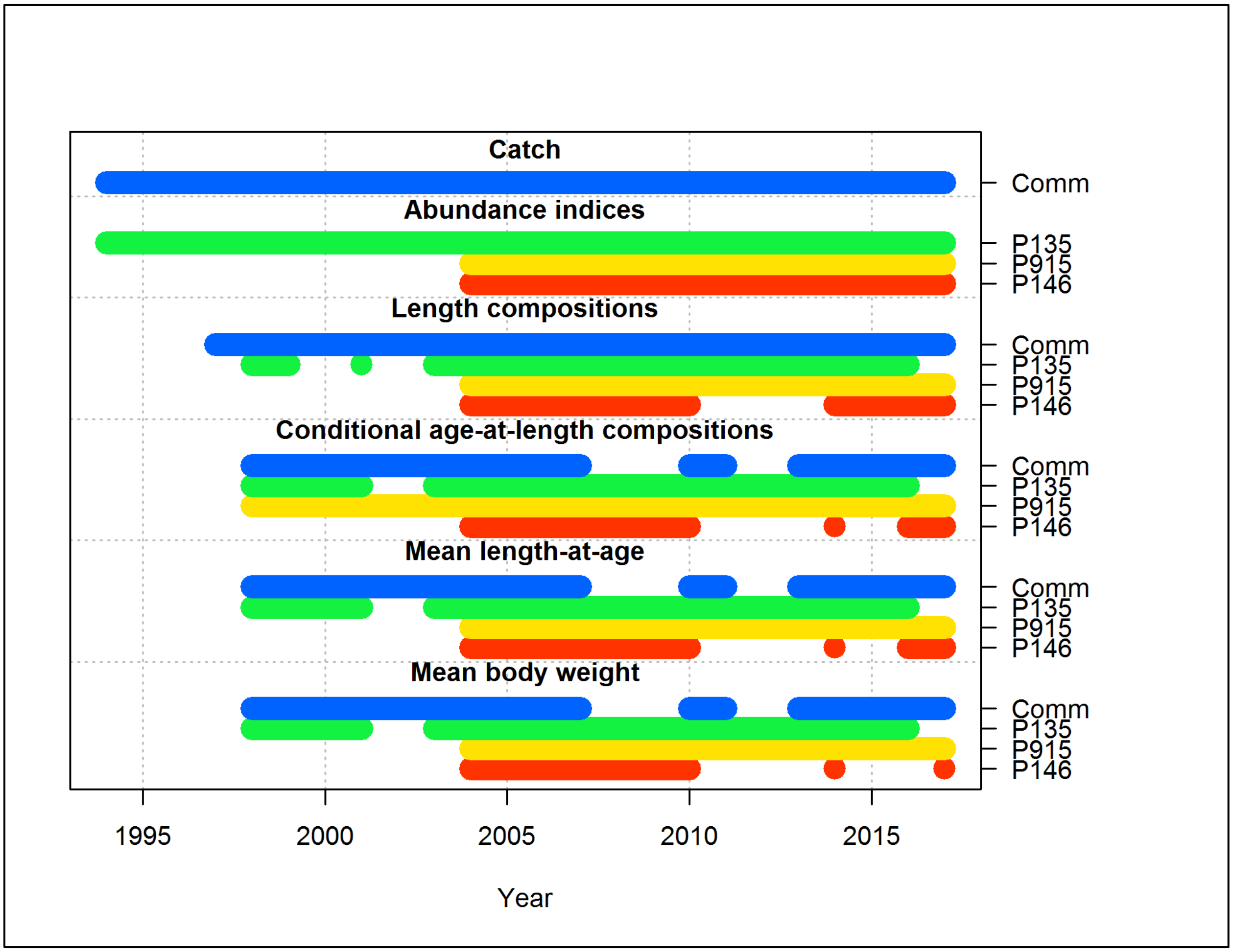

Figure 3.1. Summary of data sources and types used in the base run of the stock assessment model for striped mullet.

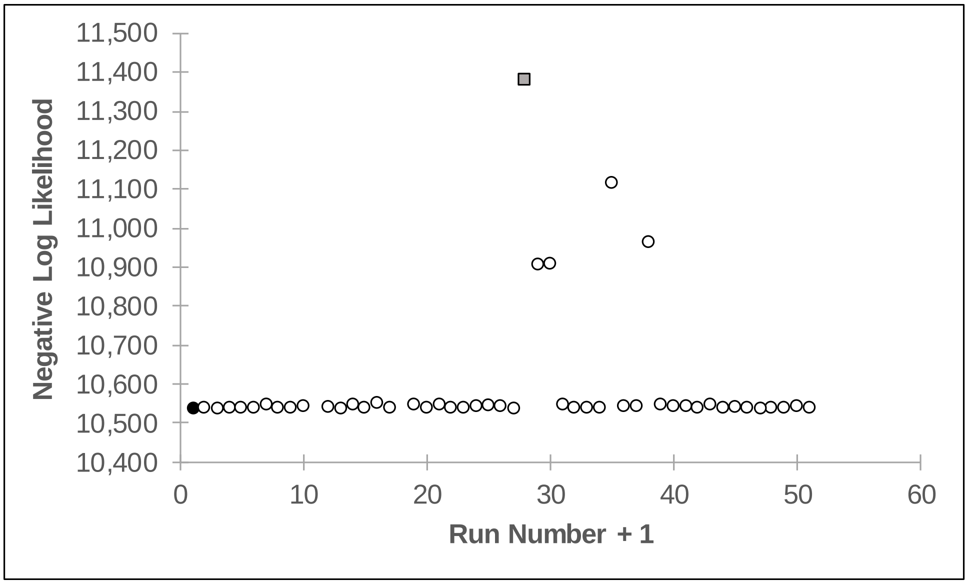

Figure 3.2. Negative log-likelihood values produced from the 50 jitter trials in which initial parameter values were jittered by 10%. The solid black circle is the value from the base run. The solid grey square is from run 27, which produced estimates of female SSB and *F* that were different than the base run.

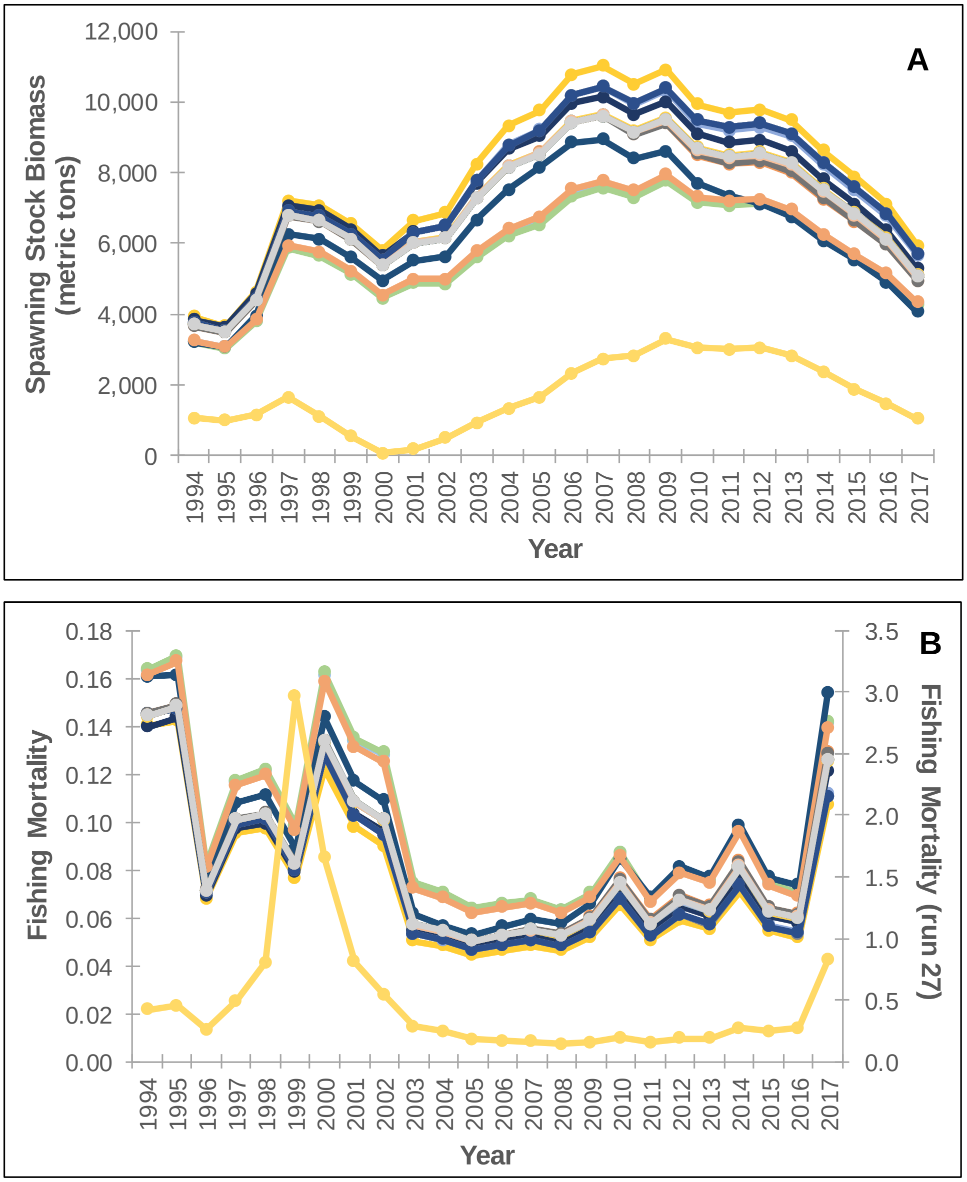

Figure 3.3. Predicted (A) female SSB and (B) *F* (numbers-weighted, ages 1–5) from the jitter analysis (10%) applied to the base run of the stock assessment model, 1994–2017.

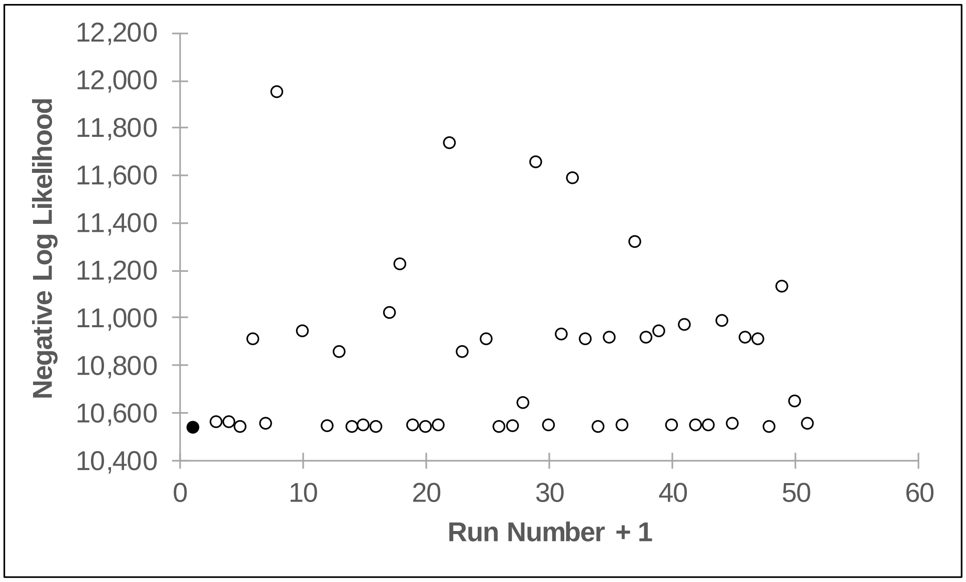

Figure 3.4. Negative log-likelihood values produced from the 50 jitter trials in which initial parameter values were jittered by 25%. The solid black circle is the value from the base run.

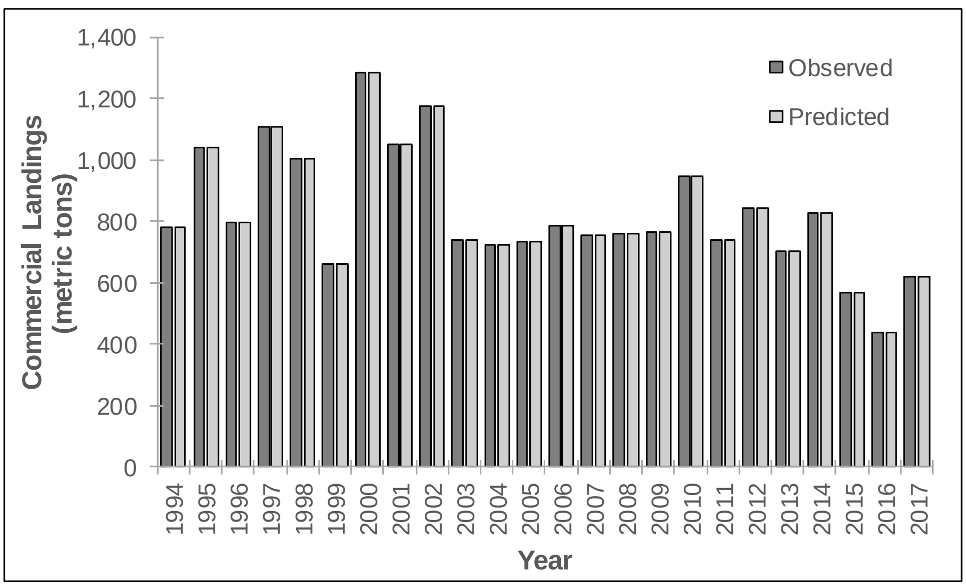

Figure 3.5. Observed and predicted commercial landings from the base run of the stock assessment model, 1994–2017.

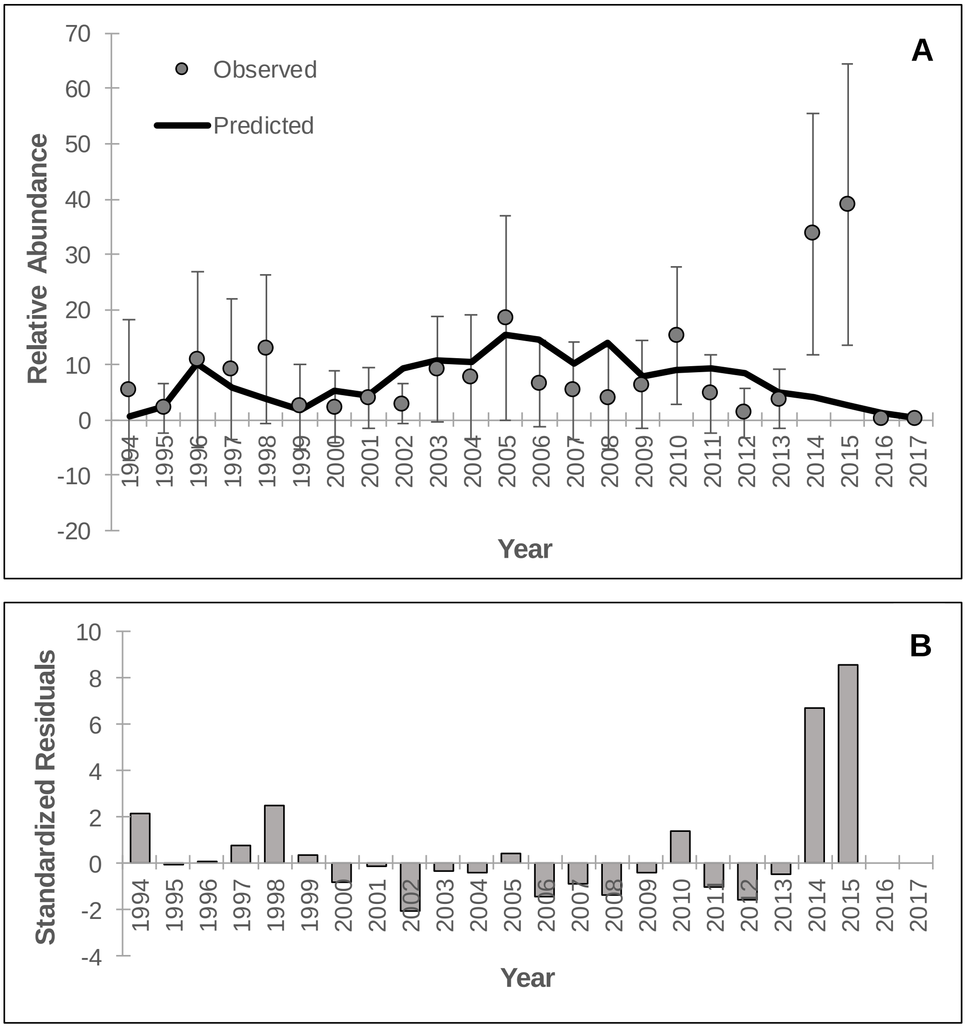

Figure 3.6. (A) Observed and predicted relative abundance and (B) associated standardized residuals for the Program 135 survey index from the base run of the stock assessment model, 1994–2017.

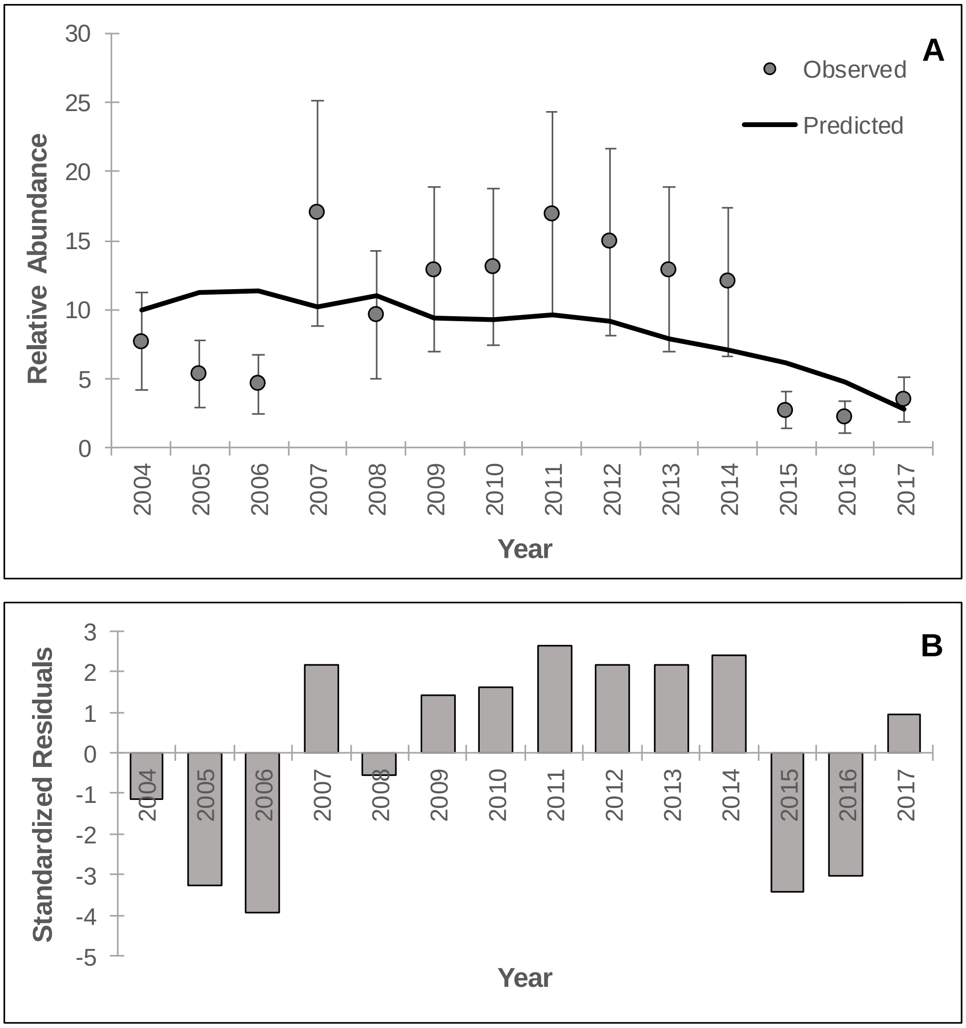

Figure 3.7. (A) Observed and predicted relative abundance and (B) associated standardized residuals for the Program 915 survey index from the base run of the stock assessment model, 2004–2017.

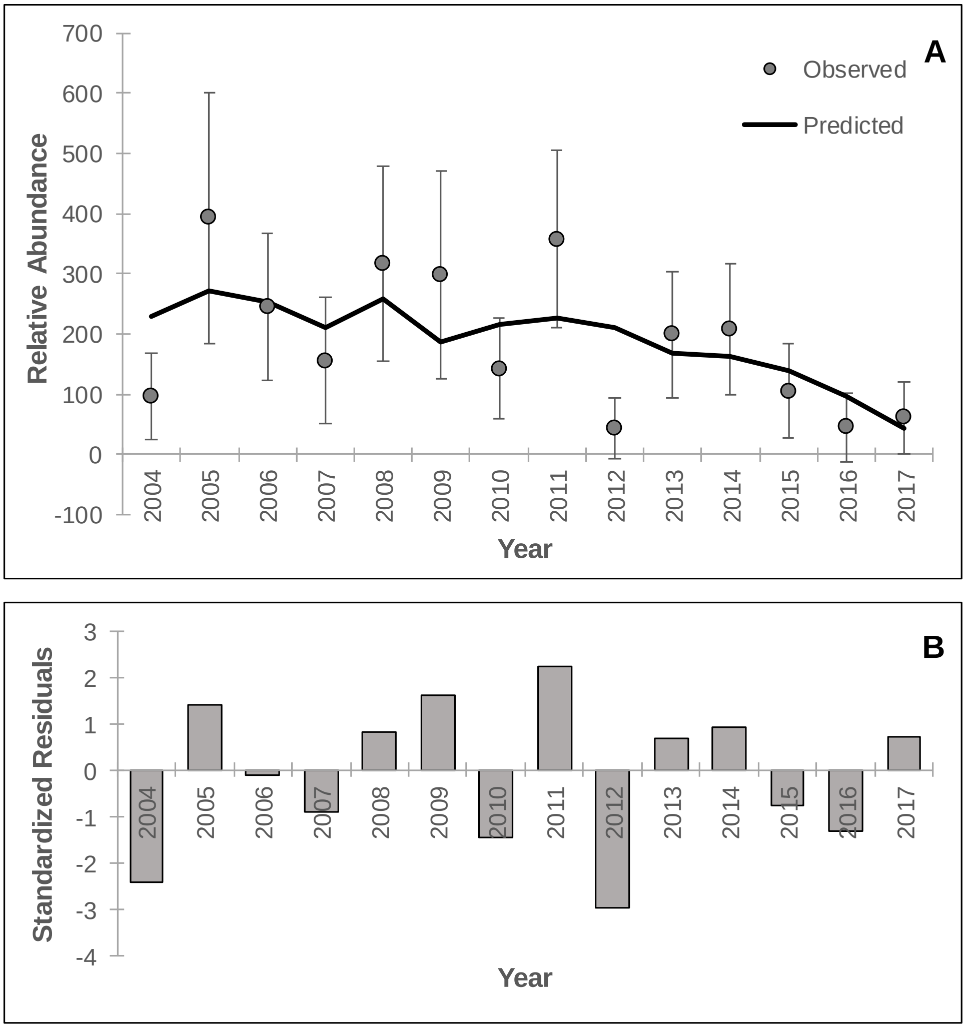

Figure 3.8. (A) Observed and predicted relative abundance and (B) associated standardized residuals for the Program 146 survey index from the base run of the stock assessment model, 2004–2017.

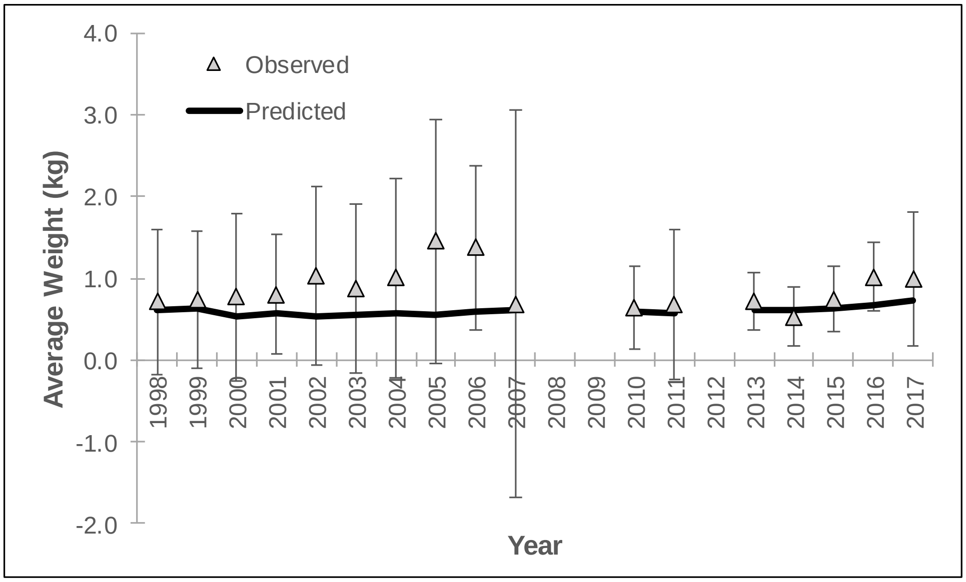

Figure 3.9. Observed and predicted average body weight for striped mullet sampled from the commercial landings, 1998–2017. The error bars represent ± 2 standard deviations of the observed values.

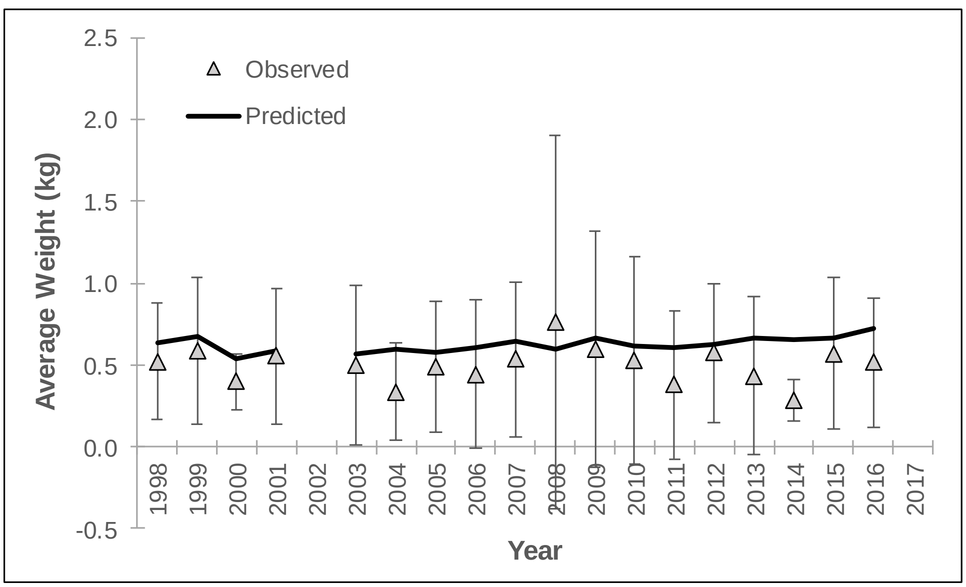

Figure 3.10. Observed and predicted average body weight for striped mullet sampled from the Program 135 survey, 1998–2017. The error bars represent ± 2 standard deviations of the observed values.

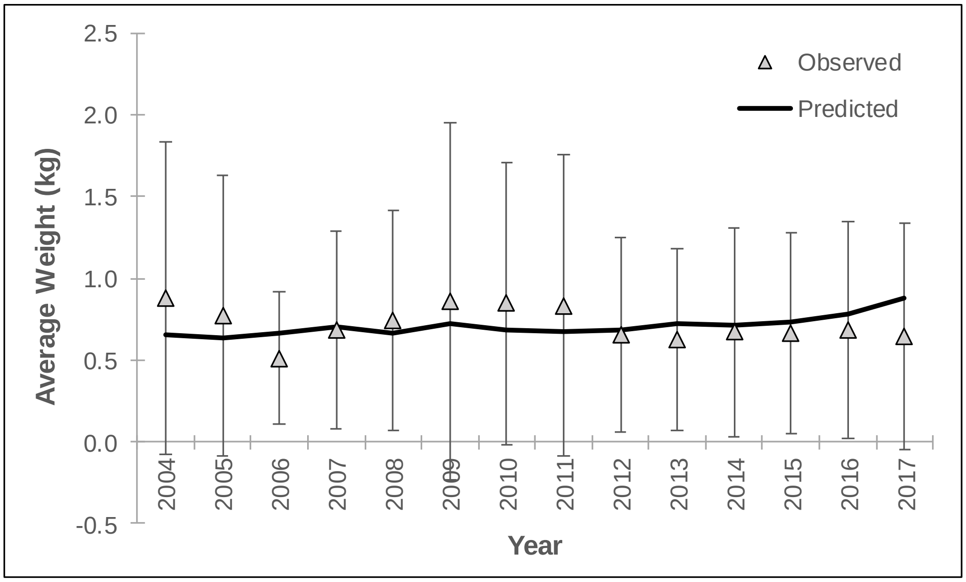

Figure 3.11. Observed and predicted average body weight for striped mullet sampled from the Program 915 survey, 2004–2017. The error bars represent ± 2 standard deviations of the observed values.

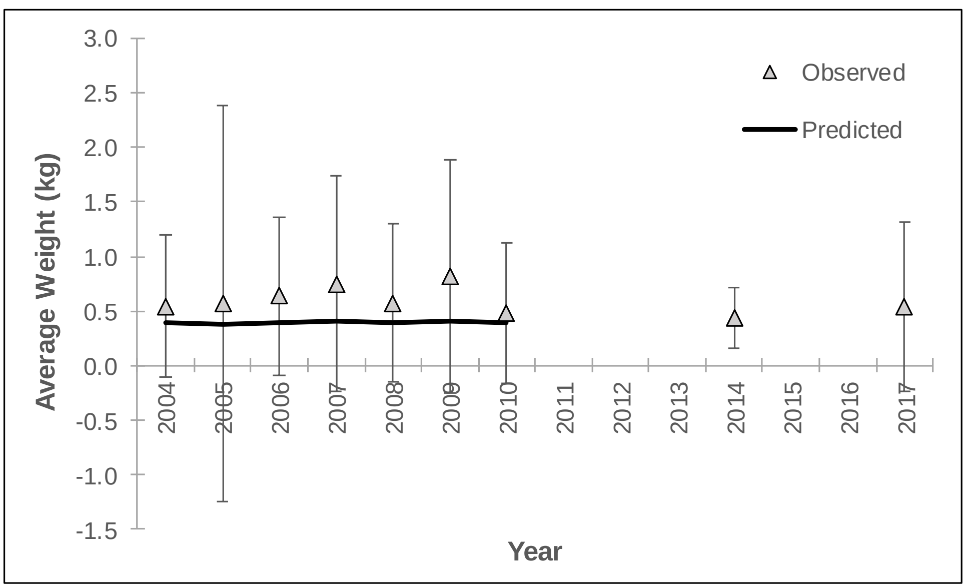

Figure 3.12. Observed and predicted average body weight for striped mullet sampled from the Program 146 survey, 2004–2017. The error bars represent ± 2 standard deviations of the observed values.

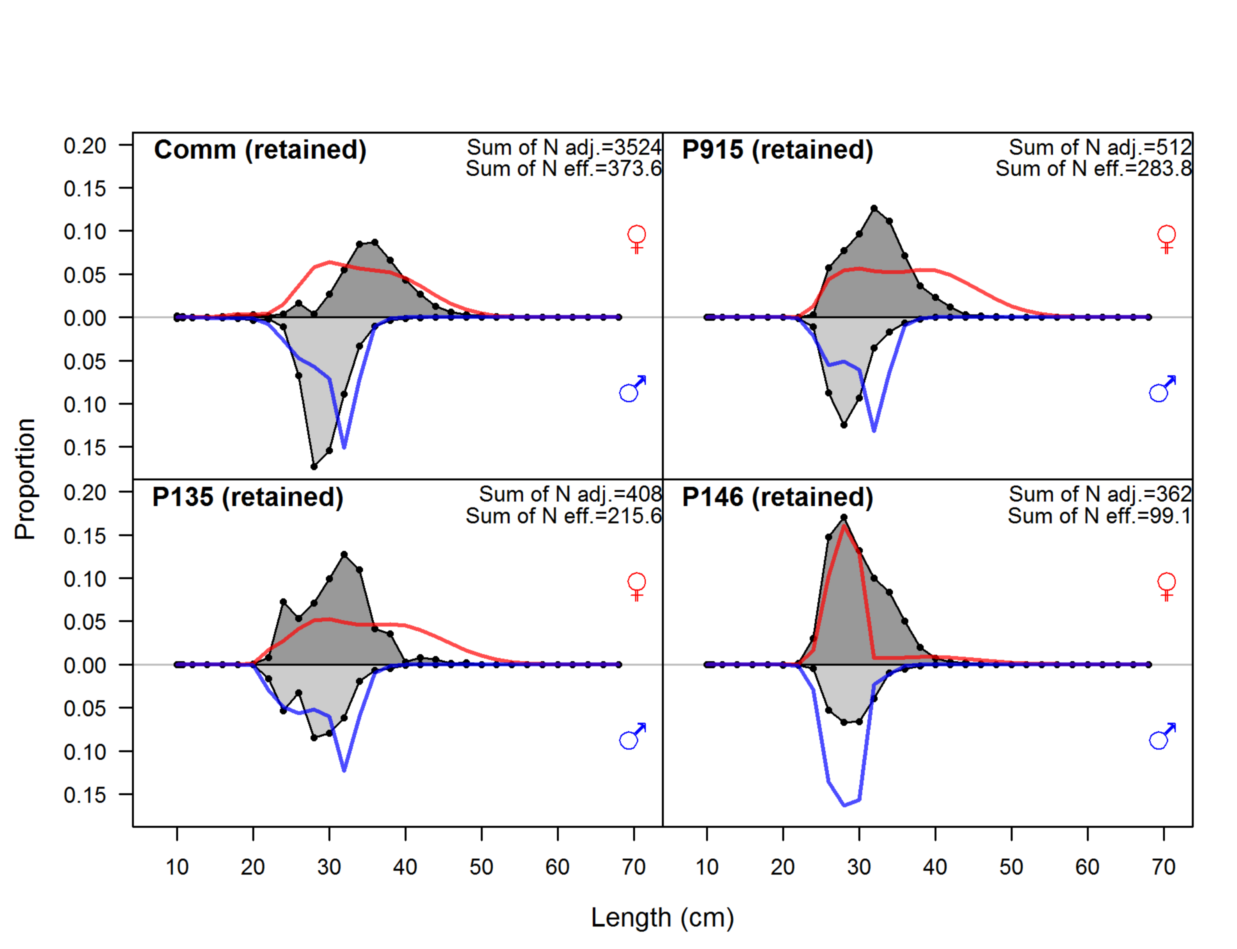

Figure 3.13. Observed and predicted length compositions for each data source from the base run of the stock assessment model aggregated across time. N adj. represents the input effective sample size (number of trips sampled) and N eff. represents the model estimate of effective sample size.

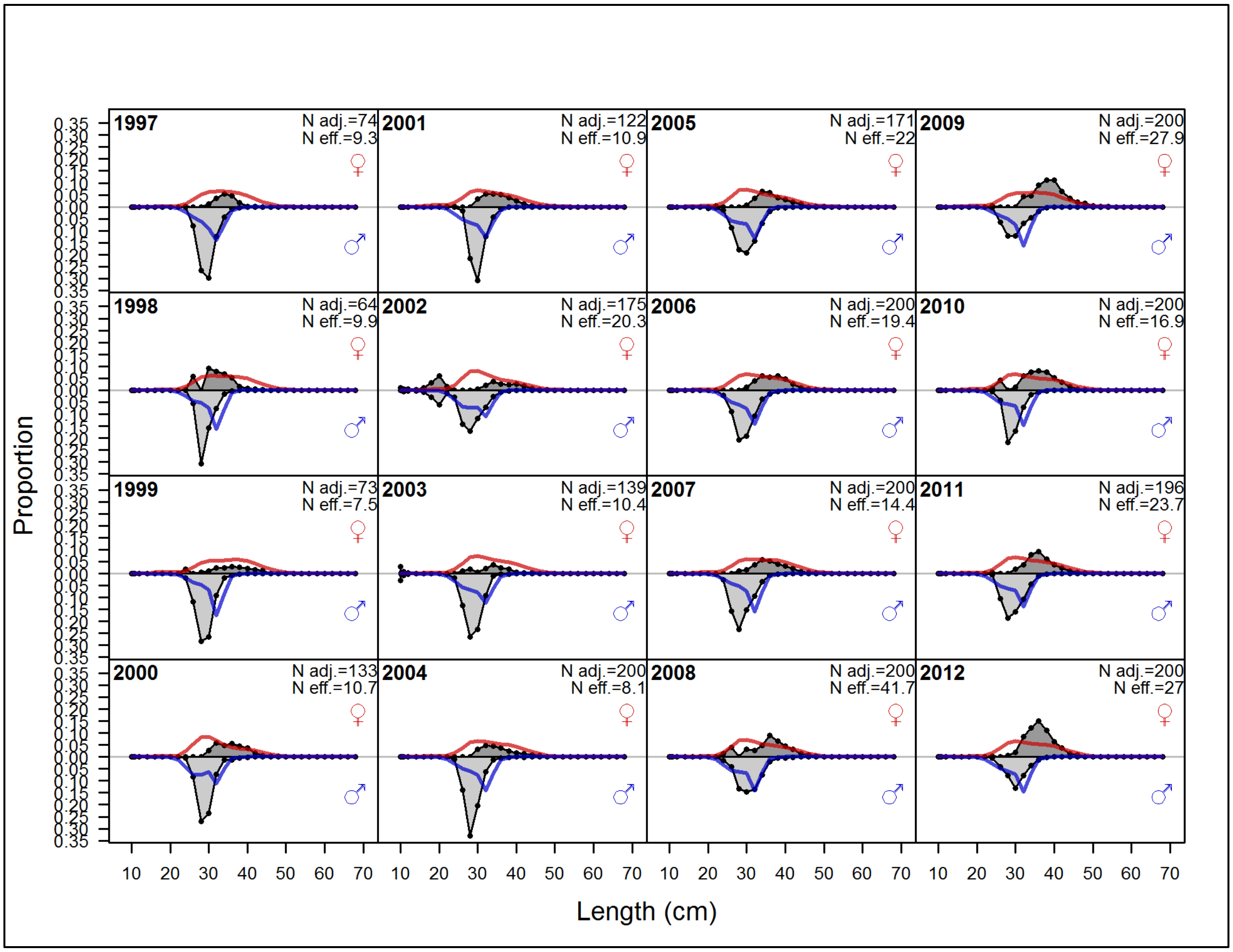

Figure 3.14. Observed and predicted length compositions for the commercial landings from the base run of the stock assessment model, 1997–2012. N adj. represents the input effective sample size (number of trips sampled) and N eff. represents the model estimate of effective sample size.

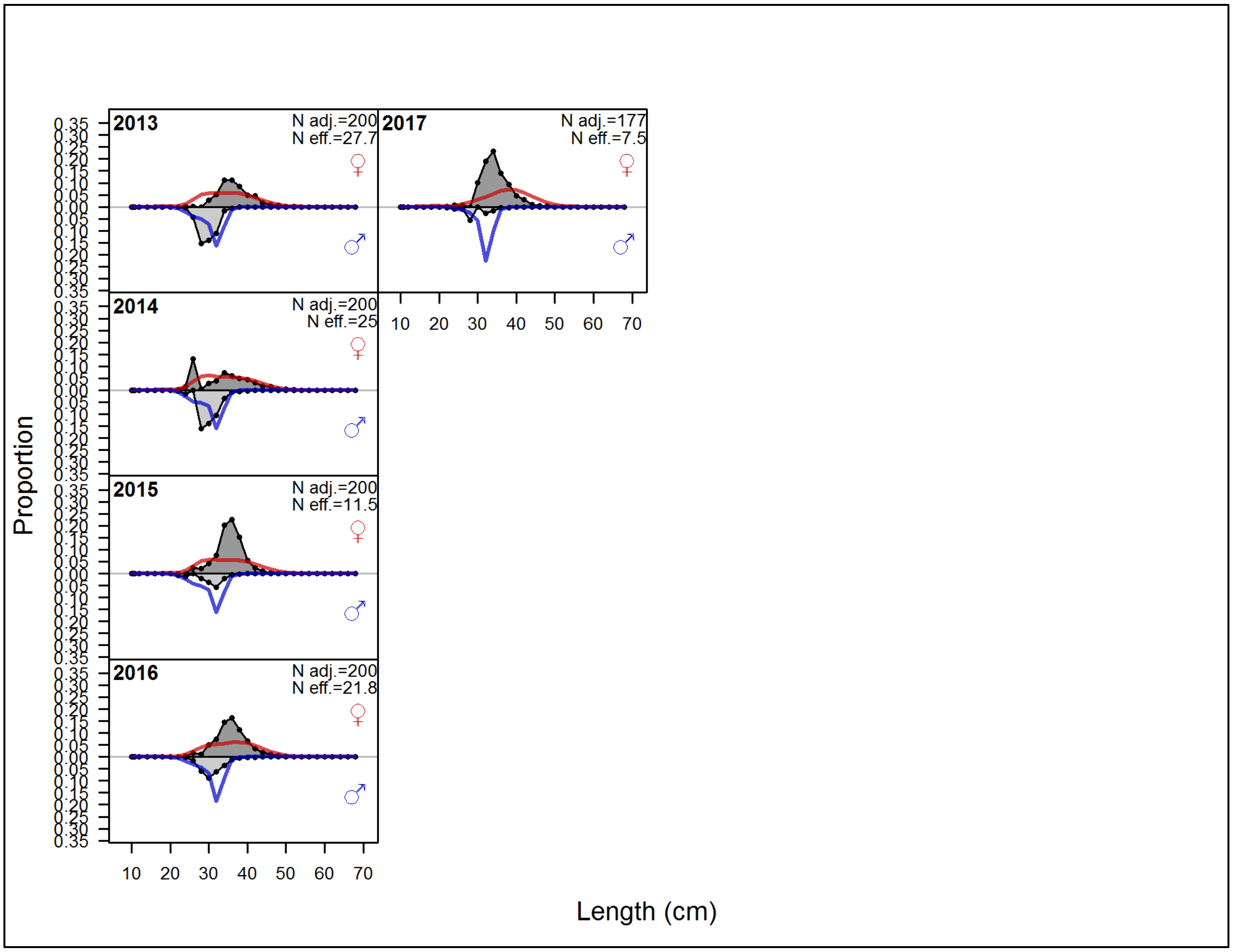

Figure 3.15. Observed and predicted length compositions for the commercial landings from the base run of the stock assessment model, 2013–2017. N adj. represents the input effective sample size (number of trips sampled) and N eff. represents the model estimate of effective sample size.

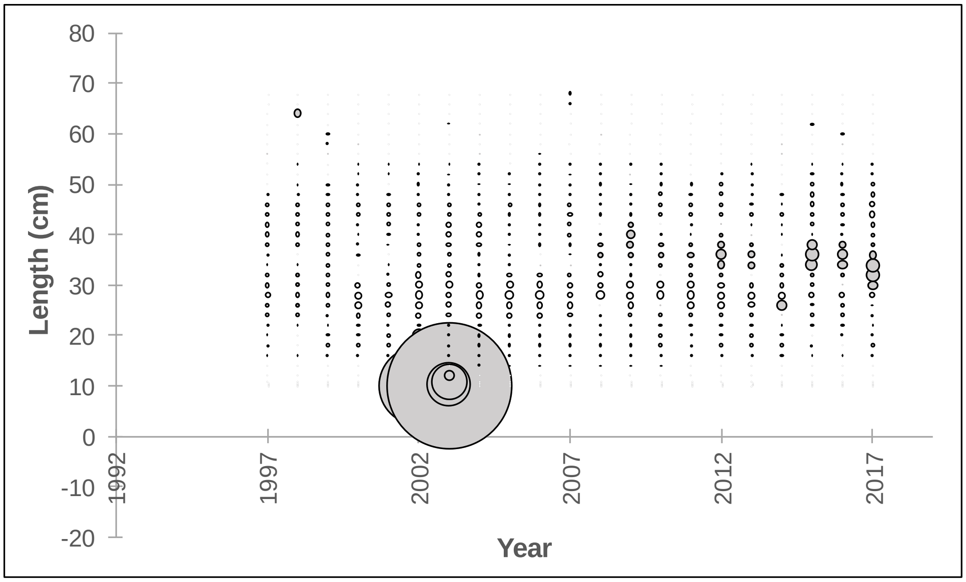

Figure 3.16. Standardized residuals for the female commercial landings length composition data from the base run of the stock assessment model, 1997–2017. Gray circles represent positive residuals while white circles represent negative residuals. The area of the circles is proportional to the size of the residuals.

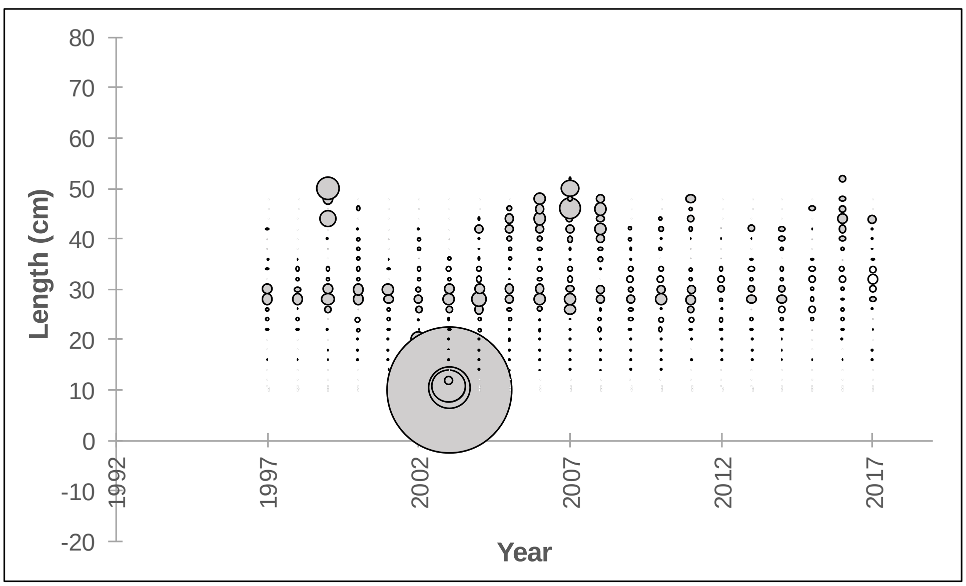

Figure 3.17. Standardized residuals for the male commercial landings length composition data from the base run of the stock assessment model, 1997–2017. Gray circles represent positive residuals while white circles represent negative residuals. The area of the circles is proportional to the size of the residuals.

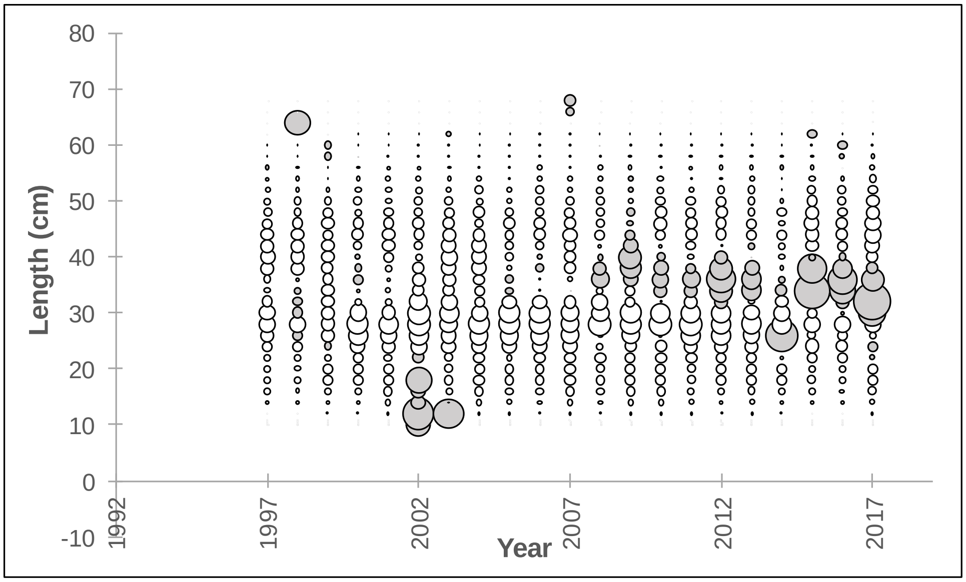

Figure 3.18. Standardized residuals for the female commercial landings length composition data from the base run of the stock assessment model, 1997–2017. Residuals with absolute values greater than 10 have been removed. Gray circles represent positive residuals while white circles represent negative residuals. The area of the circles is proportional to the size of the residuals.

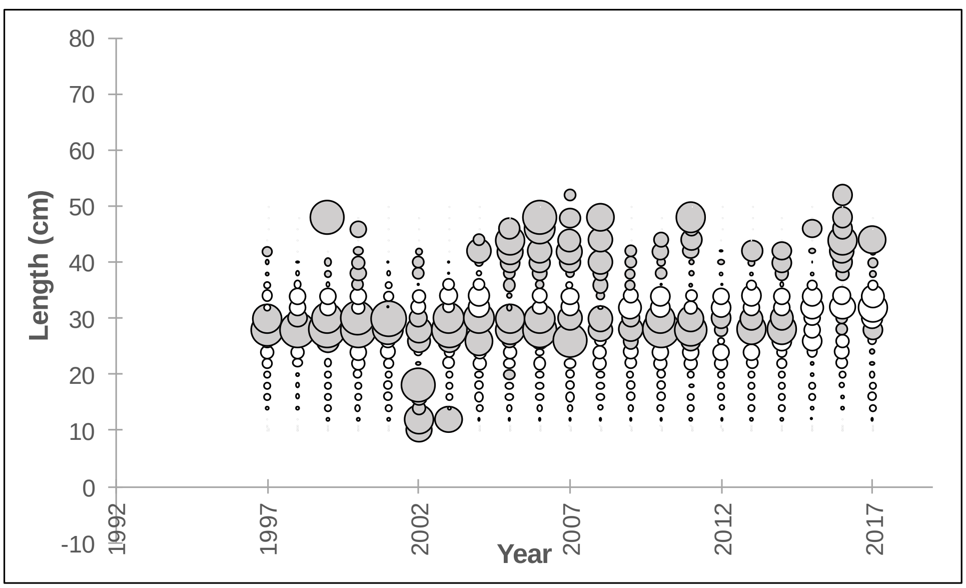

Figure 3.19. Standardized residuals for the male commercial landings length composition data from the base run of the stock assessment model, 1997–2017. Residuals with absolute values greater than 10 have been removed. Gray circles represent positive residuals while white circles represent negative residuals. The area of the circles is proportional to the size of the residuals.

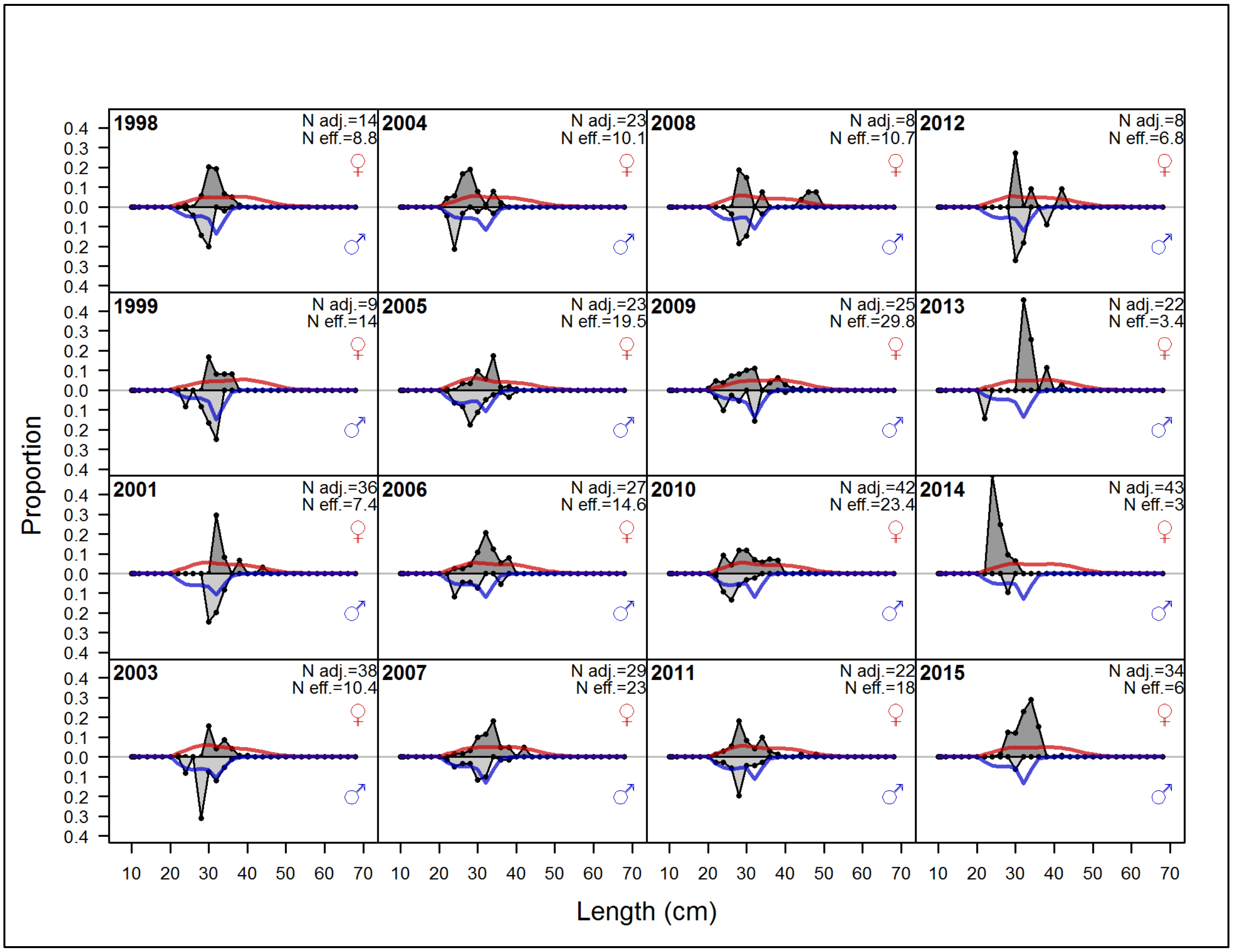

Figure 3.20. Observed and predicted length compositions for the Program 135 survey from the base run of the stock assessment model, 1998–2015. N adj. represents the input effective sample size (number of trips sampled) and N eff. represents the model estimate of effective sample size.

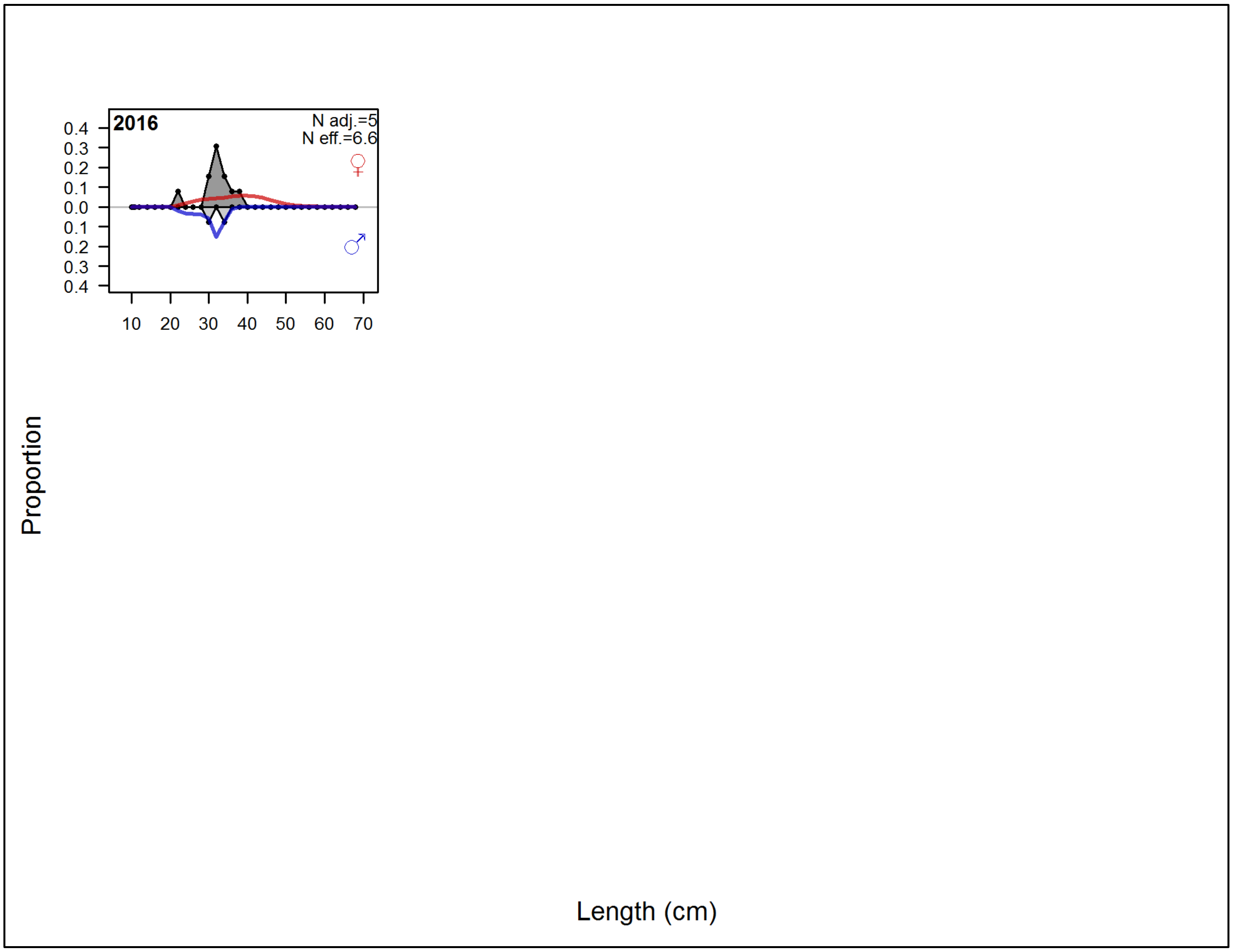

Figure 3.21. Observed and predicted length compositions for the Program 135 survey from the base run of the stock assessment model, 2016. N adj. represents the input effective sample size (number of trips sampled) and N eff. represents the model estimate of effective sample size.

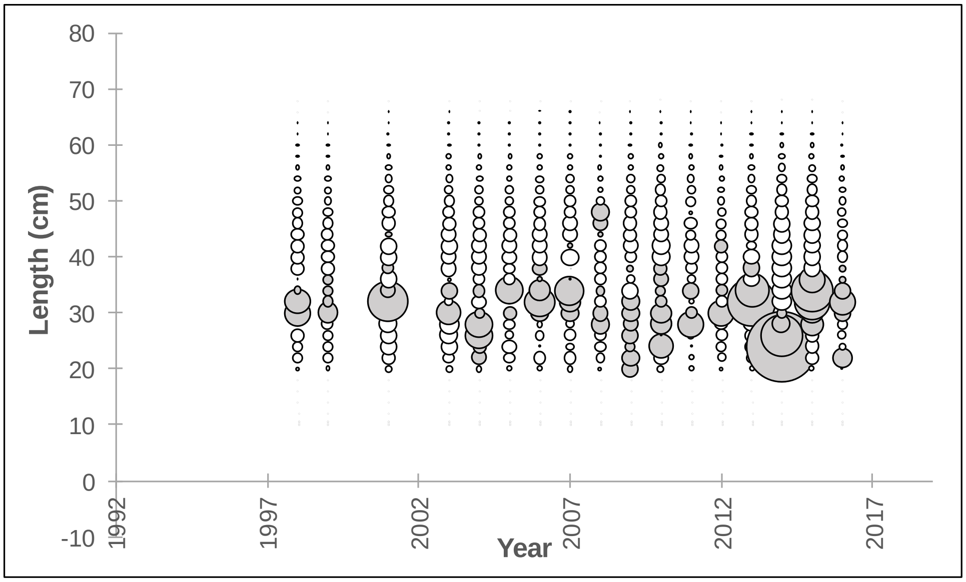

Figure 3.22. Standardized residuals for the female Program 135 length composition data from the base run of the stock assessment model, 1998–2016. Gray circles represent positive residuals while white circles represent negative residuals. The area of the circles is proportional to the size of the residuals.

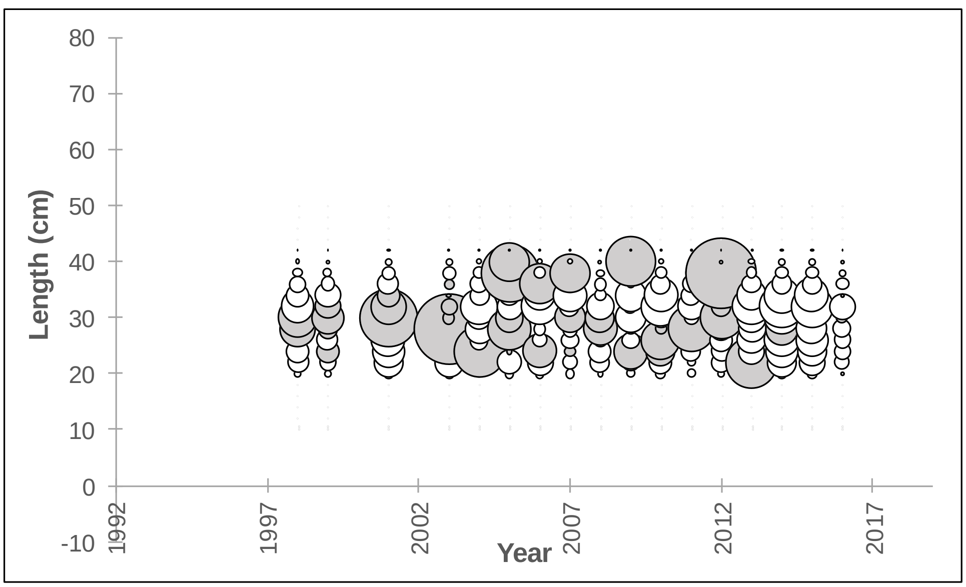

Figure 3.23. Standardized residuals for the male Program 135 length composition data from the base run of the stock assessment model, 1998–2016. Gray circles represent positive residuals while white circles represent negative residuals. The area of the circles is proportional to the size of the residuals.

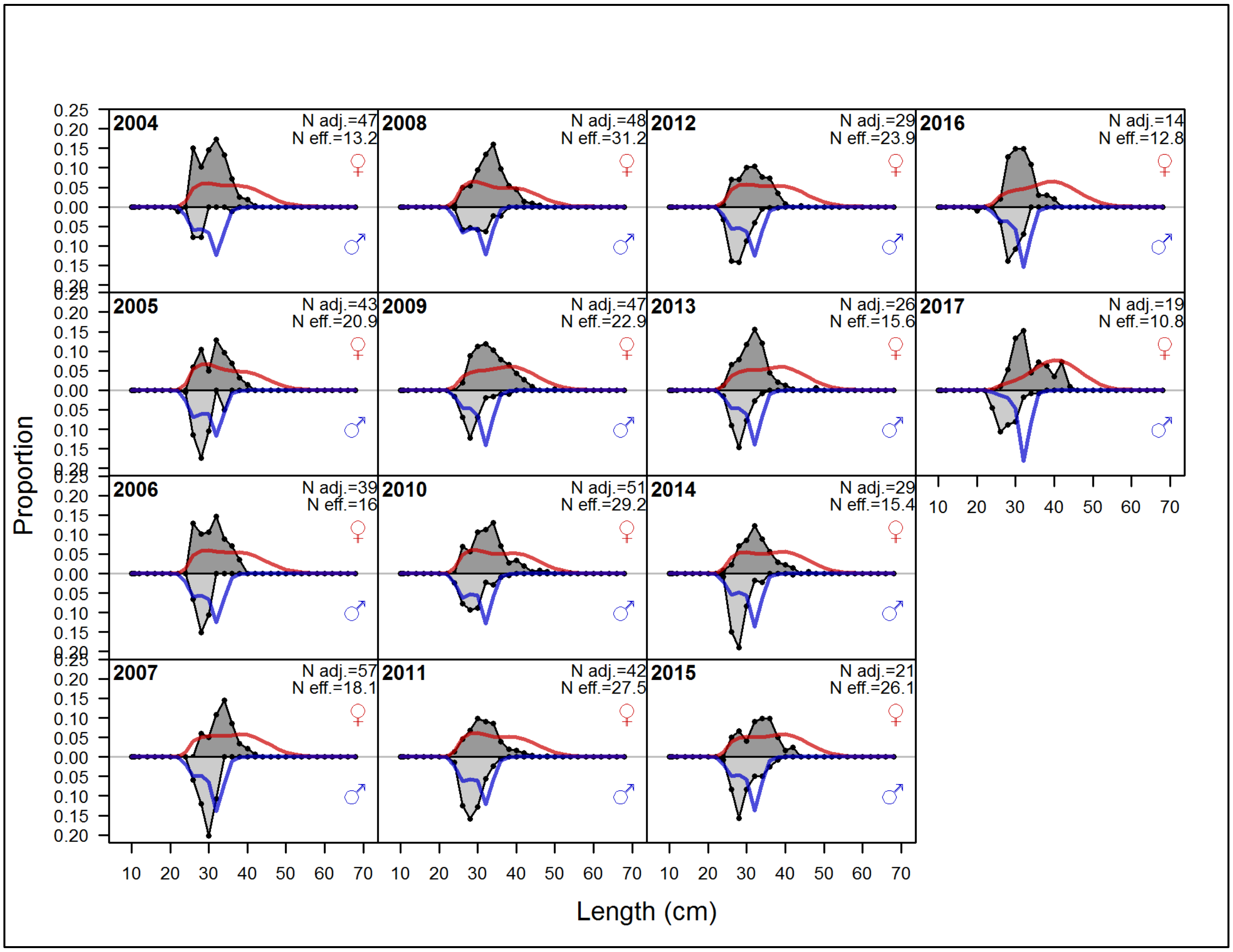

Figure 3.24. Observed and predicted length compositions for the Program 915 survey from the base run of the stock assessment model, 2004–2017. N adj. represents the input effective sample size (number of trips sampled) and N eff. represents the model estimate of effective sample size.

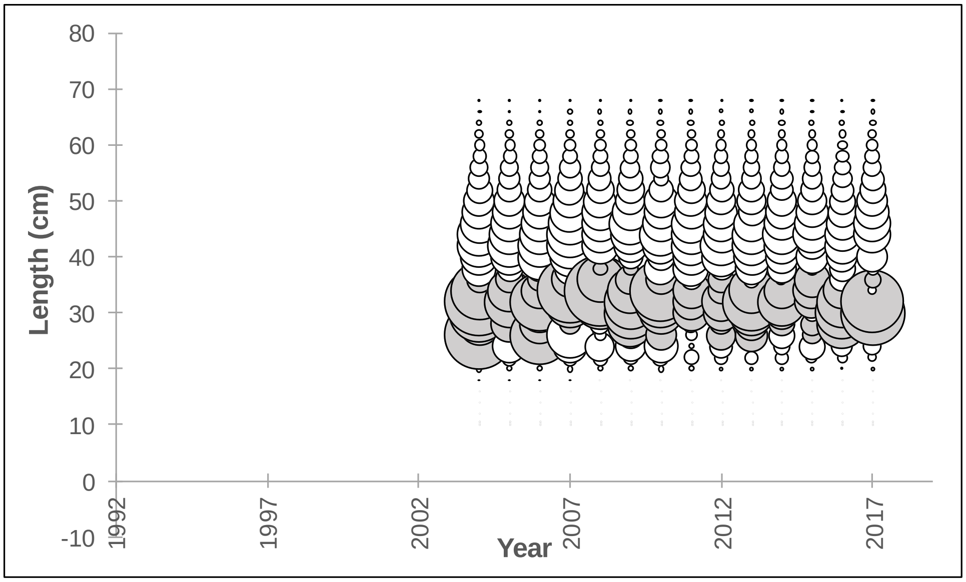

Figure 3.25. Standardized residuals for the female Program 915 length composition data from the base run of the stock assessment model, 2004–2017. Gray circles represent positive residuals while white circles represent negative residuals. The area of the circles is proportional to the size of the residuals.

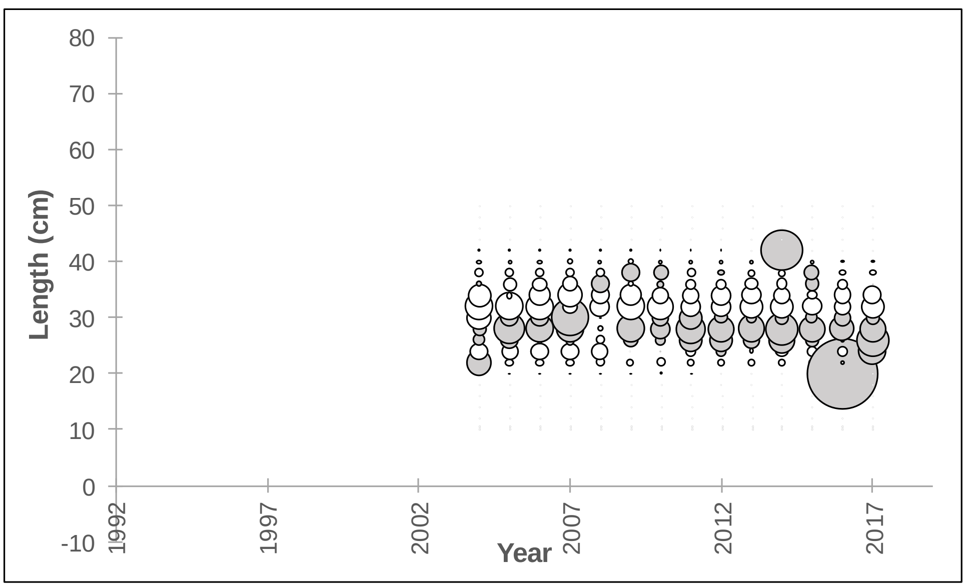

Figure 3.26. Standardized residuals for the male Program 915 length composition data from the base run of the stock assessment model, 2004–2017. Gray circles represent positive residuals while white circles represent negative residuals. The area of the circles is proportional to the size of the residuals.

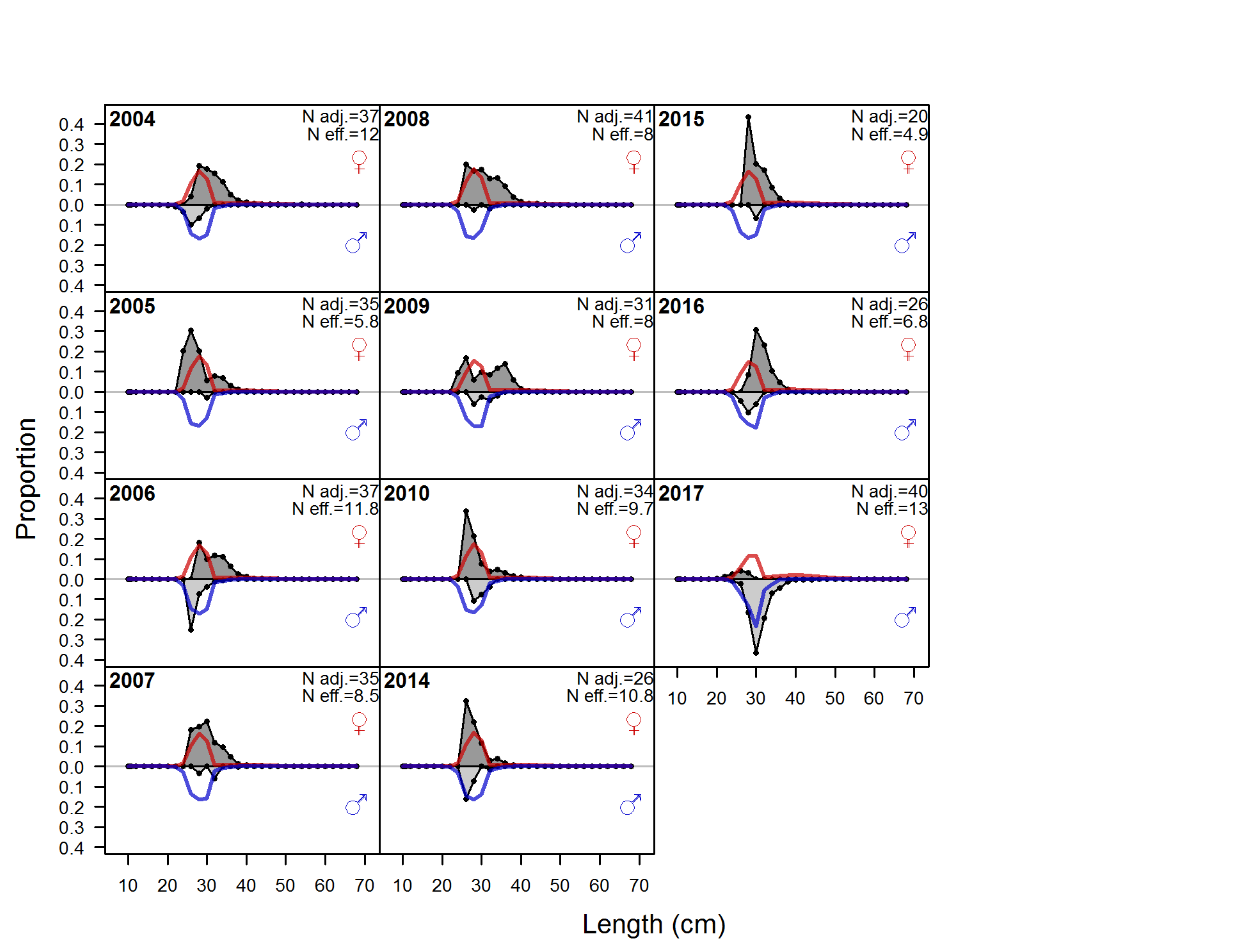

Figure 3.27. Observed and predicted length compositions for the Program 146 survey from the base run of the stock assessment model, 2004–2017. N adj. represents the input effective sample size (number of trips sampled) and N eff. represents the model estimate of effective sample size.

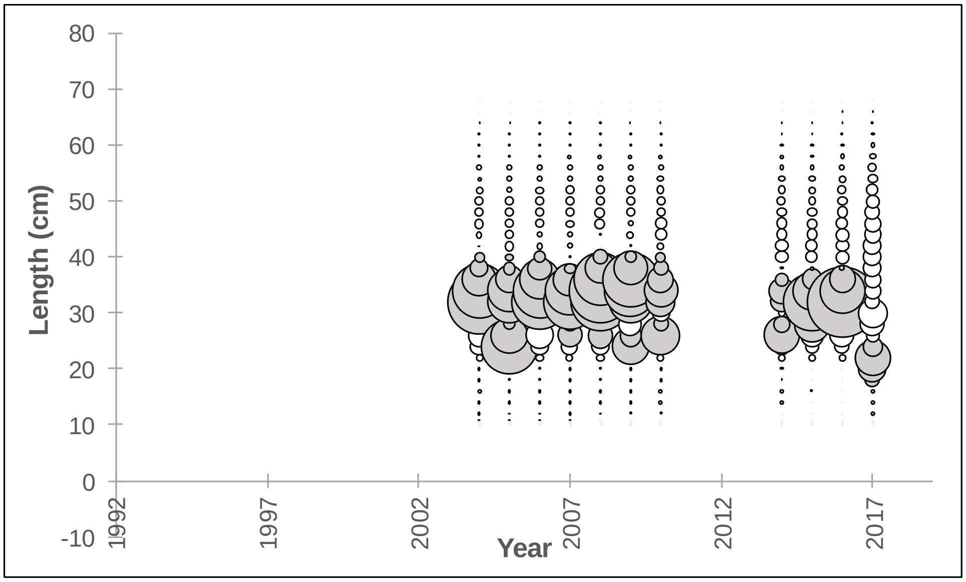

Figure 3.28. Standardized residuals for the female Program 146 length composition data from the base run of the stock assessment model, 2004–2017. Gray circles represent positive residuals while white circles represent negative residuals. The area of the circles is proportional to the size of the residuals.

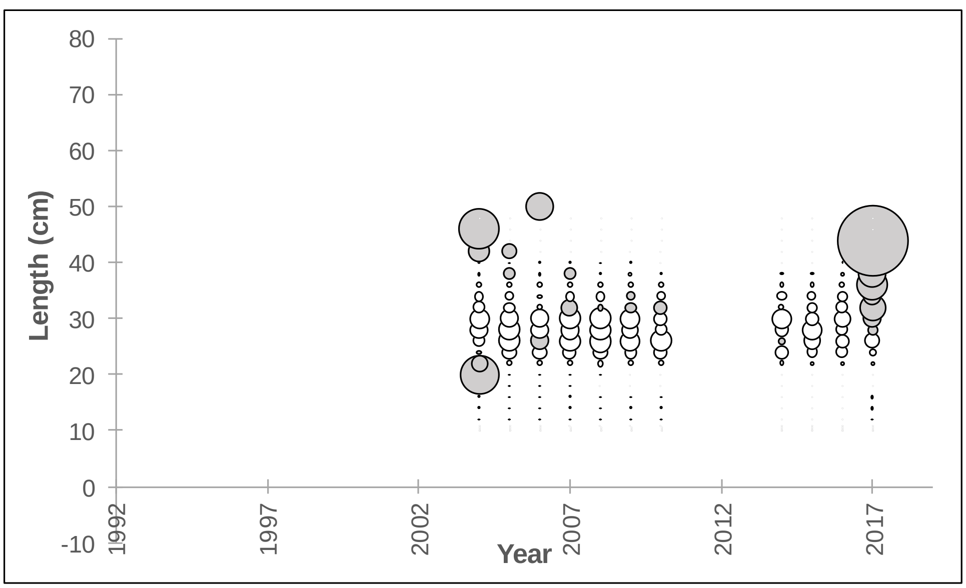

Figure 3.29. Standardized residuals for the male Program 146 length composition data from the base run of the stock assessment model, 2004–2017. Gray circles represent positive residuals while white circles represent negative residuals. The area of the circles is proportional to the size of the residuals.

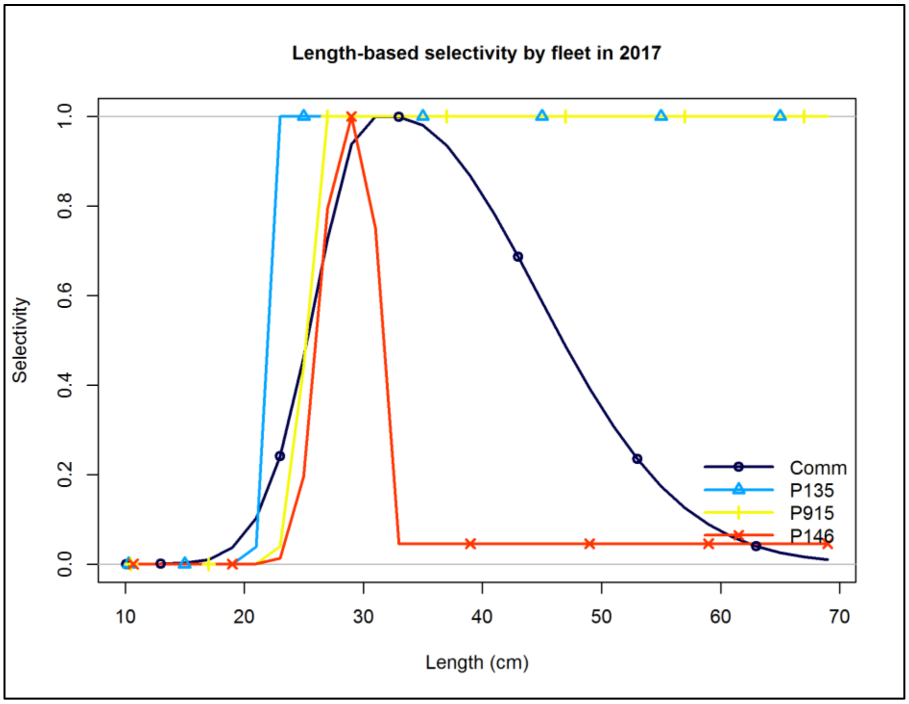

Figure 3.30. Predicted length-based selectivity for the commercial fleet and three fisheries-independent surveys from the base run of the stock assessment model.

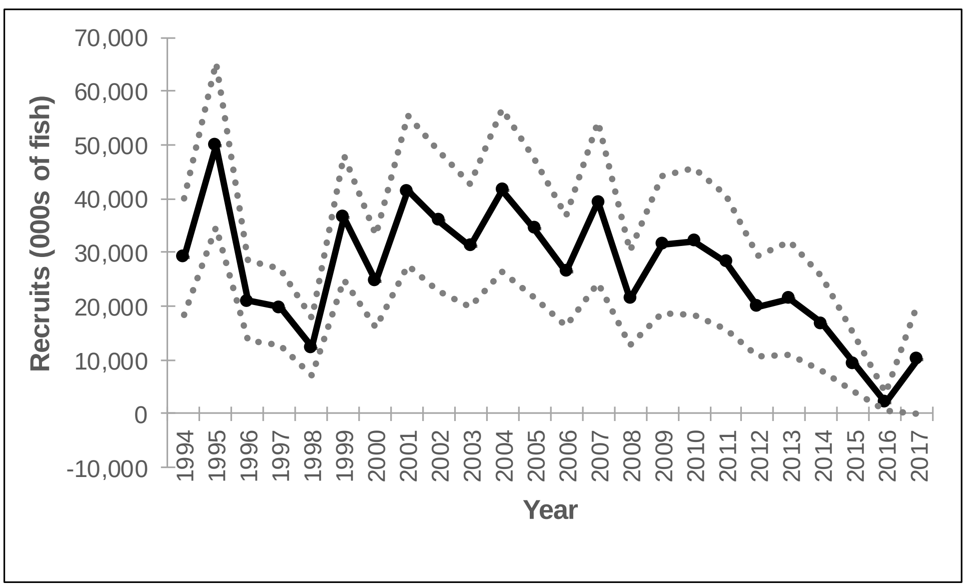

Figure 3.31. Annual predicted recruitment from the base run of the stock assessment model, 1994–2017.

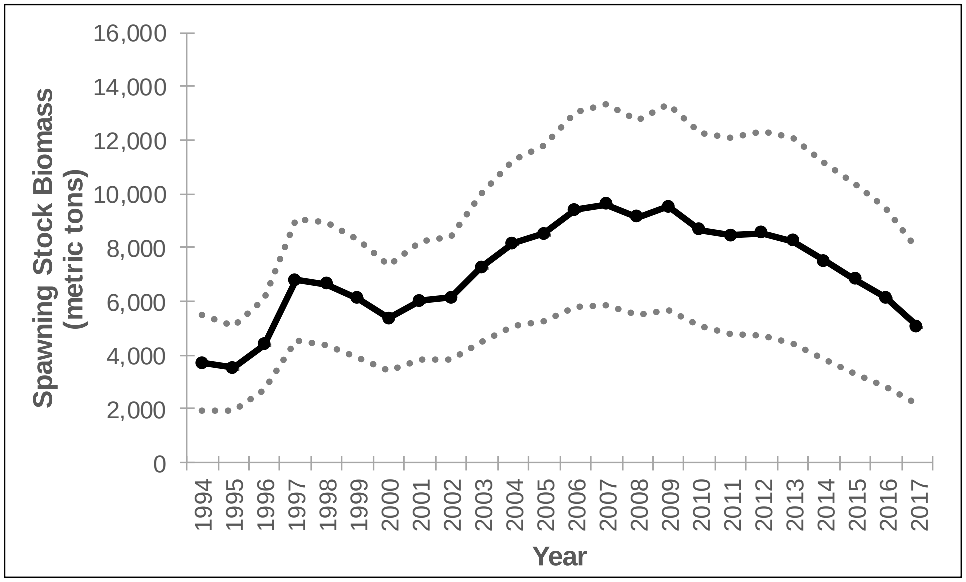

Figure 3.32. Annual predicted female spawning stock biomass from the base run of the stock assessment model, 1994–2017.

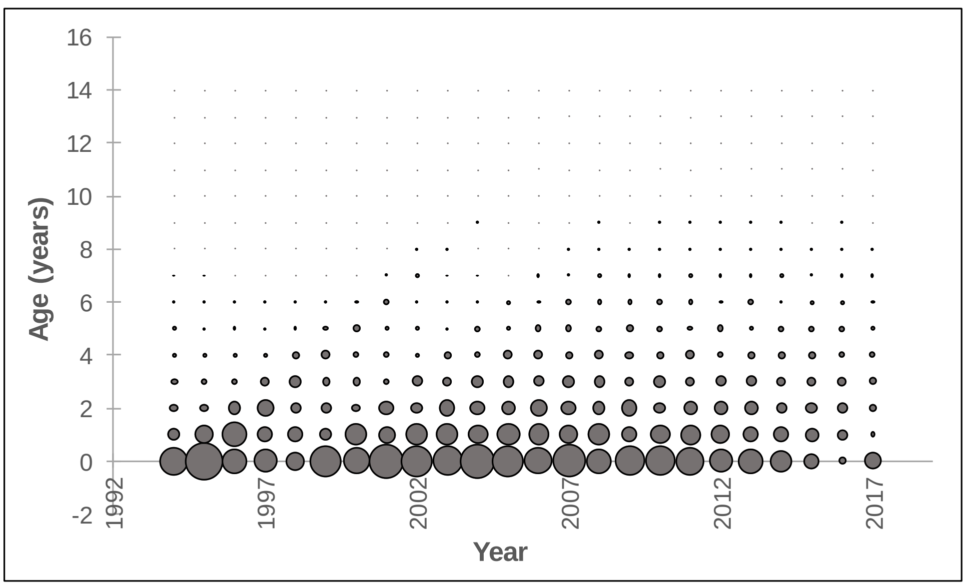

Figure 3.33. Predicted stock numbers at age from the base run of the stock assessment model, 1994–2017. The area of the circles is proportional to the size of the age class.

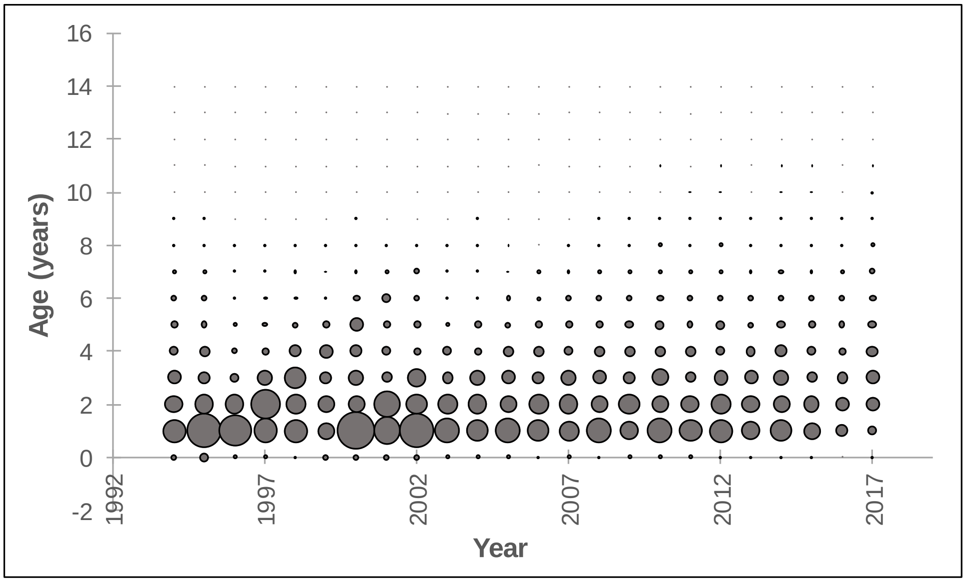

Figure 3.34. Predicted commercial landings at age from the base run of the stock assessment model, 1994–2017. The area of the circles is proportional to the size of the age class.

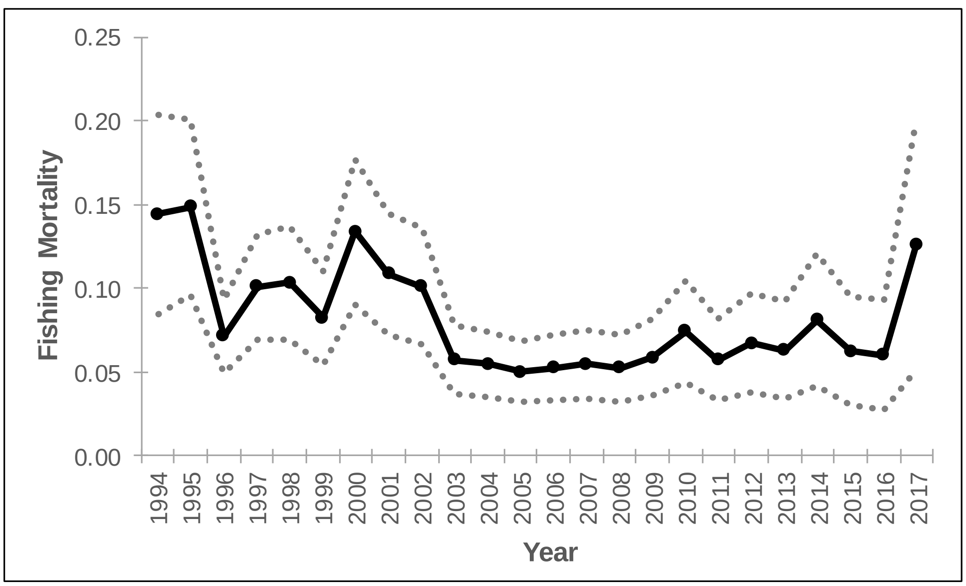

Figure 3.35. Annual estimates of fishing mortality (numbers-weighted, ages 1–5) from the base run of the stock assessment model, 1994–2017.

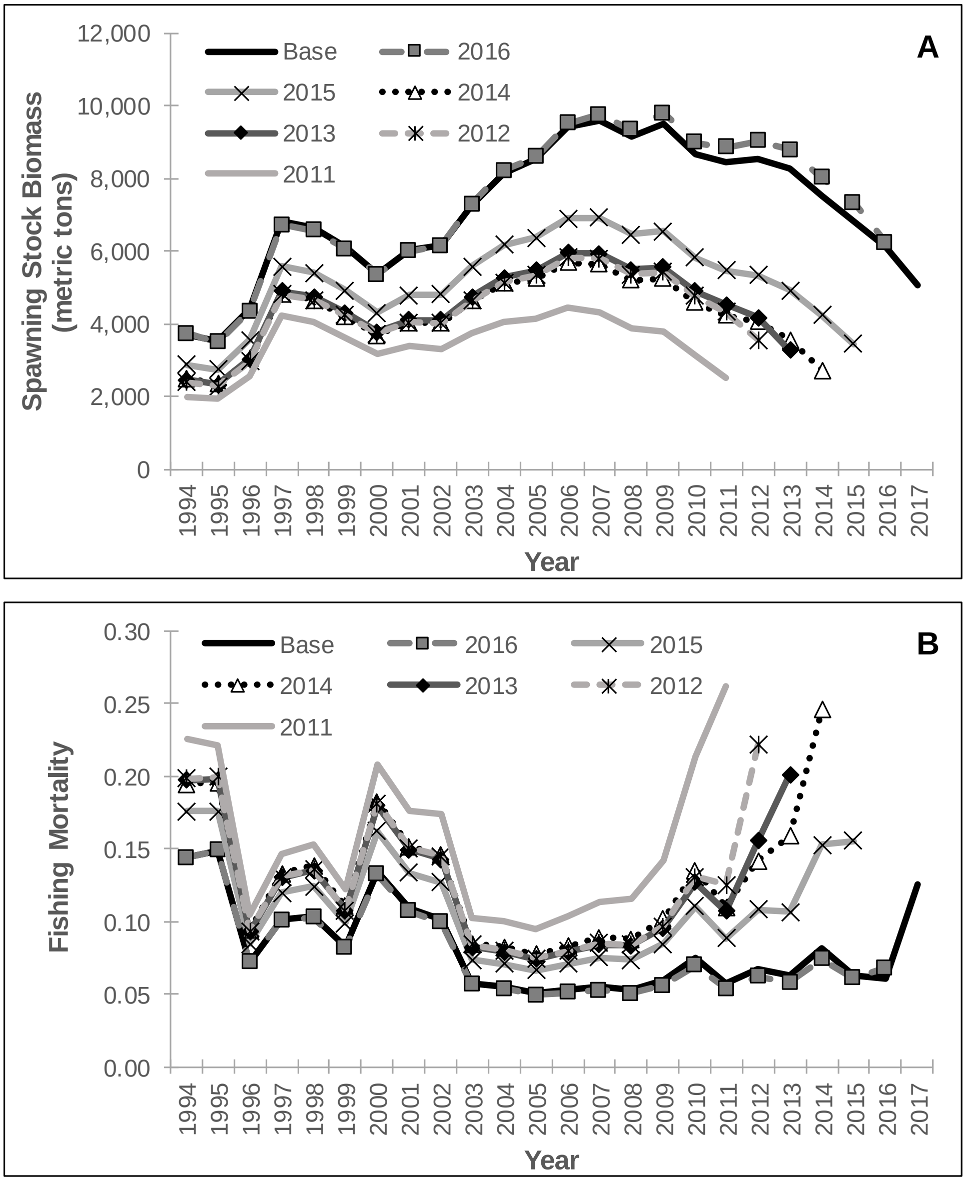

Figure 3.36. Predicted (A) female spawning stock biomass and (B) fishing mortality (numbers-weighted, ages 1–5) from a retrospective analysis of the base run of the stock assessment model, 1994–2017.

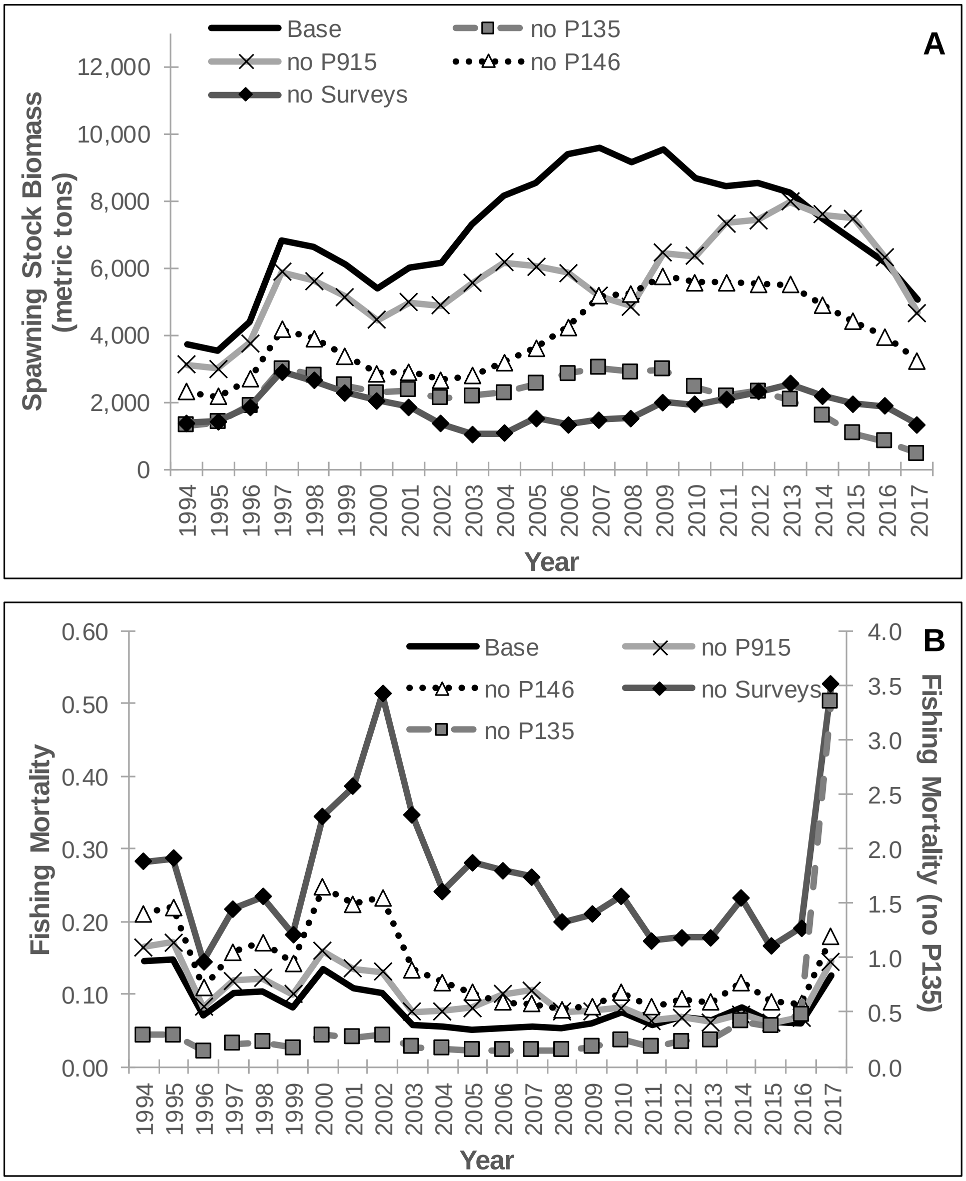

Figure 3.37. Sensitivity of model-predicted (A) female spawning stock biomass and (B) fishing mortality (numbers-weighted, ages 1–5) to removal of different fisheries-independent data from the base run of the stock assessment model, 1994–2017.

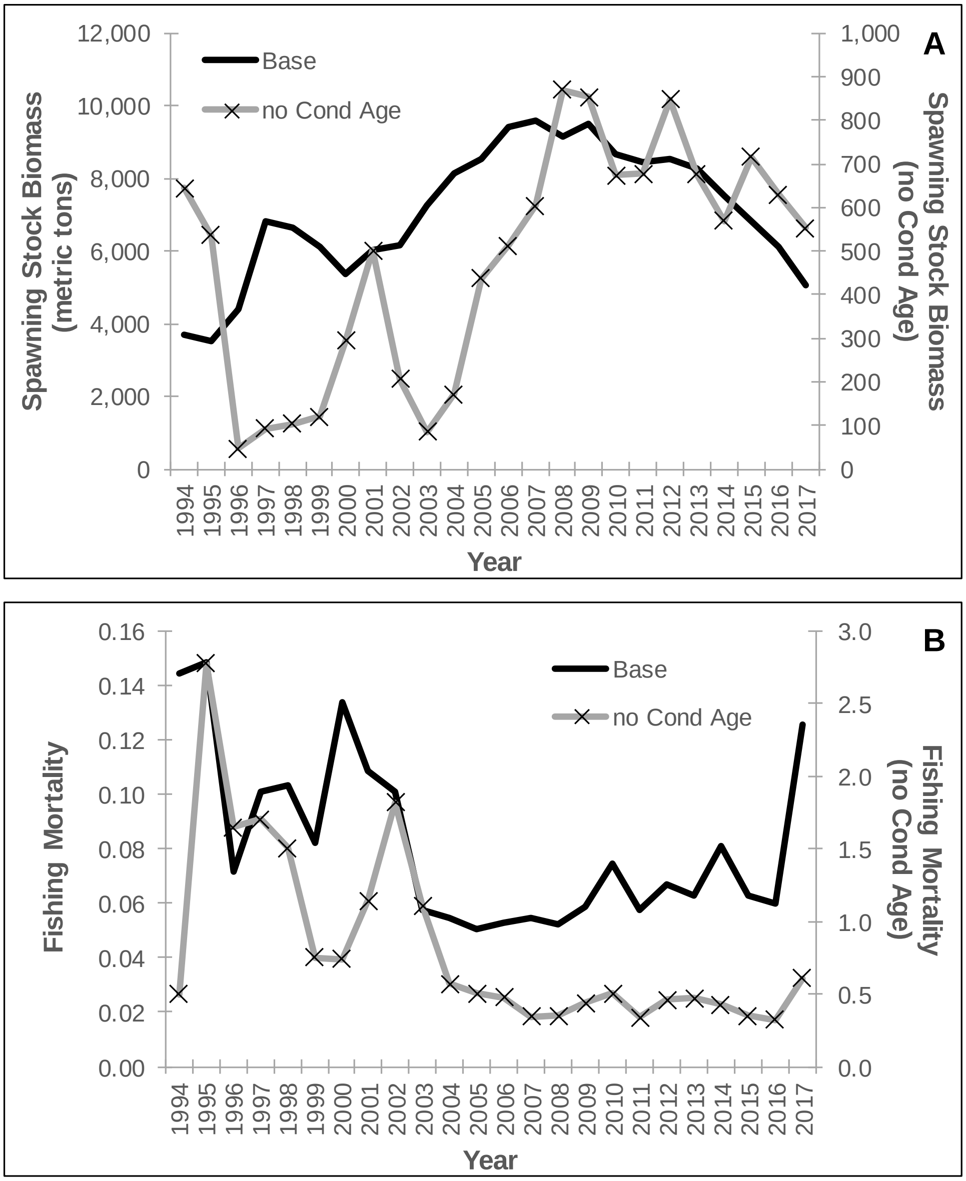

Figure 3.38. Sensitivity of model-predicted (A) female spawning stock biomass and (B) fishing mortality (numbers-weighted, ages 1–5) to removal of the conditional age-at-length data from the base run of the stock assessment model, 1994–2017.

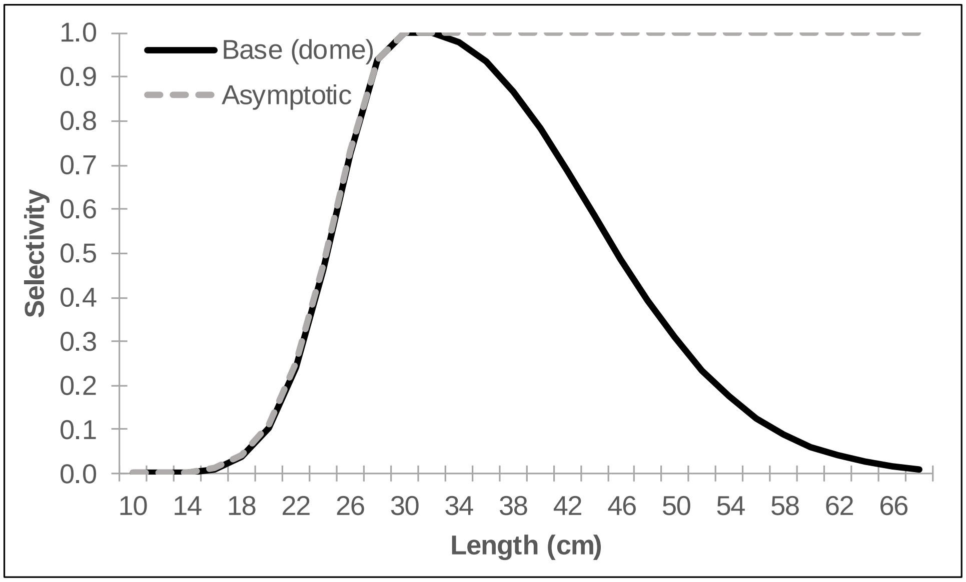

Figure 3.39. Comparison of predicted selectivity curves for the commercial fleet between the base run and the run in which asymptotic selectivity was assumed.

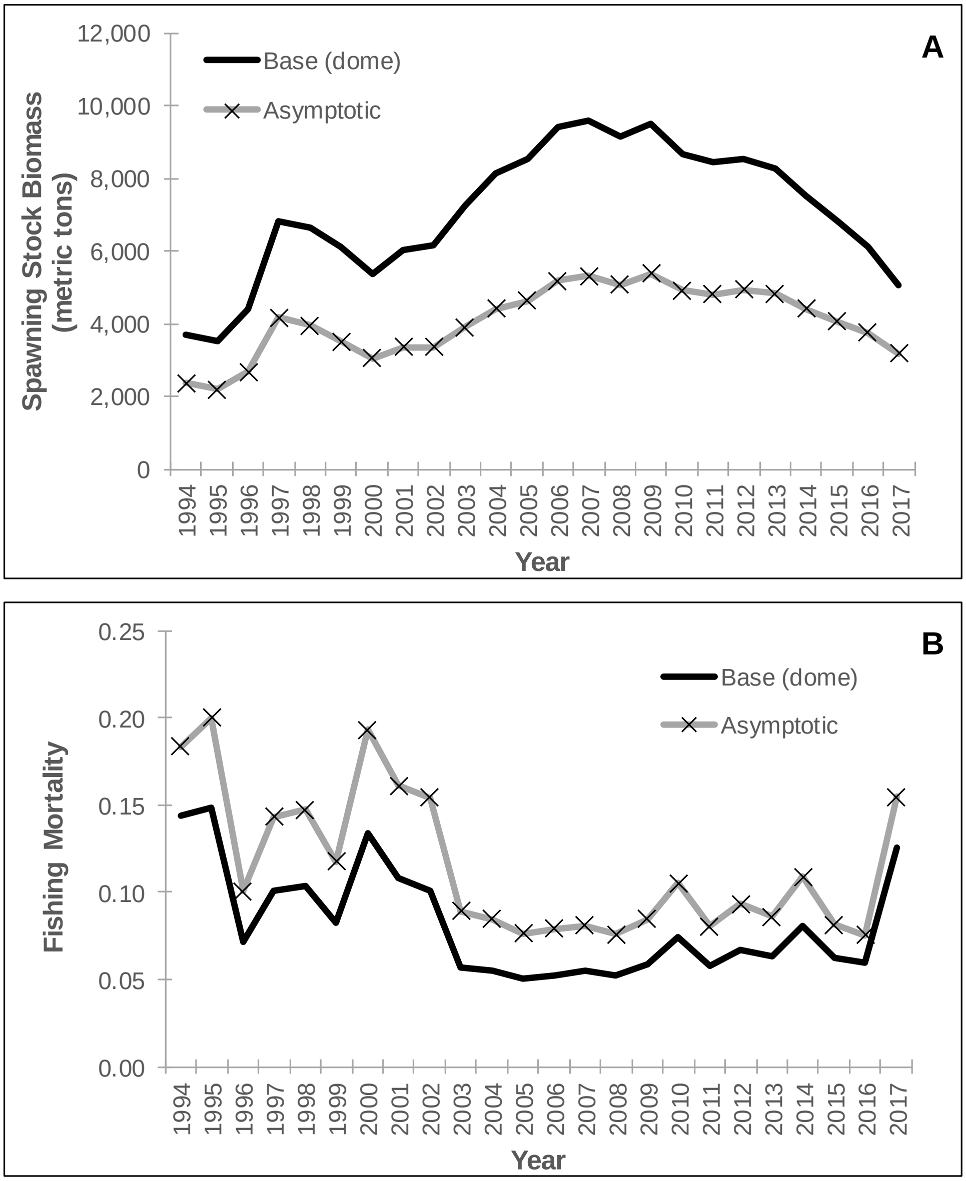

Figure 3.40. Sensitivity of model-predicted (A) female spawning stock biomass and (B) fishing mortality (numbers-weighted, ages 1–5) to the assumed shape of the selectivity pattern for the commercial fleet, 1994–2017.

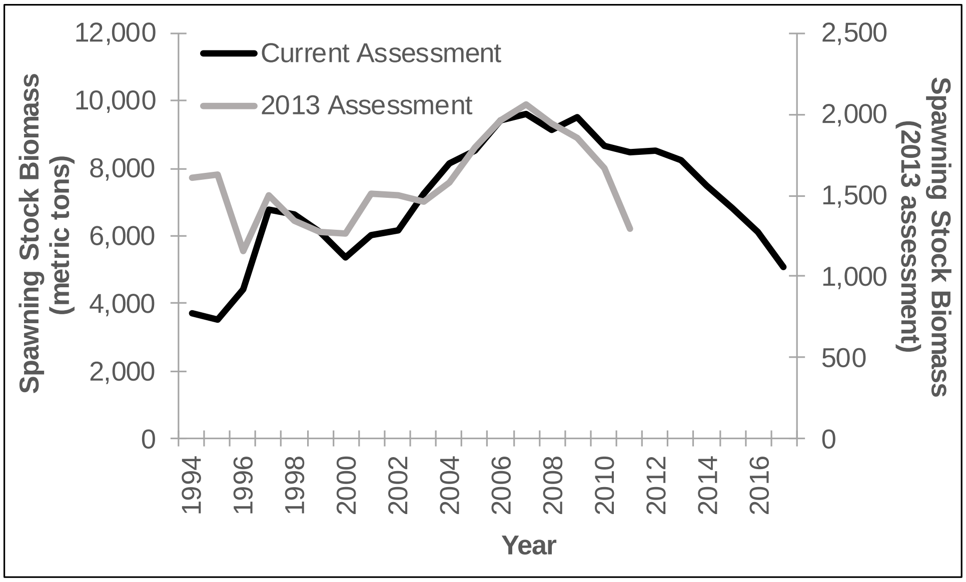

Figure 3.41. Comparison of estimates of female spawning stock biomass from the current and previous NCDMF stock assessments.

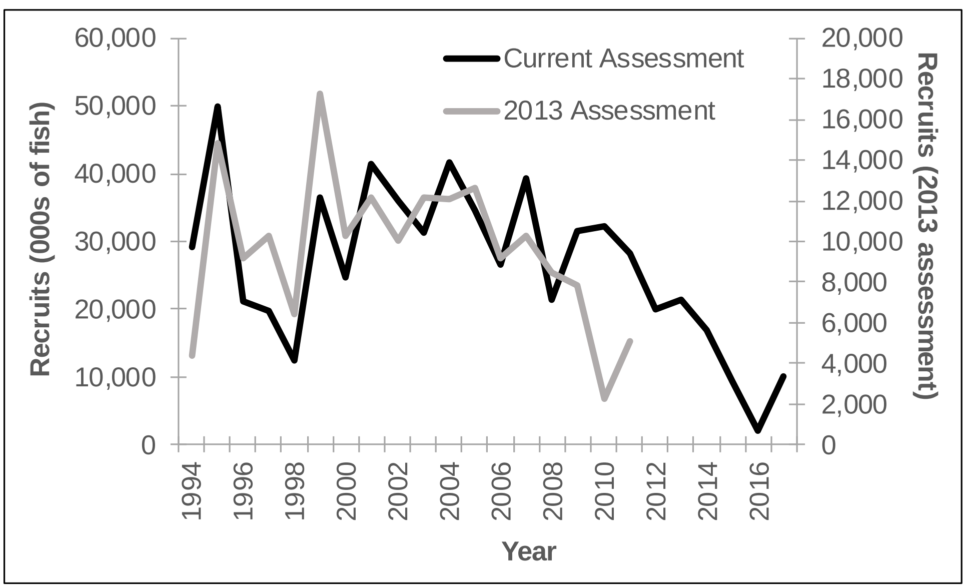

Figure 3.42. Comparison of estimates of recruitment from the current and previous NCDMF stock assessments.

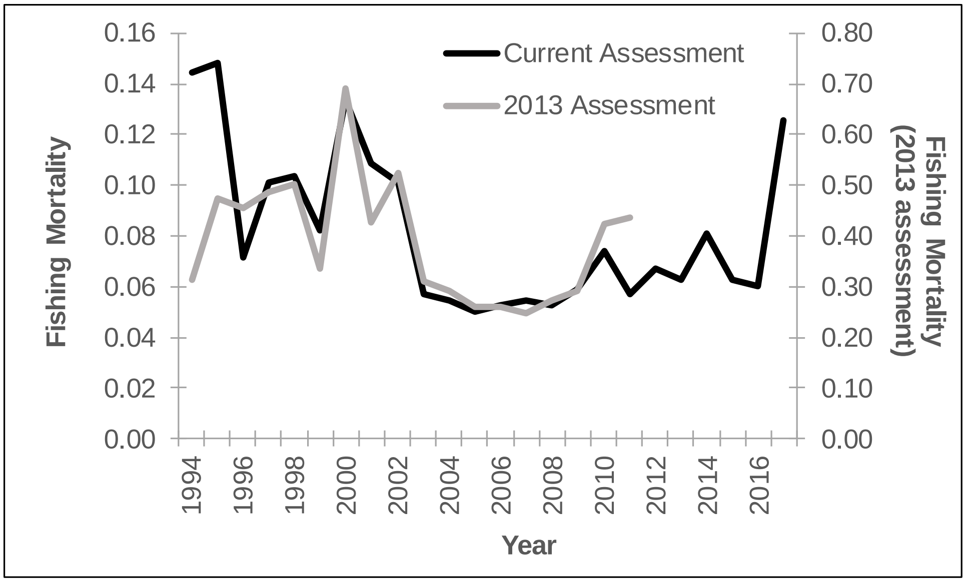

Figure 3.43. Comparison of estimates of fishing mortality from the current (numbers-weighted, ages 1–5) and previous (numbers-weighted, ages 2–5) NCDMF stock assessments.

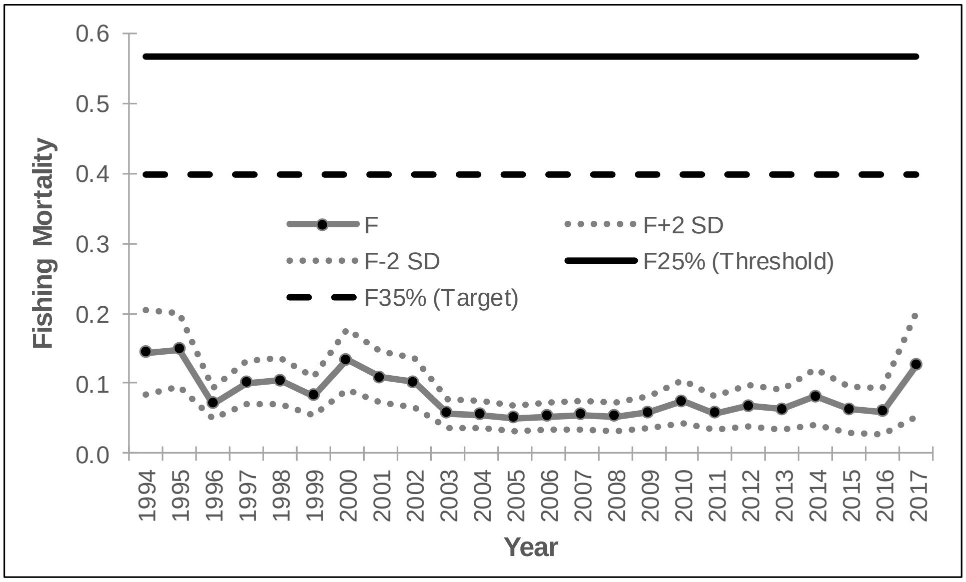

Figure 4.1. Comparison of annual estimates of fishing mortality (numbers weighted, ages 1–5) from the base run to estimates of the fishing mortality target ($F_{35\%}$) and threshold ($F_{25\%}$).