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

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Prepared by

North Carolina Division of Marine Fisheries
Striped Mullet Plan Development Team

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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.

A forward-projecting, length-based, age-structured model was applied to data characterizing commercial landings, recreational harvest, fisheries-independent survey indices, and biological data collected from 1950 through 2019. Both the observed data and the model predictions suggest a decreased presence of larger, older striped mullet in the population. The model has estimated declining trends in age-0 recruitment and female spawning stock biomass (SSB) over the last several decades. Estimates of fishing mortality (F) exhibit an increasing trend. Model results also indicate consistent overestimation of biomass and the highest risk for overfishing.

Amendment 1 to the NCDMF FMP for striped mullet adopted a fishing mortality threshold of $F_{25\%}$ and a fishing mortality target of $F_{35\%}$. The working group recommended complementary reference points for stock size based on female SSB, $SSB_{25\%}$ and $SSB_{35\%}$. The stock assessment model estimated a value of 0.37 for $F_{25\%}$ and a value of 0.26 for $F_{35\%}$. These estimates represent numbers-weighted values for ages 1 through 5. Predicted F in 2019 is 0.42, which is larger than the $F_{25\%}$ threshold and so suggests that overfishing is occurring. The model estimated a value of 619 mt for the $SSB_{25\%}$ threshold and a value of 1,015 mt for the $SSB_{35\%}$ target. Female SSB in 2019 was estimated at 263 mt, which is smaller than the $SSB_{25\%}$ threshold and so suggests the stock is overfished.

An independent, external peer review of this stock assessment approved the stock assessment for use in management for at least the next five years.

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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).

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 waters (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 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 and are 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). Partial migration, where only a proportion of a population migrates during a season, has been observed to occur in striped mullet populations on the east coast of Florida (Myers et al. 2020) and the eastern coast of Australia (Fowler et al. 2016) and is suggested to occur in relation to skipped spawning.

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 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

Otoliths and scales have been validated as ageing structures for striped mullet (Hsu and Tzeng 2009). 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). A 15-year-old striped mullet of unknown sex was observed in 2017 by the North Carolina Division of Marine Fisheries (NCDMF). Maximum reported sizes ranged from 698 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 growth slows during the time they deplete 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 at this stage 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

Biological samples were obtained from various fisheries-independent and fisheries-dependent sources and collected by the NCDMF.

Age-Length

Available otolith-based age data were fit with a von Bertalanffy age-length model to estimate growth parameters for both female and male striped mullet. Length at age was modeled using the von Bertalanffy (1938) growth model as:

$$L_{i,j} = L_{\infty,j}(1 - \exp\left(-K_j\left(t_{i,j} - t_{0,j}\right)\right))\exp(\varepsilon_{L,i,j})$$

$$\varepsilon_{L,i,j} \sim N(0, \sigma^2_{L,j})$$

where j indexes the sex, L_i and t_i are the fork length (cm) and age (fractional age in years) of individual i, respectively, and the parameters to be estimated were the asymptotic length L_∞, the growth coefficient K, and the theoretical age at which a fish has a length of zero t_0. The length $L_{i,j}$ of individual fish sampled was assumed to follow a lognormal distribution.

A Bayesian hierarchical approach was used to estimate parameters with a hierarchical structure for growth parameters priors. Growth parameters $L_{\infty,j}$, K_j, and $t_{0,j}$ were assumed to vary by sex and the logarithm of sex-specific parameters were assumed to be multivariate normally distributed (*MVN*), and $t_{0,j}$ was assumed to follow a normal distribution controlled by sex-average parameters:

$$\begin{bmatrix} lnL_{\infty,j} \\ lnK_j \end{bmatrix} \sim MVN\left(\begin{bmatrix} ln\bar{L}_\infty \\ ln\bar{K} \end{bmatrix}, \Sigma\right),$$

$$t_{0,j} \sim N\left(\overline{t_0}, \sigma^2_{t_0}\right),$$

where $\bar{L}_\infty$, $\bar{K}$, and $\overline{t_0}$ are sex-average parameters with uniform distributions and the standard deviation σ_{t_0} was also assumed to be uniformly distributed. The variance-covariance matrix Σ was modeled with an inverse-Wishart distribution (Gelman and Hill 2007) as:

$$\Sigma = \begin{bmatrix} \sigma^2_{L\infty} & \varphi \\ \varphi & \sigma^2_K \end{bmatrix},$$

where σ_{L_∞} and σ_K are standard deviations of lnL_∞ and lnK across sexes and represent variability in growth between sexes; φ is the covariance of lnL_∞ and lnK across sexes. High negative correlation of L_∞ and K have previously been observed in the von Bertalanffy growth model

(Kimura 2008; Midway et al. 2015); therefore, in order to improve model convergence, L_∞ and K parameters were modeled jointly with a negative correlation.

Posterior distributions were obtained using the Metropolis-Hasting algorithm using Markov Chain Monte Carlo simulation (Hilborn et al. 1994; Hoff 2009). Three concurrent chains were run with a total of 100,000 iterations for each chain. The first 70,000 iterations were discarded as burn-in and every 10th of the remaining samples from each chain were saved for analysis. The JAGS (version 4.3.0) was used to run the Bayesian analysis.

The predicted growth curves appeared to fit the observations well for females (Figure 1.1) and males (Figure 1.2). The estimated parameters from this and previous studies are presented in Table 1.1.

Length-Weight

Parameters of the 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 using non-linear least squares. Weight (W) at length (L) was modeled as:

$$W_i \sim a * L_i{}^b$$

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 it is generally 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. Skipped spawning has also been exhibited by striped mullet on the east coast of Florida (Myers et al. 2020) and on the eastern coast of Australia (Fowler et al. 2016), though factors influencing skipped spawning are unknown (Myers et al. 2020).

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).

Previous NCDMF stock assessments of striped mullet (Wong 2006; NCDMF 2103, 2018) applied maturity parameters derived from macroscopic analysis of reproductive tissues. Because this approach relies on visual examination, it is considered subjective and can lead to inaccurate estimates of maturation, which, in turn, can lead to biased estimates of both spawning stock biomass and associated reference points as well as distorting the stock-recruitment relationship (Murawski et al. 2001; Morgan 2008). The NCDMF conducted a maturity study using three different maturity staging methods (macroscopic, whole mount, histological) to estimate the maturity ogive for striped mullet and other species in order to improve the accuracy of NCDMF management targets and assessments of fishery stock viability (NCDMF 2021). The histological method is considered more objective, accurate, and reliable of the three approaches (e.g., Vitale et al. 2006; Midway and Scharf 2012). Logistic regression was applied to the maturity samples from female striped mullet to estimate the length at 50% maturity (L_{50}) and slope. Based on the histological data, the value of L_{50} for females was estimated as 31.9 cm and the estimated slope was -0.375 (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. Few studies exist directed at the natural mortality of striped mullet. Stomach content analyses of bottlenose dolphin (*Tursiops truncatus*) in Florida found 16.7% frequency occurrence of mullet (*Mugil* spp.; Barros and Odell 1990). Another study of bottlenose dolphin stomach contents in Florida found <1% frequency of occurrence of striped mullet (Pate and McFee 2012). Finally, a North Carolina study found a 3% frequency of occurrence of striped mullet in the stomach contents of bottlenose dolphins (Gannon and Waples 2004).

Several approaches have been developed to provide indirect estimates of M at age (Peterson and Wroblewski 1984; Boudreau and Dickie 1989; Lorenzen 1996, 2005). Here, the Lorenzen (1996) approach was used to produce estimates of M at age. This approach is based on the relationship of body weight to natural mortality and requires estimates of parameters from the von Bertalanffy age-length growth function, estimates of parameters from the length-weight relationship, and the range of ages over which M will be estimated. Based on empirical age data collected by the NCDMF, a maximum age of 13 was used for females and a maximum age of 14 was used for males (section 1.2.3). As expected, estimates of M decrease with increasing age (Table 1.3).

1.2.7 Food & Feeding Habits

Striped mullet are recognized as an important ecological bridge among a wide range of trophic levels. They connect 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; Binion-Rock 2018); however, striped mullet likely contribute minimally to the diets of juvenile and adult red drum (Facendola and Scharf 2012; Peacock 2014), striped bass (Rudershausen et al. 2005) and other finfish species (Binion-Rock 2018) in North Carolina estuaries. 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 plays a major role on habitat use and distribution of both adult and juvenile mullet (Cardona 2000). Striped mullet 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). 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). 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 and prefer depths of 3 m or less.

1.3.1 Spawning Habitat

As discussed in section 1.2.5, the spawning location of striped mullet 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.

1.3.2 Nursery & Juvenile Habitat

Juvenile striped mullet spend most of their life in estuarine rivers and marshes, with abundance highest in May and lowest in September (Bretsch and Allen 2006; McDonough and Wenner 2003). Juvenile striped mullet use wetlands for foraging and refuge from predators. Striped mullet have been observed in both 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 use 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 move offshore to their spawning grounds.

1.3.4 Habitat Issues & Concerns

Suitable 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 estuarine habitat and water quality are probably one of the most important factors in providing sustainable striped mullet stocks. All 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 larval striped mullet estuarine ingress and adult egress, terminal groins may threaten 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

The striped mullet commercial fishery played a prominent role early in the 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 commercial fishery operated at an average of over 1,200 metric tons (mt) annually during the late 1800s (Figure 1.6). Peak commercial landings of over 3,000 mt and 2,300 mt were harvested in 1902 and 1908 (Chestnut and Davis 1975). The commercial fishery was highly seasonal and occurred primarily during the fall spawning migration, but commercial landings occurred throughout the year (Taylor 1951; Woodward 1956). Enormous catches—greater than 450 mt (1 million pounds) of mullet landed 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, commercial landings exceeded 1,300 mt for the first time in 28 years. From 1988 to 2002, North Carolina's commercial fishery landed an average of 1,032 mt of striped mullet per year. Annual commercial landings ranged from a low 438 mt in 2016 to a high of 945 mt in 2010 between 2003 and 2019. During this same time period, commercial landings averaged 715 mt per year.

Because the commercial fishery primarily targets striped mullet roe, the fishery is seasonal with the highest demand and landings occurring in the fall when large schools form during the spawning migration to the ocean. From 1994 to 2019, a total of 110,220 commercial trips reported striped mullet landings in September, October, and November. A total of 65% of striped mullet commercial landings are reported in the fall months of September, October, and November and the highest commercial landings occur in October (Table 1.4). The percentage of commercial landings that occur during the winter and summer are similar at 13% and 14%, respectively, while spring accounts for 7.4% of the overall commercial landings.

From 1887 to 1978, a total of 60% of the commercial landings were from seines and 39% were from gill nets (Chestnut and Davis 1975; NCDMF, unpublished data). Since 1989, gill nets (runaround, set, and drift) have replaced seines as the dominant gear type in the commercial fishery. Gill nets have been the dominant commercial gear from 1994 through 2019 (Figure 1.7). Although still in use, seines and stop nets account for less than five percent of the commercial landings from 1994 to 2019.

Hurricanes occur frequently in eastern North Carolina, particularly in the fall during peak striped mullet fishing periods and can have significant impacts on the striped mullet fishery, though impacts are inconsistent and largely influenced by timing of the hurricane. Hurricanes can damage fishing gear, prevent fishermen from fishing, or can cause striped mullet to leave the estuarine system earlier than normal (Burgess et al. 2007); however, the potential reduction in fishing mortality during hurricane years would likely have a positive effect on spawning stock biomass of the striped mullet stock in subsequent years.

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; NCDMF 2020). YOY mullet, 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 July, August, September, and October (NCDMF 2020).

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 fishery management plans (FMPs) that apply specifically to the striped mullet fishery in North Carolina.

1.5.2 Management Unit Definition

The management unit includes 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 (NCMFC) adopted the FMP for striped mullet in joint and coastal waters of North Carolina. The 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.

Few regulations exist that pertain directly to striped mullet. Most regulations that affect 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 mullet (striped and white combined) per person per day
- 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 NCMFC'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.
    - 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.

- 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.

1.5.4 Current Regulations

Detailed information regarding North Carolina's current commercial and recreational fishery regulations is available on the NCDMF website (https://deq.nc.gov/about/divisions/marine-fisheries/rules-proclamations-and-size-and-bag-limits).

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). In 2020, the stop net fishery was open from October 15 through December 31 (Proclamation M-17-2020). 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 with a minimum of 8 inches stretched mesh and the remaining section of the net must be constructed of webbing with 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.

1.5.5 Management Performance

The North Carolina commercial fishery for striped mullet (*Mugil cephalus*) is one of the largest along the U.S. Atlantic seaboard and is a predominately fall, roe-targeting, gill-net fishery. Strong demand from Asia for striped mullet roe and competing roe-exporting companies combined to create a highly profitable roe fishery in North Carolina. Rapid surges in roe values in the late 1980s, followed by rising commercial fishing effort and landings through the mid-1990s, caused concern for the North Carolina striped mullet stock. Striped mullet was officially recognized as a species of concern by the state of North Carolina in 1999, though no formal stock assessment had been conducted at that time. The North Carolina FMP for Striped Mullet was adopted in April 2006 and reclassified the stock as viable (NCDMF 2006). The first assessment of the North Carolina striped mullet stock was performed in association with the development of the NCDMF Striped Mullet FMP (Wong 2006). The results of the assessment indicated the stock was not undergoing overfishing in the terminal year of the assessment, 2002. Stock status with respect to the overfished condition could not be reliably determined and was considered uncertain.

While the North Carolina striped mullet stock was not experiencing overfishing in 2002, it was being fished near the maximum exploitation level that could maintain sustainability (Wong 2006). The 2006 FMP established minimum and maximum commercial landings thresholds of 1.3 and 3.1 million pounds, respectively (NCDMF 2006). If commercial landings fell below the minimum threshold, the NCDMF would initiate further analysis of the data to determine if the decrease in commercial landings was attributed to a stock decline or decreased fishing effort. If commercial landings exceeded the maximum threshold, the NCDMF would initiate analysis to determine if commercial harvest is sustainable and assess factors that may be driving the increase in harvest.

Amendment 1 to the NCDMF Striped Mullet FMP was adopted in November 2015 (NCDMF 2015). Amendment 1 maintained the stock status classification as viable based on results of the stock assessment completed in 2013. Amendment 1 also raised the fishing mortality target from $F_{30\%}$ spawning potential ratio (SPR) to $F_{35\%}$ SPR to account for the potential role of striped mullet as a forage species. Although overfishing was not occurring in 2011, fishing mortality had been increasing and recruitment had been declining (NCDMF 2013). The 2015 FMP updated the minimum and maximum commercial landings thresholds using commercial landings from 1994 through 2011 (NCDMF 2015). The updated minimum and maximum commercial landings thresholds were set at 1.13 and 2.76 million pounds, respectively. Amendment 1 also implemented adaptive management for striped mullet. This allows management measures, if needed to maintain sustainable harvest, to be implemented using proclamation authority of the NCDMF director. Any potential management measures will be developed by the Plan Development Team (PDT) in conjunction with the advisory committee and approved by the North Carolina Marine Fisheries Commission (NCMFC) prior to implementation.

Commercial landings in 2016 were 965,198 pounds, which is below the minimum landings trigger of 1.13 million pounds. As required by the FMP, the NCDMF initiated data analysis in July 2017 to determine whether the decrease was attributed to a stock decline, decreased fishing effort, or both. The NCDMF presented the findings from preliminary analysis and recommendations to the NCMFC during its November 2017 business meeting. It was determined by the NCDMF that no management actions were necessary at that time, but a more comprehensive analysis with data through 2017 was needed.

The NCDMF presented results of their comprehensive analysis at the February 2018 NCMFC business meeting and concluded that the stock had likely declined since completion of the 2013 stock assessment, which had a terminal year of 2011. The NCDMF recommended updating the 2013 stock assessment model to include data through 2017 prior to taking management action. As an assessment update, there were no changes to model parameters and peer review was not required as the configuration of the model that previously passed peer review was maintained.

The most recent stock assessment of the North Carolina striped mullet stock was completed in 2018 and used data from 1994 through 2017 (NCDMF 2018). Results of the stock assessment indicated that spawning stock biomass increased from 2003 through 2007 but declined through 2017. Recruitment also declined in the latter portion of the time series, though a slight increase was observed in 2017. Fishing mortality (F) had little variation for most of the time series, with a slight increase in 2017. F in the terminal year (F_{2017} = 0.13) was below both the fishing mortality target ($F_{35\%}$ = 0.40) and threshold ($F_{25\%}$ = 0.57). Because F_{2017} was less than the threshold value, the stock was not undergoing overfishing in 2017. 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 was considered unknown.

Subsequent management options were developed by the NCDMF and presented to the Finfish, Southern, and Northern advisory committees in July 2018 to receive input prior to finalizing the NCDMF recommendation. Recommendations were then presented to the NCMFC at its August 2018 business meeting. The NCDMF and the advisory committees recommended that no management action be taken since the stock assessment update indicated overfishing was not occurring. The NCDMF would continue to monitor trends in the commercial fishery and fisheries-independent indices. The recommendation was approved by the NCMFC.

Review of the 2019 and 2020 commercial landings, while reduced, indicate neither the maximum nor minimum triggers had been exceeded.

1.6 Assessment History

1.6.1 Review of Previous Methods & Results

The first stock assessment of the striped mullet stock in North Carolina waters completed by the NCDMF for management purposes was performed in association with the development of the original Striped Mullet FMP (see section 1.5.5; NCDMF 2006; Wong 2006). The assessment applied a sex-specific, forward-projecting statistical catch-at-age model to estimate population size and fishing mortality rates for the 1994- to 2002-time period. Input data included commercial landings, recreational harvest, three seine surveys, one gill-net survey, and one trammel net survey. Yield-per-recruit and spawning stock biomass-per-recruit analyses were used to estimate appropriate reference points. The results of the assessment indicated the stock was not undergoing overfishing in the terminal year of the assessment, 2002. Stock status with respect to the overfished condition could not be reliably determined and was considered uncertain.

The most recent benchmark stock assessment of North Carolina's striped mullet stock was performed in association with the development of Amendment 1 to the Striped Mullet FMP (see section 1.5.5; NCDMF 2013, 2015). All NCDMF benchmark stock assessments are subject to an external peer review. The 2013 stock assessment applied a sex-specific, forward-projecting statistical catch-at-age model to estimate population size, fishing mortality rates, and reference points (NCDMF 2013). 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. Estimates of biomass-based reference points were considered unreliable due to the assumed poor stock-recruit relationship and this prevented determination of overfished status. Note that the 2013 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.

An update of the 2013 NCDMF stock assessment of striped mullet was completed in 2018 in response to tripping of the minimal commercial landings trigger (section 1.5.5; NCDMF 2018). Since the 2018 stock assessment was an update and not a benchmark, the stock assessment was not subject to peer review. The data used in the 2013 stock assessment were updated through 2017 and applied to the same model as in the 2013 stock assessment. All assumptions made in the 2013 stock assessment were maintained as well. The results of the NCMDF 2013 stock assessment of striped mullet suggested that the stock was not experiencing overfishing in 2017. As with the 2006 and 2013 stock assessment, biomass-based reference point estimates were considered unreliable and so status relative to overfished condition could not be determined.

1.6.2 Progress on Research Recommendations

Research recommendations put forward in the 2018 NCDMF stock assessment of striped mullet (NCDMF 2018) are listed below and progress, if any, is discussed.

- Improve 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

  Historical estimates of recreational fisheries statistics are limited and/or unreliable (see sections 2.1.2 and 2.1.3). The NCDMF began a mail survey in October 2011 to develop catch and effort estimates for recreational cast net and seine use (section 2.1.2). This mail survey was established as a direct response to a lack of precision in the Marine Recreational Information Program (section 2.1.3). While the mail survey provides estimates of recreational harvest, releases, and effort, it does not collect biological data.

- Development of a reliable fisheries-independent index of juvenile abundance

The Beaufort Bridgenet Ichthyoplankton Sampling Program (BBISP) is a volunteer-supported long-term, fixed-site, monitoring survey for larval fish recruitment (see section 2.2.4). The survey began in 1986 and while sampling only occurs at one North Carolina inlet (Beaufort Inlet), it was considered as an index of age-0 recruitment in the initial base run of the current stock assessment; however, the peer review panel had some concerns about the limited spatial scope of the survey and it was not included in the final base run. An expansion of the NCDMF Program 100 seine survey to the Pamlico, Neuse, and Cape Fear rivers occurred in 2017 and may provide juvenile abundance information in the future as the time series builds up.

- Increase the number of age samples from both fisheries-dependent and fisheries-independent sources

  Collection of striped mullet age samples is ongoing through existing fisheries-dependent and fisheries-independent sampling programs and there has been an increased focus on collecting age samples from important commercial fisheries.

- Investigate how catchability of striped mullet by Program 146 (Striped Mullet Electrofishing Survey) is affected by variations in salinity and conductivity

  Surface conductivity has been collected in Program 146 since 2004 (section 2.2.1), but it's impact on catchability has not yet been evaluated.

- Initiate an adult striped mullet survey in the Core and Bogue sound areas where approximately 20% of the striped mullet harvest occurs

  In 2019, Program 915 (Fisheries-Independent Gill-Net Survey; section 2.2.3) was expanded as part of a Coastal Recreational Fishing License grant to include Core Sound, West Bay, Newport River, Bogue Sound, and the White Oak River. Other area segments of this survey are used in this assessment, but the expanded area was not included due to the short time series. The expanded area will be used in future assessments once an adequate time series is achieved. In addition, Program 146 was expanded in October 2021 to include the White Oak River.

- Explore the NOAA Bridgenet Survey as a possible larval/juvenile abundance index for striped mullet

  This survey considered in the initial base run in the current assessment as an index of age-0 recruitment (see sections 2.2.3); however, the peer review panel had some concerns about the limited spatial scope of the survey and it was not included in the final base run.

- Consider sex-specific selectivity curves in future modeling work

  No progress has been made on this recommendation.

- 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 natural mortality (*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 *M*s for fish of this size based on a meta-analysis

  No progress has been made on this recommendation; however, the NCDMF has an existing multi-species tagging program that could incorporate striped mullet.

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 fisherman to the dealer. The data reported on these forms include transaction date, area fished, gear used, and landed species as well as fisherman and dealer information.

Most 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 increases the accuracy of reporting by documenting the correct relationship between gear and species but is not universally used by finfish dealers in North Carolina.

2.1.1.2 Sampling Intensity

North Carolina dealers are required to record the transaction at the time of the transaction 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.

A 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, based on commercial fish house sampling, the proportion of white mullet that occur in North Carolina's commercial landings is considered very small. Striped mullet make up approximately 99% of the total mullet catch based on fishery-dependent sampling (NCDMF, unpublished data).

2.1.1.5 Development of Estimates

Commercial landings were summarized by year using the NCDMF TTP data. Commercial effort was calculated for select gears known to currently or historically target striped mullet. The number of targeted trips for anchored gill nets, runaround gill nets, and stop nets was calculated by year. Targeted trips were defined as those trips that caught only striped mullet or those trips that caught multiple species and at least 100 pounds of striped mullet.

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. The age compositions 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 between 1994 and 2019 (Table 2.1; Figure 2.1). Most commercial targeted trips for striped mullet in recent years occurred in the runaround gill-net fishery (Table 2.1; Figure 2.2). While the stop net fishery was important historically and can be a high volume striped mullet fishery, it has had relatively few trips since 1994.

The availability of striped mullet length samples from the commercial fishery was relatively low in the mid-1990s but substantially increased after 1996 (Table 2.2). The availability of sex-specific age samples has been low throughout the time series of interest.

Length-frequency distributions of striped mullet from the commercial fishery have been relatively consistent throughout the time series (Figure 2.3). The commercial landings are dominated by age-1 and age-2 striped mullet and there is some evidence the age distribution of the landings has truncated in recent years (Figure 2.4).

2.1.2 Recreational Fishery Mail Survey

2.1.2.1 Survey Design & Methods

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 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 Marine Recreational Information Program (see section 2.1.3) estimates for difficult to sample or overlooked recreational fisheries and activities.

2.1.2.2 Sampling Intensity

Surveys are administered at bimonthly intervals or waves. Wave 1 includes January and February, wave 2 includes March and April, and so on. At the conclusion of a particular wave, surveys are mailed to approximately 1,300 randomly selected individuals who indicate participation in the cast net fishery at the time of Coastal Recreational Fishing License (CRFL) purchase. This survey samples approximately 8,000 individuals per year.

2.1.2.3 Biological Sampling

Biological samples have not been collected in conjunction with the mail survey.

2.1.2.4 Potential Biases & Uncertainties

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 among 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).

2.1.2.5 Development of Estimates

Recreational harvest, releases, and effort were summarized by year using the mail survey data.

2.1.2.6 Estimates of Recreational Fishery Statistics

Excluding estimates for 2011, due to only a partial year sampled, annual recreational harvest of mullet (white plus striped) has averaged just over 700 thousand fish per year from 2012 through 2019 (Table 2.3; Figure 2.5). Recreational releases of mullet (white plus striped) have averaged over 230 thousand fish per year during the same time period.

Annual trends in effort have been similar to trends in harvest over the available time series (Figure 2.6). The number of annual recreational trips for mullet (white plus striped) has ranged from nearly 89 thousand trips to over 200 thousand trips between 2012 and 2019 (Table 2.3; Figure 2.6).

2.1.3 Marine Recreational Information Program

2.1.3.1 Survey Design & Methods

The Marine Recreational Information Program (MRIP) is designed to provide annual and bi-monthly estimates of marine recreational fisheries catch and effort data. Information on commercial fisheries has long been collected by the NMFS; however, data on marine recreational fisheries were not collected in a systematic manner by the NMFS until implementation of the Marine Recreational Fishery Statistics Survey (MRFSS) in 1979. The purpose of the MRFSS was to provide regional estimates of effort and catch from the recreational sector. Importantly, the National Research Council (NRC) identified under-coverage, inefficiency, and bias issues within the MRFSS survey and estimation methodologies (NRC 2006). These deficiencies spurred the development of the MRIP as an alternative data collection program to the MRFSS. The MRIP is a national program that uses several component surveys to obtain timely and accurate estimates of marine recreational fisheries catch and effort and provide reliable data to support stock assessment and fisheries management decisions. The program is reviewed periodically and undergoes modifications as needed to address changing management needs. A detailed overview of the program can be found online at https://www.fisheries.noaa.gov/topic/recreational-fishing-data.

The MRIP uses three complementary surveys: (1) the Fishing Effort Survey (FES), a mail survey of households to obtain trip information from private boat and shore-based anglers; (2) the For-

Hire Telephone Effort Survey (FHTES) to obtain trip information from charter boat operators; and (3) the Access Point Angler Intercept Survey (APAIS), a survey of anglers at fishing access sites to obtain catch rates and species composition from all modes of fishing. The data from these surveys are combined to provide estimates of the total number of fish caught, released, and harvested; the weight of the harvest; the total number of trips; and the number of people participating in marine recreational fishing. In 2005, the MRIP began at-sea sampling of headboat (party boat) fishing trips.

The APAIS component was improved in 2013 to sample throughout the day (24-hour coverage) and remove any potential bias by controlling the movement of field staff to alternative sampling sites. The MRFSS allowed samplers to move from their assigned site to more active fishing locations but could not statistically account for this movement when calculating estimates. The MRIP implemented the FES in 2018 to replace the Coastal Household Telephone Survey (CHTS) due to concerns of under-coverage of the angling public, declining number of households using landline telephones, reduced response rates, and memory recall issues.

2.1.3.2 Sampling Intensity

Creel clerks collect intercept data year-round (in two-month waves) by interviewing anglers completing fishing trips in one of four fishing modes (man-made structures, beaches, private boats, and for-hire vessels). Intercept sampling is separated by wave, mode, and area fished. Sites are chosen for interviewing by randomly selecting from access sites that are weighted by estimates of expected fishing activity. The intent of the weighting procedure is to sample in a manner such that each angler trip has a representative probability of inclusion in the sample. Sampling is distributed among weekdays, weekends, and holidays. In North Carolina, strategies have been developed to distribute angler interviews in a manner to increase the likelihood of intercepting anglers landing species of management concern.

The FES mail survey employs a dual-frame design with non-overlapping frames (1) state residents are sampled from the United States Postal Service computerized delivery sequence file (CDS) and (2) non-residents are individuals who are licensed to fish in one of the target states but live in a different state and are sampled from state-specific lists of licensed saltwater anglers. Sampling from the CDS uses a stratified design in which households with licensed anglers are identified prior to data collection. The address frame for each state is stratified into coastal and non-coastal strata defined by geographic proximity to the coast. For each wave and stratum, a simple random sample of addresses is selected from the CDS and matched to addresses of anglers who are licensed to fish within their state of residence. Non-resident anglers are sampled directly from state license databases. The sample frame for each of the targeted states consists of unique household addresses that are not in the targeted state but have at least one person with a license to fish in the targeted state during the wave.

The FES mail survey collects fishing effort data for all household residents, including the number of saltwater fishing trips by fishing mode (shore and private boat). The FES is a self-administered mail survey, administered for six two-month reference waves annually. The initial survey mailing is sent one week prior to the end of the reference wave so that materials are received right at the end of that wave. This initial mailing is delivered by regular, first-class mail and includes a cover letter stating the purpose of the survey, a survey questionnaire, a post-paid return envelope, and a $2 cash incentive. One week after the initial mailing, a follow-up thank you and reminder postcard is mailed via regular first-class mail to all sampled addresses. For addresses that could be matched to a landline telephone number, an automated voice message is also delivered as a reminder to complete and return the questionnaire. Three weeks after the initial survey mailing, a final mailing is delivered to all addresses that have not yet responded to the survey.

2.1.3.3 Biological Sampling

Fish that are available during APAIS interviews for identification, enumeration, weighing, and measuring by the interviewers are called landings or Type A catch. Fish not brought ashore in whole form but used as bait, filleted, discarded dead, or are otherwise unavailable for inspection are called Type B1 catch. Finally, fish released alive are called Type B2 catch. Type A and Type B1 together comprise harvest, while all three types (A, B1, and B2) represent total catch. The APAIS interviewers routinely sample fish of Type A catch that are encountered. Fish discarded during the at-sea headboat survey are also sampled. The headboat survey is the only source of biological data characterizing discarded catch that are collected by the MRIP; however, this number has been negligible (0 striped mullet headboat discards between 2005 and 2019). The sampled fish are weighed to the nearest five one-hundredth (0.05) of a kilogram or the nearest tenth (0.10) of a kilogram (depending on scale used) and measured to the nearest millimeter for the centerline length.

2.1.3.4 Potential Biases & Uncertainties

The MRIP was formerly known as the MRFSS. Past concerns regarding the timeliness and accuracy of the MRFSS program prompted the NMFS to request a thorough review of the methods used to collect and analyze marine recreational fisheries data. The NRC convened a committee to perform the review, which was completed in 2006 (NRC 2006). The review resulted in several recommendations for improving the effectiveness and use of sampling and estimation methods. In response to the recommendations, the NMFS initiated the MRIP, a program designed to improve the quality and accuracy of marine recreational fisheries data. The MRIP estimation method and sampling design for the APAIS were implemented in 2013, replacing MRFSS. In 2016, the NMFS requested that the NRC, now referred to as the National Academies of Sciences, perform a second review to evaluate how well and to what extent the NMFS has addressed the NRC’s original recommendations (NASEM 2017). The review noted the impressive progress made since the earlier review and complimented the major improvements to the survey designs. The review also noted some remaining challenges and offered several recommendations to continue to improve the MRIP surveys. MRIP implemented the FES in 2018 to address the concerns of under-coverage of the angling public, declining number of households using landline telephones, reduced response rates, and memory recall issues of the CHTS.

The 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).

2.1.3.5 Development of Estimates

The online MRIP query tool was used to pull annual estimates of recreational harvest (A, B1, A + B1) and associated PSE values for striped mullet, white mullet, and mullet genus (striped or white mullet that could not be identified to species; National Marine Fisheries Service, Fisheries Statistics Division, personal communication). The online query tool was also used to pull annual estimates of the average individual weight of harvested striped mullet. The raw SAS data files were queried to summarize the annual number of assignments and intercepts in North Carolina as well as the number of assignments and intercepts that encountered striped mullet and mullet genus. The raw SAS data files were also queried to summarize the annual number of directed trips where directed trips were defined as those trips targeting striped mullet, white mullet, or mullet genus as well as trips that caught either striped mullet or mullet genus (two different time series). Estimates of live releases were not considered for inclusion in the stock assessment because mullet are primarily captured by recreational anglers for use as live bait and releases are assumed to have no associated post-release mortality and the assessment model only considers dead fish.

2.1.3.6 Estimates of Recreational Fishery Statistics

Annual recreational harvest (Type A + B1) of striped mullet has exhibited high inter-annual variability in terms of both numbers and weight from 1981 through 2019 (Table 2.4; Figures 2.7 and 2.8). The estimates of recreational harvest for striped mullet are associated with high uncertainty as PSE values for both numbers and weight typically exceed 50% (Table 2.4). Estimates of recreational harvest (Type A + B1) for white mullet are also highly variable and associated with high imprecision (Table 2.5; Figures 2.7 and 2.8). The recreational harvest (Type A + B1) estimates of mullet genus are also variable but demonstrate better precision, especially in 2000 and after (Table 2.6; Figures 2.7 and 2.8). Beginning in 2002, APAIS began deferring to mullet genus to classify unobserved type B1 and B2 catch. Similar identification challenges exist for other ambiguous congener species such as flounder and kingfish, which are also recorded to the genus level for both type B1 and B2 catch. As a result, the magnitude of recreational harvest for mullet genus in units of numbers far exceeds that of both striped mullet and white mullet (Figure 2.7).

A closer inspection of the recreational harvest estimates for striped mullet suggests that a significant proportion of harvest is reported (Type B1; Table 2.7; Figure 2.9). As such, the species is identified by the individual angler and not the APAIS interviewer. In contrast, most of the recreational harvest estimates for white mullet are derived from observed harvest (Type A; Table 2.8). Almost all of the recreational harvest estimates for mullet genus come from reported harvest (Type B1; Table 2.9). This explains why there are so few estimates of recreational harvest in units of weight for mullet genus (Table 2.6) as the fish were not physically available to the interviewer for inspection.

The high uncertainty associated with the estimates of recreational harvest for the mullet species is partly due to the rarity with which they are encountered during APAIS interviews. On average, APAIS interviews encounter striped mullet in 1.5% of their assignments (locations) per year and in only 0.16% of intercepts per year (Table 2.10); however, the mullet genus is encountered more frequently. On average, APAIS interviewers encounter mullet genus in 3.8% of their assignments per year and in 0.64% of intercepts per year (Table 2.11). The higher frequency with which mullet genus are encountered relative to striped mullet suggests anglers have difficulty distinguishing between mullet species (recall that most of the mullet genus harvest is derived from reported harvest—harvest reported by the angler).

An evaluation of directed trips for mullet indicates a significant increase in 2002 relative to the earlier part of the time series (Table 2.12; Figure 2.10). Here, directed trips are defined as those trips that targeted striped mullet, white mullet, or mullet genus or trips that caught striped mullet (one time series) or mullet genus (second time series). Prior to 2002, striped mullet directed trips often exceeded those for mullet genus; this pattern switched in 2002 when mullet genus directed trips exceeded striped mullet directed trips in all remaining years. The deferred classification of mullet to the genus level was driven by concerns regarding species identification and a similar approach was used for unobserved catch for other ambiguous species such as flounder and kingfish.

The APAIS collects data from intercepted anglers concerning the primary fishing gear used. Gear options include hook and line, dip net, cast net, gill net, seine, trawl, trap, spear, hand, and other. Approximately 96% of intercepted anglers with mullet catch reported hook and line as their primary gear (Table 2.13). Gill net and cast net each comprise approximately 2% of reported gear with <1% reporting all other gear types. Trips that targeted mullet and reported mullet harvest indicated cast nets as their primary gear for ~67% of these intercepts (Table 2.14). Additionally, hook-and-line trips with reported mullet harvest predominately targeted flounder, red drum, and spotted seatrout and these trips represented ~85% of all intercepts. These data suggest that mullet are primarily used as baitfish and not necessarily caught using the primary gear reported for most trips (i.e., hook and line). Finally, trips that reported gill nets as their primary gear and targeted or caught mullet of any species represented ~53% of all gear specific intercepts. This suggests that in North Carolina the recreational mullet gill-net fishery is targeted, albeit *de minimis* to the hook-and-line fishery.

The average length of striped mullet encountered in North Carolina's MRIP survey has ranged from a minimum of 0.61 cm in 1988 to a maximum of 43.2 cm in 1993 (Table 2.15). The average of the annual average lengths over the 1981 to 2019 time series is 27.9 cm, which corresponds to an age of 1.7 years for striped mullet based on the von Bertalanffy age-length function. Average weights have ranged from a minimum of less than 0.1 kg in 1988 to a maximum of 1 kg in 1993, 1994, and 1995. Both the average lengths and the average weights in almost all years of the time series are associated with high degrees of imprecision.

The working group recommended for the base run of the stock assessment that the sum of recreational harvest for striped mullet and a proportion of the recreational harvest for mullet genus be used for removals by the recreational fleet. The proportion of mullet genus recreational harvest that was recommended was 29%, a value derived from a study by the NCDMF of cast net recreational harvest for striped mullet. Sensitivity analyses was performed on this value as well as the overall magnitude of the recreational harvest (section 3.1.7.3).

Historically, the MRFSS was limited in its ability to capture both striped and white mullet as evidenced by annual gaps in the production of estimates and notoriously high PSEs in years with estimates. Additionally, the increased proportion of reported unobserved type B1 harvest further exasperated the uncertainty of species specific contributions. Due to the angling communities perceived inability to differentiate among ambiguous congener species (i.e., white and striped mullet) a methodological improvement was implemented in 2002 where unobserved type B1 and B2 catch is recorded at the genus level. A similar approach was adopted for other ambiguous species including flounder, kingfish, and trout. This methodological improvement served to greatly increase the precision of estimates albeit without species level resolution. As such, estimates of recreational harvest for mullet prior to 2002 are considered unreliable and estimates prior to 2002 (back to 1950) were be assumed equal to the median of the 2002 to 2019 time series.

The length-frequencies distributions collected in North Carolina's MRIP survey are considered to be an inaccurate representation of the recreational fishery (Figures 2.11 and 2.12). This is due to biases in the methodology of the program and angler behavior. Lengths collected in North Carolina's MRIP survey are recorded at the dock and therefore only represent fish brought back to be kept by the angler. Anglers typically only keep the largest mullet, whether it be for personal consumption, or to be saved for use as cut bait. This bias toward keeping only the largest striped mullet has caused them to be disproportionately represented in the MRIP data. The vast majority of striped mullet harvested in the recreational fishery are used as live bait for other fisheries. For this type of fishing, “finger mullet”, or age-0 fish approximately 10 cm in total length are used. The length distribution of striped mullet harvested in the recreational fishery is better represented by the length-frequencies distributions collected from the fishery-independent cast net survey (section 2.2.4). This survey does show catches of the larger fish represented in the MRIP data, but they make up a small proportion of the catch.

2.2 Fisheries-Independent

2.2.1 Striped Mullet Electrofishing Survey (Program 146)

2.2.1.1 Survey Design & Methods

The NCDMF Striped Mullet Electrofishing Survey, also known as Program 146, was initiated in 2003 to produce a fisheries-independent index of relative abundance for 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 (Batchelor Creek, Hancock Creek, Slocum Creek, and Neuse River in New Bern; Figure 2.13). The Neuse River area is an important year-round habitat and a major migration path for striped mullet in North Carolina.

Electrofishing 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 Stratton 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 (spring) and October through December (autumn); each station is sampled once per month for an annual total of 84 samples; however, sampling deviations have occurred throughout the time series due to mechanical problems and environmental variability beyond the limits of electrofishing gear.

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, including striped mullet. 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 survey the NCDMF conducts that is designed to target striped mullet. Currently this program 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

Indices were calculated for both the spring and autumn components of the survey. Since the survey primarily catches adult striped mullet, juveniles were excluded from the calculations. Only data collected from Hancock and Slocum creeks were included in the development of the index because the original purpose of the upriver stations (the Neuse River in New Bern and Batchelor Creek) was to capture striped mullet during summer sampling. Summer sampling has since been discontinued. Catch of striped mullet in spring and autumn months is low at these stations; only 8% of the total number of striped mullet were caught in Batchelor Creek and 4% in the Neuse River in New Bern. There were 22 sampling trips from 2006 to 2008 that were not attempted due to high salinity and were therefore removed from analysis. There was no sampling conducted during November and December of 2005 and 2006 as well as January 2007 due to the mechanical errors.

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 ($\alpha = 0.01$) using the statistical test appropriate for the distribution. Non-significant covariates were removed using backwards selection to find the best-fitting predictive model.

Annual length and age compositions were computed based on the same reference data used to calculate the index. The age compositions were computed by sex.

2.2.1.6 Estimates of Survey Statistics

Available covariates were year, area, depth, water temperature, salinity, dissolved oxygen, sediment size, bottom composition, weather, wind direction, wind speed, and precipitation. Year, area, sediment size, bottom composition, 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 for the spring component of the survey was a quasi-Poisson model and included year, area, dissolved oxygen, bottom composition, weather, and wind direction as significant covariates. The spring index is variable and no discernable trend is apparent over the time series (Figure 2.14). For the autumn component of the survey, the best-fitting model was a quasi-Poisson and included year, area, and depth as significant covariates. The autumn index is also variable with no apparent overall trend over the time series (Figure 2.15).

The availability of biological samples from Program 146 has been variable over the years (Table 2.16). The number of annual length samples appears adequate, especially for the spring component of the survey; however, the number of sex-specific age samples, especially for males in both seasons, has been low over the time series and suggests inferences made from the age compositions should be interpreted with caution.

The annual length frequencies of striped mullet observed in the spring component of Program 146 has narrowed in recent years relative to the wider distributions observed in late 2000s through early 2010s (Figure 2.16). The age-frequency distributions of adult striped mullet collected by Program 146 in the spring are dominated by age-2 fish (Figure 2.17). The spring age-frequency distributions have contracted in recent years.

Similar to the length compositions in the spring component, the length-frequency distributions in the autumn component of Program 146 have exhibited a narrower range in recent years than that observed in the late 2000s and early 2010s (Figure 2.18). The age composition data show that the autumn component of the Program 146 survey is dominated by age-1 fish in most years (Figure 2.19). Striped mullet older than age 3 are rarely observed.

2.2.2 Fisheries-Independent Gill-Net Survey (Program 915)

2.2.2.1 Survey Design & Methods

The Fisheries-Independent Gill-Net Survey, also known as Program 915, began on March 1, 2001 and includes Hyde and Dare counties (Figure 2.20). In July 2003, sampling was expanded to include the Neuse, Pamlico, and Pungo rivers (Figures 2.21, 2.22). Additional areas in the Southern District including the New and Cape Fear rivers were added in April 2008 (Figure 2.23).

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. Only shallow water samples are collected in the Cape Fear River. Gill nets are typically deployed within an hour of sunset and fished 11.5 hours later, except from May 1 to August 31 when nets are deployed 1.5 hours prior to sunset. Efforts are made to keep all soak times within 12 hours except in the Southern District where soak times are reduced to four hours from April 1 through September 30 and nets are deployed two hours prior to sunset. 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. In Hyde and Dare counties (Pamlico Sound area), 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 river area is divided into four regions in the Neuse River (Upper, Upper-Middle, Lower-Middle, and Lower), three regions in the Pamlico River (Upper, Middle, and Lower), and only one region for the Pungo River. The upper Neuse region was reduced to avoid damage to gear from obstructions, and the lower Neuse was expanded to increase coverage in the downstream area. The Pungo region was expanded to include a greater number of upstream sites where a more representative catch of striped bass may be acquired. The southern area is divided into three regions: upper New River (from Wilson Bay to Hines Point line extending eastward to French’s Creek), lower New River (Hines Point to the intersection of the New River and the Intracoastal Waterway), and the Cape Fear River (the northern end of U.S. Army Corps of Engineer’s Island 13 south to the mouth of the river).

2.2.2.2 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; shallow and deep) in Pamlico Sound. Beginning in 2012 in Pamlico Sound Region 1, Area 1 is not sampled from June 1 through August 31—only 28 samples are collected during these months. In the Pamlico/Pungo and Neuse rivers, a total of 32 samples are completed each month (eight areas × twice a month × two samples; shallow and deep). In the Southern District, a total of 12 samples are completed each month (New River: two areas × twice a month × two samples; shallow and deep; Cape Fear River: one area × four times a month × one shallow sample).

2.2.2.3 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.

2.2.2.4 Potential Biases & Uncertainties

Although striped mullet are considered 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 account for 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).

2.2.2.5 Development of Estimates

To provide the most relevant indices, data were limited to those collected from shallow water during August through December, when the majority of striped mullet occur. Separate indices were initially developed for the southern (New River) and northern (Neuse, Pamlico, and Pungo rivers, and Pamlico Sound) areas. A combined index was also calculated. The Cape Fear River was excluded from analysis due to widely varying catches. Since the survey primarily catches adult striped mullet, juveniles were excluded from the calculations. The GLM method used to model the relative abundance of 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 915.

Annual length and age compositions were computed based on the same reference data used to calculate the index. The age compositions were computed by sex.

2.2.2.6 Estimates of Survey Statistics

Available covariates were year, stratum, stratum weight, depth, water temperature, salinity, dissolved oxygen, sediment size, bottom composition, weather, wind direction, wind speed, and precipitation. Year, stratum, sediment size, bottom composition, 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 for the southern area of the survey assumed a quasi-Poisson distribution and included year and dissolved oxygen as significant covariates. The southern area index exhibits a general declining trend over the time series (Figure 2.24). For the northern area of the survey, the best-fitting model assumed a quasi-Poisson distribution and included year, stratum, depth, salinity, dissolved oxygen, and sediment size as significant covariates. The Program 915 northern area index shows higher values in the early part of the time series and a decrease beginning in 2015 where it remains at lower, but slightly increasing, levels through 2019 (Figure 2.25). For the combined index, the best-fitting model assumed a quasi-Poisson distribution and included year, stratum weight, bottom salinity, bottom DO, and bottom composition as significant covariates. The northern and southern area combined index is higher in the initial part of the time series and shows a decrease to 2015 where it remains at lower, but slightly increasing levels through the end of the time series (Figure 2.26).

Biological samples are available from each area of Program 915 throughout the duration of the survey (area-specific; Table 2.17). The majority of striped mullet length and sex-specific age samples collected in Program 915 were collected from the northern area because of the longer time series and higher striped mullet catches.

Length-frequency distributions of adult striped mullet in the southern area of Program 915 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 2.27). Catches in the southern area of Program 915 are predominantly comprised of age-1 and age-2 fish with few fish over age-3 observed in any year (Figure 2.28).

The lengths of striped mullet observed in the northern area of Program 915 show an expansion in the most recent years of the available time series (Figure 2.29). Northern area catches are dominated by age-1 and age-2 striped mullet and striped mullet older than age 3 are infrequent (Figure 2.30).

2.2.3 Beaufort Bridgenet Ichthyoplankton Sampling Program

2.2.3.1 Survey Design & Methods

The Beaufort Bridgenet Ichthyoplankton Sampling Program (Bridgenet Survey), initiated in 1986, is a volunteer-supported long-term, fixed-site, monitoring survey for larval fish recruitment. The objective of sampling is to contribute to the understanding of estuarine-dependent species including spawning data, larval growth, and age at ingress.

The Bridgenet Survey involves once-weekly, flood-tide, nighttime samples collected at a fixed platform on Pivers Island Bridge, Beaufort, NC (Figure 2.31). The Bridge spans a 40-m wide and 7-m deep (maximum) channel 1.5 km upstream from the Beaufort Inlet. An estimated 10% of the water flowing into the Beaufort Inlet flows through this channel. Temperature (℃), salinity (ppt), and dissolved oxygen (mg/L) are recorded at the beginning and/or end of each sampling event. Note, from 2000 to 2010, temperature and salinity were generally not recorded and missing information was filled in with the closest National Estuarine Research Reserve System System-Wide Monitoring Program or National Oceanographic and Atmospheric Administration (NOAA) National Water Level Observation Network tide gauge station.

The program uses a 2-m^2 neuston plankton net with 1-mm mesh fitted with a General Oceanics' flowmeter that has a digital readout for total distance and tow duration. Tow duration varies according to a target of 50-m distances to achieve a target sampling volume of 100 m^3. Starting in December 2016, tows were targeted at five minutes (or three minutes if large volumes of ctenophores present or other issues). During 2007 and 2008, a 1-m hoop net with 500-um mesh and 10-minute fixed tow duration was used instead of a neuston net.

2.2.3.2 Sampling Intensity

Since November 1986, samples have been collected once weekly during the core sampling season, which is defined as November through April. A sample consists of four replicate net tows; however, prior to November 1988, only three net tows were used in a sample and other inconsistencies in the number of tows in a sampling event exist throughout the time series. The average starting week of the sampling season is defined as week 46 of the calendar year where week one is assigned based on the first week of the year that contains January 1st and weeks start on Sunday. A total of 25 weeks make up the sampling season for a season total of 25 samples, but this number is variable season to season. Sampling outside the core season and additional sampling effort has occurred including year-round sampling in 2003 and 2007 to 2008. Net tows are fished at the surface about 2.5 hours before the predicted high tide.

2.2.3.3 Biological Sampling

After each tow, the net is rinsed through a 1-mm mesh sleeve and the larval catch is preserved in ethanol alcohol. If advanced juvenile or adult forms of fish are collected in the net (>35 mm), they are either discarded or sorted, identified, and measured. Prior to 2001, larvae were sorted, identified, and counted at the NOAA Beaufort Laboratory. Since 2001, fish larvae have been sorted, identified, counted, and measured at the Sea Fisheries Institute, Plankton Sorting and Identification Center (Gdynia and Szczecin, Poland). Starting in 2001, measurements to the nearest

0.1 mm in body length were recorded for up to ten individuals of specific taxa, including striped mullet. Starting in 2017, the maximum number of individuals measured from a net tow increased to 20.

2.2.3.4 Potential Biases & Uncertainties

North Carolina has many coastal inlets where estuarine ingress of striped mullet larvae is likely to occur; however, sampling only occurs at a single, fixed location and may not be representative of striped mullet larval abundance if larval ingress exhibits high spatial and temporal variability. Indices based on fixed-station surveys 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. There are two years in the time series (2007 and 2008) where changes in sample gear occurred and is not comparable to the standard gear.

2.2.3.5 Development of Estimates

Ten samples from 2007 to 2008 that used only hoop gear instead of neuston gear were removed from the analysis. A nominal index was computed for the Bridgenet Survey as there were insufficient data on covariates collected throughout the time series to apply the GLM approach. Data collected in November and December were grouped with data from January through April of the following year. The average density (numbers of striped mullet/volume filtered) was calculated for each sampling event from the replicate tows. The annual index of relative recruit abundance was calculated as the annual average density of age-0 striped mullet.

Length data collected since 2001 were summarized over the time series to provide an overall representative length-frequency distribution.

2.2.3.6 Estimates of Survey Statistics

The trend in relative abundance of age-0 striped mullet is highly variable and generally declining over the time series (Figure 2.32). The index suggests a relatively low year class occurred in 2000.

Striped mullet observed in the Bridgenet Survey have ranged in length from 11 mm to 33 mm (Figure 2.33). The modal length occurs at 22 mm.

2.2.4 Cast Net Study (Program 121)

2.2.4.1 Survey Design & Methods

Sampling took place in Dare and Carteret counties in 2002 and 2003 and also in New Hanover County in 2003. Fixed stations were chosen based on different habitats (i.e., ocean, inlet and estuarine locations). Ocean stations were located on piers and on the ocean side of inlets. Inlet stations were shallow water habitats located in the sounds and rivers within 5 miles (8 km) from the closest inlet. Estuarine stations were shallow water habitats located in the sounds and rivers greater than 5 miles (8 km) from the closest inlet. A typical, six-foot radius monofilament cast net (3/8 in. bar mesh and ¾ lb. of lead per radius foot) commonly used by recreational bait harvesters was used in the study. Samples were sorted by station location and by month to analyze differences in proportions of striped and white mullet.

2.2.4.2 Sampling Intensity

At total of 72 cast net samples were collected from late August to November 2002 and from June to November 2003. Most samples (n = 37) were collected at near coastal inlets, 25 were estuarine collected at estuarine stations, and 10 were collected from ocean stations. No sampling occurred from December through May because very little cast netting for mullets occurs during these months. Ocean stations were only sampled from August through November, since mullets are typically scarce and are not targeted by cast netters in the ocean in June and July. A target number of 100 mullets and a maximum of 50 cast net throws were made at each station. Water temperature (°C), salinity (ppt), dissolved oxygen (mg/L), bottom substrate, tidal stage (when applicable), and water depth (m) were recorded at each location.

2.2.4.3 Biological Sampling

Finfish and crustaceans were identified to species, enumerated, and measured.

2.2.4.4 Potential Biases & Uncertainties

Fishery-independent cast net samples were used as a proxy for the proportion of striped mullet and white mullet in the recreational cast net mullet harvest. While methodology and gear between recreational cast net sampling and fishery-independent cast net sampling is similar, the true species composition in cast net samples is likely influenced by spatial and temporal patterns in effort, environmental conditions, and fluctuations in recruitment of both mullet species. Sampling was primarily conducted in areas of the sound in the vicinity of coastal inlets (within 5 miles). The furthest west station was located in Adams Creek, a tributary near the mouth of Neuse River whose environmental conditions are also likely influenced by connection to the Intracoastal Waterway. The ratio of striped to white mullet in locations further upriver or in areas more influenced by freshwater inputs may be different than areas closer to the coast.

2.2.4.5 Development of Estimates

Samples were sorted by station location and by month to analyze differences in proportions of striped and white mullet.

2.2.4.6 Estimates of Survey Statistics

White mullet made up the greatest proportion of the samples from June through October, but in November, striped mullet comprised 74% of the mullets in the samples. Across all months, white mullet comprised 93% of the mullets from the ocean stations and 74% of the mullets from the inlet stations, whereas 67% of the mullets from the estuarine stations were striped mullet. Overall survey data identified 29% of the cast netted mullets as striped mullet.

Striped mullet from the independent cast net samples ranged from 5–39 cm FL with 76% of the fish from 7–14 cm FL (Figure 2.34). White mullet from the independent cast net samples ranged from 4–19 cm FL with 98% of the fish between 6 and 15 cm FL. Sub-adult and adult striped mullet were occasionally caught in the independent samples, but no sub-adult or adult white mullet were captured.

3 ASSESSMENT

3.1 Method—Stock Synthesis

3.1.1 Scope

For the purposes of this stock assessment, the unit stock is defined as all striped mullet occurring in North Carolina coastal and inland waters.

3.1.2 Description

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 text version 3.30 (SS3) software

(Methot 2000; Methot and Wetzel 2013; Methot et al. 2021). Stock Synthesis is an integrated statistical catch-at-age model that is widely used for stock assessments throughout the world. SS3 was also used to estimate values for established reference points. All SS3 model input files are available upon request.

3.1.3 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; see section 1.2.1).

The time period modeled was 1950 to 2019 using an annual time step based on the calendar year. The year 1950 was recommend as the start year by the peer review panel because it was the earliest year for which commercial landings were available. The terminal year, 2019, was selected because it was the most recent year from which data were available at the start of the assessment process.

3.1.4 Structure / Configuration

3.1.4.1 Catch

The model incorporated commercial landings and recreational harvest of striped mullet in North Carolina. No commercial discards were included in the model as they are considered minimal. As only dead fish were included in the model, recreational live releases that did not survive were not considered as 100% survival is assumed.

3.1.4.2 Survey Indices

The model incorporated one annual index of relative abundance (and associated standard errors, see section 3.1.5), which was derived from the Program 915 (P915) Survey (see section 5 for decisions regarding indices to include and exclude). As described in detail in section 2.2.1.5, the P915 Survey index was 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, q, was assumed to be time-invariant for the P915 Survey. The 'float' option within SS3 was selected for the survey catchability, which means SS3 calculates an analytical solution for q rather than directly estimating the value.

The P915 Survey index was assumed to have a nonlinear relation to abundance, requiring an additional parameter to be estimated (survey 'power'). Following a recommendation by the model developer, the power parameter was assigned a prior value (R.D. Methot Jr., NOAA Fisheries, personal communication). The power parameter was assigned a prior value of 0 and assumed to follow a normal distribution.

3.1.4.3 Length Composition

Annual length frequencies were input for the commercial and recreational fleets and the P915 Survey. The P915 Survey length frequencies were calculated using the same reference data (i.e., same months and areas) used to develop the index. Length frequencies were input by 2-cm length bins ranging from 10 cm to 56 cm FL.

3.1.4.4 Age Data

Annual sex-specific age compositions were input for the commercial fishery and the P915 Survey. Age data were not available for the recreational fleet. 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 et al. 2021). Making the age composition data conditional on length also has the advantage of linking age data directly to the length data (essentially creating an age-length key) and so provides more detailed information about the relationship between length and age, enhancing the ability to estimate growth parameters (Cass-Calay et al. 2014).

As with length frequencies, the P915 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 15. Ages were assumed to be associated with small bias and negligible imprecision.

3.1.4.5 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 0.53 and for males was assumed equal to 0.56 (see section 1.2.6; Table 1.3).

Growth

Growth (age-length) was assumed to be sex specific and was modeled using the von Bertalanffy growth curve. In the SS3 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 et al. 2021). Fish then grow linearly until they reach a real age equal to a user-specified age (here, age 1). As the fish continue to age, they grow according to the von Bertalanffy growth equation.

Allowing SS3 to estimate the growth curve ensures that the assumptions about selectivity are consistent with other parts of the model and that uncertainty in the growth estimates is incorporated into the estimates of spawning stock biomass, fishing mortality, and reference points (Hall 2013). All age-length growth parameters were estimated for both sexes. The estimated growth parameters for each sex were length at age 1 ($L1$), L_∞, K, coefficient of variation (CV) for $L1$ (CV1), and CV for L_∞ (CV2). Initial values for L_∞ and K were derived by fitting the von Bertalanffy model to the available age-length data by sex (see also section 1.2.4.4; Table 1.1). The initial values for $L1$ were derived based on the estimated von Bertalanffy parameters. Initial values for the CV1 and CV2 were derived empirically for each sex. The initial values for the growth parameters were treated as diffuse priors (prior standard deviation=2.0) assuming a symmetric beta distribution. Examination of the observed data was used to set reasonable bounds on all growth parameters for males and females.

Parameters of the allometric length-weight relationship were fixed (i.e., not estimated) for both females and males. 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 using the histological data collected in the NCDMF maturity study (see section 1.2.5).

Reproduction was assumed to occur on January 1 each year.

Fecundity

The SS3 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.

3.1.4.6 Stock-Recruitment

A Beverton-Holt stock-recruitment relationship was assumed. Recruitment varied log-normally about the curve. Preliminary runs suggested that the steepness (*h*) parameter could be estimated. A likelihood profile was run on steepness to obtain a starting value based on the minimum of the profile for the total likelihood component (see section 3.1.7.4 for description of likelihood profiling). This value, 0.77, was set as a prior with a standard deviation of 0.3 and assumed a normal distribution (Figure 3.1).

Virgin recruitment (R_0) was estimated by the model using a symmetric beta prior and the standard deviation of log(recruitment), σ_R, was initially fixed at 0.74 based on the meta-analysis by Thorson et al. (2014). The value of σ_R should be selected to approximate the true average recruitment deviations (Methot et al. 2021). Preliminary runs of the model resulted in an error that the bias adjustment for the main recruitment deviations was greater than two times the ratio of the root mean square error (RMSE) to σ_R. The multivariate hierarchical life history tool FishLife (Thorson et al. 2017) was used to derive a value of σ_R, 0.38, that better aligned with the estimated variance of the recruitment deviations.

There are several options for coding the recruitment deviations. Here, the option for a deviation vector was selected. For this option, the recruitment deviations constrained to sum to zero (Methot et al. 2021). Recruitment deviations were estimated from 1988 to 2019. 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. 2021) can be used to obtain a recommendation for the time period for which to apply the full bias adjustment as well as a recommended value for the maximum bias adjustment parameter. After the recommended value for Francis weights of the composition data were obtained (see section 3.1.5), the model was rerun and the SS_plots function was applied through the R software (version 4.1.2; R Core Team 2021) several times until the recommendations converged on a recommended start (1996.3) and end (2019.2) year and the maximum bias adjustment parameter value (0.8077), which were implemented in the final base model run.

3.1.4.7 Fishing Mortality

SS3 allows several options for reporting fishing mortality (*F*). Based on a recommendation from the model developer (R.D. Methot Jr., NOAA Fisheries, personal communication), the *F* values reported here represent a real annual *F* calculated as a numbers-weighted *F* (see Methot et al. 2021) for ages 1–5, the age range that comprises the majority of the commercial landings.

3.1.4.8 Selectivity

Selectivity can be cast as length and/or age specific in the SS3 model. As the length data were considered more reliable, the length-specific option was chosen for both fleets and the fisheries-independent surveys.

It is difficult for a stock assessment model to provide a reliable fit when all selectivity parameters are freely estimated. The working group discussed the probable shapes (dome, asymptotic, or other) of the selectivity curves for the two fleets and each fisheries-independent survey. Initially, the selectivity patterns considered for each fleet and survey were based on the theoretical shape derived from underlying processes and gear experiments. For instance, landings from the commercial fishery come from both small-mesh runaround nets as well as large-mesh nets that select for larger fish. The smallest size striped mullet escape through the small mesh but there is no gear that is believed to exclude larger fish from the landings. For these reasons, an asymptotic selectivity curve was assumed for the commercial fishery fleet.

The P915 Survey is a gill-net survey and gill nets are typically assumed to follow a dome shape (Millar and Fryer 1999); however, the working group believes this survey is capable of catching the largest size striped mullet and so an asymptotic shape was assumed for the P915 Survey.

The recreational fishery targeting mullet typically uses cast nets to target juvenile or "finger mullet" for use as live bait. The mesh sizes used in a typical cast net exclude the smallest sized mullet. Angler preference for smaller mullet excludes the largest mullet from the catch, though they are sometimes encountered. For these reasons the working group believes assuming dome-shaped selectivity for the recreational fishing fleet is most appropriate.

A two-parameter logistic curve was used to describe the selectivity for both the commercial fleet and the P915 Survey. The recommended double normal selectivity pattern was used for the selectivity of the recreational fleet. This pattern is flexible in that it can take on a dome or asymptotic shape. The model had extreme difficulty in estimating the selectivity parameters for the recreational fleet. Following the recommendations of the peer review panel, the selectivity parameters of the recreational fleet were fixed at values that led to a reasonable fit to the recreational length compositions.

3.1.4.9 Equilibrium Catch

The SS3 model needs to assume an initial condition of the population dynamics for the period prior to the estimation period. Typically, two approaches are used to meet this assumption. The first approach starts the model as far back as necessary to satisfy the notion that the period prior to the estimation of dynamics was in an unfished or near unfished state. Reliable catch records back to the start of the fishery are not available for striped mullet. For this reason, the model developer recommended use of the second approach, which is to estimate (where possible) initial conditions assuming equilibrium catch (R.D. Methot Jr., NOAA Fisheries, personal communication). The equilibrium catch is the catch taken from a fish stock when it is in equilibrium with removals and natural mortality balanced by stable recruitment and growth.

The SS3 model estimates initial equilibrium catch and initial fishing mortality for each fleet. The initial fishing mortality rates are estimated based on the level of initial equilibrium catch for each fleet. Providing an initial equilibrium catch allows the model to start in a fished state prior to the start year. For the commercial fleet, the starting value provided to the model for initial equilibrium catch was set as half of the minimum observed annual landings over the 1950- to 2019-time series (161.9 mt) and associated with a standard error, SE, equal to 0.20. The initial equilibrium catch for the recreational fleet was set to half of the minimum observed annual harvest over the time series (244.7 thousand fish) and associated with a SE equal to 0.20. The starting value for the initial fishing mortality of both fleets was set at 0.40.

3.1.5 Optimization & Weighting

SS3 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 (SE = 0.01).

Survey indices were fit assuming a lognormal error distribution. The standard errors estimated either from the GLM standardization or the nominal approach were scaled to an average of 0.2 across the time series, within each survey index, but the relative annual variation was maintained in the scaling. This approach is considered more appropriate than using the standard error from the GLM standardization as it avoids the undue influence of any one index (SEDAR 2019). Because different techniques are used to compute the indices, it is not expected that the estimated standard errors would be directly comparable. Scaling each set of standard errors to a common mean allows them to be placed on equal footing within the assessment.

Composition information was fit assuming a multinomial error structure with variance described by the effective sample size. In the previous NCDMF stock assessments of striped mullet, the effective sample size was set as the number of sampled trips, assuming a maximum of 200 for each fleet or survey observation (NCDMF 2013, 2018). In order to prevent overfitting of the composition data and in order to maintain the inter-annual differences in data quality that would be lost by an arbitrary cap, the input effective sample sizes for the composition data were set equal to the square root of the observed number of sampled trips (SEDAR 2019).

Priors were assumed for the power parameters for the fisheries-independent survey indices (section 3.1.4.2), for the growth parameters (section 3.1.4.5), and for R_0 and the steepness parameter (section 3.1.4.6). 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, recreational harvest, fisheries-independent survey index, length compositions, age data, initial equilibrium catch, and recruitment deviations. The total likelihood is the weighted sum of the individual components. All likelihood components, with the exception of the age data, were assigned a lambda weight equal to 1.0 in the base run. Based on a recommendation from the model developer in a similarly structured assessment, the lambdas for the age data were reduced to 0.25 (R.D. Methot Jr., NOAA Fisheries, personal communication).

The 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 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 missspecified (Lee et al. 2014). Francis (2011) argues that abundance information should primarily come from indices of abundance and not from composition data. Following the recommendation of Francis (2011), the model was weighted in two stages. Stage 1 weights were largely empirically derived (standard errors, CVs, and effective sample sizes described earlier in this section) and applied to individual data observations. Stage 2 weights were applied to reweight the length and age composition data by adjusting the input effective sample sizes. The stage 2 weights were estimated based on method TA1.8 (Appendix A in Francis 2011) using the SSMethod.TA1.8 function within the r4ss package (Taylor et al. 2021) in R (R Core Team 2021).

3.1.6 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 (i.e., is positive definite). 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. The values of estimated parameters were checked to see if they were estimated at a bound, which could indicate problems with the data or model structure (Carvalho et al. 2021). The correlation matrix was examined to identify highly correlated (e.g., >0.95) parameter pairs. High correlation among parameters can be indicative of poor model stability. Parameters were examined for excessively high variance (>50%), which is an indication that the associated parameter does not influence the fit to the data.

Model stability was further evaluated using a "jitter" analysis. This analysis is a built-in feature of SS3 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% for a series of 100 random trials. The r4ss package (Taylor et al. 2021) in R (R Core Team 2021) provides tools for automating the jitter analysis and was used for the current stock assessment.

Additional diagnostics included evaluation of fits to commercial landings, recreational harvest, P915 Survey index, length compositions, mean lengths (derived from observed and expected length-composition data), and comparison of estimated growth parameters to their empirically-derived counterparts. 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 P915 Survey index, length composition data, and mean lengths. 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 trend in the residuals over time. This can be confirmed via the runs test, which was applied to the residuals of the fits to the P915 Survey index and mean lengths using tools in the ss3diags package (Winker et al. 2022). Outliers in the residuals can be detected using the three-sigma limit to identify whether any data point would be unlikely given a random process error in the observed residual distribution if it is further than three standard deviations away from the expected residual process average of zero (see details in Anhøj and Olesen, 2014, cited in Carvalho et al. 2021).

Finally, the SS3 model estimates of the von Bertalanffy age-length growth parameters were compared to the empirically-derived values (section 1.2.4.4).

3.1.7 Uncertainty & Sensitivity Analyses

3.1.7.1 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 ("peeling" back years of data). 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 peeling back up to five years of data using tools from the r4ss package (Taylor et al. 2021) in R (R Core Team 2021).

3.1.7.2 Sensitivity to Model Start Year

Sensitivity of the model results to the model start year was explored in one alternative model run. In this run, the start year of the model was changed to 1994, the year in which the NCDMF Trip Ticket Program was implemented (section 2.1.1).

3.1.7.3 Alternative Assumptions Regarding Recreational Removals

Two alternative assumptions regarding the magnitude of the recreational removals were considered in two alternative model runs. The first alternative run considered that the proportion of striped mullet occurring in the mullet genus harvest was higher than what was assumed in the base run (29%; section 2.2.4.6). The proportion assumed in the alternative run was assumed equal to the proportion of striped mullet that make up the sum of striped mullet and white mullet Type A recreational catch, a value equal to 86%.

The second alternative run regarding recreational removals assumed no recreational removals at all and so recreational harvest and the associated length compositions were removed for this run.

3.1.7.4 Likelihood Profile

A likelihood component profile was performed to identify potential data conflicts. Likelihood profiling allows the evaluation of model performance across a range of values of an input parameter (Cass-Calay et al. 2014). A profile is conducted by running a series of models in which the parameter of interest is fixed (i.e., not estimated) at a range of values above and below the value estimated in the base model run. The total negative log-likelihood value and the negative log-likelihood value for each data component are plotted against the profiled parameter. Ideally, the shape of the likelihood profile should be smooth whereas the presence of numerous spikes and sawtooths indicates abnormal model behavior.

Virgin recruitment, R_0, is an ideal global scaling parameter that is often profiled because the unfished (virgin) level of recruitment is proportional to unfished biomass (Lee et al. 2014; Carvalho et al. 2017, 2021). Those data components with a large amount of information on population scale will show a significant degradation in fit as the value of population scale moves away from the value estimated in the base model (i.e., the best estimate). Lee et al. (2014) suggests that catch and abundance indices should be the primary sources of information on the population scale in a model. If the base model run is good, the minima of negative log-likelihood values is well defined and has similar R_0 values among data components. If the minimum negative log-likelihood values differ among the data components, there may be either a conflict in the data or model misspecification or both.

3.1.7.5 MCMC Analysis

Monte Carlo Markov Chain (MCMC) is a method of quantifying uncertainty about model parameters and was used in this analysis to estimate uncertainty in terminal year (2019) female SSB and *F*. For three chains, a total of 7,500,000 MCMC iterations were performed but only one out of every 5,000 were saved and the first 500 were discarded to eliminate "burn-in" effects. This resulted in 1,000 samples from the posterior distribution for each parameter and each chain. Convergence of the MCMC chains was assessed by visual inspection of the posterior distributions and whether they were approximately normal, comparison of the mean of posterior distribution to maximum likelihood estimate produced by the SS model, and visual inspection of the trace plots. The Gelman-Rubin multi-chain diagnostic test was applied to compare within-chain variance to among-chain variance (Gelman and Rubin 1992). A value of 1 for the Gelman-Rubin statistic means that between-chain variance and within-chain variance are equal; larger values mean that there is a notable difference between the chains indicating non-convergence of the model. There is a rule of thumb that values less than 1.1 are deemed acceptable.

3.1.8 Results

3.1.8.1 Base Run—Diagnostics

A summary of the input data used in the base run of the striped mullet stock assessment model is shown in Figure 3.2. The final base run resulted in an inverted Hessian matrix, but the model's final convergence level was 0.00300198. 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.D. Methot Jr., NOAA Fisheries, personal communication). Additionally, successful model outcomes can be achieved despite larger final gradients (Carvalho et al. 2021). None of the estimated parameters were estimated near their bounds (Table 3.2) and no highly correlated parameter pairs were detected. None of the estimated parameters were found to have excessively high variance (proportional standard error > 50%). The parameter for virgin recruitment was associated with a large gradient (absolute value > 0.001).

Five of the 100 runs that jittered initial values by 10% did not successfully converge (Hessian did not invert). The remaining runs resulted in inverted Hessian matrices and small (<1.0) convergence values. The majority of the jitter runs resulted in an objective function value similar to that obtained in the base run of the model (Figure 3.3). 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 3.4).

The results of the base model show good agreement between observed and predicted removals for the commercial (Figure 3.5) and recreational (Figure 3.6) fleets. This is not unexpected given the small amount of error assumed for these data. The fit to the P915 Survey index was deemed reasonable (Figures 3.7). All the standardized residuals from the fit to the P915 Survey index are within one standard deviation of the observed values, suggesting good fits to the observed index. No significant trends are apparent in the standardized residuals over the various time series and this was confirmed via the runs test. No outliers are evident in the P915 Survey index residuals.

The fits to the length compositions aggregated across time provide fair fits to the observed length compositions for the commercial and recreational fleets and the P915 Survey (Figure 3.8). The observed annual length compositions in the commercial fishery were fit well by the model despite low observed effective sample sizes[1] (less than 35 each year; Figures 3.9 and 3.10). Examination of the residuals suggests the model tended to overestimate the proportions at length for commercial fishery lengths 22 cm and smaller in most years (Figure 3.11). With only two years of available length data, the fits to the recreational fishery length compositions are difficult to interpret (Figures 3.12 and 3.13). The P915 Survey observed annual length compositions are associated with effective sample sizes slightly higher than those observed for the commercial fishery length compositions (less than 50 each year) and the fits are reasonable (Figure 3.14). Evaluation of the residuals suggests no consistent patterns in over- or underestimation for the P915 Survey lengths (Figure 3.15).

Observed and predicted mean lengths were derived from observed and expected length-composition data. The comparison of observed to predicted mean lengths for the commercial fishery indicated the model tended to overestimate mean length from the mid-1990s through the early 2000s (Figure 3.16), though the results of the runs tests did not indicate any temporal trend in the residuals (Figure 3.17). One of the mean length residuals for the commercial fishery (1998) fell outside three residual standard deviations from zero, suggesting the point is an outlier. The comparison of observed and predicted mean lengths for the P915 Survey suggest consistent overestimation of mean length from 2011 through 2015 (Figure 3.18). The runs test applied to the residuals of the mean lengths for the P915 Survey suggested no temporal trends and no outliers (Figure 3.19).

Most of the von Bertalanffy age-length growth parameter values estimated by SS3 were similar to those derived empirically (Table 3.3; Figure 3.20). The SS3 model did underestimate K for females and overestimate K for males, relative to the empirically-derived values. The values for CV2 for both females and males were underestimated as well, suggesting precision is higher for the length at older ages than what was derived empirically.

3.1.8.2 Base Run—Selectivity & Population Estimates

The predicted selectivity curves for the fleets and surveys are shown in Figure 3.21. The recreational fishery selects for the smallest size striped mullet relative to the commercial fishery and P915 Survey. The commercial fishery selects for larger striped mullet relative to the P915 Survey and recreational fishery.

The predicted recruitment deviations vary randomly about zero with no apparent trend throughout the time series (Tables 3.4 and 3.5; Figure 3.22). Annual predicted recruitment shows a variable but generally declining trend starting in the late 1980s (Tables 3.4 and 3.5; Figure 3.23). Female

[1] Observed effective sample sizes were input as the square root of the number of sampled trips; see section 3.1.5

SSB shows an initial drop at the start of the time series through the mid-1960s followed by an increase through the mid-1970s (Tables 3.4 and 3.5; Figure 3.24). The trend in female SSB through the remainder of the time series is generally declining. Estimates of spawning potential ratio (SPR) vary between 0.096 (2002) and 0.64 (1971) over the time series (Tables 3.4 and 3.5; Figure 3.25). SPR peaked in 1971 and generally declined to its lowest point in 2002. Since 2004, estimates of SPR have been variable without obvious trend.

Predicted stock numbers at age for striped mullet indicate the stock has been dominated by age-0 fish over time (Tables 3.6–3.9). Predictions of stock biomass at age indicate that most of the population's biomass is found in age classes 1, 2, and 3 (Tables 3.10–3.13).

The predictions of commercial landings at age demonstrate that fish age 1 and 2 dominate the commercial landings (Tables 3.14 and 3.15). Fish at ages 1 through 5 make up the majority (>95%) of the commercial landings. The recreational harvest is dominated by age-0 fish while fish older than age 3 are rarely captured (Tables 3.16 and 3.17).

Estimates of fishing mortality (numbers-weighted, ages 1–5) show a decrease from the early 1960s through the early 1970s (Tables 3.18 and 3.19; Figure 3.26). Starting in the mid-1980s, *F* is variable but increasing through the rest of the time series, though shows evidence of a decrease in 2018 and 2019.

3.1.8.3 Retrospective Analysis

The results of the retrospective analysis do not suggest an obvious consistent bias in estimates of female SSB or *F* in the terminal year of the base model (Figure 3.27). The calculated values of the modified Mohn's ρ for female SSB (0.22) and *F* (-0.22) are just within the "acceptable" range (-0.22 to 0.30) for shorter-lived species and provide further evidence for a lack of a retrospective pattern in these estimates.

3.1.8.4 Sensitivity to Model Start Year

The model results were relatively insensitive to model start year (Figure 3.28). There were some differences in female SSB and *F* between the base model run and the run that started in 1994 during the mid- to late 1990s, but predicted values between the two runs were similar for the remaining years.

3.1.8.5 Alternative Assumptions Regarding Recreational Removals

Changing the assumption regarding the magnitude of recreational removals had a negligible impact on model results (Figure 3.29). The run in which the proportion of striped mullet occurring in the mullet genus harvest was assumed to be 86% resulted in a slightly lower estimate of *F* in the terminal year (2019). Assuming no recreational fishery had nearly identical results to the results of the base run.

3.1.8.6 Likelihood Profile

The base model run estimated a value of 9.73 for $\log_e[R_0]$. The likelihood profile on R_0 for the total objective function is consistent with the model having converged to a global optimum (Figure 3.30). The estimate from the base model run is also supported by the profiles for the length and age data. The survey and recruitment profiles support a smaller value for R_0 than the length and age data.

3.1.8.7 MCMC Analysis

Convergence diagnostics indicated that the MCMC simulation to estimate the posterior distribution of SS3 model parameters converged. The posterior distributions for the terminal year (2019) estimate of female SSB (Figure 3.31) and fishing mortality (Figure 3.32) are approximately normally distributed across all three chains. The SS3 model estimate of female SSB in 2019 (263 mt) is similar to the mean estimate from the MCMC posterior distributions (220 mt), which is an indication of the robustness of the model. Likewise, fishing mortality in 2019 estimated from the SS3 model (0.42) is similar to the mean estimate from the MCMC posterior distributions (0.43). No issues were detected in the trace plots for female SSB in 2019 (Figure 3.31) or fishing mortality in 2019 (Figure 3.32). The Gelman-Rubin multi-chain diagnostic test for these parameters also supported model convergence. The Gelman-Rubin statistic for female SSB in 2019 is 1.09 and for fishing mortality the value is 1.08.

3.2 Discussion of Results

The model performed well and showed good stability across most of the diagnostics. Fits to the commercial landings and P915 fisheries-independent survey are generally good and the length compositions were also fit well.

Not all likelihood components for the various data sources are consistent with the estimate of population scale. While the likelihood profiles for the length and age data are consistent with the profile for the total likelihood, the likelihood profile for the survey data suggests a smaller estimate of population scale. This is an indication of conflicting signals between the composition data and the survey index data. Francis (2011) has argued that information on abundance should primarily come from abundance indices and not the composition data. Future stock assessment modeling work may want to consider alternative weightings of the different data sources.

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 P915 Survey index started in the late 2000s and both the observed and predicted index suggest current relative abundance is lower than what was observed in the late 2000s and early 2010s. Length-frequencies from the fisheries-independent surveys and age composition data from both the commercial fishery and fisheries-independent surveys suggest a truncation of the length and age structure in recent years. Few fish older than age 3 have been observed in North Carolina’s monitoring programs and this is concerning for a species that has been observed to live 15 years. The predicted numbers and biomass at age further suggest a truncation of the population age distribution in the last two decades. Predicted declines in recruitment and female SSB coupled with an increasing trend in predicted fishing mortality are further warning signs of a declining stock. The results of the retrospective analysis suggest consistent overestimation of biomass and the highest risk for overfishing (positive values of Mohn’s ρ for biomass and negative values for fishing mortality). Concerns for the population are warranted given both the observed data and model predictions.

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 0.37 for $F_{25\%}$ and a value of 0.26 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 2019 is 0.42. As such, overfishing is currently occurring in the striped mullet stock ($F_{2019} > F_{25\%}$; Figure 4.1).

The corresponding spawning stock reference points were also estimated by the Stock Synthesis model. The spawning stock biomass threshold, $SSB_{25\%}$, was estimated at 619 mt while the spawning stock biomass target, $SSB_{35\%}$, was estimated at 1,015 mt. The stock assessment model estimate of spawning stock biomass in 2019 is 263 mt, which is less than the threshold value and indicates the stock is currently overfished ($SSB_{2019} < SSB_{25\%}$; Figure 4.2).

The probabilities associated with overfishing and the overfished state were calculated based on the posterior distributions of spawning stock biomass, fishing mortality, and the associated thresholds across all three chains from the MCMC analysis (section 3.1.7.5). There is a 95% probability that the stock is overfished based on the MCMC results. The probability that the stock is undergoing overfishing is 80%.

5 SUITABILITY FOR MANAGEMENT

Stock assessments performed by the NCDMF in support of management plans are subject to an extensive review process, including a review by an external panel of experts. External reviews are designed to provide an independent peer review and are conducted by experts in stock assessment science and experts in the biology and ecology of the species. The goal of the external review is to ensure the stock assessment results are based on the best science available and provide a valid basis for management.

The review workshop allows for discussion between the working group and review panel, enabling the reviewers to ask for and receive timely updates to the models as they evaluate the sensitivity of the results to different model assumptions. The workshop also allows the public to observe the peer review process to better understand the development of stock assessments.

The external peer review panel first met with the working group via webinar in November 2021. The working group gave formal presentations on life history and stock structure, fisheries and management, fisheries-dependent monitoring, fisheries-independent sampling, stock assessment history, input data to the stock assessment model, stock assessment model structure, stock assessment model results, stock status, and research recommendations. The main concern identified by the peer review panel was the lack of inclusion of recreational removals in the original base run of the model. Despite the high uncertainty associated with the recreational data, the peer review panel pointed out that it was important to include all substantial sources of removals because they characterize absolute losses (i.e., deaths) from the population, rather than providing a relative measure of some aspect of the population like other data sources (i.e., indices and compositions). Additionally, despite the uncertainty of the recreational data, it was deemed the best available characterization of recreational losses.

At this first peer review workshop, the peer review panel also recommended removal of the P146_spring and P146_autumn indices and associated biological data. The P146 Survey is spatially limited and the same sampling area is already covered by the P915 survey. The review panel also suggested changing the start year from 1994 to 1950, which required extending the time series of commercial landings and recreational harvest back in time. The peer review panel recommended implementing Francis (2011) reweighting of the length and age composition data. The working group agreed with the peer reviewers recommended changes, including some minor changes to the configuration of input parameters, and a second peer review workshop was scheduled for February 2022.

At the second peer review workshop, the base run of the model was further refined. One of the new major changes was the exclusion of the Bridgenet Survey. The peer review panel, and working group agreed, that the survey was geographically limited—only operating at a single point in the dynamic estuarine waters of North Carolina—and likely not representative of the entire stock area. The removal of the Bridgenet Survey also improved model fit and stability. The final major change was the combining of the P915 northern and southern area indices into a single, combined index. The recommendation to combine these indices was based on the likelihood that the fish being encountered in the northern and southern areas mix substantially over the course of the year and their selectivity patterns were already being described by the same function and parameter values.

Overall, the peer review panel concluded that the assessment model and results represent the best scientific information available and are suitable for providing management advice.

6 RESEARCH RECOMMENDATIONS

The following research recommendations are offered to improve future stock assessments of the North Carolina striped mullet stock:

<u>High</u>

- Increase sampling of recreational mullet catches to determine the proportion of striped versus white mullet and improve estimates of recreational landings
- Improve characterization of the length and age structure of recreational fisheries removals by increasing the number of age samples and number of trips sampled for lengths and ages from fisheries-dependent sources
- Develop a reliable fisheries-independent abundance index for larger juveniles to characterize trends in recruitment
- Consider expanding Program 915 to include the northern part of the state (Albemarle Sound and major tributaries)
- Evaluate the current sampling methodology of Program 146 and effectiveness for sampling striped mullet; since this survey was not considered useful for the assessment of striped mullet, consider dropping this survey and focusing effort elsewhere if it is not contributing to management of other species
- Consider running a simpler, single-sex version of the stock assessment model

<u>Medium</u>

- Consider a tagging program to provide estimates of stock size, *F*, and *M*
- Consider a genetic and/or tagging studies to examine extent of the unit stock on a regional basis for the south Atlantic as well as the Gulf of Mexico
- Expand ichthyoplankton survey to other inlets throughout the state
- Conduct an age validation study of known age fish to provide estimates of ageing error

- Consider alternative weighting of data sources in future stock assessments
- Develop estimates of fecundity for North Carolina striped mullet

<u>Low</u>

- Perform an acoustic tagging study to evaluate spatial and temporal variation in habitat use to more effectively design and conduct fisheries-independent surveys
- Investigate the predation impact on striped mullet; striped mullet is widely believed to be an important forage species but there is little evidence to support this claim in the North Carolina stock
- Investigate environmental factors that influence the spatial and temporal distribution of larval striped mullet

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8 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	NCDMF 2018
North Carolina	1996–2017	Various	FI & FD	4,782	Male	50.7	0.195	-2.73	NCDMF 2018
North Carolina	1996–2019	Various	FI & FD	12,647	Female	48.7	0.401	-0.410	current study
North Carolina	1996–2019	Various	FI & FD	6,942	Male	42.2	0.430	-0.571	current study

Table 1.2. Estimated parameter values of the 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	NCDMF 2018
North Carolina	1996–2017	Various	FI & FD	7,338	Male	1.71E-05	2.95	NCDMF 2018
North Carolina	1996–2019	Various	FI & FD	13,128	Female	1.82E-05	2.94	current study
North Carolina	1996–2019	Various	FI & FD	6,002	Male	2.02E-05	2.91	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	Female	Male
0	1.8	1.4
1	0.72	0.72
2	0.53	0.56
3	0.45	0.49
4	0.41	0.45
5	0.39	0.43
6	0.38	0.42
7	0.37	0.41
8	0.36	0.41
9	0.36	0.40
10	0.36	0.40
11	0.35	0.40
12	0.35	0.40
13	0.35	0.40
14		0.40

Table 1.4. Total number of striped mullet commercially landed (metric tons) and total number of commercial fishery trips reporting landings of striped mullet by season and month summed over 1994 to 2019.

Season	Month	Commercial Landings (mt)	Commercial Trips (number)
Winter	December	869	13,877
	January	1,124	16,773
	February	780	19,994
Spring	March	529	17,521
	April	484	16,768
	May	534	12,619
Summer	June	675	12,333
	July	936	13,834
	August	1,425	19,037
Autumn	September	1,572	22,048
	October	7,476	50,030
	November	4,667	38,142

Table 2.1. Annual commercial landings (metric tons) of striped mullet and effort (number of trips, by select gears) in North Carolina, 1994–2019.

Year	Commercial Landings (metric tons)	Commercial Effort (n trips)		
		Anchored Gill Net	Runaround Gill Net	Stop Net
1994	783.0	2,276	1,488	32
1995	1,043	2,465	2,301	17
1996	796.9	2,352	2,408	14
1997	1,108	2,488	2,796	44
1998	1,006	2,128	2,282	19
1999	662.6	1,991	1,473	10
2000	1,283	3,183	2,273	29
2001	1,051	1,852	2,153	21
2002	1,178	1,975	1,972	25
2003	739.1	1,814	1,390	4
2004	725.1	1,356	1,484	28
2005	735.0	1,055	1,662	12
2006	784.1	999	1,671	13
2007	757.0	1,087	1,631	7
2008	760.2	968	1,585	5
2009	764.6	848	1,532	3
2010	944.8	1,208	2,248	2
2011	738.4	1,238	1,632	2
2012	843.5	1,090	1,956	6
2013	702.7	905	1,930	17
2014	829.3	1,089	1,705	10
2015	565.7	767	1,668	6
2016	437.9	547	1,392	6
2017	619.8	568	1,632	10
2018	595.2	636	1,595	2
2019	617.9	527	1,724	6

Table 2.2. Number of available biological samples of striped mullet sampled from North Carolina commercial fisheries' landings, 1990–2019.

	Length	Age	
Year	**pooled**	**female**	**male**
1990	102		
1991	526		
1992	310		
1993	383		
1994	198		
1995	227		
1996	89	108	51
1997	1,367	183	69
1998	1,186	276	130
1999	1,283	185	118
2000	4,866	173	71
2001	3,591	77	51
2002	6,131	95	30
2003	4,438	119	32
2004	7,117	94	36
2005	5,636	44	10
2006	7,199	56	11
2007	7,340	8	1
2008	8,341		
2009	5,693		
2010	7,561	13	7
2011	5,339	15	4
2012	8,796		
2013	6,488	27	7
2014	5,390	11	
2015	5,373	40	74
2016	5,388	25	3
2017	4,119	22	5
2018	3,489	59	24
2019	4,758	87	36

Table 2.3. Annual harvest (numbers of fish), releases (numbers of fish), effort (number of trips) and associated estimates of proportional standard error (PSE) for mullet (white plus striped) in North Carolina's recreational fishery, 2011–2019. Note that the mail survey from which the estimates were derived began in October 2011 so the estimates for 2011 are not for the entire year.

Year	Harvest	PSE[Harvest]	Release	PSE[Release]	Effort	PSE[Effort]
2011	74,461	25	31,210	36	16,007	17
2012	693,262	8.9	220,205	12	125,623	6.2
2013	711,307	10	229,509	14	139,286	6.3
2014	783,058	9.4	251,504	11	197,257	6.8
2015	942,521	8.4	296,039	12	206,876	6.0
2016	748,394	11	219,892	14	191,922	6.4
2017	722,929	8.8	239,998	11	182,861	6.7
2018	347,187	30	108,904	45	88,939	12
2019	688,815	10	320,885	16	162,941	7.1

Table 2.4. Annual recreational harvest (Type A + B1) estimates for striped mullet in North Carolina as estimated by the MRIP, 1981–2019. Proportional standard error (PSE) values greater than 50 indicate an imprecise estimate and are highlighted in pink.

Year	Numbers	PSE[Numbers]	Weight (kg)	PSE[Weight]
1981	11,528	95.8	4,846	95.8
1982	694,103	51.8	160,883	49.1
1983	1,180,943	94.4	146,231	86.7
1984	880,129	21.1	46,182	19.9
1985	721,090	67.6	258,393	64.1
1986	92,858	61.7	37,132	59.4
1987	3,093,510	70.7	275,299	64.4
1988	555,518	59.9	4,527	80.6
1989	192,232	41.9	68,012	38.7
1990	307,489	84.3	79,754	81.1
1991	52,759	46.2	17,865	45.4
1992	1,543,433	88.5	536,262	87.6
1993	295,610	57.5	306,828	70.4
1994	280,168	59.5	271,330	55.4
1995	113,207	64.2	108,174	77.4
1996	35,762	49.9	31,150	54.2
1997	91,702	69.1	78,328	82.4
1998	18,609	66.3	6,163	66.5
1999	17,674	57.3	5,198	55.7
2000	142,083	73.5	85,332	83
2001	2,734,116	38.9	953,028	43.1
2002	4,668,427	18	848,923	24.2
2003	3,368,881	29.6	737,422	38.8
2004	5,496	101.7	1,231	101.7
2005	10,795	61.5	6,200	63.1
2006	15,706	63.5	6,945	53.7
2007	301,004	81.3	93,766	74.8
2008	3,458	65	1,111	63.1
2009	83,480	90.6	9,996	62.5
2010	126,250	44.7	46,340	58
2011	80,267	28.6	28,048	38.5
2012	351,960	79.5	100,621	80
2013	150,020	53.9	56,754	54.8
2014	50,381	67	26,962	70.1
2015	142,696	64.5	82,492	69.6
2016	29,965	50.6	13,444	51.7
2017	37,791	43.9	12,479	43.5
2018	35,565	59.3	11,380	56.7
2019	324,986	52	158,475	56.7

Table 2.5. Annual recreational harvest (Type A + B1) estimates for white mullet in North Carolina as estimated by the MRIP, 1981–2019. Proportional standard error (PSE) values greater than 50 indicate an imprecise estimate and are highlighted in pink.

Year	Numbers	PSE[Numbers]	Weight (kg)	PSE[Weight]
1981	10,848	99.6	3,471	99.6
1982	86,103	98.3	25,877	98.1
1983	8,403	100.2	1,700	100.2
1984	2,725	104.6	275	104.6
1985	241,352	36.3	40,933	35.5
1986				
1987	2,092,801	90.2	93,472	89.3
1988				
1989	10,060	61.9	2,886	63.2
1990				
1991				
1992				
1993				
1994	6,475	98.4	647	98.4
1995	4,785	100.3	1,587	100.3
1996				
1997				
1998				
1999				
2000				
2001				
2002				
2003				
2004				
2005				
2006	50,742	95.3	13,193	95.3
2007				
2008				
2009	1,759	100	528	100
2010	7,176	78.2	1,560	83.9
2011	38,562	67.2	2,468	63.6
2012	25,295	71.8	1,569	67.8
2013	68,205	83	12,554	95.3
2014	11,676	44.6	934	44.6
2015	6,535	99.6	5,947	99.6
2016				
2017	4,680	100.9	622	100.9
2018	79,863	51.8	14,594	81.4
2019	98,134	26.6	2,933	40.6

Table 2.6. Annual recreational harvest (Type A + B1) estimates for the mullet genus in North Carolina as estimated by the MRIP, 1981–2019. Proportional standard error (PSE) values greater than 50 indicate an imprecise estimate and are highlighted in pink.

Year	Numbers	PSE[Numbers]	Weight (kg)	PSE[Weight]
1981				
1982	9,118	94.9	912	94.9
1983	625,777	105.3	15,145	105.3
1984	11,372	71.9	1,137	71.9
1985	21,999	67.7	2,778	64.9
1986	1,047	99.8	209	99.8
1987	47,552	60.6	0	
1988				
1989	28,848	107.2	1,731	107.2
1990				
1991				
1992				
1993				
1994				
1995	108,218	67.8	0	
1996	1,894	70.8	0	
1997	923	74.6	0	
1998				
1999				
2000	479,051	47.4	0	
2001				
2002	4,480,197	36.3	0	
2003	2,487,885	20.4	0	
2004	4,790,382	16.1	0	
2005	4,487,719	21.4	0	
2006	3,599,098	21.4	0	
2007	5,052,995	22.3	0	
2008	4,097,156	14.4	0	
2009	3,736,571	14.3	0	
2010	4,113,171	14.3	0	
2011	3,653,514	14.3	0	
2012	3,510,395	16.3	0	
2013	4,493,166	20.5	0	
2014	4,490,722	26.2	0	
2015	4,405,800	21.5	0	
2016	5,039,891	55.6	0	
2017	5,170,318	55.2	0	
2018	1,564,676	31.7	0	
2019	817,596	25.3	0	

Table 2.7. Annual recreational observed (Type A) and reported (Type B1) harvest estimates for striped mullet in North Carolina as estimated by the MRIP in units of numbers of fish, 1981–2019. Proportional standard error (PSE) values greater than 50 indicate an imprecise estimate and are highlighted in pink.

Year	Observed Harvest	PSE[Observed]	Reported Harvest	PSE[Reported]
1981	1,637	95.8	9,891	95.8
1982	139,069	71.2	555,034	59.4
1983	1,026,962	93.4	153,981	101
1984	265,394	51.8	614,735	20.2
1985	77,703	60.1	643,387	75.4
1986	5,924	79	86,933	66.1
1987	3,035,900	71.4	57,610	67
1988	241,623	89.3	313,895	78.4
1989	88,022	45.5	104,210	67.2
1990	45,484	58.5	262,005	98.5
1991	25,536	63.9	27,224	63.4
1992	1,405,151	97	138,282	56
1993	155,746	51.6	139,864	70.3
1994	277,218	60.1	2,950	102.8
1995	102,249	70.6	10,959	76.1
1996	13,865	59.7	21,897	73.5
1997	91,702	69.1		
1998	1,899	72.4	16,710	73.4
1999	11,740	70.1	5,934	100.4
2000	3,769	88.9	138,314	75.4
2001	98,848	86.6	2,635,268	37.4
2002	419,828	45.7	4,248,599	19.2
2003	159,467	91.3	3,209,414	30.7
2004			5,496	101.7
2005	10,795	61.5		
2006	6,945	65.1	8,761	101.4
2007	277,160	87.8	23,844	101.1
2008	3,458	65		
2009	83,480	90.6		
2010	67,261	45.8	58,989	53.5
2011	27,793	44.6	52,474	33.6
2012	199,033	83.7	152,927	76.9
2013	54,100	58.8	95,920	66.4
2014	49,011	68.8	1,370	101
2015	126,328	71.7	16,368	72.3
2016	29,965	50.6		
2017	35,627	46.1	2,164	99.9
2018	31,224	66.9	4,341	70.4
2019	9,572	64.1	315,414	53.6

Table 2.8. Annual recreational observed (Type A) and reported (Type B1) harvest estimates for white mullet in North Carolina as estimated by the MRIP in units of numbers of fish, 1981–2019. Proportional standard error (PSE) values greater than 50 indicate an imprecise estimate and are highlighted in pink.

Year	Observed Harvest	PSE[Observed]	Reported Harvest	PSE[Reported]
1981			10,848	99.6
1982	86,103	98.3		
1983	8,403	100.2		
1984	2,725	104.6		
1985	163,264	40.1	78,088	49.2
1986				
1987	2,092,801	90.2		
1988				
1989	9,285	66.5	775	100.3
1990				
1991				
1992				
1993				
1994	6,475	98.4		
1995	4,785	100.3		
1996				
1997				
1998				
1999				
2000				
2001				
2002				
2003				
2004				
2005				
2006	14,754	95.3	35,988	95.3
2007				
2008				
2009	1,759	100		
2010	7,176	78.2		
2011	38,562	67.2		
2012	25,295	71.8		
2013	68,205	83		
2014	11,676	44.6		
2015	6,535	99.6		
2016				
2017	468	100.9	4,212	100.9
2018	20,960	101.9	58,903	60.1
2019	93,378	27.5	4,756	100.8

Table 2.9. Annual recreational observed (Type A) and reported (Type B1) harvest estimates for the mullet genus in North Carolina as estimated by the MRIP in units of numbers of fish, 1981–2019. Proportional standard error (PSE) values greater than 50 indicate an imprecise estimate and are highlighted in pink.

Year	Observed Harvest	PSE[Observed]	Reported Harvest	PSE[Reported]
1981				
1982			9,118	94.9
1983	625,777	105.3		
1984			11,372	71.9
1985			21,999	67.7
1986			1,047	99.8
1987			47,552	60.6
1988				
1989	28,848	107.2		
1990				
1991				
1992				
1993				
1994				
1995			108,218	67.8
1996			1,894	70.8
1997			923	74.6
1998				
1999				
2000			479,051	47.4
2001				
2002			4,480,197	36.3
2003			2,487,885	20.4
2004			4,790,382	16.1
2005			4,487,719	21.4
2006			3,599,098	21.4
2007			5,052,995	22.3
2008			4,097,156	14.4
2009			3,736,571	14.3
2010			4,113,171	14.3
2011			3,653,514	14.3
2012			3,510,395	16.3
2013			4,493,166	20.5
2014			4,490,722	26.2
2015			4,405,800	21.5
2016			5,039,891	55.6
2017			5,170,318	55.2
2018			1,564,676	31.7
2019			817,596	25.3

Table 2.10. Annual number of assignments total and with striped mullet and annual number of intercepts total and with striped mullet in North Carolina's MRIP survey, 1981–2019.

Year	Assignments			Intercepts		
	n Total	n with Striped Mullet	% with Striped Mullet	n Total	n with Striped Mullet	% with Striped Mullet
1981	89	1	1.1	1,077	3	0.28
1982	164	7	4.3	1,989	12	0.60
1983	104	4	3.8	1,308	6	0.46
1984	104	4	3.8	1,518	6	0.40
1985	145	8	5.5	1,980	11	0.56
1986	188	4	2.1	2,470	6	0.24
1987	547	9	1.6	7,347	17	0.23
1988	568	8	1.4	8,054	9	0.11
1989	697	17	2.4	10,851	19	0.18
1990	655	13	2.0	10,898	17	0.16
1991	843	6	0.71	15,569	7	0.045
1992	761	12	1.6	12,876	15	0.12
1993	839	14	1.7	13,728	17	0.12
1994	1,061	14	1.3	19,158	16	0.084
1995	1,128	14	1.2	20,124	14	0.070
1996	1,259	8	0.64	24,296	10	0.041
1997	1,317	6	0.46	22,757	7	0.031
1998	1,271	4	0.31	21,200	4	0.019
1999	1,080	4	0.37	17,729	5	0.028
2000	966	7	0.72	17,849	8	0.045
2001	1,188	29	2.4	21,305	78	0.37
2002	1,145	53	4.6	17,840	121	0.68
2003	1,035	42	4.1	16,021	93	0.58
2004	978	1	0.10	15,052	1	0.0066
2005	822	3	0.36	13,651	3	0.022
2006	907	6	0.66	14,760	6	0.041
2007	887	3	0.34	14,571	3	0.021
2008	1,044	3	0.29	16,134	3	0.019
2009	1,030	5	0.49	12,893	5	0.039
2010	1,834	14	0.76	21,647	16	0.074
2011	1,771	17	0.96	20,757	18	0.087
2012	2,072	12	0.58	24,471	13	0.053
2013	1,469	11	0.75	13,339	12	0.090
2014	1,273	5	0.39	13,635	6	0.044
2015	1,274	11	0.86	14,040	12	0.085
2016	1,224	5	0.41	14,257	6	0.042
2017	1,488	10	0.67	16,345	11	0.067
2018	1,442	7	0.49	16,705	8	0.048
2019	1,438	12	0.83	14,966	15	0.10

Table 2.11. Annual number of assignments total and with mullet genus and annual number of intercepts total and with mullet genus in North Carolina's MRIP survey, 1981–2019.

	Assignments			Intercepts		
Year	**n Total**	**n with Mullet genus**	**% with Mullet genus**	**n Total**	**n with Mullet genus**	**% with Mullet genus**
1981	89			1,077		
1982	164	1	0.61	1,989	1	0.050
1983	104	1	0.96	1,308	1	0.076
1984	104	2	1.9	1,518	2	0.13
1985	145	2	1.4	1,980	4	0.20
1986	188	1	0.53	2,470	1	0.040
1987	547	4	0.73	7,347	4	0.054
1988	568			8,054		
1989	697	1	0.14	10,851	1	0.0092
1990	655			10,898		
1991	843			15,569		
1992	761			12,876		
1993	839			13,728		
1994	1,061			19,158		
1995	1,128	2	0.18	20,124	2	0.0099
1996	1,259	2	0.16	24,296	3	0.012
1997	1,317	2	0.15	22,757	2	0.0088
1998	1,271			21,200		
1999	1,080			17,729		
2000	966	5	0.52	17,849	12	0.067
2001	1,188			21,305		
2002	1,145	24	2.1	17,840	47	0.26
2003	1,035	35	3.4	16,021	61	0.38
2004	978	91	9.3	15,052	242	1.6
2005	821	62	7.6	13,651	140	1.0
2006	907	86	9.5	14,760	214	1.4
2007	887	82	9.2	14,571	230	1.6
2008	1,044	85	8.1	16,134	220	1.4
2009	1,030	76	7.4	12,893	203	1.6
2010	1,834	116	6.3	21,647	306	1.4
2011	1,771	98	5.5	20,757	222	1.1
2012	2,073	129	6.2	24,471	257	1.1
2013	1,469	78	5.3	13,339	180	1.3
2014	1,273	64	5.0	13,635	130	0.95
2015	1,274	70	5.5	14,040	177	1.3
2016	1,224	41	3.3	14,257	76	0.53
2017	1,488	51	3.4	16,345	77	0.47
2018	1,442	29	2.0	16,705	44	0.26
2019	1,438	37	2.6	14,966	55	0.37

Table 2.12. Annual number of directed trips for mullet species in North Carolina as estimated by the MRIP, 1981–2019. Directed trips are defined as those trips that target striped mullet, white mullet, or mullet genus or trips that catch the specified species (striped mullet or mullet genus). Proportional standard error (PSE) values greater than 50 indicate an imprecise estimate and are highlighted in pink.

	Striped Mullet		Mullet genus	
Year	**n Trips**	**PSE**	**n Trips**	**PSE**
1981				
1982	38,644	41.4	12,781	76.9
1983	101,118	51.8	32,623	70.8
1984	46,305	32.5	21,854	45.1
1985	113,446	31.9	98,682	40.9
1986	16,093	48.6	524	100
1987	77,760	49.1	4,119	63
1988	69,339	61.4	39,785	100
1989	33,519	41.3	8,757	41.8
1990	22,378	35.1	2,679	67.8
1991	18,819	27	11,814	32.5
1992	27,380	35	1,563	68.7
1993	45,226	30.9	22,990	38.3
1994	35,846	30.2	6,108	48.2
1995	43,895	29.5	26,102	36.8
1996	18,854	29.5	50,748	21.7
1997	20,693	32.9	31,192	28.2
1998	9,891	44.3	5,116	51.8
1999	15,876	35.3	28,225	30.2
2000	17,823	40.4	34,225	27.6
2001	86,461	20.9	24,260	62.4
2002	187,692	14.8	117,033	26.8
2003	163,191	17.4	114,626	17.5
2004	916	100	248,564	12.6
2005	5,573	65.2	196,281	14.8
2006	10,773	45.9	278,899	17.5
2007	13,148	59.3	322,750	13.1
2008	4,365	45.3	290,531	12.5
2009	10,321	57.3	292,348	13.4
2010	21,705	30	257,473	12.5
2011	27,503	34.7	240,957	12.2
2012	35,160	34.1	204,069	11.8
2013	36,487	33.7	299,809	15.3
2014	25,126	56.1	276,872	21.2
2015	39,956	36.8	284,786	17.1
2016	27,229	47.2	166,027	22.3
2017	151,399	79.4	307,579	53.2
2018	26,903	46.7	127,213	26.8
2019	39,665	20.3	124,124	22.1

Table 2.13. Number of intercepts in which the indicated species was harvested by gear type, summed over 1981–2019.

Gear	Striped Mullet	White Mullet	Mullet genus	Total
Cast Net	37	5	22	64
Gill Net	43	4	12	59
Hook & Line	367	41	2,363	2,771
Other	2			2
Spear	2		1	3
Trawl	1			1
Total	452	50	2,398	2,900

Table 2.14. Number of intercepts in which the indicated species was harvested by gear type and primary target species, summed over 1981–2019.

Primary Target Species	Species Harvested by Gear Type						Total
	Striped Mullet		White Mullet		Mullet genus		
	Cast Net	Hook & Line	Cast Net	Hook & Line	Cast Net	Hook & Line	
Lefteye Flounder genus	2	196		3	4	1,710	1,915
Red Drum	4	41		7	1	297	350
Spotted Seatrout	1	18		3		119	141
Spanish Mackerel	1	14		1		52	68
Bluefish	5	16	1	2		42	66
King Mackerel		18		2		45	65
Mullet genus	9	5	3	2	16	7	42
Spot	1	3	1	10		12	27
Sheepshead		11		1		13	25
Striped Mullet	11	8					19
Seatrout genus		7				10	17
Summer Flounder		5		5		4	14
Mackerel genus						10	10
Unidentified (Sharks)						10	10
Weakfish		2				7	9
Black Drum		4				4	8
Kingfish genus		3				4	7
Mullet family	2	3			1		6
Lefteye Flounder family		5					5
White Mullet				4		1	5
Atlantic Croaker		1				3	4
Cobia		1				3	4
Striped Bass		3					3
Black Sea Bass						2	2
Southern Flounder		1				1	2
Atlantic Sharpnose Shark						1	1
Atlantic Spadefish						1	1
Atlantic Tarpon		1					1
Cero						1	1
Dolphin		1					1
Drum family						1	1
Florida Pompano						1	1
Gulf Menhaden	1						1

Table 2.15. Average length and weight of individual striped mullet intercepted by APAIS interviewers in North Carolina, 1981–2019. Proportional standard error (PSE) values greater than 50 indicate an imprecise estimate and are highlighted in pink.

Year	Avg Length (cm)	PSE[Length]	Avg Weight (kg)	PSE[Weight]
1981	29.2	135.4	0.4	135.4
1982	23.59	73.7	0.2	71.3
1983	20.57	132.2	0.1	128.2
1984	12.4	29.5	0.1	29
1985	28.26	93.9	0.4	93.2
1986	29.91	86.7	0.4	85.6
1987	15.31	97.4	0.1	95.7
1988	0.61	99.7	0	100.4
1989	29.48	57.5	0.4	57.1
1990	25.39	117.7	0.3	117
1991	26.24	64.7	0.3	64.7
1992	28.1	125	0.3	124.5
1993	43.17	84.6	1	90.9
1994	41.67	82.7	1	81.3
1995	40.35	95.8	1	100.5
1996	37.94	71.8	0.9	73.7
1997	37.76	102	0.9	107.6
1998	29.18	93.6	0.3	93.9
1999	28.75	79.6	0.3	79.9
2000	32.94	103.9	0.6	110.9
2001	30.39	55	0.3	58
2002	20.75	26	0.2	30.2
2003	23.46	44.9	0.2	48.8
2004	25.3	143.8	0.2	143.8
2005	34.48	87.2	0.6	88.1
2006	30.17	86.4	0.4	83.1
2007	26.89	113.5	0.3	110.4
2008	27.55	90.9	0.3	90.6
2009	18.17	122.9	0.1	110.1
2010	26.31	63.7	0.4	73.2
2011	27.22	41.4	0.3	48
2012	26.6	112.5	0.3	112.8
2013	27.39	74.9	0.4	76.8
2014	32.76	96.4	0.5	97
2015	31.61	91.7	0.6	94.9
2016	30.25	71.7	0.4	72.3
2017	27.41	62.3	0.3	61.8
2018	27.58	83.3	0.3	82
2019	31.82	73.9	0.5	77

Table 2.16. Number of available biological samples of striped mullet sampled from Program 146, 2003–2019.

	Spring			Autumn		
	Length	Age		Length	Age	
Year	pooled	female	male	pooled	female	male
2003	413	39	5	580	48	18
2004	776	139	8	881	69	3
2005	1,462	64	3	57		
2006	1,636	44	8	61		
2007	957	83	4		13	2
2008	1,719	60	3	635	36	2
2009	1,150	61	4	494		
2010	864	22	5	601		
2011	1,452	47	9	520	33	4
2012	454	42	2	656		
2013	1,368			627	37	26
2014	829	50	8	435	13	2
2015	606			328	14	
2016	710	54	5	158	62	14
2017	562	69	15	470	46	19
2018	1,010	45	18	21	17	1
2019	452	34	3	769	34	2

Table 2.17. Number of available biological samples of striped mullet sampled from Program 915 by area, 1994–2019.

	Southern			Northern		
	Length	Age		Length	Age	
Year	pooled	female	male	pooled	female	male
2004				824	54	12
2005				574	32	11
2006				559	27	18
2007				791	40	21
2008	167	68	26	521	39	19
2009	134	61	19	619	49	22
2010	356	63	21	854	135	46
2011	91	49	23	898	109	50
2012	95	54	26	803	204	143
2013	105	36	19	784	232	118
2014	215	72	45	740	177	134
2015	77	38	20	272	88	78
2016	156	35	16	307	110	63
2017	53	25	32	321	101	67
2018	50	26	15	477	146	91
2019	21	10	2	347	131	66

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

Type	Parameter	Initial Value	Min	Max	Prior Type
Growth	L1, female	21.0	10	40	Sym_Beta
	Linf, female	48.7	20	70	Sym_Beta
	K, female	0.40	0.05	0.8	Sym_Beta
	CV1, female	0.28	0.01	0.5	Sym_Beta
	CV2, female	0.21	0.01	0.5	Sym_Beta
	L1, male	20.7	10	40	Sym_Beta
	Linf, male	42.2	20	70	Sym_Beta
	K, male	0.43	0.05	0.8	Sym_Beta
	CV1, male	0.25	0.01	0.5	Sym_Beta
	CV2, male	0.14	0.01	0.5	Sym_Beta
Initial conditions	SR_LN(R0)	10	6	20	Sym_Beta
	SR_BH_steep	0.77	0.2	1	Normal
	InitF_seas_1_flt_1Comm	0.4	0	1	No_prior
	InitF_seas_1_flt_2Rec	0.4	0	1	No_prior
Catchability	LnQ_base_P915(3)	0	-25	25	No_prior
	Q_power_P915(3)	0	-25	25	Normal
Selectivity	Size_inflection_Comm(1)	32	0	60	No_prior
	Size_95%width_Comm(1)	6.2	0.01	40	No_prior
	Size_inflection_P915_north(3)	29	0	60	No_prior
	Size_95%width_P915_north(3)	2.6	0.01	40	No_prior

Table 3.2. Estimated values, standard deviations (SD), bounds (min and max), and phase of estimation for parameters in the base run of the stock assessment model. Standard deviation values marked with an asterisk (*) indicate excessively large (>100%) proportional standard errors.

Type	Parameter	Estimated Value	SD[Value]	Phase
Growth	L1, female	21	1.2	2
	Linf, female	50	2.6	4
	K, female	0.39	0.064	4
	CV1, female	0.25	0.024	3
	CV2, female	0.091	0.021	3
	L1, male	22	1.4	2
	Linf, male	41	0.97	5
	K, male	0.66	0.077	5
	CV1, male	0.28	0.029	3
	CV2, male	0.042	0.012	3
Initial conditions	SR_LN(R0)	9.7	0.092	1
	SR_BH_steep	0.73	0.043	3
	InitF_seas_1_flt_1Comm	0.027	0.0069	1
	InitF_seas_1_flt_2Rec	0.023	0.0055	1
Catchability	LnQ_base_P915(3)	-11		-8
	Q_power_P915(3)	0.69	0.28	9
Selectivity	Size_inflection_Comm(1)	31	0.43	5
	Size_95%width_Comm(1)	5.8	0.48	6
	Size_inflection_P915_north(3)	28	0.25	3
	Size_95%width_P915_north(3)	2.3	0.39	4

Table 3.3. Comparison of empirically-derived estimates of the von Bertalanffy age-length parameters to those estimated by the base run of the Stock Synthesis model.

Sex	Parameter	Empirical	Stock Synthesis
female	$L1$ (cm)	21	21
	L_∞ (cm)	49	50
	K	0.40	0.39
	CV1	0.28	0.25
	CV2	0.21	0.091
male	$L1$ (cm)	21	22
	L_∞ (cm)	42	41
	K	0.43	0.66
	CV1	0.25	0.28
	CV2	0.14	0.042

Table 3.4. Annual estimates of recruitment (thousands of fish), female spawning stock biomass (SSB; metric tons), and spawning potential ratio (SPR) and associated standard deviations from the base run of the stock assessment model, 1950–1984.

	Recruitment		SSB		SPR	
Year	**Value**	**SD**	**Value**	**SD**	**Value**	**SD**
1950	16,710	1,520	3,222	350	0.46	0.034
1951	16,352	1,462	2,657	336	0.37	0.037
1952	15,746	1,396	2,019	320	0.32	0.042
1953	15,021	1,363	1,539	303	0.37	0.049
1954	14,721	1,356	1,392	293	0.44	0.052
1955	14,722	1,347	1,392	288	0.42	0.051
1956	14,671	1,338	1,370	283	0.38	0.051
1957	14,497	1,332	1,296	276	0.38	0.052
1958	14,366	1,327	1,245	271	0.36	0.052
1959	14,203	1,326	1,185	266	0.34	0.053
1960	14,005	1,329	1,119	262	0.25	0.050
1961	13,304	1,378	923	252	0.31	0.059
1962	13,264	1,383	913	251	0.30	0.059
1963	13,136	1,408	883	252	0.33	0.063
1964	13,229	1,412	905	256	0.44	0.065
1965	13,696	1,379	1,025	266	0.45	0.061
1966	14,025	1,361	1,125	272	0.44	0.058
1967	14,205	1,350	1,186	274	0.52	0.053
1968	14,524	1,335	1,307	277	0.52	0.050
1969	14,737	1,327	1,399	277	0.55	0.047
1970	14,936	1,323	1,494	277	0.55	0.044
1971	15,086	1,321	1,573	276	0.64	0.037
1972	15,322	1,328	1,712	277	0.57	0.040
1973	15,383	1,327	1,751	276	0.58	0.038
1974	15,453	1,330	1,798	275	0.44	0.042
1975	15,234	1,312	1,658	270	0.45	0.044
1976	15,090	1,304	1,576	267	0.42	0.045
1977	14,929	1,296	1,491	264	0.44	0.046
1978	14,866	1,293	1,460	263	0.45	0.047
1979	14,839	1,291	1,447	261	0.45	0.047
1980	14,808	1,289	1,432	260	0.39	0.047
1981	14,614	1,283	1,345	257	0.50	0.047
1982	14,789	1,286	1,423	259	0.48	0.046
1983	14,859	1,287	1,456	259	0.56	0.043
1984	15,049	1,293	1,553	261	0.47	0.044

Table 3.5. Annual estimates of recruitment (thousands of fish), female spawning stock biomass (SSB; metric tons), and spawning potential ratio (SPR) and associated standard deviations from the base run of the stock assessment model, 1985–2019.

Year	Recruitment		SSB		SPR	
	Value	SD	Value	SD	Value	SD
1985	15,008	1,289	1,531	260	0.50	0.044
1986	15,037	1,290	1,547	260	0.44	0.045
1987	14,922	1,284	1,487	258	0.36	0.045
1988	14,578	1,275	1,330	253	0.30	0.046
1989	14,032	1,280	1,128	246	0.36	0.052
1990	12,472	3,545	1,117	246	0.27	0.044
1991	12,804	3,366	952	231	0.40	0.048
1992	11,694	3,011	1,005	210	0.35	0.039
1993	10,006	2,307	984	182	0.22	0.029
1994	10,633	2,079	736	136	0.29	0.031
1995	14,849	2,401	682	99	0.23	0.028
1996	14,431	2,361	580	83	0.29	0.032
1997	8,827	1,759	694	102	0.23	0.029
1998	16,898	2,431	719	114	0.26	0.032
1999	9,430	1,975	659	113	0.33	0.028
2000	13,923	1,809	807	93	0.23	0.021
2001	9,063	1,847	672	75	0.22	0.017
2002	16,856	1,970	630	45	0.096	0.015
2003	12,621	1,867	457	27	0.13	0.017
2004	9,433	1,758	424	50	0.21	0.021
2005	11,894	1,807	411	51	0.22	0.023
2006	10,764	1,503	420	51	0.24	0.023
2007	7,451	1,029	484	59	0.20	0.019
2008	12,582	1,175	520	53	0.25	0.021
2009	9,586	1,186	468	46	0.24	0.018
2010	9,469	912	507	40	0.20	0.016
2011	9,095	905	474	32	0.24	0.017
2012	9,453	763	471	31	0.19	0.015
2013	8,312	760	424	27	0.20	0.014
2014	5,801	572	419	24	0.15	0.013
2015	6,673	605	334	16	0.16	0.014
2016	9,137	746	270	18	0.20	0.015
2017	6,673	535	267	21	0.15	0.012
2018	7,333	550	270	16	0.21	0.015
2019	8,315	3,134	263	15	0.21	0.018

Table 3.6. Predicted stock numbers (thousands of fish) at age at the beginning of the year from the base run of the stock assessment model, 1950–1984. Values rounded to the nearest integer.

Year	0	1	2	3	4	5	6	7+
1950	16,710	6,604	3,406	1,937	1,150	700	432	735
1951	16,352	5,942	3,107	1,636	927	555	341	579
1952	15,746	5,787	2,685	1,348	685	388	234	394
1953	15,021	5,543	2,545	1,089	517	261	148	244
1954	14,721	5,259	2,512	1,121	466	221	113	172
1955	14,722	5,140	2,447	1,188	527	221	106	138
1956	14,671	5,138	2,380	1,143	549	245	104	116
1957	14,497	5,116	2,340	1,066	499	240	108	99
1958	14,366	5,047	2,326	1,045	464	218	106	92
1959	14,203	4,994	2,274	1,015	441	196	93	85
1960	14,005	4,928	2,226	966	414	179	80	74
1961	13,304	4,842	2,054	796	314	132	57	50
1962	13,264	4,571	2,113	832	305	120	51	41
1963	13,136	4,551	1,977	837	310	113	44	34
1964	13,229	4,502	2,014	832	337	125	46	32
1965	13,696	4,543	2,093	962	396	162	61	38
1966	14,025	4,727	2,125	1,012	465	194	80	49
1967	14,205	4,859	2,202	1,014	481	223	94	64
1968	14,524	4,934	2,317	1,115	521	251	118	84
1969	14,737	5,061	2,353	1,170	570	270	132	107
1970	14,936	5,147	2,430	1,208	611	303	145	130
1971	15,086	5,227	2,475	1,251	633	326	163	151
1972	15,322	5,289	2,559	1,333	696	360	187	184
1973	15,383	5,381	2,553	1,326	705	374	196	205
1974	15,453	5,406	2,607	1,336	710	384	207	225
1975	15,234	5,430	2,523	1,237	629	337	184	210
1976	15,090	5,344	2,538	1,204	587	301	163	193
1977	14,928	5,286	2,477	1,185	556	273	141	169
1978	14,866	5,222	2,465	1,178	560	265	131	152
1979	14,839	5,197	2,441	1,180	561	269	129	139
1980	14,808	5,186	2,426	1,164	560	269	130	131
1981	14,614	5,171	2,369	1,094	513	247	120	118
1982	14,789	5,099	2,456	1,183	551	262	128	125
1983	14,859	5,166	2,408	1,207	584	275	132	129
1984	15,049	5,197	2,487	1,244	636	313	149	144

Table 3.7. Predicted stock numbers (thousands of fish) at age at the beginning of the year from the base run of the stock assessment model, 1985–2019. Values rounded to the nearest integer.

Year	0	1	2	3	4	5	6	7+
1985	15,008	5,269	2,446	1,210	605	313	155	148
1986	15,037	5,255	2,499	1,214	604	306	160	158
1987	14,921	5,264	2,447	1,182	570	286	146	154
1988	14,578	5,215	2,370	1,061	495	238	121	128
1989	14,032	5,075	2,259	933	391	181	87	92
1990	12,472	4,863	2,286	987	395	166	77	78
1991	12,804	4,244	2,052	853	340	134	56	53
1992	11,694	4,371	1,941	944	387	155	62	51
1993	10,006	3,938	1,954	849	401	165	67	49
1994	10,632	3,264	1,576	656	255	118	48	34
1995	14,849	3,498	1,400	630	248	96	44	31
1996	14,431	5,146	1,419	466	187	71	28	22
1997	8,827	5,013	2,220	553	170	67	26	18
1998	16,898	2,834	2,045	793	180	54	22	14
1999	9,430	5,949	1,190	736	260	58	17	12
2000	13,923	3,088	2,629	516	309	109	25	12
2001	9,063	4,779	1,247	869	152	89	31	11
2002	16,856	2,916	1,925	430	271	46	27	13
2003	12,621	3,462	958	545	106	65	11	10
2004	9,433	2,858	1,248	321	167	32	19	6
2005	11,894	2,997	1,135	418	97	49	9	8
2006	10,764	4,004	1,204	376	123	28	14	5
2007	7,451	3,715	1,636	409	115	37	8	6
2008	12,582	2,082	1,467	596	138	38	12	5
2009	9,586	4,327	861	515	189	43	12	5
2010	9,469	3,205	1,778	304	165	60	14	5
2011	9,095	3,059	1,251	563	85	45	16	5
2012	9,453	3,006	1,253	442	181	27	14	7
2013	8,312	3,020	1,168	395	123	49	7	6
2014	5,801	2,539	1,194	399	122	37	15	4
2015	6,673	1,614	915	344	99	29	9	4
2016	9,137	1,880	603	286	95	27	8	4
2017	6,673	2,804	743	205	88	28	8	3
2018	7,333	1,858	1,010	213	51	21	7	3
2019	8,315	2,642	724	294	53	12	5	2

Table 3.8. Predicted stock numbers (thousands of fish) at age at mid-year from the base run of the stock assessment model, 1950–1984. Values rounded to the nearest integer.

Year	0	1	2	3	4	5	6	7+
1950	9,964	4,530	2,360	1,340	799	488	303	519
1951	9,727	3,994	2,046	1,058	599	360	222	379
1952	9,342	3,837	1,710	835	423	240	145	246
1953	8,888	3,731	1,689	712	338	171	98	162
1954	8,699	3,587	1,728	768	321	153	78	120
1955	8,698	3,498	1,672	807	359	151	73	96
1956	8,664	3,468	1,592	755	363	163	69	78
1957	8,554	3,450	1,563	703	330	159	72	66
1958	8,470	3,388	1,536	679	301	142	69	61
1959	8,366	3,334	1,482	648	281	125	60	55
1960	8,235	3,182	1,331	551	234	101	45	42
1961	7,798	3,198	1,307	493	194	82	36	31
1962	7,769	3,006	1,330	508	185	73	31	25
1963	7,690	3,027	1,282	531	196	72	28	22
1964	7,752	3,070	1,392	574	234	87	32	23
1965	8,047	3,107	1,455	669	277	114	43	27
1966	8,255	3,227	1,468	698	322	135	56	35
1967	8,372	3,355	1,567	727	347	162	68	47
1968	8,573	3,407	1,646	797	375	182	86	62
1969	8,709	3,507	1,685	846	415	198	97	80
1970	8,835	3,569	1,743	874	446	222	107	97
1971	8,932	3,657	1,817	933	477	247	124	116
1972	9,080	3,674	1,842	970	510	265	139	137
1973	9,119	3,746	1,846	970	520	278	146	154
1974	9,160	3,693	1,796	917	489	266	144	157
1975	9,023	3,712	1,743	852	435	234	129	147
1976	8,931	3,638	1,735	818	400	206	112	134
1977	8,829	3,610	1,708	815	383	189	98	119
1978	8,789	3,571	1,705	813	388	184	92	107
1979	8,772	3,551	1,686	812	388	187	90	98
1980	8,750	3,505	1,629	773	372	179	87	89
1981	8,632	3,563	1,674	776	367	178	86	86
1982	8,741	3,504	1,721	831	389	186	91	90
1983	8,787	3,585	1,730	876	427	203	98	96
1984	8,905	3,565	1,735	868	446	220	106	103

Table 3.9. Predicted stock numbers (thousands of fish) at age at mid-year from the base run of the stock assessment model, 1985–2019. Values rounded to the nearest integer.

Year	0	1	2	3	4	5	6	7+
1985	8,880	3,629	1,723	855	431	224	112	107
1986	8,897	3,586	1,719	831	416	212	111	110
1987	8,821	3,532	1,611	765	369	186	95	101
1988	8,601	3,432	1,486	644	299	144	73	78
1989	8,261	3,406	1,493	607	255	118	57	61
1990	7,275	3,159	1,396	580	230	97	45	46
1991	7,481	2,870	1,392	575	230	91	38	36
1992	6,786	2,922	1,284	615	252	102	41	34
1993	5,715	2,491	1,132	466	217	89	36	27
1994	6,098	2,137	996	403	156	72	30	21
1995	8,742	2,228	807	343	133	51	24	17
1996	8,506	3,380	886	281	112	43	17	13
1997	5,002	3,202	1,326	316	96	38	15	10
1998	10,026	1,837	1,226	454	102	31	12	8
1999	5,397	3,954	784	477	168	38	11	8
2000	8,157	1,962	1,511	280	165	58	13	7
2001	5,141	3,033	732	485	84	49	17	6
2002	7,639	1,671	1,024	214	132	23	13	6
2003	6,006	2,079	555	302	58	35	6	5
2004	5,317	1,801	723	176	91	17	11	3
2005	6,901	1,900	653	227	52	26	5	4
2006	6,323	2,560	702	207	67	15	8	3
2007	3,939	2,334	987	238	66	21	5	3
2008	7,379	1,339	869	336	77	21	7	3
2009	5,543	2,774	511	292	106	24	7	3
2010	5,382	2,002	1,000	160	86	31	7	3
2011	5,229	1,957	743	319	47	25	9	3
2012	5,343	1,874	704	233	94	14	7	4
2013	4,593	1,899	683	220	67	27	4	3
2014	3,059	1,524	641	199	60	18	7	2
2015	3,542	986	512	181	51	15	5	2
2016	5,061	1,182	351	158	52	15	4	2
2017	3,521	1,683	398	102	43	14	4	2
2018	4,401	1,160	545	106	25	10	3	1
2019	4,991	1,649	391	147	26	6	2	1

Table 3.10. Predicted stock biomass (metric tons) at age at the beginning of the year from the base run of the stock assessment model, 1950–1984. Values rounded to the nearest integer.

Year	0	1	2	3	4	5	6	7+
1950	431	1,149	1,584	1,423	1,089	773	528	1,025
1951	422	1,034	1,444	1,202	878	613	417	807
1952	406	1,007	1,248	991	650	429	286	549
1953	388	964	1,183	801	491	289	181	340
1954	380	915	1,168	825	442	246	138	239
1955	380	894	1,138	874	500	245	130	192
1956	379	894	1,106	840	521	272	127	161
1957	374	890	1,088	783	474	266	133	136
1958	371	878	1,081	768	440	241	130	127
1959	367	869	1,057	746	419	217	114	117
1960	361	857	1,035	710	393	199	98	101
1961	343	842	955	585	299	147	70	68
1962	342	795	982	612	290	133	62	57
1963	339	792	919	616	295	125	55	47
1964	341	783	936	612	321	138	56	44
1965	353	790	973	707	376	180	74	52
1966	362	823	988	744	441	215	99	67
1967	367	845	1,024	745	456	247	115	86
1968	375	858	1,077	820	494	277	144	114
1969	380	880	1,094	860	541	299	161	146
1970	385	895	1,130	887	579	335	178	177
1971	389	909	1,151	919	600	360	200	205
1972	395	920	1,190	980	659	398	229	250
1973	397	936	1,187	974	668	414	239	280
1974	399	941	1,212	981	673	425	252	307
1975	393	945	1,173	909	596	373	225	287
1976	389	930	1,180	885	556	333	199	265
1977	385	920	1,152	871	527	302	173	233
1978	384	909	1,146	866	531	293	161	208
1979	383	904	1,135	867	532	298	158	192
1980	382	902	1,128	856	531	297	160	181
1981	377	900	1,101	804	487	274	147	162
1982	382	887	1,142	869	523	290	157	171
1983	383	899	1,120	887	554	305	162	177
1984	388	904	1,157	914	602	346	183	197

Table 3.11. Predicted stock biomass (metric tons) at age at the beginning of the year from the base run of the stock assessment model, 1985–2019. Values rounded to the nearest integer.

Year	0	1	2	3	4	5	6	7+
1985	387	917	1,137	889	574	346	190	202
1986	388	914	1,162	892	573	339	196	215
1987	385	916	1,138	869	540	316	179	210
1988	376	907	1,102	780	470	264	148	175
1989	362	883	1,050	686	372	200	107	126
1990	322	846	1,063	726	375	184	95	106
1991	330	738	954	628	323	149	69	73
1992	302	761	903	694	368	172	76	70
1993	258	685	908	624	381	183	82	67
1994	274	568	732	482	243	131	59	47
1995	383	609	651	463	236	106	54	43
1996	372	895	659	342	177	79	34	30
1997	228	872	1,032	407	161	75	32	25
1998	436	493	950	583	172	60	27	19
1999	243	1,035	553	541	247	65	22	16
2000	359	537	1,222	380	294	122	30	17
2001	234	831	579	639	144	98	38	14
2002	435	507	895	317	258	51	33	17
2003	326	603	445	401	101	72	14	13
2004	243	498	580	236	159	36	24	8
2005	307	522	528	308	92	55	12	10
2006	278	697	559	276	117	31	17	7
2007	192	646	760	301	109	41	10	8
2008	325	362	682	438	131	42	15	6
2009	247	753	400	379	180	48	15	7
2010	244	558	826	223	157	66	17	7
2011	235	532	581	414	81	50	20	7
2012	244	523	582	325	172	30	17	9
2013	214	526	543	291	117	54	9	8
2014	150	442	555	294	116	41	18	5
2015	172	281	425	253	94	32	11	6
2016	236	327	280	210	90	30	10	5
2017	172	488	345	150	83	32	10	5
2018	189	323	470	157	48	23	8	4
2019	215	460	337	217	50	13	6	3

Table 3.12. Predicted stock biomass (metric tons) at age at mid-year from the base run of the stock assessment model, 1950–1984. Values rounded to the nearest integer.

Year	0	1	2	3	4	5	6	7+
1950	718	1,434	1,431	1,137	825	570	384	737
1951	700	1,264	1,241	899	619	421	282	539
1952	673	1,214	1,037	709	437	280	184	349
1953	640	1,181	1,024	605	350	201	124	230
1954	626	1,136	1,047	653	332	180	99	170
1955	626	1,107	1,014	686	372	177	93	136
1956	624	1,098	966	641	376	191	88	111
1957	616	1,092	948	597	341	187	92	93
1958	610	1,072	932	577	312	166	88	85
1959	602	1,055	899	551	291	147	76	77
1960	593	1,007	807	468	242	119	58	59
1961	562	1,012	793	419	201	96	45	43
1962	559	952	806	432	192	86	39	35
1963	554	958	778	452	204	84	36	31
1964	558	972	844	488	242	102	41	32
1965	579	984	883	568	287	134	55	38
1966	594	1,022	890	592	333	158	72	48
1967	603	1,062	950	617	359	190	87	65
1968	617	1,079	998	677	388	212	109	85
1969	627	1,110	1,022	718	429	232	123	110
1970	636	1,130	1,057	742	461	260	136	134
1971	643	1,158	1,101	791	493	289	158	161
1972	654	1,163	1,117	823	527	310	176	191
1973	657	1,186	1,120	823	537	325	185	215
1974	660	1,169	1,089	778	505	311	182	219
1975	650	1,175	1,057	723	449	274	163	206
1976	643	1,152	1,052	694	413	241	142	187
1977	636	1,143	1,035	692	397	221	125	166
1978	633	1,130	1,034	690	402	216	117	150
1979	632	1,124	1,022	690	401	219	114	137
1980	630	1,110	988	656	385	210	111	124
1981	622	1,128	1,015	659	379	208	110	120
1982	629	1,109	1,044	705	403	218	116	125
1983	633	1,135	1,049	743	442	237	124	135
1984	641	1,129	1,052	736	460	258	134	143

Table 3.13. Predicted stock biomass (metric tons) at age at mid-year from the base run of the stock assessment model, 1985–2019. Values rounded to the nearest integer.

Year	0	1	2	3	4	5	6	7+
1985	640	1,149	1,045	726	445	261	142	149
1986	641	1,135	1,042	706	429	247	141	153
1987	635	1,118	977	650	381	217	121	141
1988	619	1,086	901	547	309	169	93	109
1989	595	1,078	906	516	264	138	73	85
1990	524	1,000	847	493	238	113	57	64
1991	539	909	844	488	238	107	49	51
1992	489	925	779	523	261	119	52	47
1993	412	788	686	396	225	105	46	37
1994	439	677	604	343	162	85	38	29
1995	630	705	489	292	138	60	30	24
1996	613	1,070	537	239	116	51	21	19
1997	360	1,013	804	269	100	45	19	14
1998	722	581	744	386	106	36	16	11
1999	389	1,252	475	406	175	45	15	11
2000	587	621	916	238	172	69	17	9
2001	370	960	444	413	87	58	22	8
2002	550	529	621	182	137	27	17	9
2003	433	659	336	257	61	42	8	7
2004	383	570	438	150	94	20	14	5
2005	497	601	396	193	54	31	6	6
2006	455	810	426	176	70	18	10	4
2007	284	739	599	202	68	25	6	5
2008	531	424	527	286	80	25	9	4
2009	399	878	310	248	110	28	9	4
2010	388	634	606	136	89	36	9	4
2011	377	620	451	271	49	29	12	4
2012	385	593	427	198	97	16	9	5
2013	331	601	414	187	70	32	5	4
2014	220	482	388	169	62	21	9	3
2015	255	312	310	154	53	18	6	3
2016	365	374	213	135	54	17	5	3
2017	254	533	241	87	44	16	5	2
2018	317	367	331	90	26	12	4	2
2019	359	522	237	125	27	7	3	2

Table 3.14. Predicted commercial landings (thousands of fish) at age from the base run of the stock assessment model, 1950–1984. Values rounded to the nearest integer.

Year	0	1	2	3	4	5	6	7+
1950	11	326	441	328	210	131	82	141
1951	16	448	599	407	248	152	94	162
1952	19	533	622	399	217	126	77	130
1953	14	395	466	258	132	68	39	65
1954	10	279	349	203	91	44	23	35
1955	11	289	360	228	109	47	23	30
1956	13	345	413	257	133	61	26	29
1957	13	347	410	242	122	60	27	25
1958	14	372	440	255	122	59	29	25
1959	15	401	465	267	125	57	27	25
1960	23	602	663	363	166	73	33	31
1961	16	446	476	236	100	43	19	16
1962	17	445	515	259	102	41	17	14
1963	14	375	415	226	90	33	13	10
1964	9	225	265	143	63	24	9	6
1965	8	213	260	156	70	29	11	7
1966	9	239	282	176	87	37	16	10
1967	6	170	206	125	64	31	13	9
1968	7	177	221	140	71	35	17	12
1969	6	159	198	130	69	33	16	14
1970	6	158	200	132	72	37	18	16
1971	4	97	124	84	46	24	12	11
1972	6	153	199	137	77	41	22	21
1973	5	142	182	125	72	39	21	22
1974	10	283	357	239	137	76	41	45
1975	10	276	337	216	118	65	36	41
1976	11	301	373	231	121	64	35	42
1977	10	273	336	210	106	53	28	34
1978	10	261	324	203	104	50	25	29
1979	10	264	326	206	106	52	25	27
1980	13	339	410	256	132	65	32	32
1981	7	201	245	149	75	37	18	18
1982	8	219	280	177	89	43	21	21
1983	6	154	193	128	67	32	16	16
1984	9	238	300	197	109	55	26	26

Table 3.15. Predicted commercial landings (thousands of fish) at age from the base run of the stock assessment model, 1950–1984. Values rounded to the nearest integer.

Year	0	1	2	3	4	5	6	7+
1985	8	214	263	171	92	49	25	24
1986	10	279	347	220	118	61	32	32
1987	15	396	471	294	152	78	40	43
1988	19	518	588	336	168	83	42	45
1989	13	371	424	227	102	48	24	25
1990	19	542	629	345	147	63	30	30
1991	10	253	319	173	74	30	13	12
1992	11	316	361	227	100	41	17	14
1993	18	532	638	348	175	73	30	22
1994	13	307	374	199	83	39	16	12
1995	28	487	466	262	110	43	20	14
1996	20	524	360	150	64	25	10	8
1997	14	604	658	207	68	27	11	8
1998	28	344	604	295	72	22	9	6
1999	9	440	227	181	69	16	5	3
2000	27	433	882	216	138	50	11	6
2001	16	614	390	342	64	38	14	5
2002	33	463	749	208	139	24	14	7
2003	19	434	303	218	45	28	5	4
2004	17	385	408	132	73	14	9	3
2005	23	418	380	175	43	22	4	3
2006	20	536	388	152	53	12	6	2
2007	11	417	462	147	44	14	3	2
2008	22	263	450	230	57	16	5	2
2009	16	538	261	197	77	18	5	2
2010	19	476	629	134	77	28	7	3
2011	15	379	379	215	34	19	7	2
2012	19	447	444	195	85	13	7	3
2013	14	390	369	157	52	21	3	2
2014	13	418	467	193	63	19	8	2
2015	13	237	325	152	47	14	4	2
2016	16	246	193	115	41	12	3	2
2017	15	463	291	99	45	15	4	2
2018	18	317	397	103	26	11	4	1
2019	20	450	285	142	27	6	3	1

Table 3.16. Predicted recreational harvest (thousands of fish) at age from the base run of the stock assessment model, 1950–1984. Values rounded to the nearest integer.

Year	0	1	2	3	4	5	6	7+
1950	1,185	161	13	1	0	0	0	0
1951	1,200	147	12	1	0	0	0	0
1952	1,202	148	11	1	0	0	0	0
1953	1,199	150	11	1	0	0	0	0
1954	1,201	147	11	1	0	0	0	0
1955	1,205	144	11	1	0	0	0	0
1956	1,206	144	11	1	0	0	0	0
1957	1,205	145	11	1	0	0	0	0
1958	1,206	144	11	1	0	0	0	0
1959	1,206	143	10	1	0	0	0	0
1960	1,210	140	10	1	0	0	0	0
1961	1,203	147	10	1	0	0	0	0
1962	1,210	140	10	1	0	0	0	0
1963	1,209	142	10	1	0	0	0	0
1964	1,208	142	10	1	0	0	0	0
1965	1,211	139	10	1	0	0	0	0
1966	1,209	141	10	1	0	0	0	0
1967	1,206	144	11	1	0	0	0	0
1968	1,206	142	11	1	0	0	0	0
1969	1,205	144	11	1	0	0	0	0
1970	1,204	145	11	1	0	0	0	0
1971	1,202	146	12	1	0	0	0	0
1972	1,204	145	12	1	0	0	0	0
1973	1,202	147	12	1	0	0	0	0
1974	1,204	145	11	1	0	0	0	0
1975	1,202	147	11	1	0	0	0	0
1976	1,203	146	11	1	0	0	0	0
1977	1,202	146	11	1	0	0	0	0
1978	1,203	145	11	1	0	0	0	0
1979	1,204	145	11	1	0	0	0	0
1980	1,205	144	11	1	0	0	0	0
1981	1,201	147	11	1	0	0	0	0
1982	1,205	144	11	1	0	0	0	0
1983	1,203	146	11	1	0	0	0	0
1984	1,205	144	11	1	0	0	0	0

Table 3.17. Predicted recreational harvest (thousands of fish) at age from the base run of the stock assessment model, 1985–2019. Values rounded to the nearest integer.

Year	0	1	2	3	4	5	6	7+
1985	1,203	146	11	1	0	0	0	0
1986	1,204	145	11	1	0	0	0	0
1987	1,205	144	11	1	0	0	0	0
1988	1,206	144	10	1	0	0	0	0
1989	1,202	148	11	1	0	0	0	0
1990	1,194	155	11	1	0	0	0	0
1991	1,211	138	11	1	0	0	0	0
1992	1,196	153	11	1	0	0	0	0
1993	1,193	156	12	1	0	0	0	0
1994	1,223	128	10	1	0	0	0	0
1995	1,258	96	6	0	0	0	0	0
1996	1,211	144	6	0	0	0	0	0
1997	1,130	216	15	1	0	0	0	0
1998	1,282	70	8	0	0	0	0	0
1999	1,111	242	8	1	0	0	0	0
2000	1,258	91	12	0	0	0	0	0
2001	1,149	203	8	1	0	0	0	0
2002	5,584	353	36	1	0	0	0	0
2003	3,701	371	16	1	0	0	0	0
2004	1,259	127	8	0	0	0	0	0
2005	1,206	100	6	0	0	0	0	0
2006	939	114	5	0	0	0	0	0
2007	1,487	260	18	1	0	0	0	0
2008	1,124	61	7	0	0	0	0	0
2009	1,011	151	5	0	0	0	0	0
2010	1,176	131	11	0	0	0	0	0
2011	1,018	114	7	1	0	0	0	0
2012	1,232	129	8	0	0	0	0	0
2013	1,285	158	9	1	0	0	0	0
2014	1,167	173	12	1	0	0	0	0
2015	1,302	107	9	1	0	0	0	0
2016	1,390	97	5	0	0	0	0	0
2017	1,339	190	7	0	0	0	0	0
2018	450	36	3	0	0	0	0	0
2019	509	51	2	0	0	0	0	0

Table 3.18. Annual estimates of fishing mortality (numbers-weighted, ages 1–5) and associated standard deviations from the base run of the stock assessment model, 1950–1984.

	Fishing Mortality	
Year	**Value**	**SD**
1950	0.17	0.018
1951	0.25	0.031
1952	0.29	0.043
1953	0.22	0.036
1954	0.17	0.028
1955	0.18	0.030
1956	0.21	0.035
1957	0.21	0.036
1958	0.23	0.040
1959	0.25	0.044
1960	0.36	0.072
1961	0.27	0.056
1962	0.29	0.062
1963	0.25	0.054
1964	0.16	0.033
1965	0.15	0.030
1966	0.16	0.030
1967	0.12	0.021
1968	0.12	0.020
1969	0.11	0.017
1970	0.11	0.016
1971	0.074	0.0099
1972	0.10	0.014
1973	0.097	0.012
1974	0.17	0.023
1975	0.17	0.023
1976	0.18	0.026
1977	0.17	0.024
1978	0.16	0.024
1979	0.17	0.024
1980	0.21	0.031
1981	0.13	0.019
1982	0.14	0.021
1983	0.11	0.015
1984	0.15	0.021

Table 3.19. Annual estimates of fishing mortality (numbers-weighted, ages 1–5) and associated standard deviations from the base run of the stock assessment model, 1985–2019.

	Fishing Mortality	
Year	**Value**	**SD**
1985	0.14	0.019
1986	0.17	0.024
1987	0.24	0.035
1988	0.30	0.049
1989	0.22	0.038
1990	0.34	0.059
1991	0.19	0.031
1992	0.23	0.031
1993	0.43	0.055
1994	0.30	0.030
1995	0.40	0.048
1996	0.27	0.031
1997	0.35	0.040
1998	0.38	0.051
1999	0.21	0.016
2000	0.44	0.043
2001	0.37	0.016
2002	0.61	0.033
2003	0.45	0.035
2004	0.40	0.038
2005	0.39	0.041
2006	0.35	0.035
2007	0.36	0.023
2008	0.40	0.031
2009	0.33	0.019
2010	0.44	0.025
2011	0.36	0.019
2012	0.44	0.024
2013	0.39	0.017
2014	0.53	0.022
2015	0.49	0.029
2016	0.39	0.023
2017	0.47	0.020
2018	0.46	0.023
2019	0.42	0.024

9 FIGURES

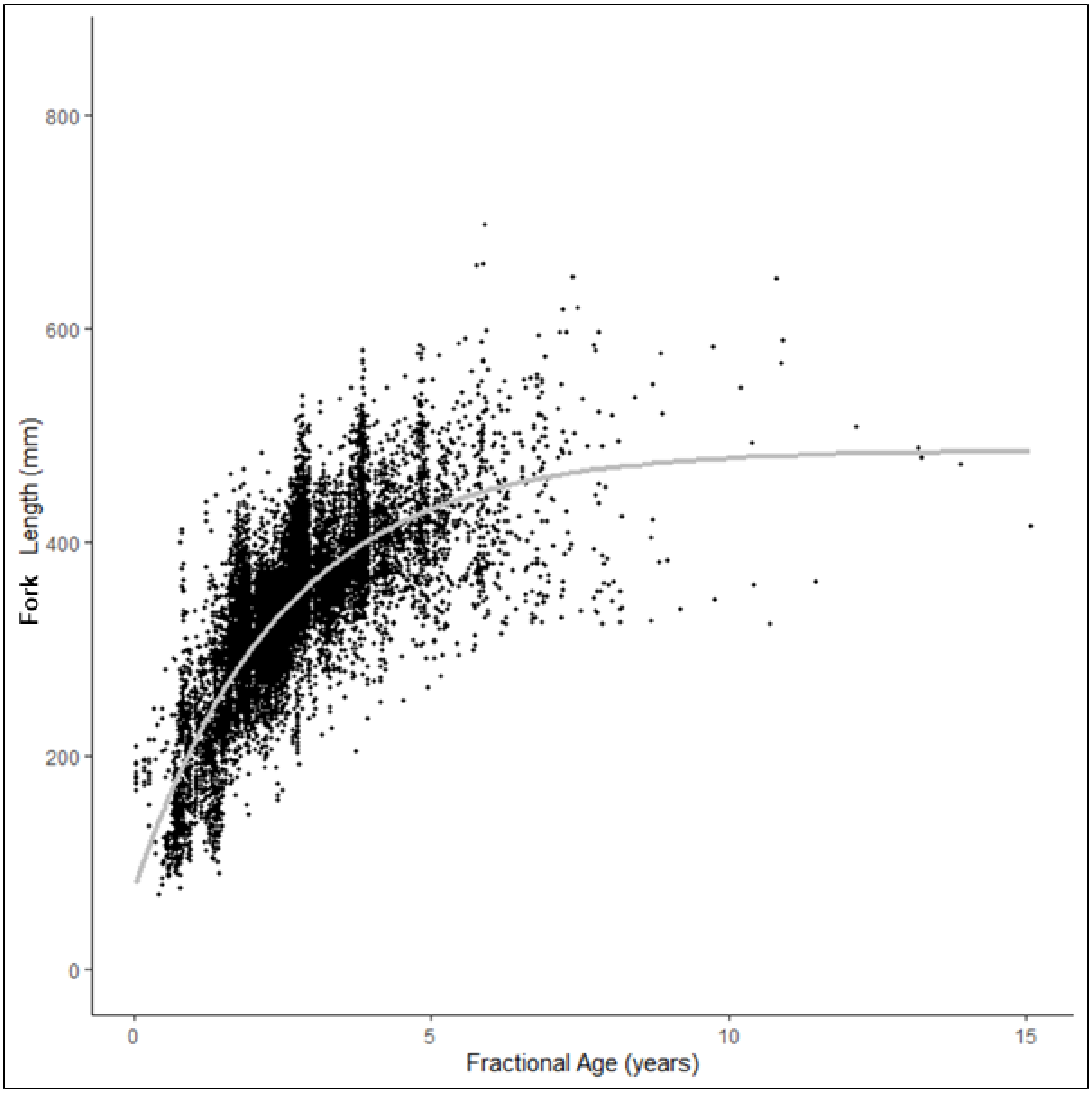


Figure 1.1. Fit of the von Bertalanffy age-length model to available biological data for female and unknown sex striped mullet.

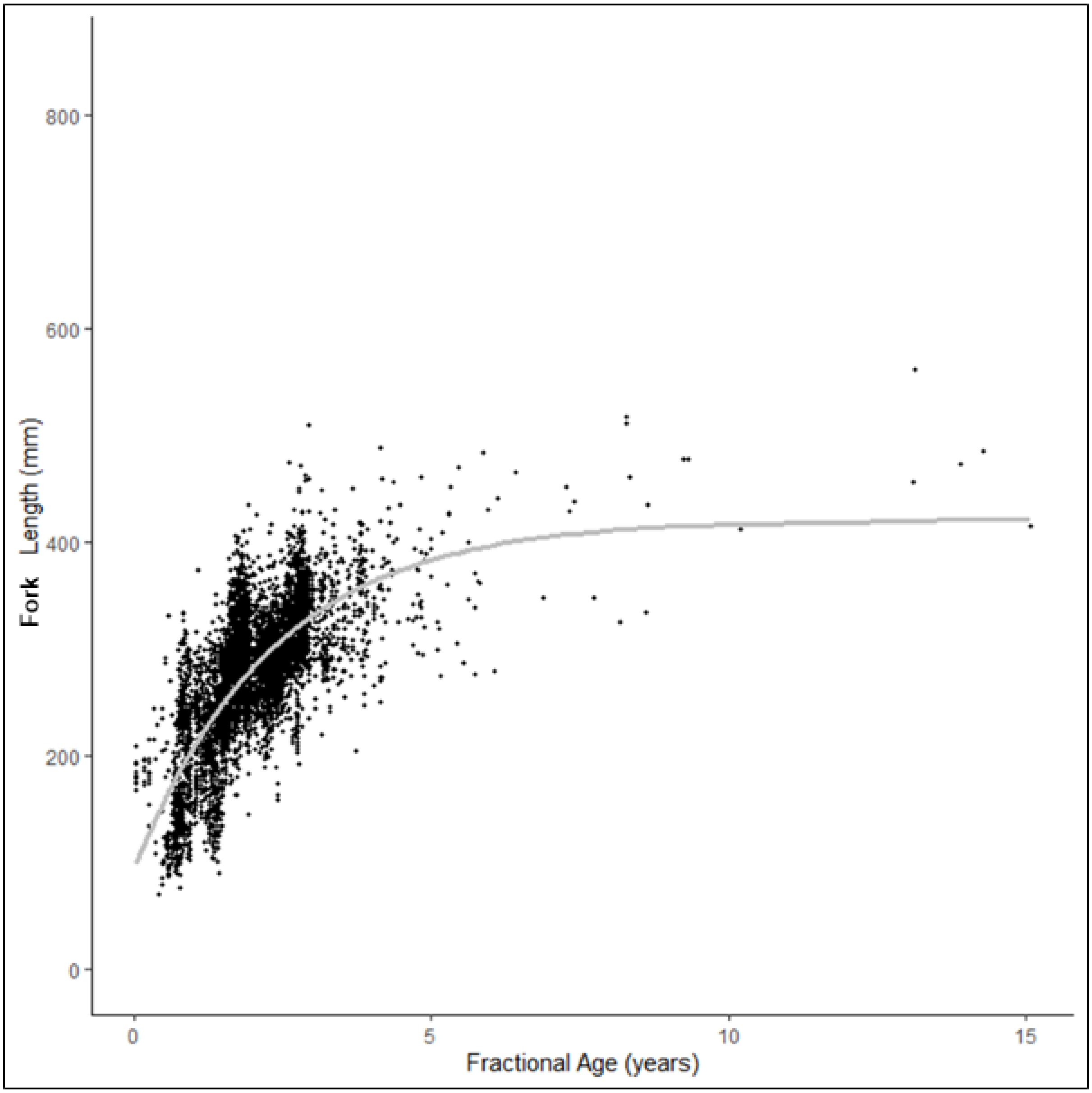


Figure 1.2. Fit of the von Bertalanffy age-length model to available biological data for male and unknown sex striped mullet.

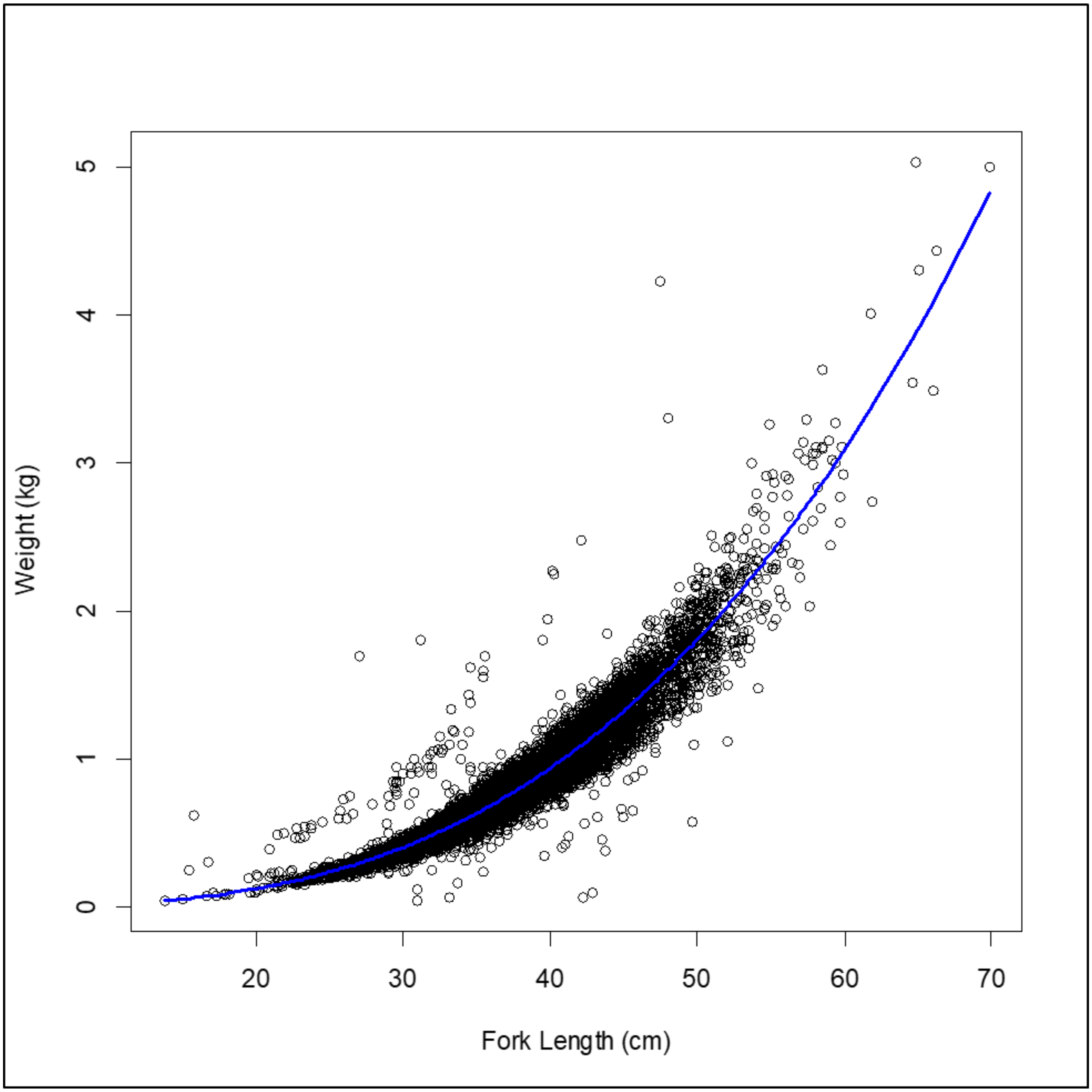


Figure 1.3. Fit of the length-weight model to female striped mullet data collected in North Carolina.

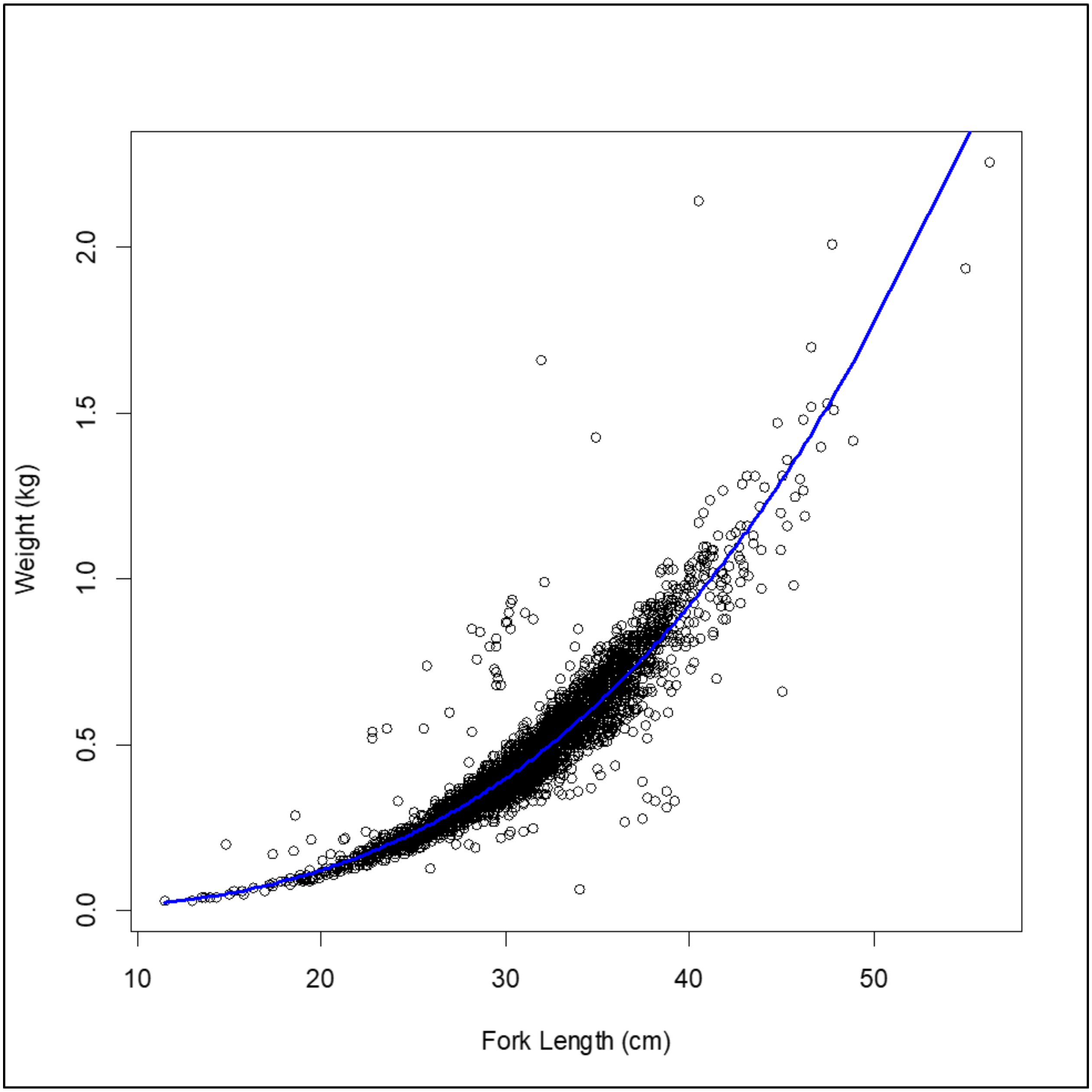


Figure 1.4. Fit of the length-weight model to male striped mullet data collected in North Carolina.

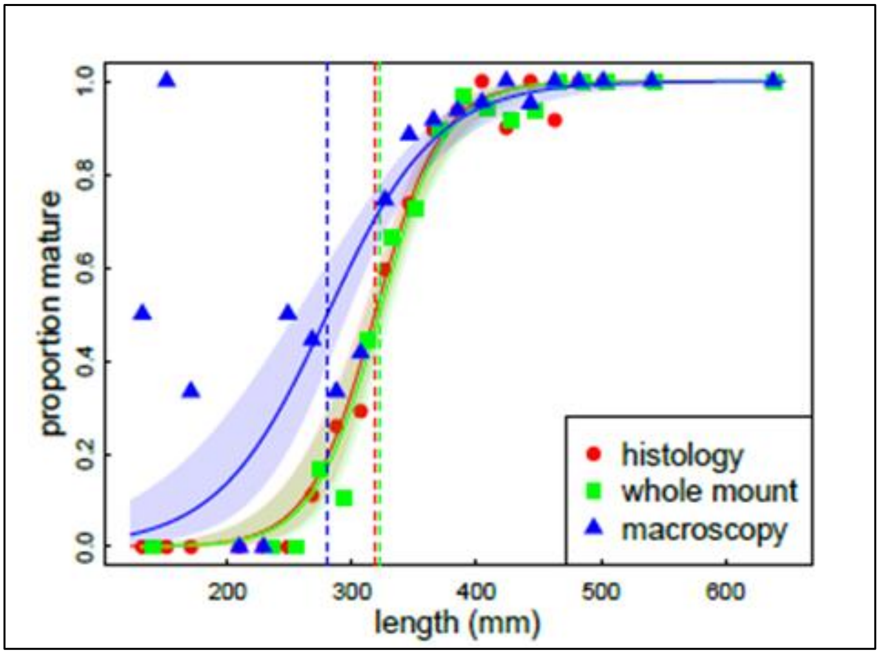


Figure 1.5. Fit of maturity curves to female striped mullet data collected in North Carolina for three maturity staging methods. The solid lines represent the best-fitting logistic regression and the shaded area represent the 95% confidence bands. The vertical dashed lines represent the predicted length at 50% maturity, L_{50}. The points represent the observed data. (Source: NCDMF 2021.)

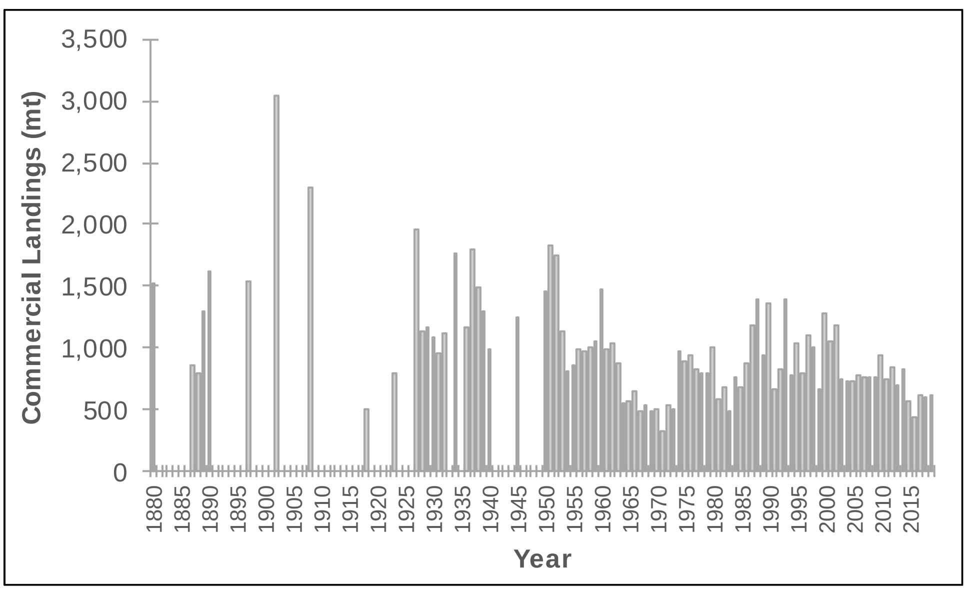


Figure 1.6. Annual commercial landings of striped mullet in North Carolina, 1880–2019. Note that commercial landings data were not available for all years.

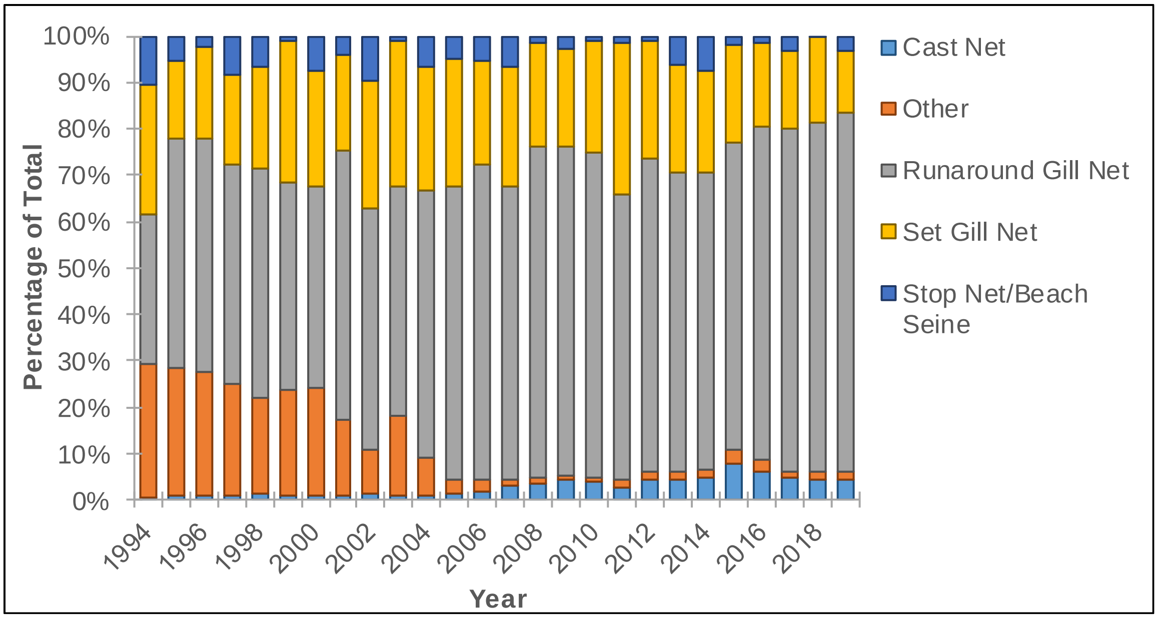


Figure 1.7. Percentages of North Carolina's commercial landings of striped mullet attributed to major commercial gear types, 1994–2019.

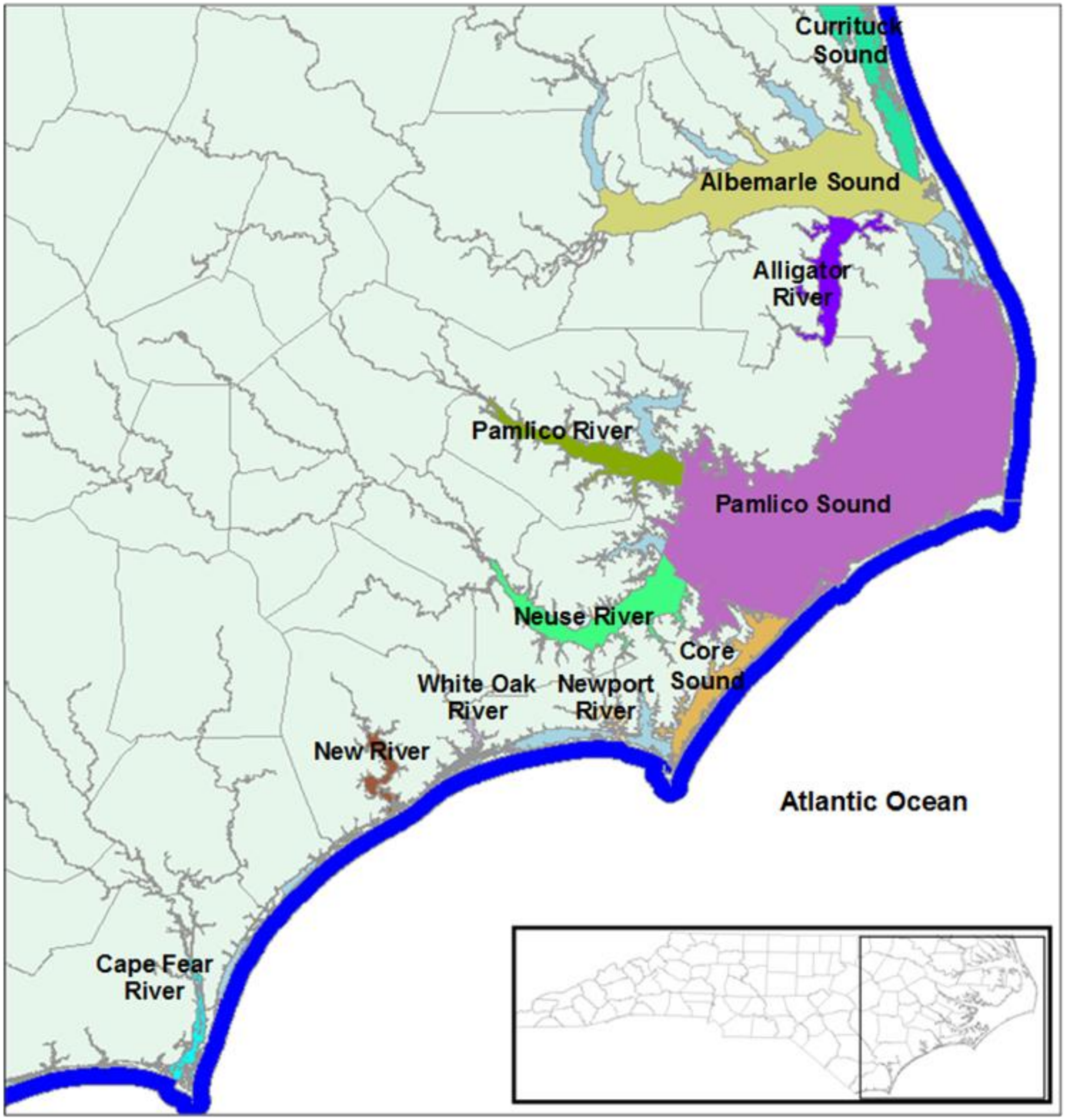


Figure 1.8. Major water bodies within and around North Carolina. The dark blue area represents the extent of the state's coastal fishing waters, which extend to three miles offshore.

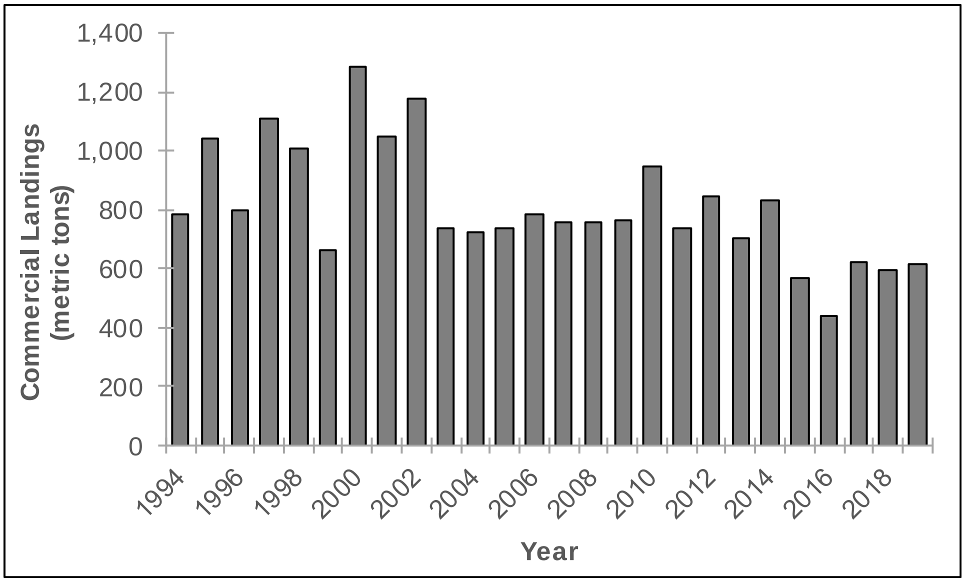


Figure 2.1. Annual commercial landings of striped mullet in North Carolina, 1994–2019.

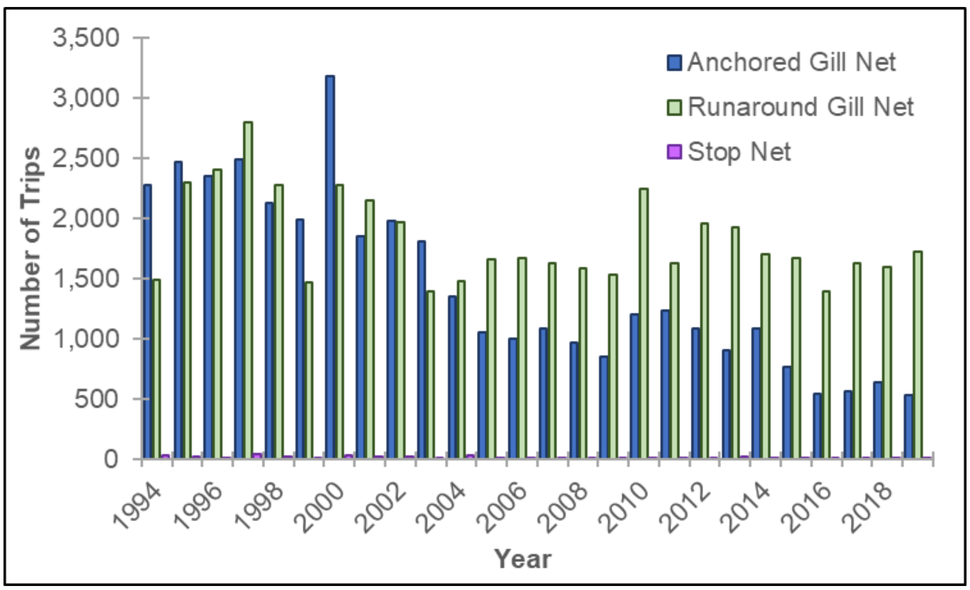


Figure 2.2. Commercial effort for striped mullet in North Carolina by select gears, 1994–2019.

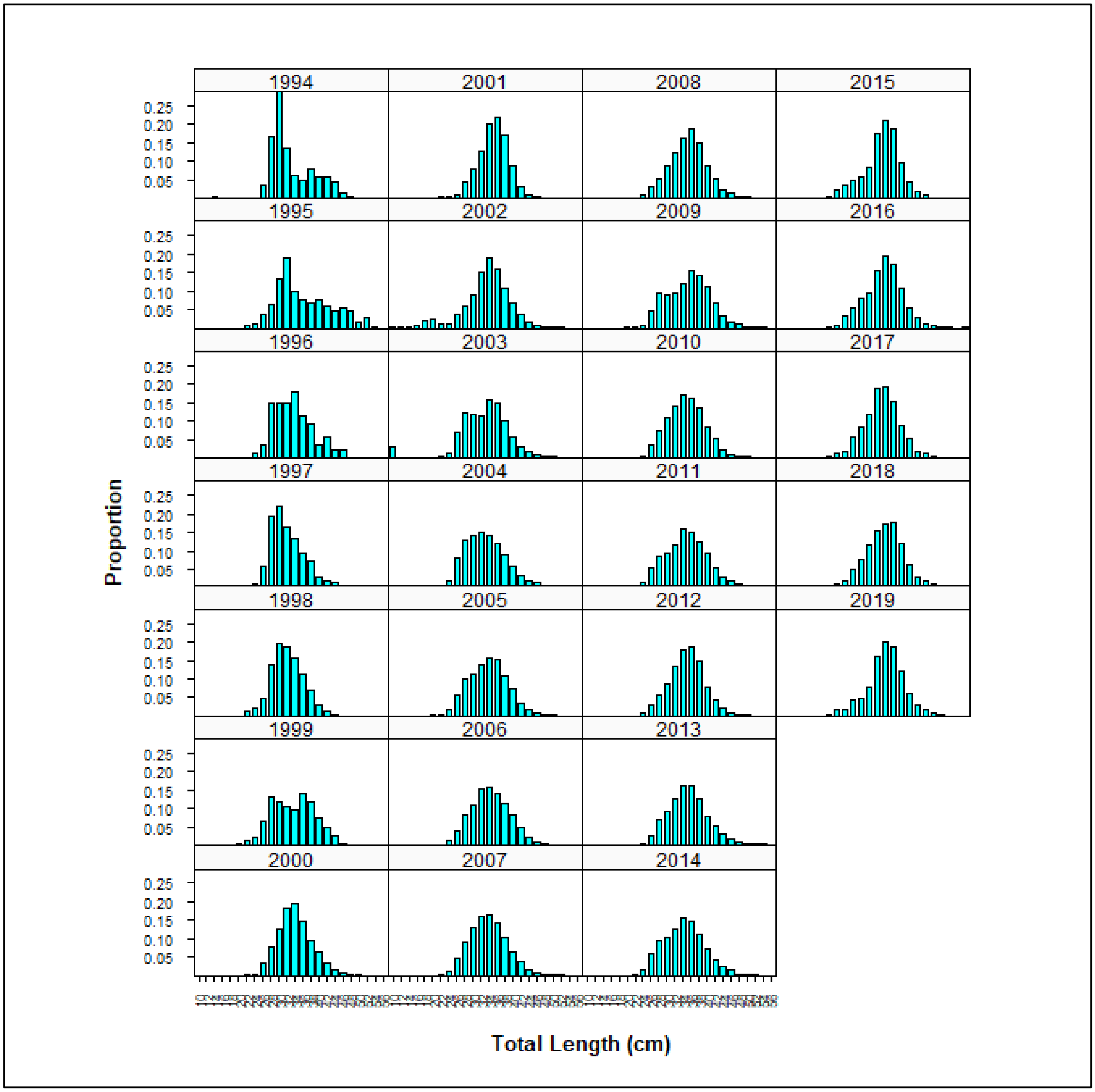


Figure 2.3. Annual length-frequency distributions of striped mullet sampled from North Carolina commercial fisheries' landings, 1994–2019.

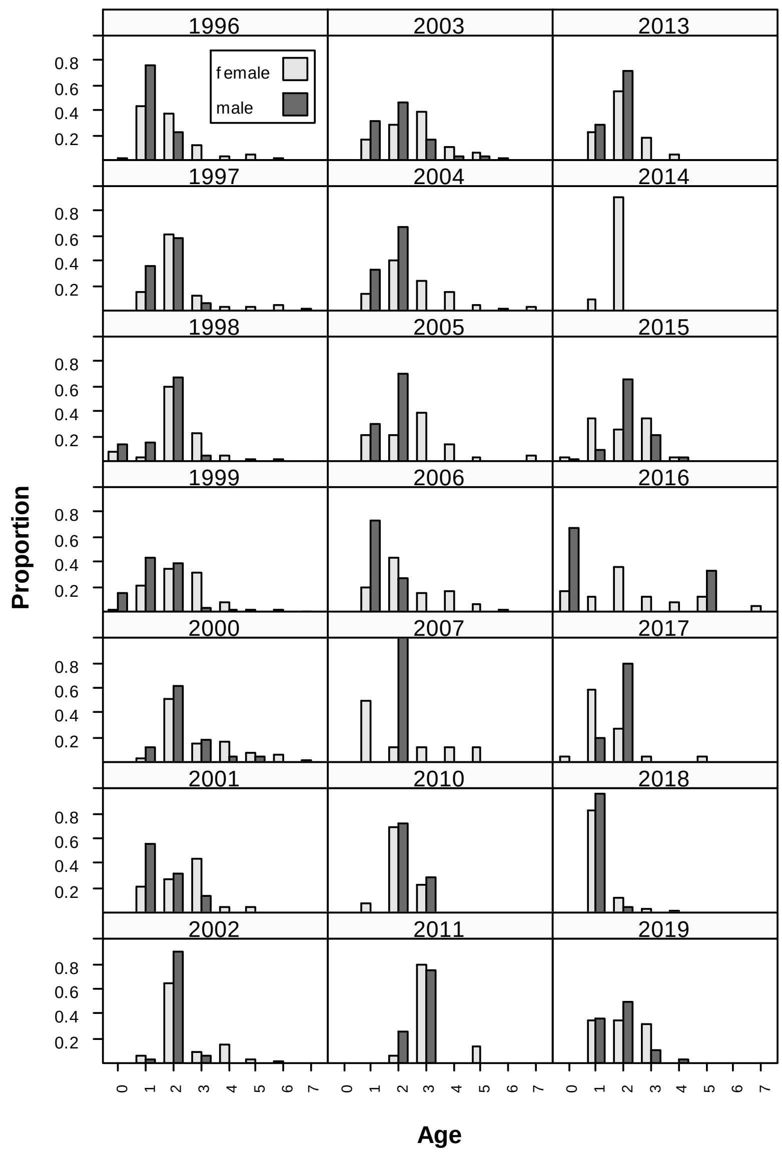


Figure 2.4. Annual age-frequency distributions of striped mullet sampled from North Carolina commercial fisheries' landings by sex, 1996–2019. Note that age 7 represents a plus group.

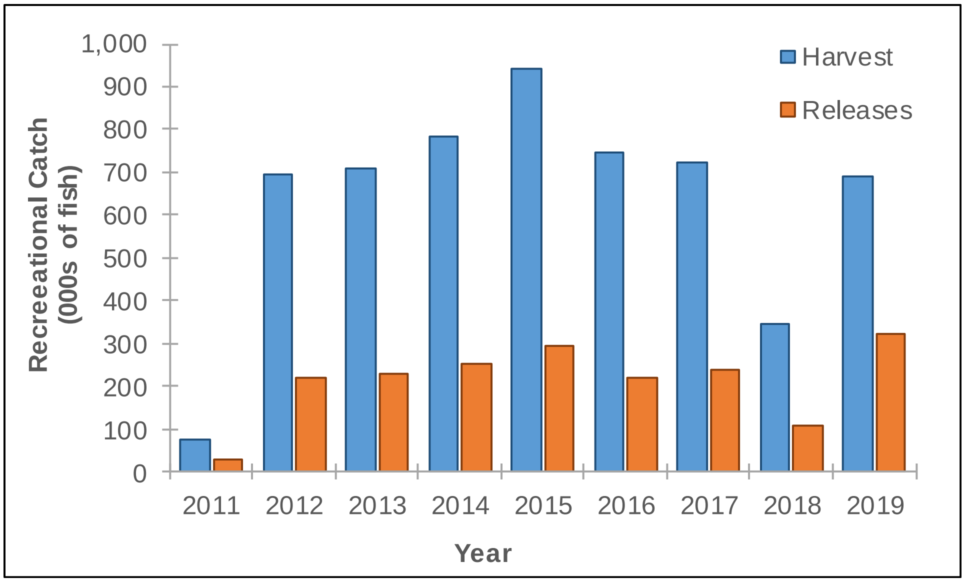


Figure 2.5. Annual harvest and releases of mullet (white plus striped) in North Carolina's recreational fishery, 2011–2019. Note that the mail survey from which the estimates were derived began in October 2011 so the estimates for 2011 are not for the entire year.

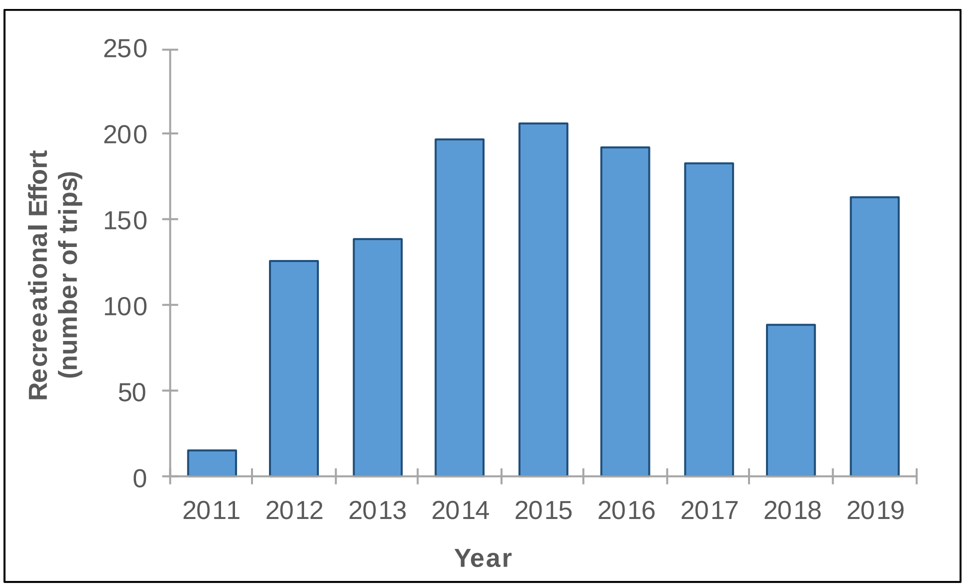


Figure 2.6. Annual effort for mullet (white plus striped) in North Carolina's recreational fishery, 2011–2019. Note that the mail survey from which the estimates were derived began in October 2011 so the estimates for 2011 are not for the entire year.

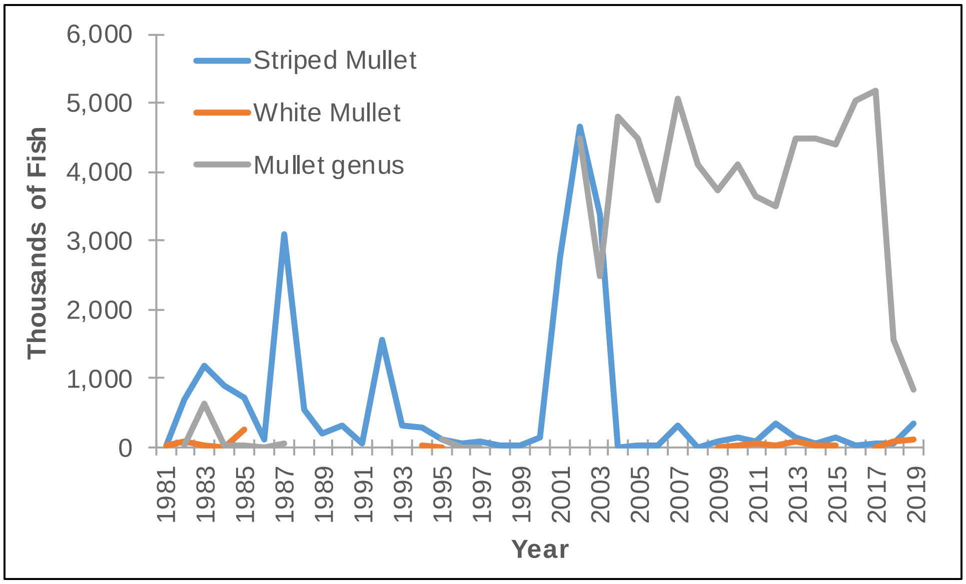


Figure 2.7. Annual recreational harvest (Type A + B1) estimates in numbers of fish for select species in North Carolina as estimated by the MRIP, 1981–2019.

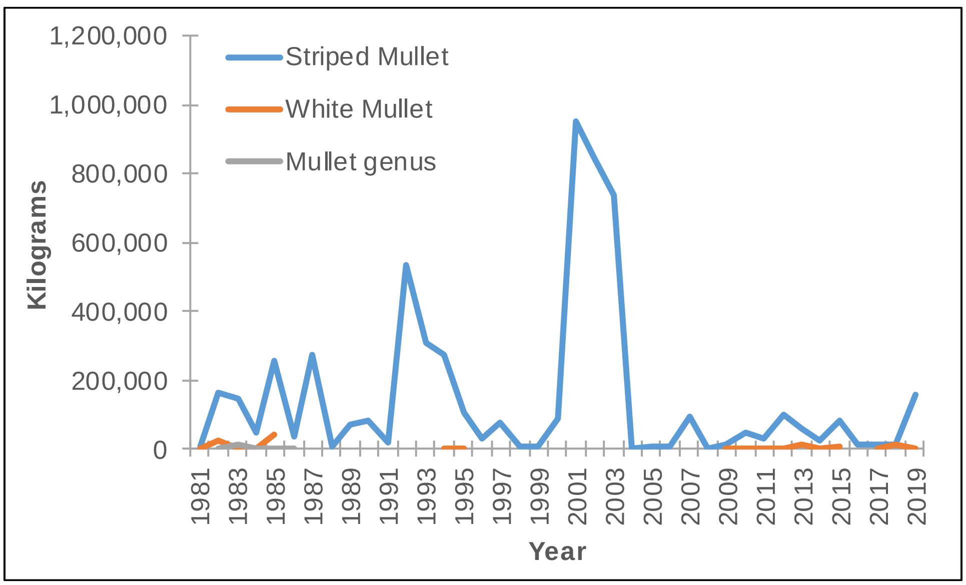


Figure 2.8. Annual recreational harvest (Type A + B1) estimates in weight (kilograms) for select species in North Carolina as estimated by the MRIP, 1981–2019.

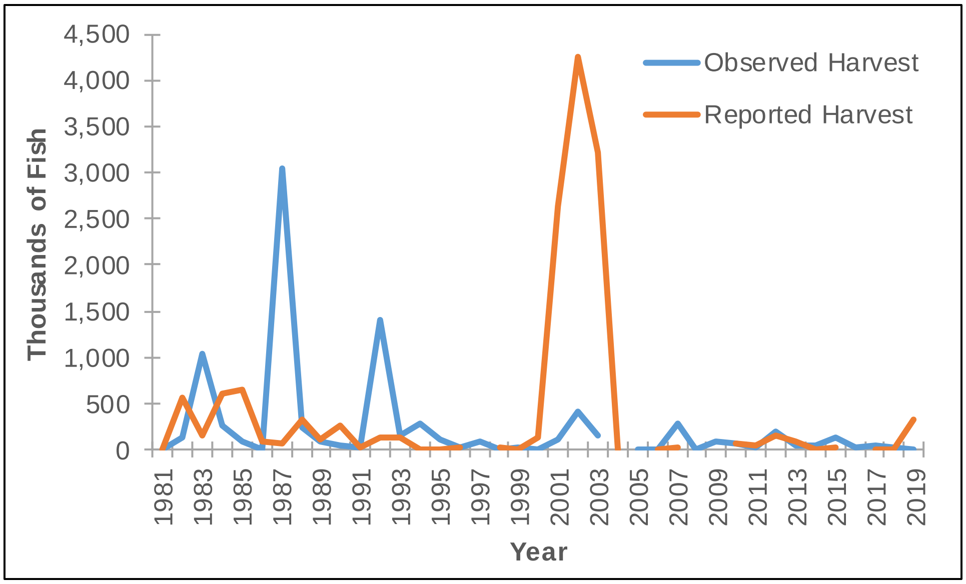


Figure 2.9. Annual recreational observed (Type A) and reported (Type B1) harvest estimates in numbers of fish for striped mullet in North Carolina as estimated by the MRIP, 1981–2019.

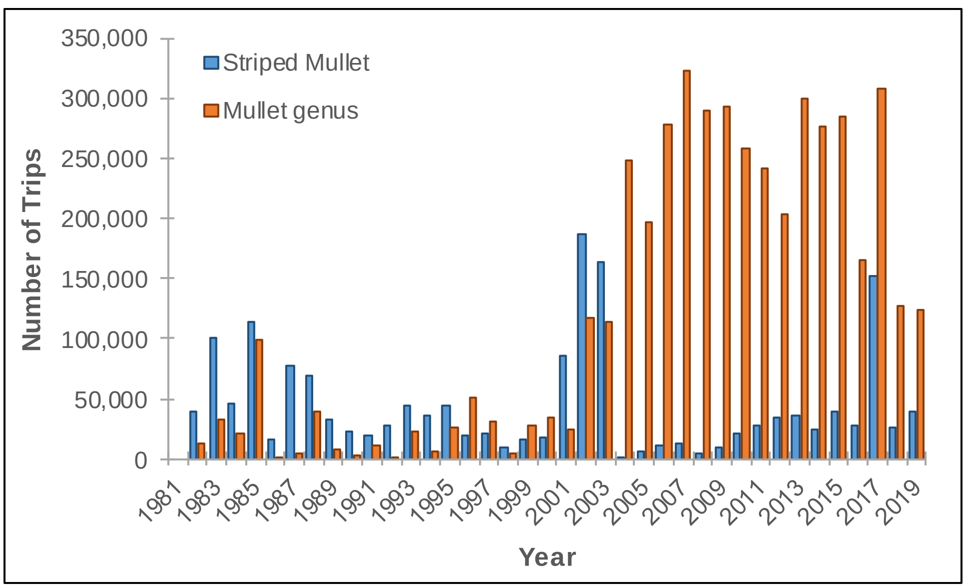


Figure 2.10. Annual number of directed trips for mullet species in North Carolina as estimated by the MRIP, 1981–2019. Directed trips are defined as those trips that target striped mullet, white mullet, or mullet genus or trips that catch the specified species (striped mullet or mullet genus).

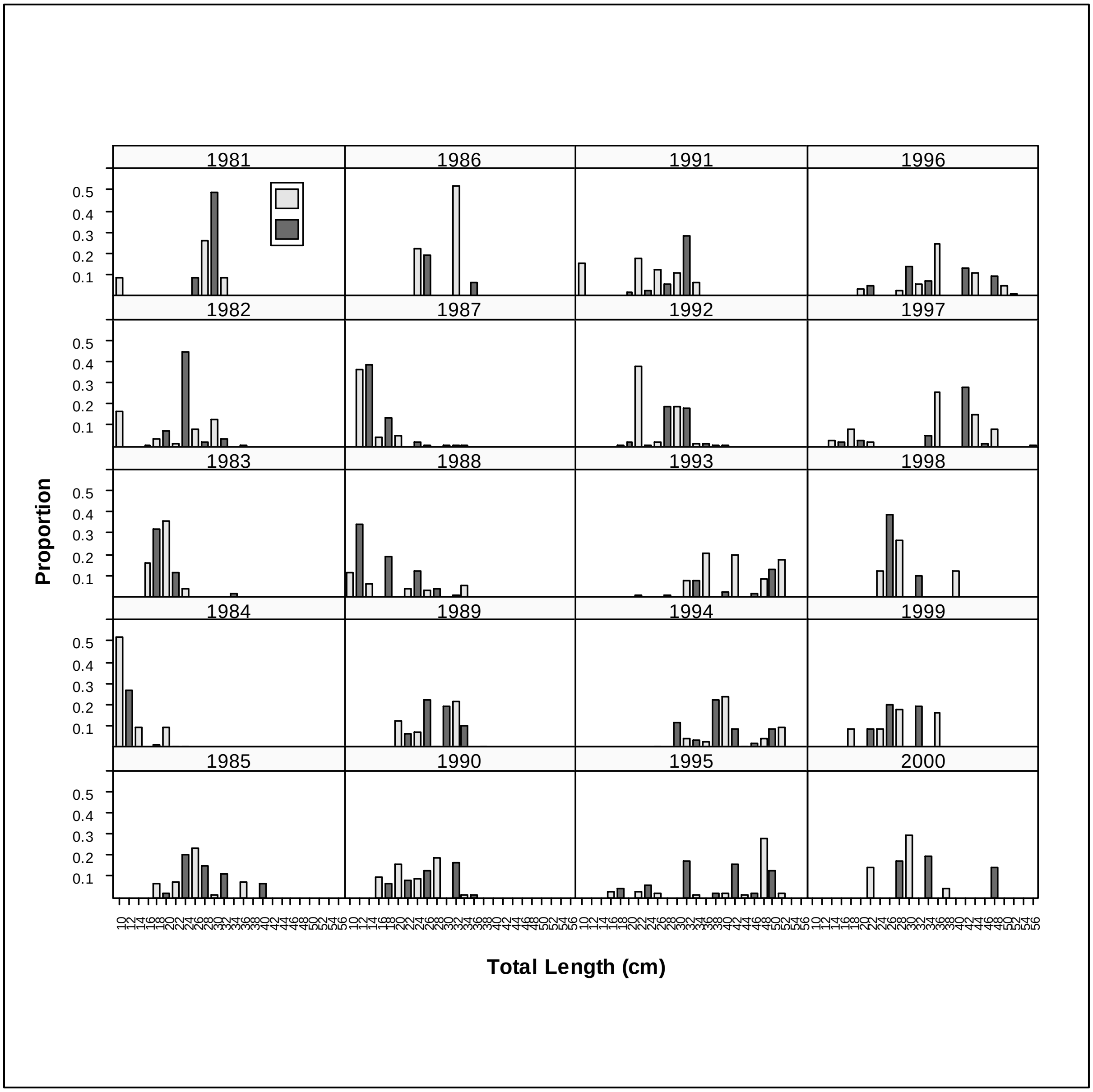


Figure 2.11. Expanded length-frequency distributions of striped mullet harvested by North Carolina's recreational fishery as estimated by the MRIP, 1981–2000.

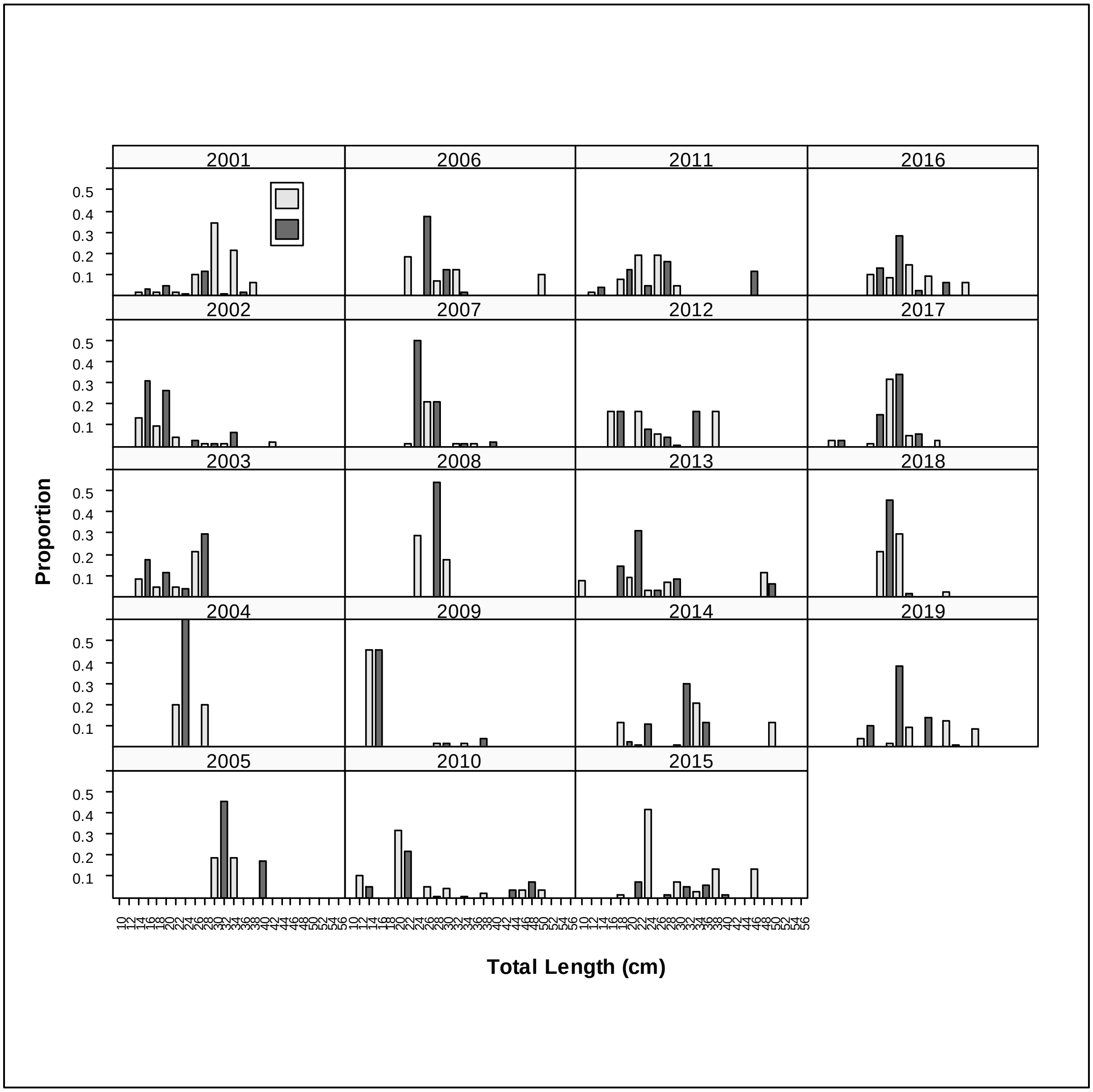


Figure 2.12. Expanded length-frequency distributions of striped mullet harvested by North Carolina's recreational fishery as estimated by the MRIP, 2001–2019.

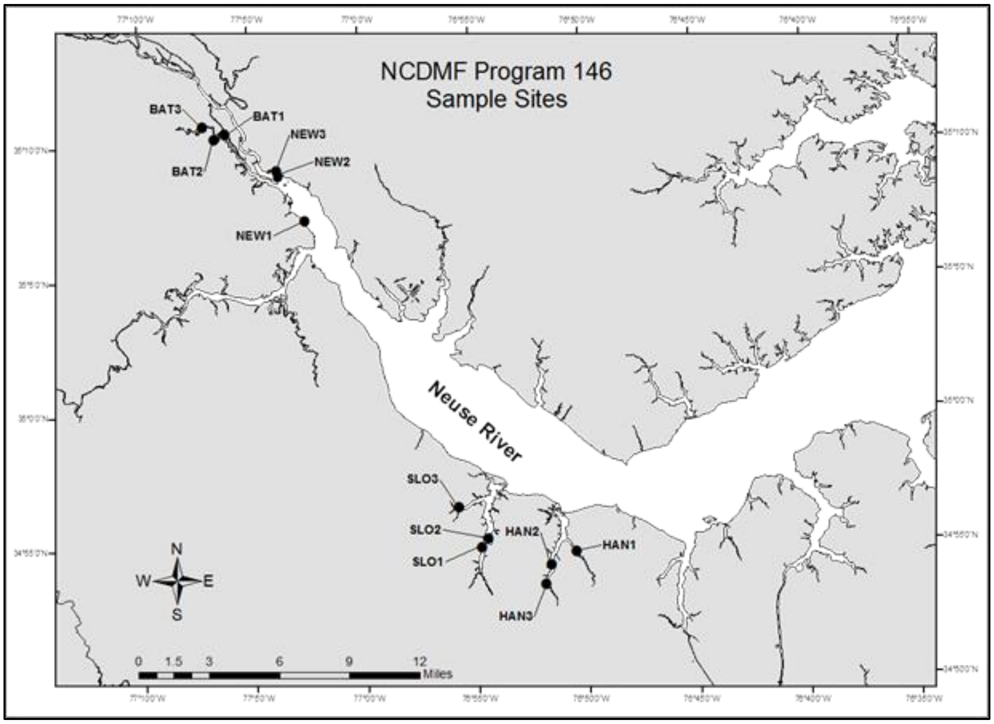


Figure 2.13. Map of sampling locations for Program 146.

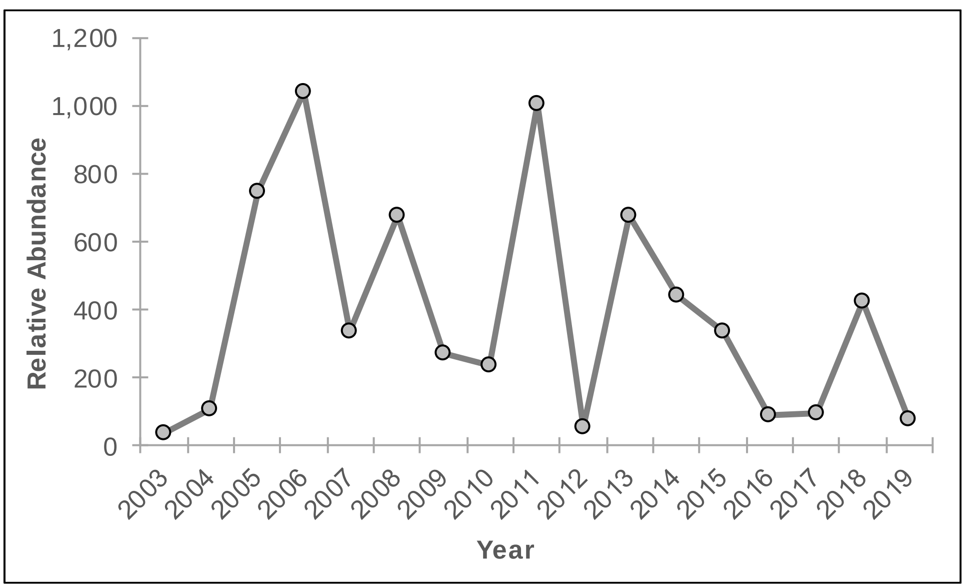


Figure 2.14. GLM-standardized index of relative abundance for adult striped mullet collected in the spring component of Program 146, 2003–2019.

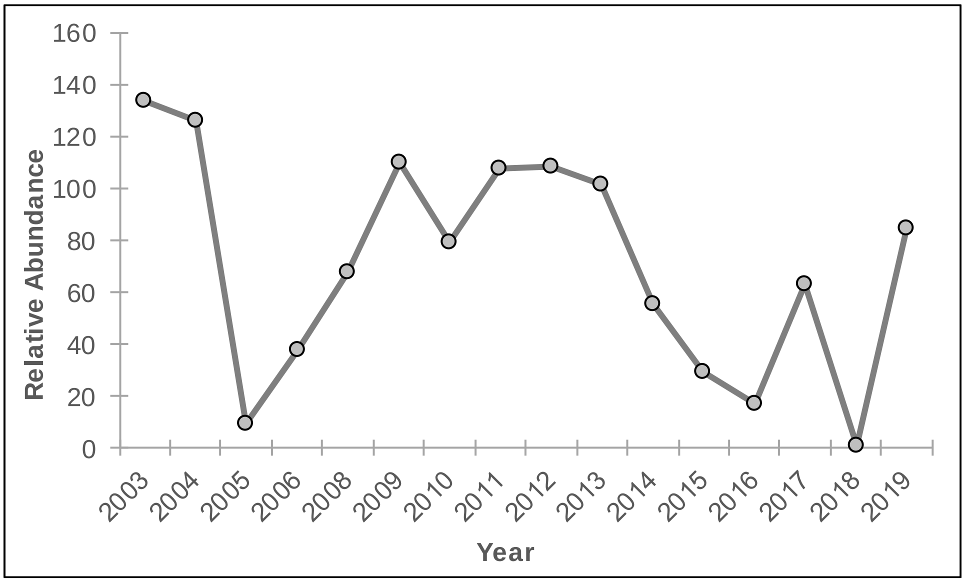


Figure 2.15. GLM-standardized index of relative abundance for adult striped mullet collected in the autumn component of Program 146, 2003–2019.

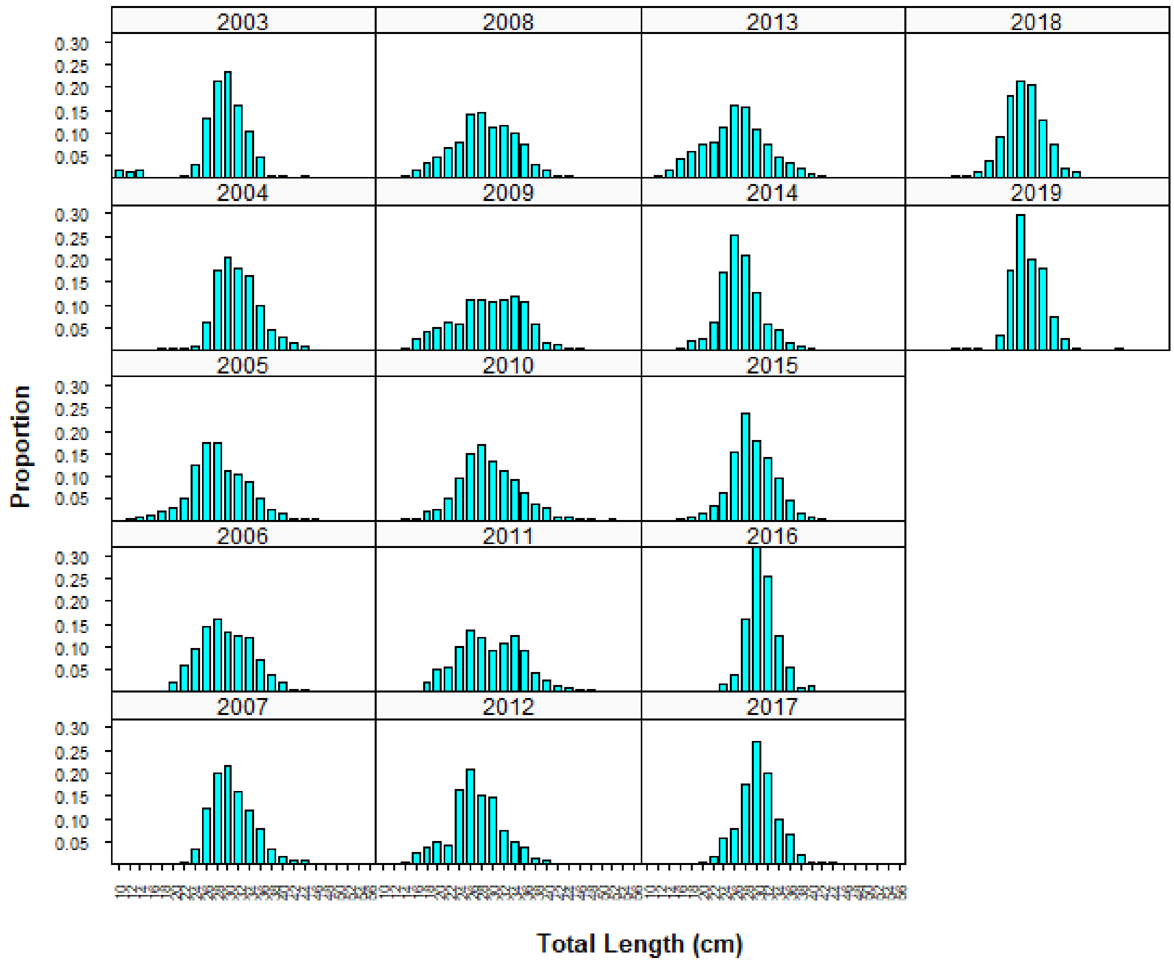


Figure 2.16. Annual length-frequency distributions of adult striped mullet collected in the spring component of Program 146, 2003–2019.

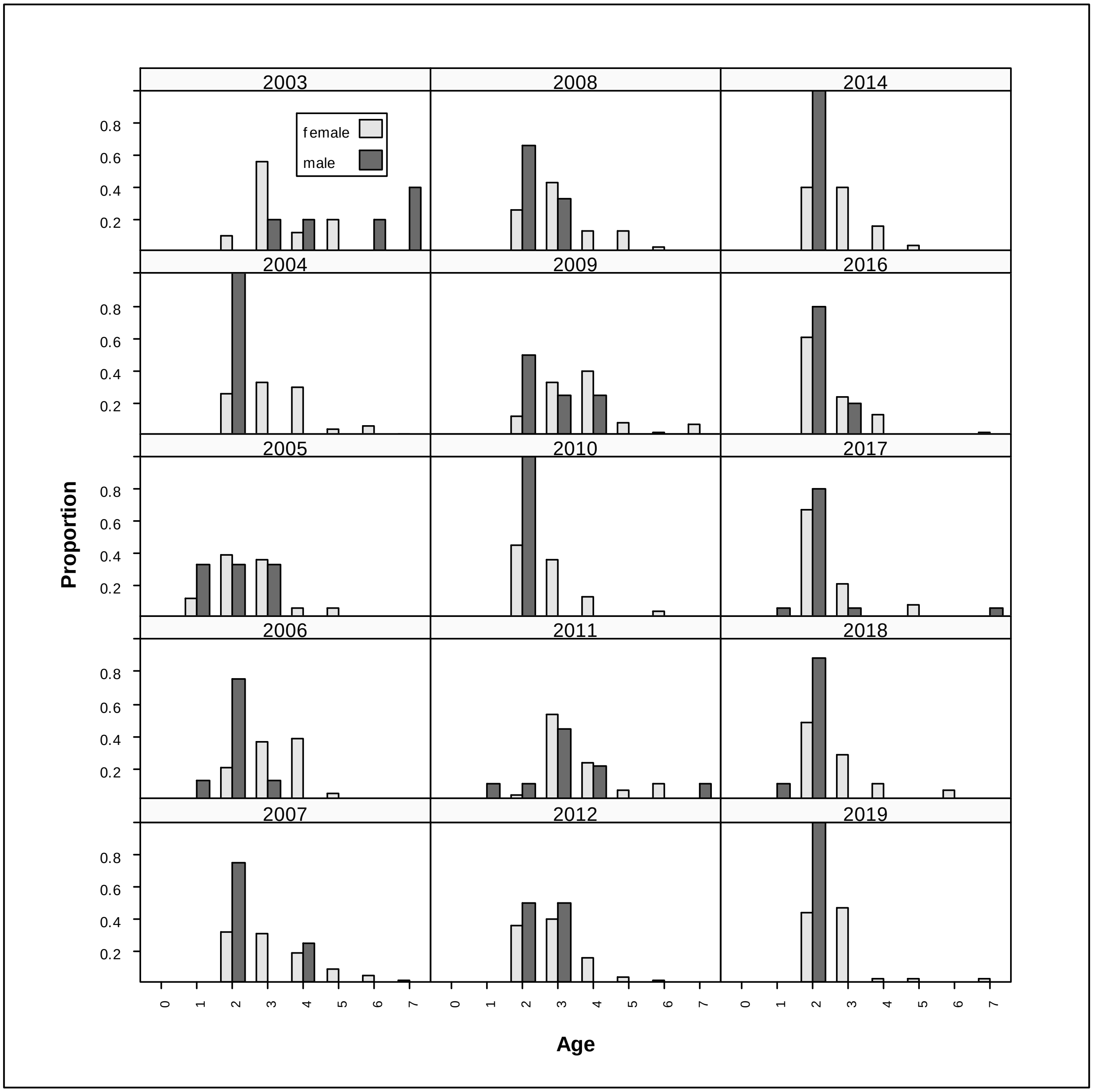


Figure 2.17. Annual age-frequency distributions of adult striped mullet collected in the spring component of Program 146 by sex, 2003–2019. Note that age 7 represents a plus group.

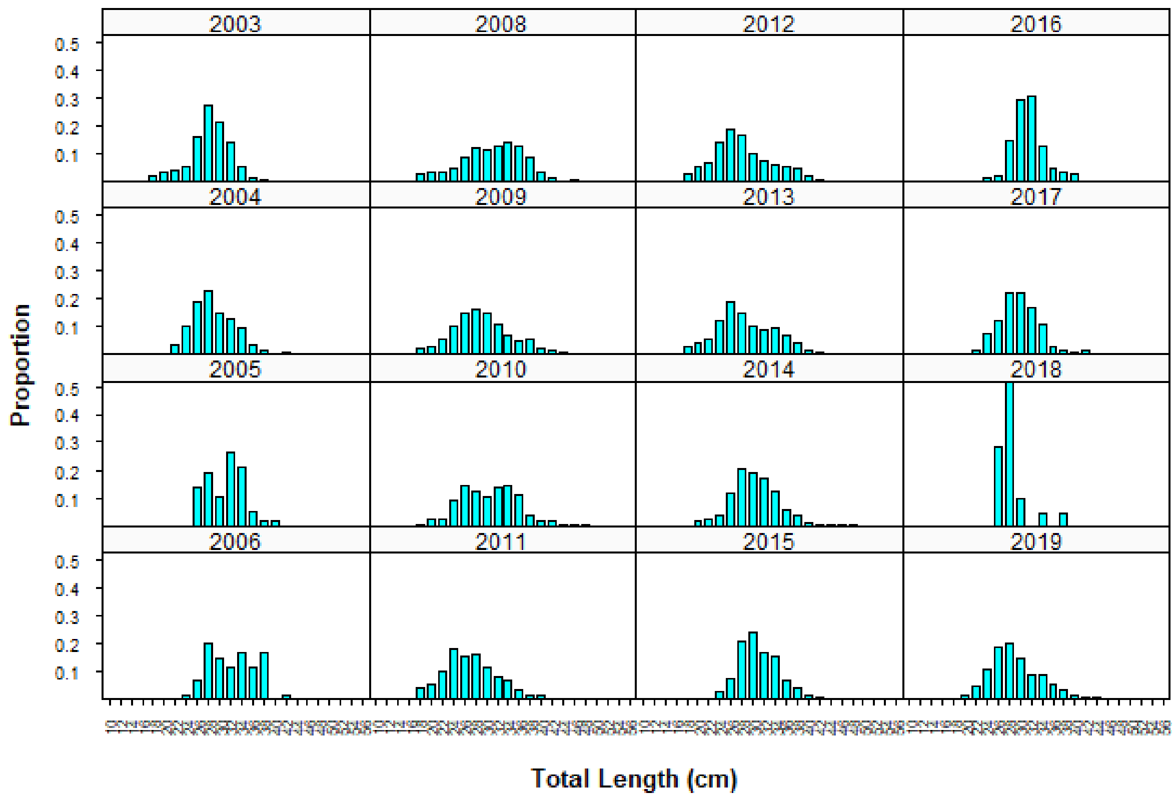


Figure 2.18. Annual length-frequency distributions of adult striped mullet collected in the autumn component of Program 146, 2003–2019.

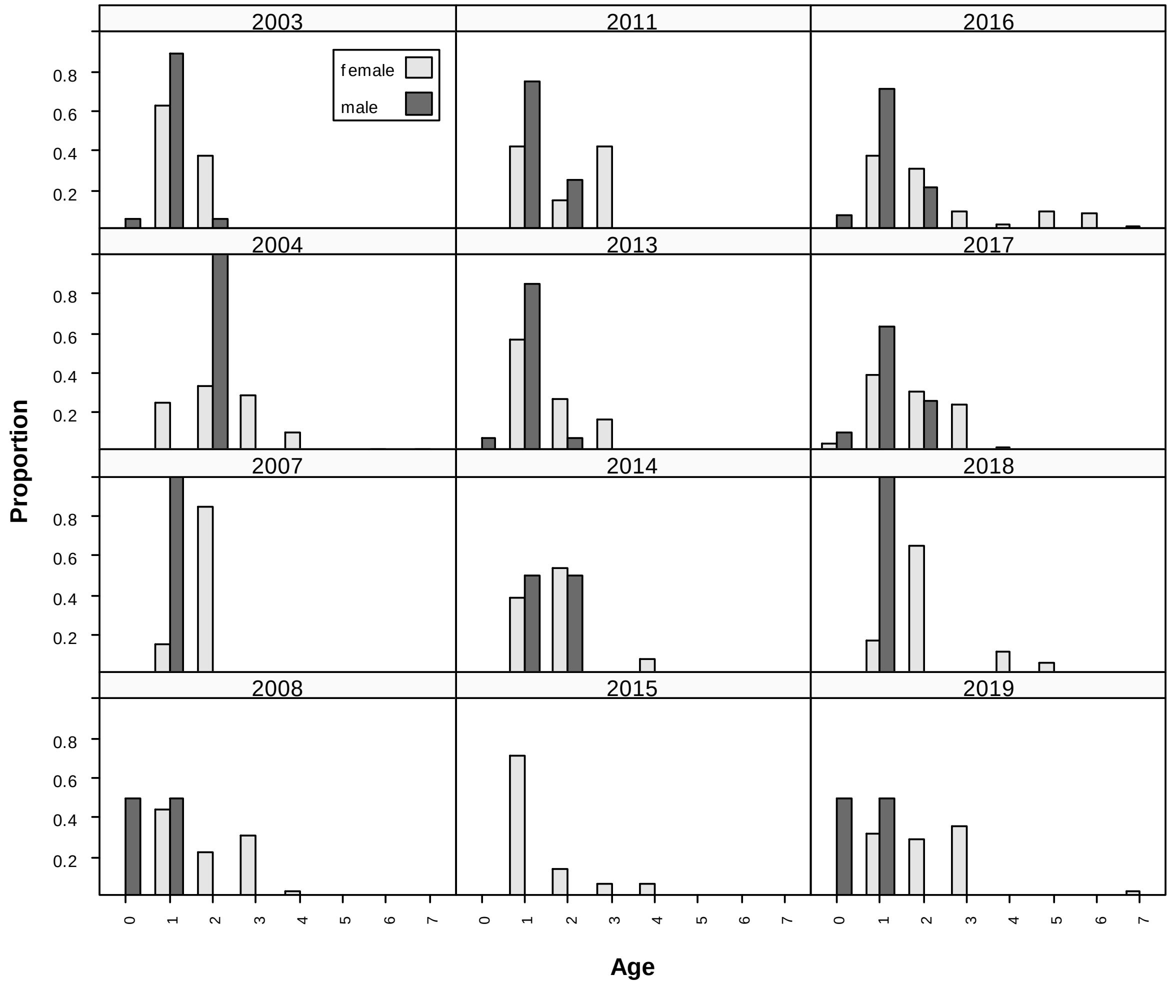


Figure 2.19. Annual age-frequency distributions of adult striped mullet collected in the autumn component of Program 146 by sex, 2003–2019. Note that age 7 represents a plus group.

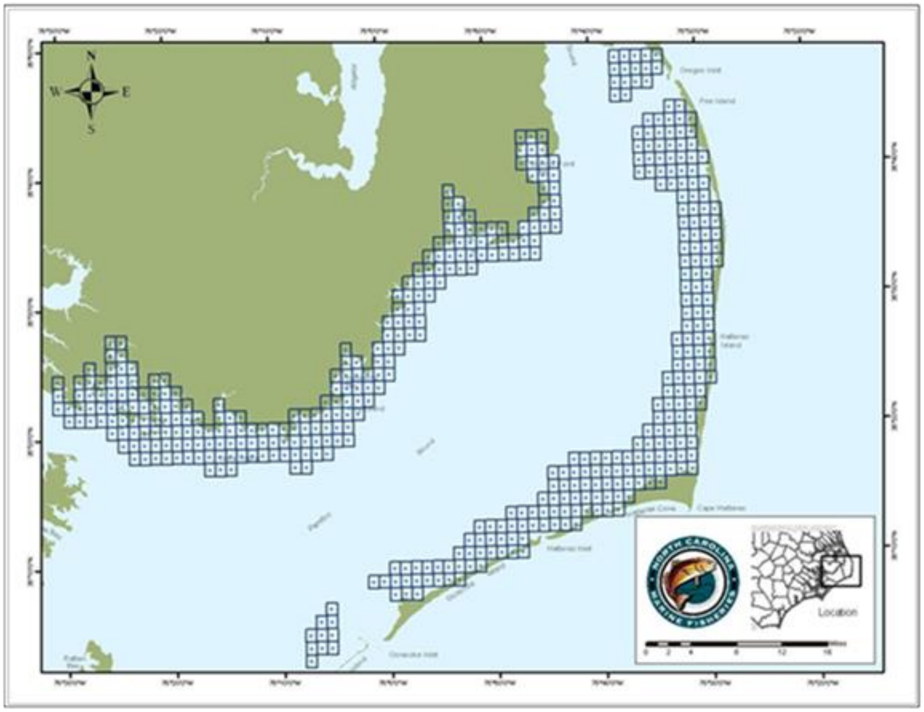


Figure 2.20. The sample regions and grid system for the Pamlico Sound portion of Program 915.

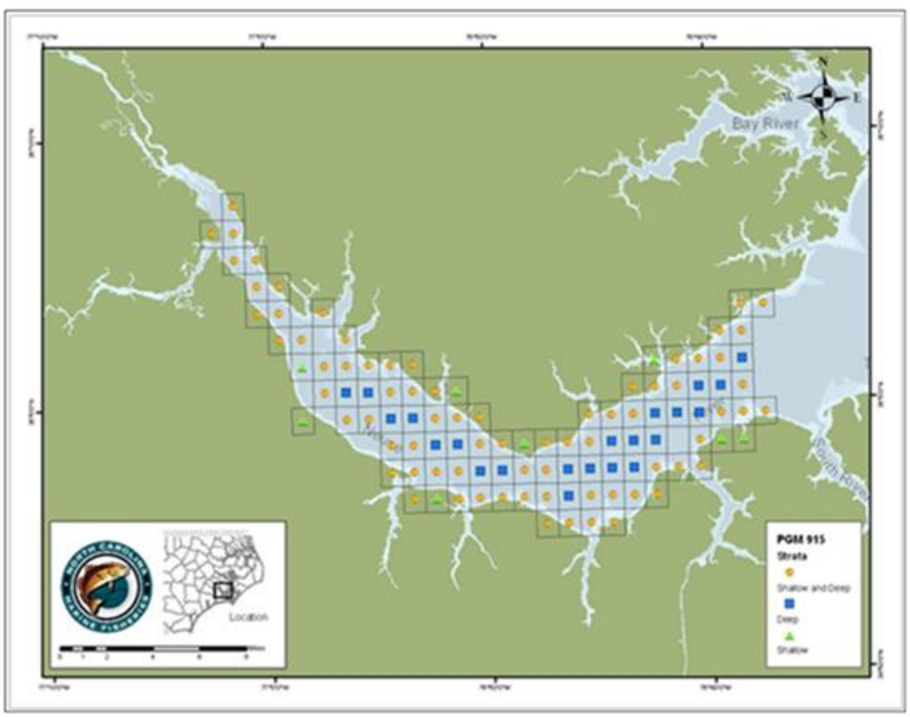


Figure 2.21. The sample regions and grid system for the Neuse River portion of Program 915.

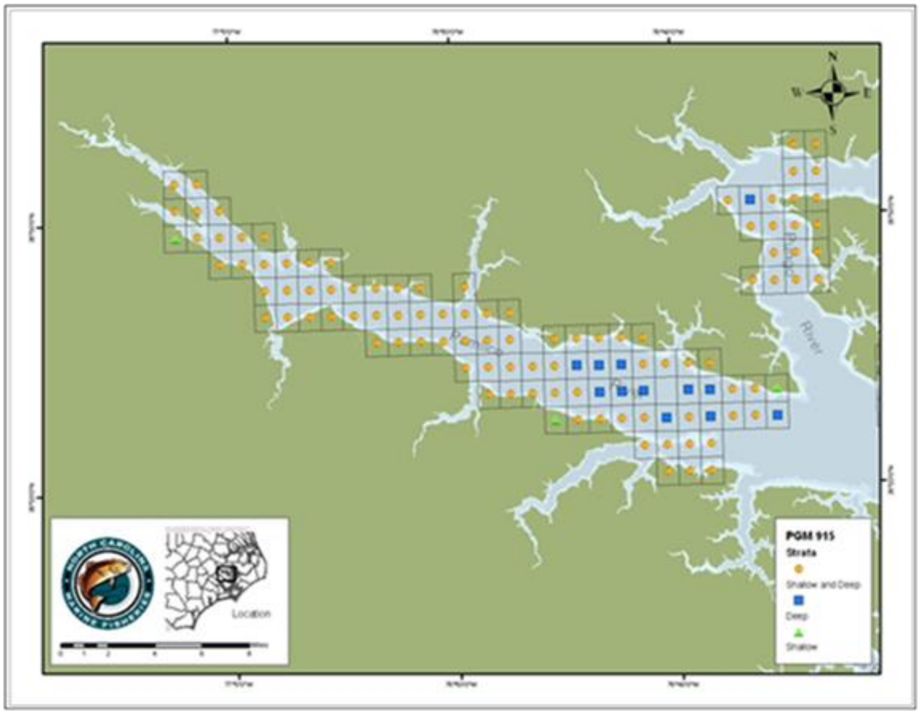


Figure 2.22. The sample regions and grid system for the Pamlico and Pungo river portions of Program 915.

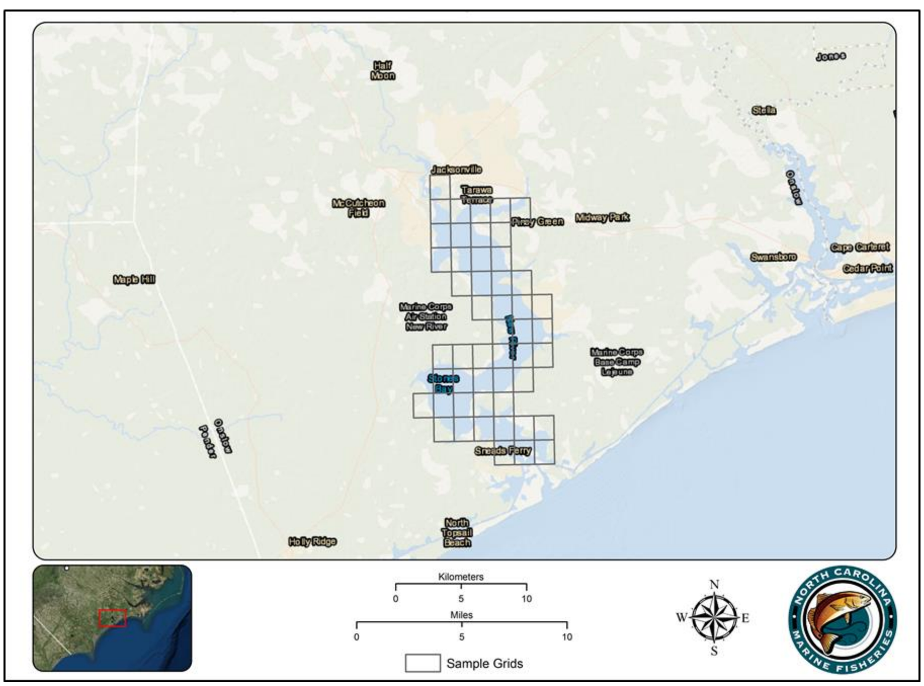


Figure 2.23. Map for Southern District of Program 915.

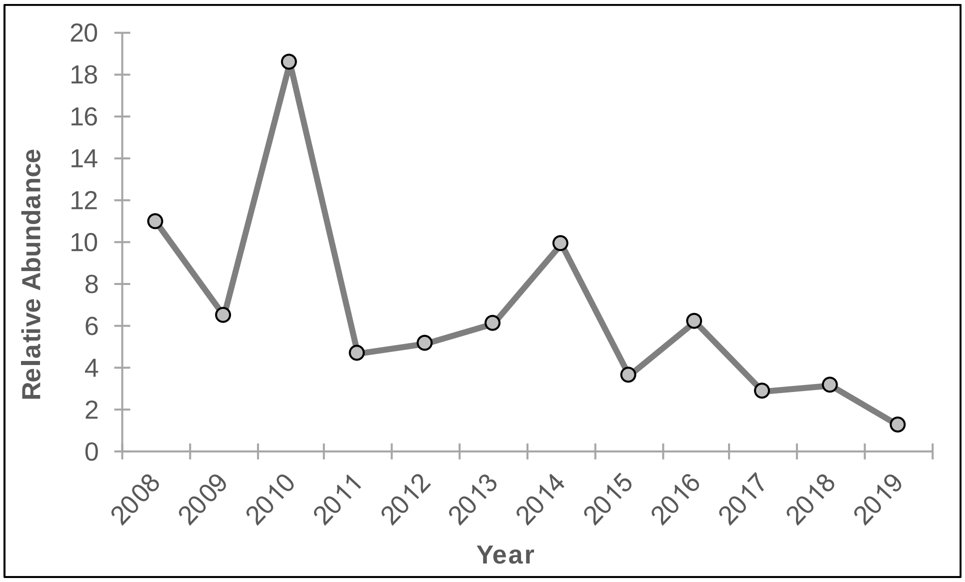


Figure 2.24. GLM-standardized index of relative abundance for adult striped mullet collected in the southern area of Program 915, 2008–2019.

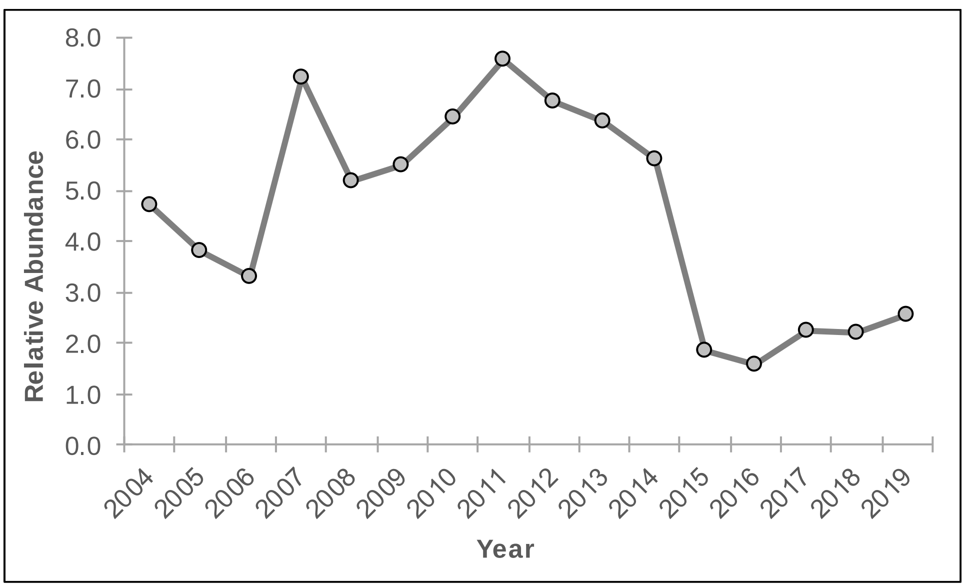


Figure 2.25. GLM-standardized index of relative abundance for adult striped mullet collected in the northern area of Program 915, 2004–2019.

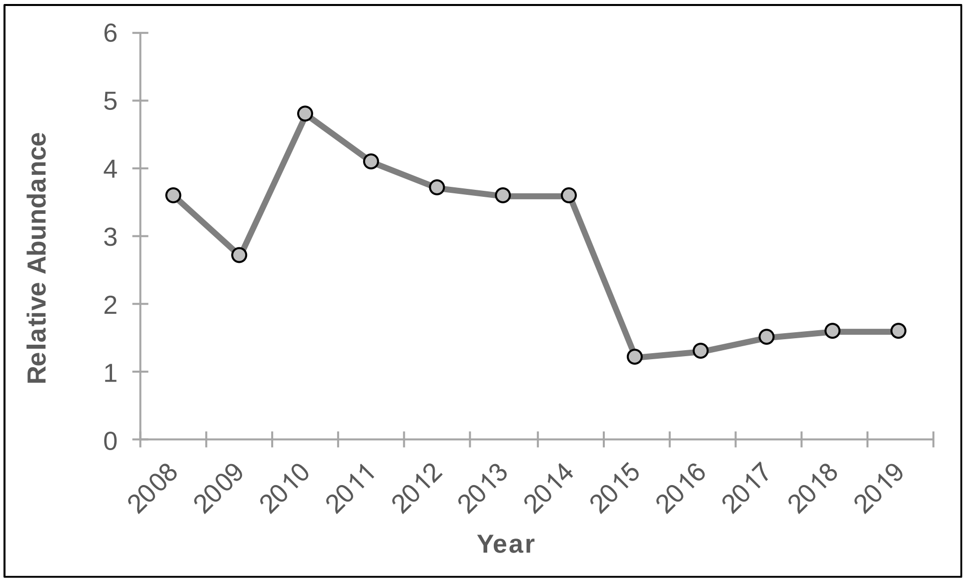


Figure 2.26. GLM-standardized index of relative abundance for adult striped mullet collected in the northern and southern areas combined of Program 915, 2008–2019.

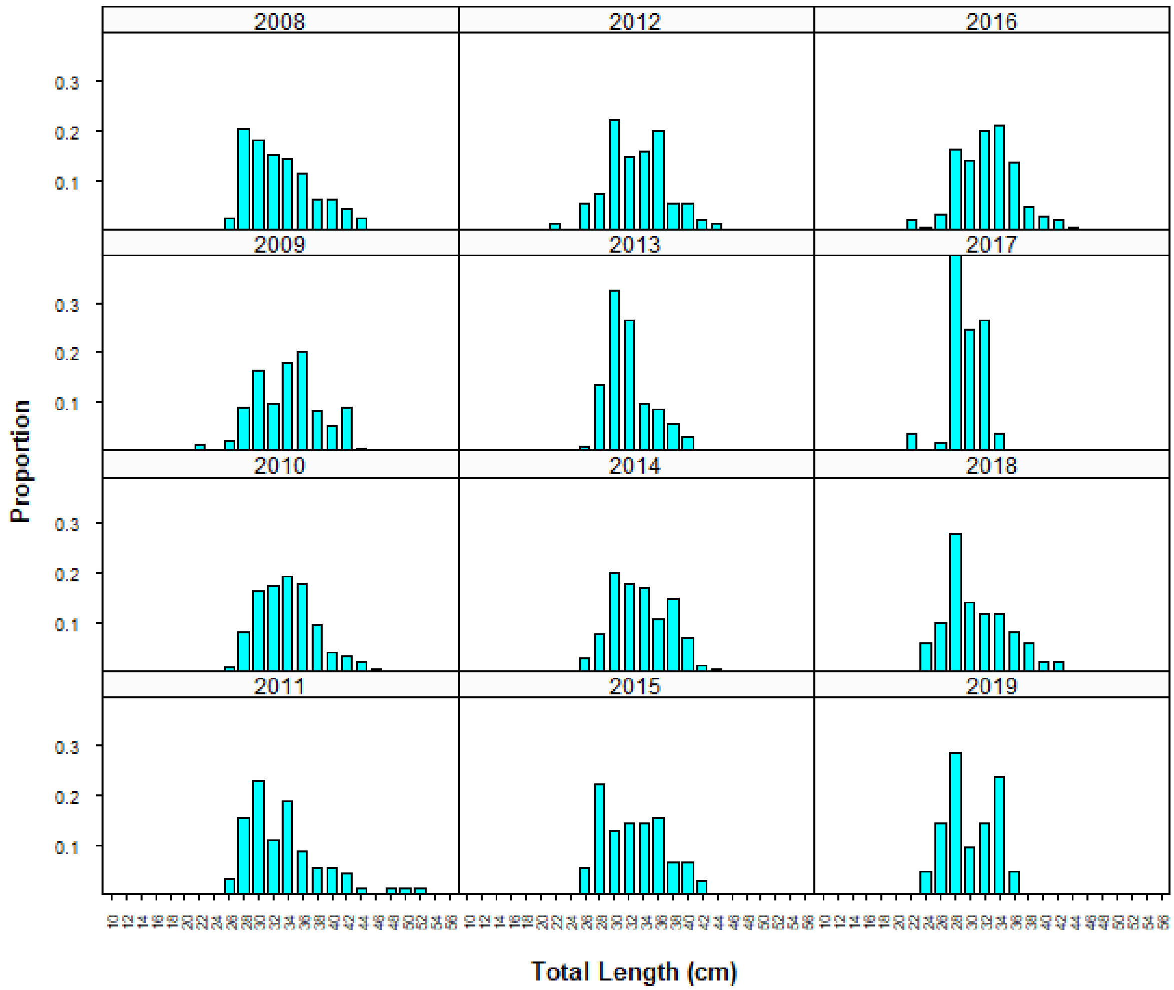


Figure 2.27. Annual length-frequency distributions of adult striped mullet collected in the southern area of Program 915, 2008–2019.

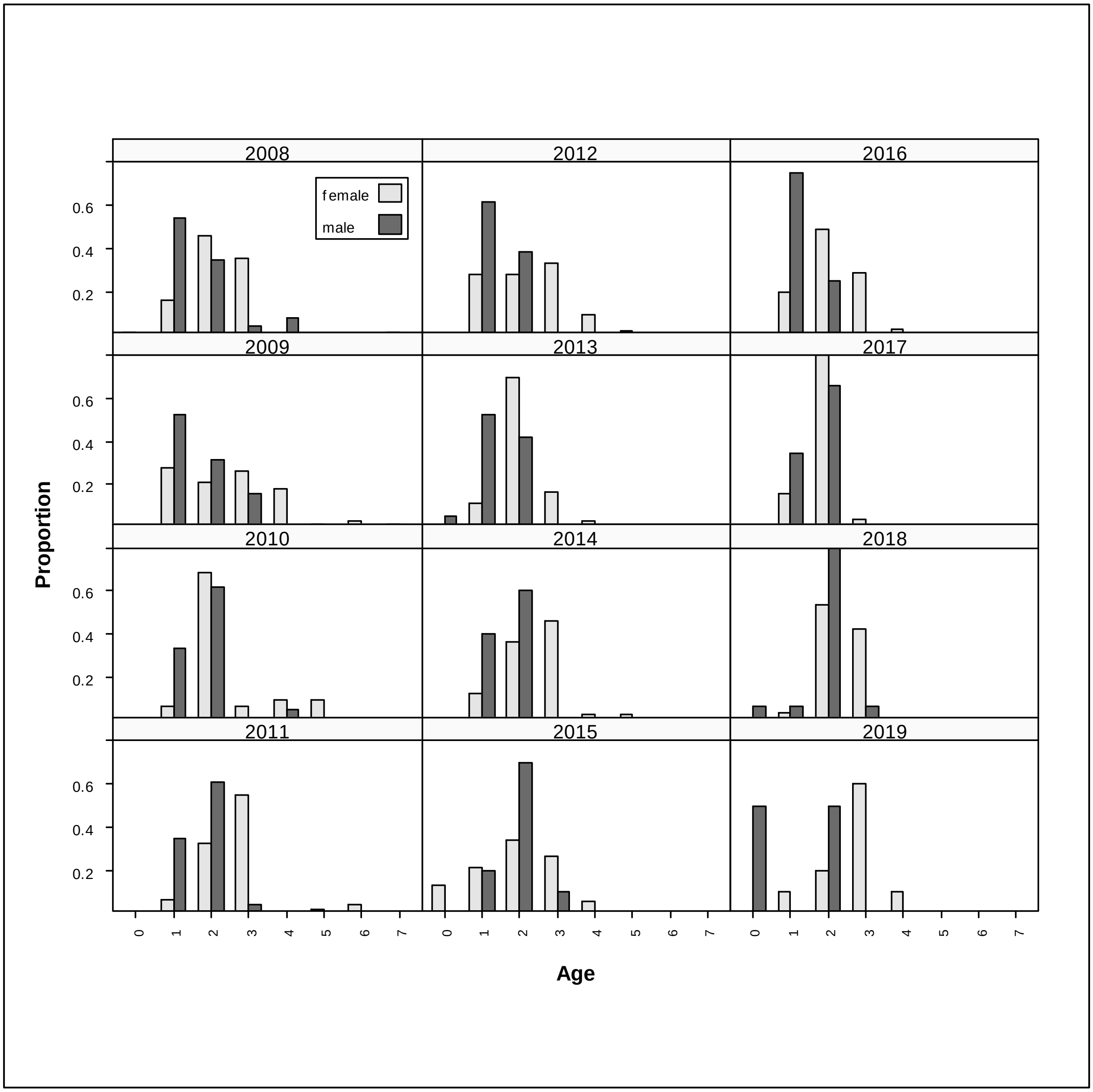


Figure 2.28. Annual age-frequency distributions of adult striped mullet collected in the southern area of Program 915 by sex, 2008–2019. Note that age 7 represents a plus group.

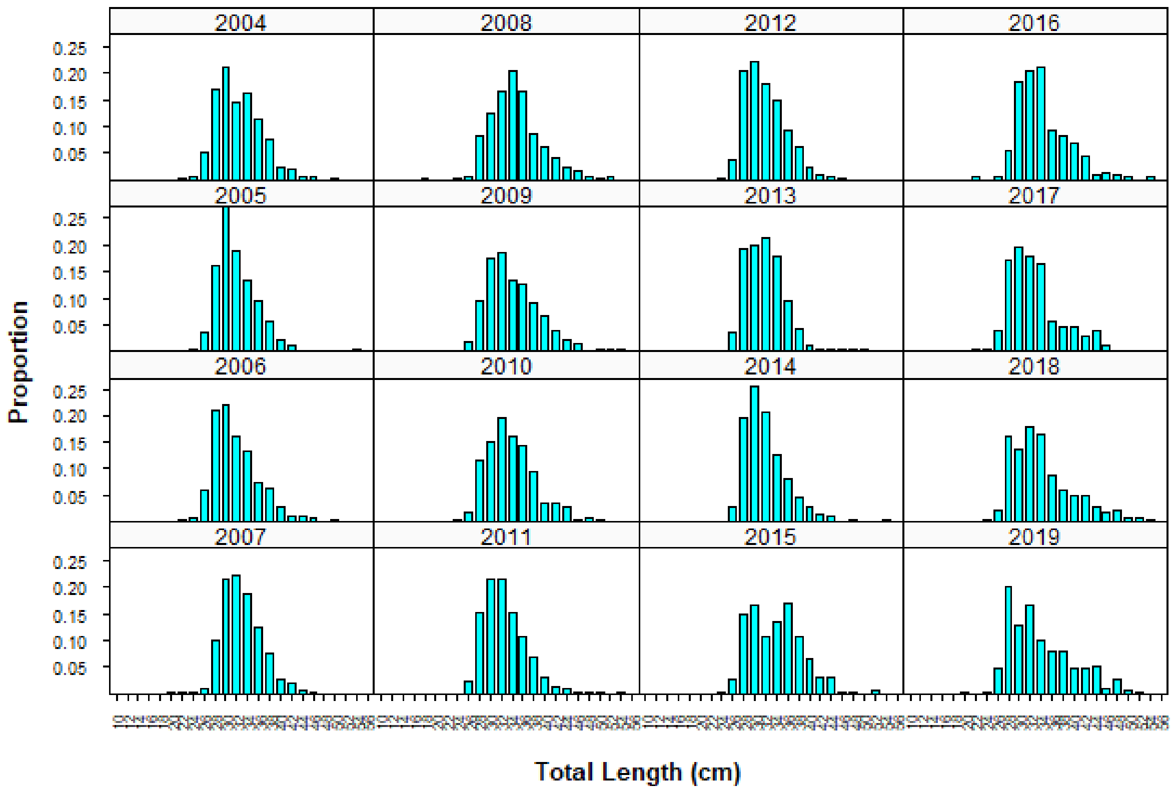


Figure 2.29. Annual length-frequency distributions of adult striped mullet collected in the northern area of Program 915, 2004–2019.

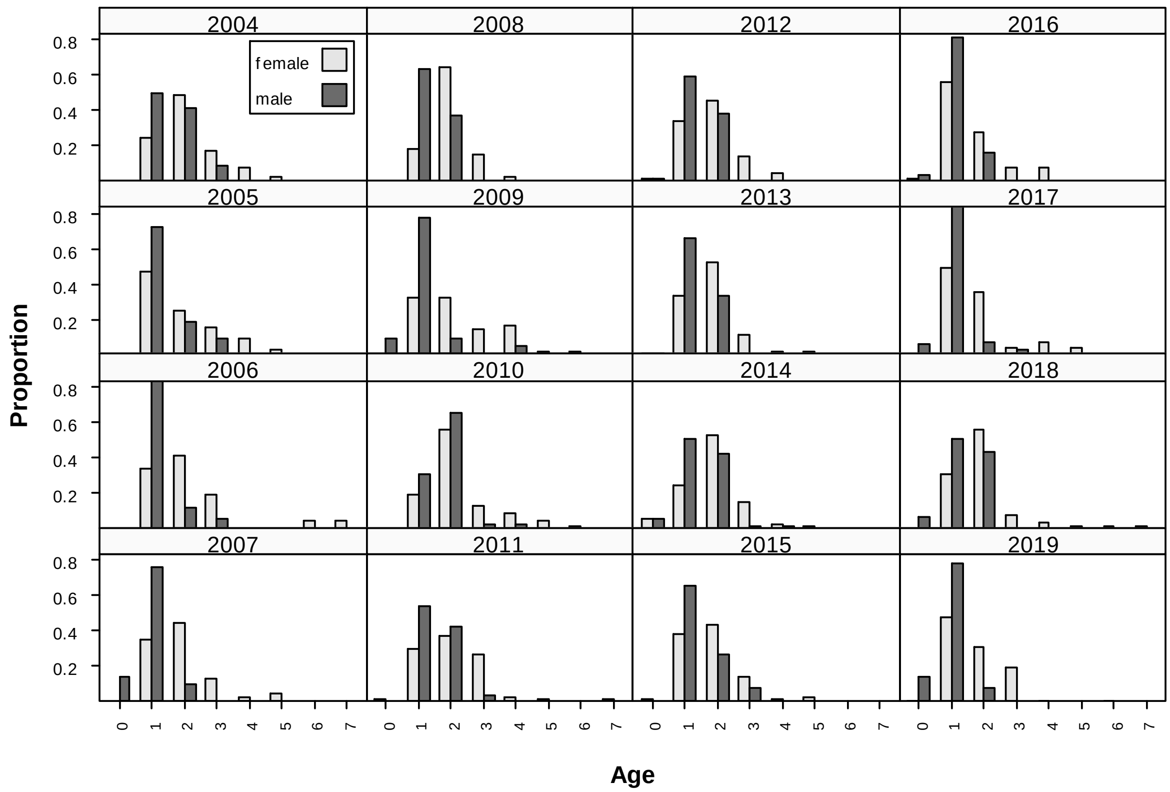


Figure 2.30. Annual age-frequency distributions of adult striped mullet collected in the northern area of Program 915 by sex, 2004–2019. Note that age 7 represents a plus group.

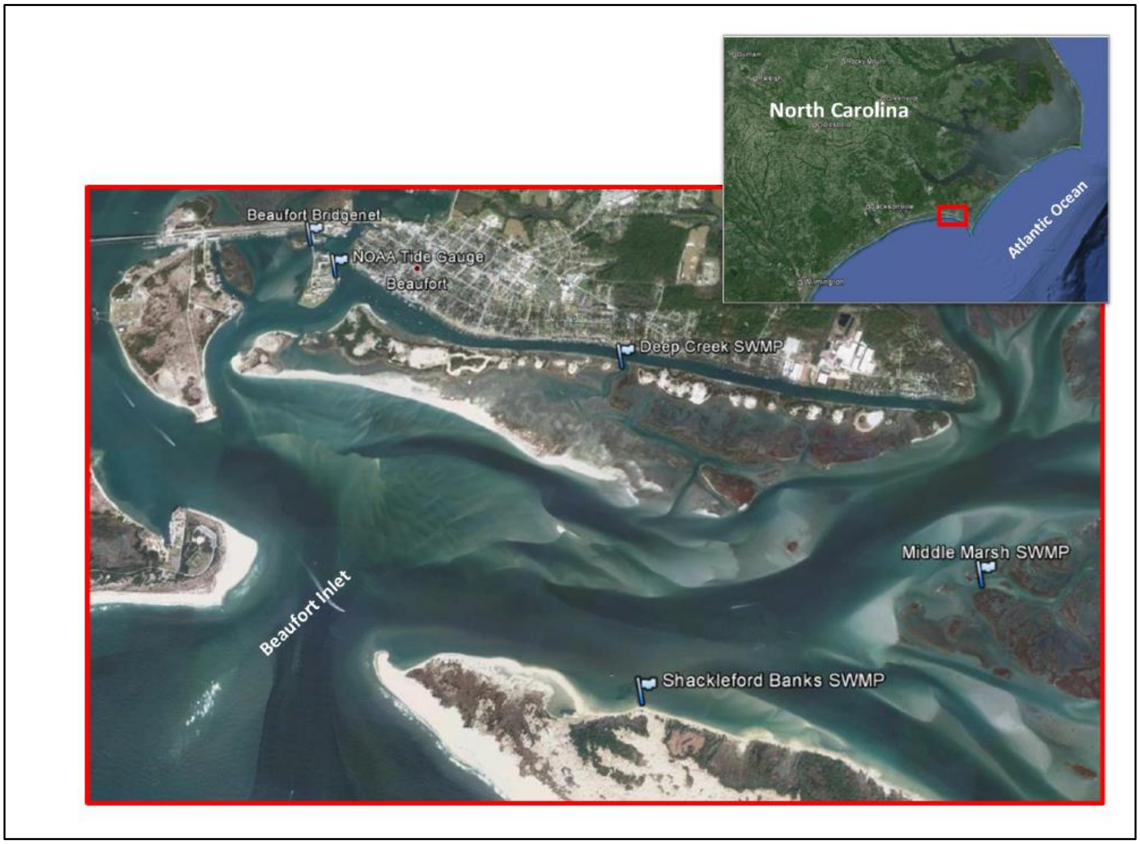


Figure 2.31. Location of the Beaufort Bridgenet Ichthyoplankton Sampling Program (BBISP) station (N 34°43’12.69”, W 76°40’23.90”) on the Pivers Island Bridge in Beaufort, North Carolina, which is 1.5 km upstream from the Beaufort Inlet in the Newport River Estuary.

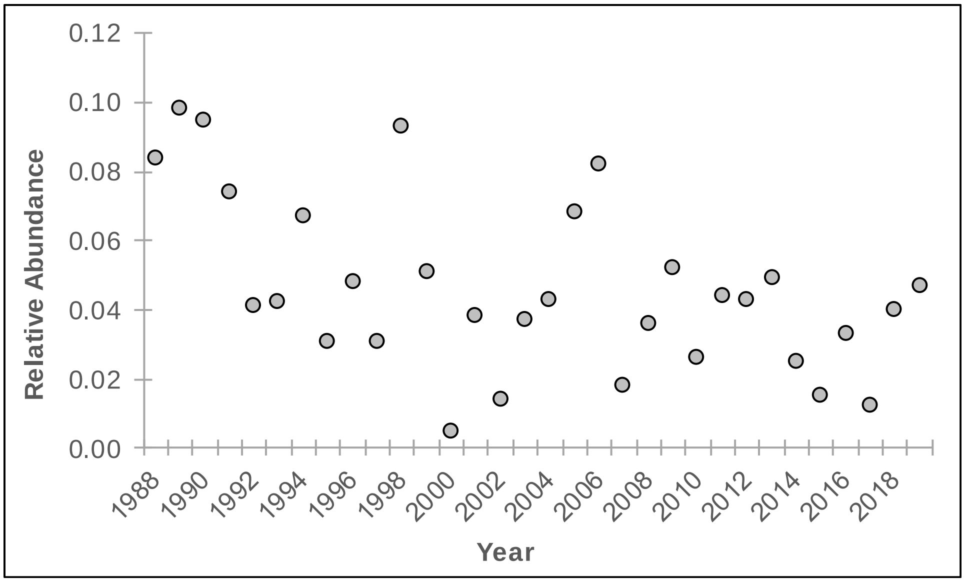


Figure 2.32. Nominal index of relative abundance for age-0 striped mullet collected in the Beaufort Bridgenet Ichthyoplankton Sampling Program, 1988–2019.

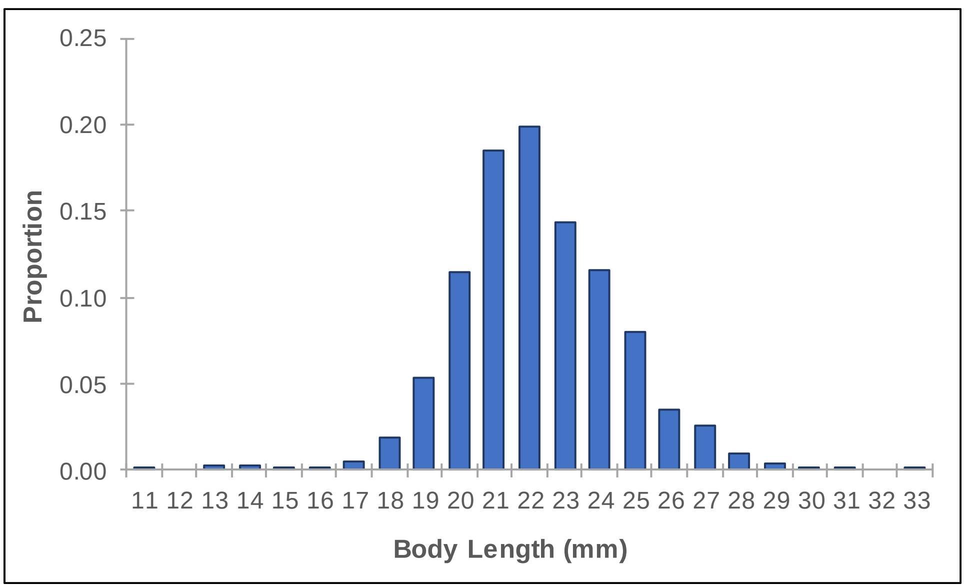


Figure 2.33. Length-frequency distribution of age-0 striped mullet collected in the Beaufort Bridgenet Ichthyoplankton Sampling Program, pooled over 2001 to 2019.

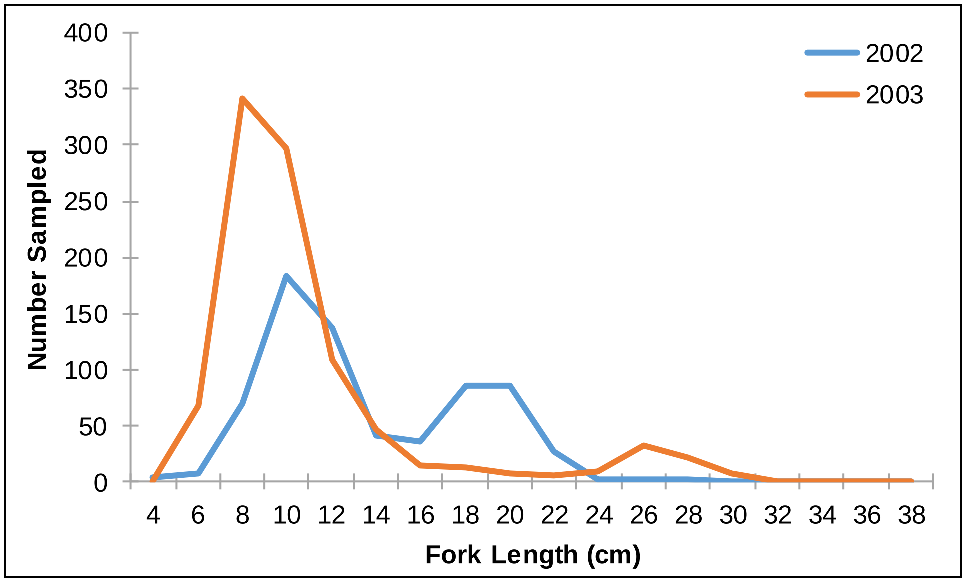


Figure 2.34. Length-frequency distributions of striped mullet collected in the NCDMF fisheries-independent cast net study, 2002 and 2003.

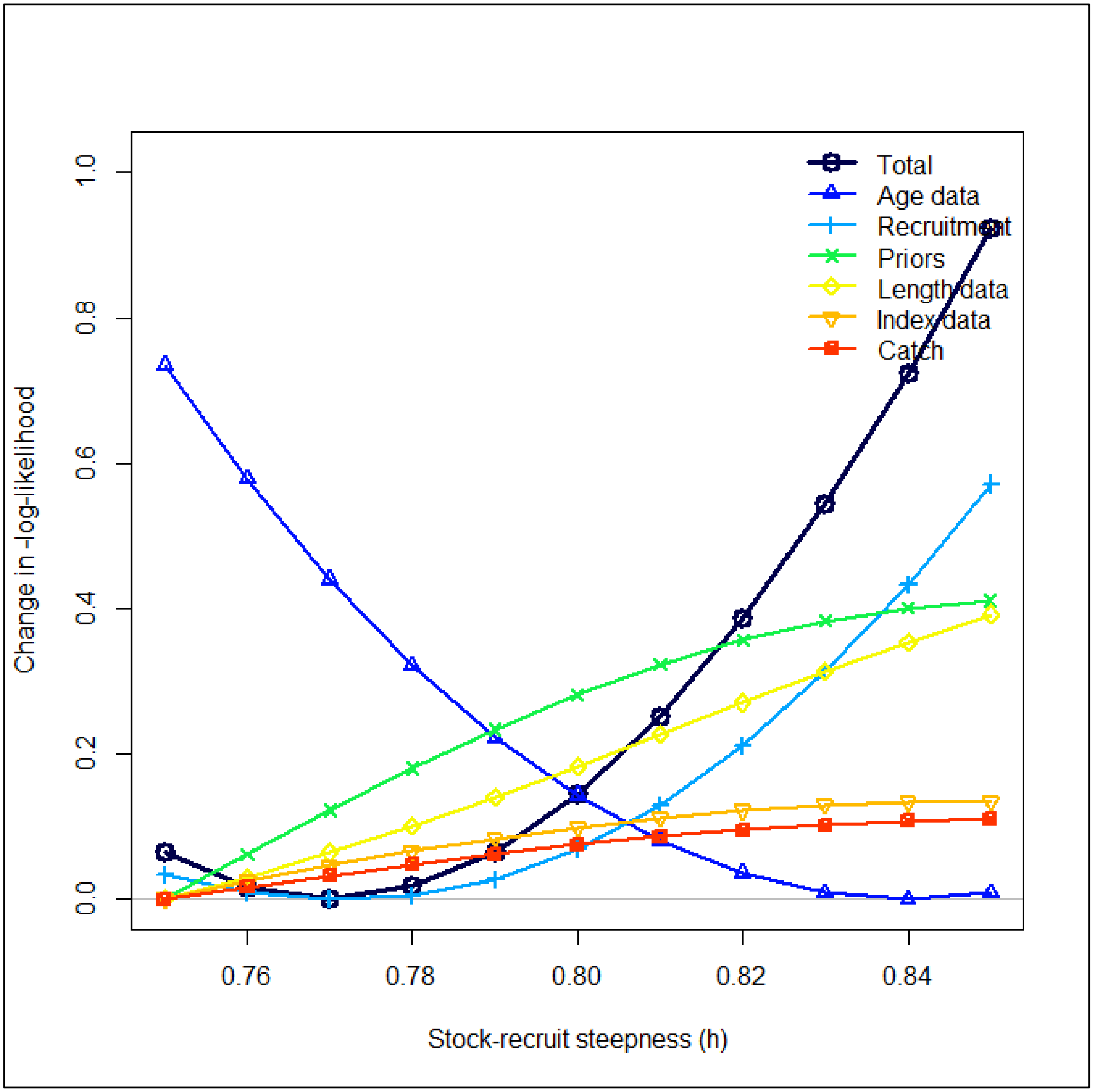


Figure 3.1. Likelihood profile on steepness, *h*, by data component.

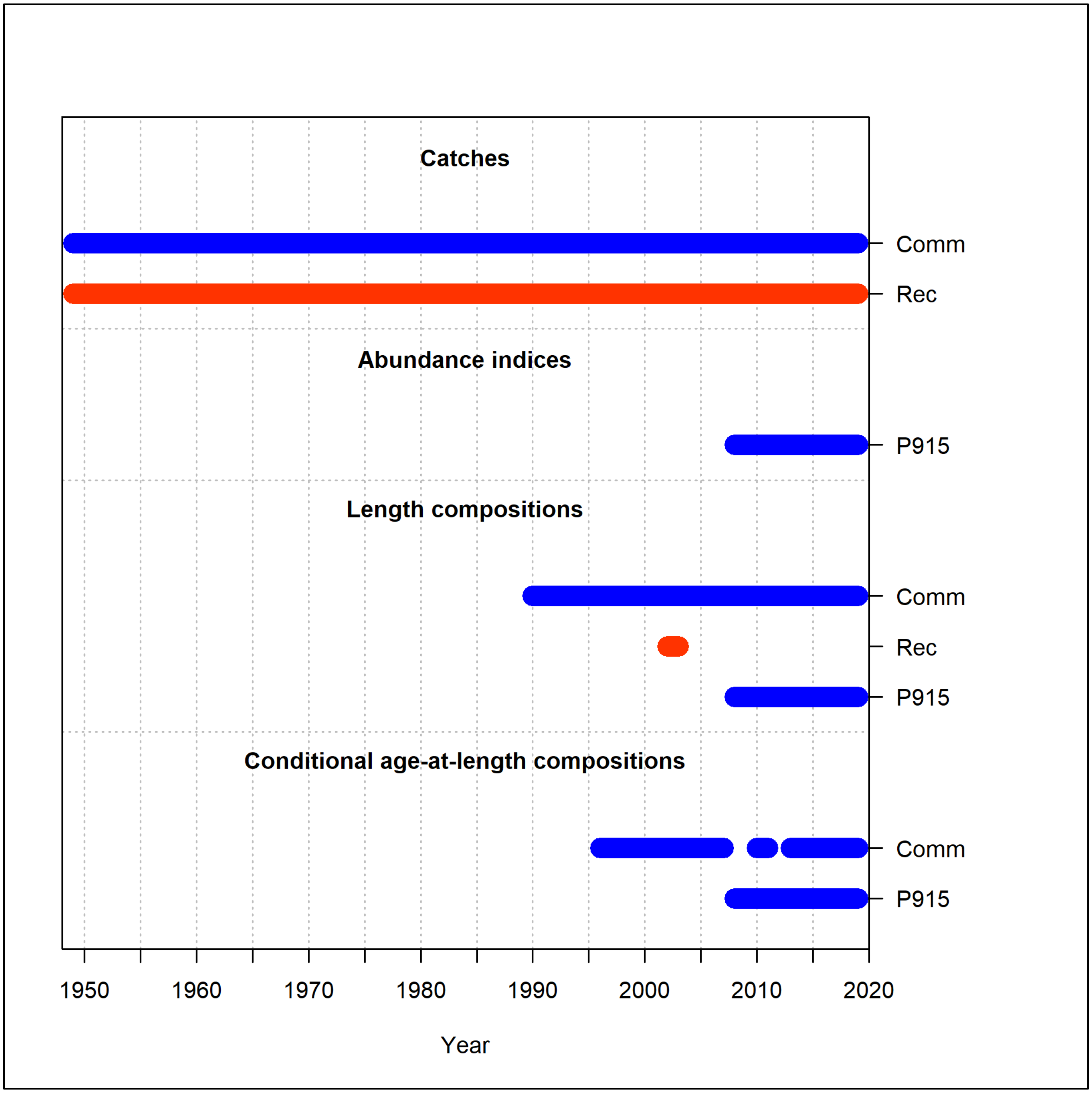


Figure 3.2. Summary of data sources and types used in the base run of the stock assessment model for striped mullet.

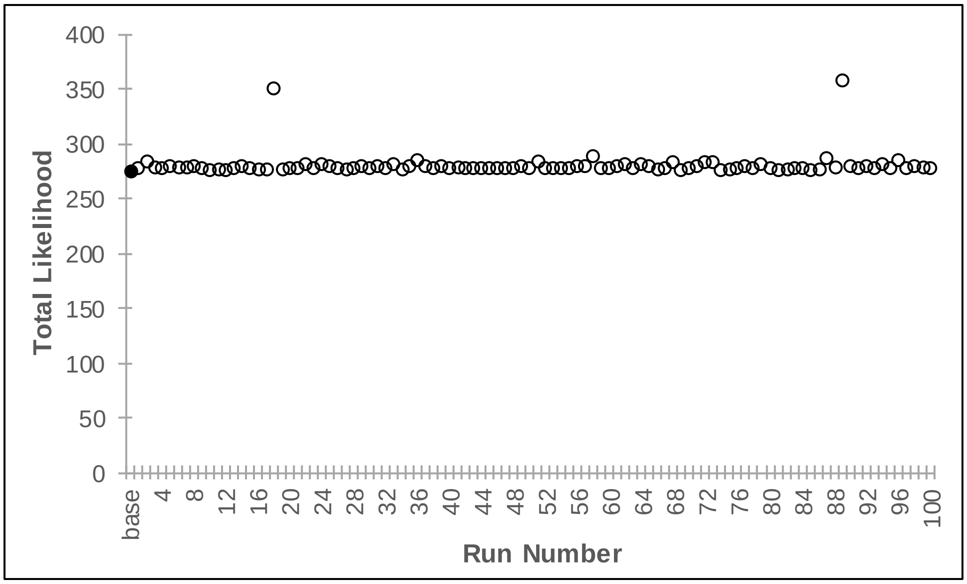
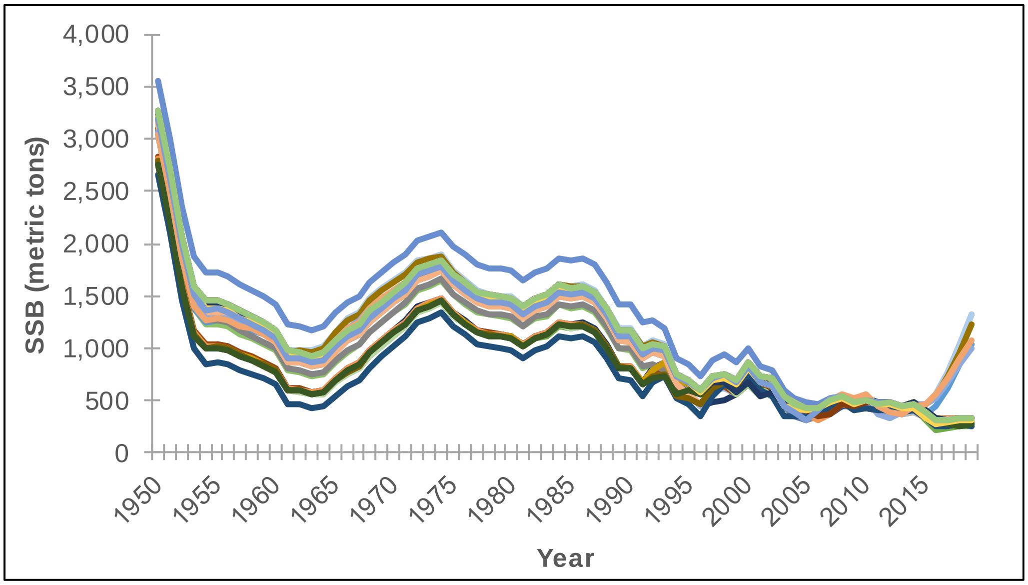


Figure 3.3. Negative log-likelihood values produced from the 100 jitter trials in which initial parameter values were jittered by 10%.



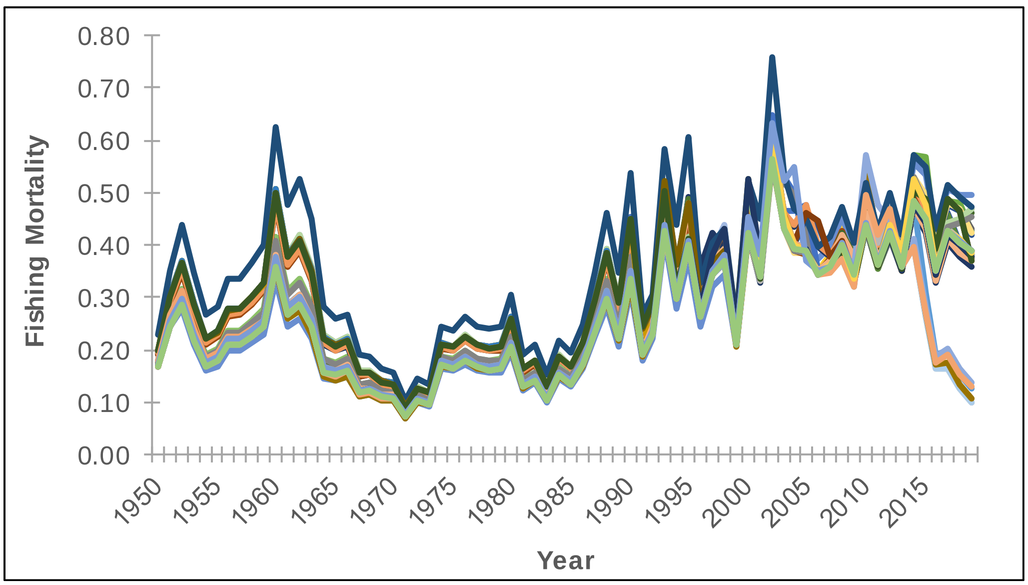


Figure 3.4. Predicted female SSB (top graph) and *F* (numbers-weighted, ages 1–5; bottom graph) from the jitter analysis (10%) applied to the base run of the stock assessment model, 1950–2019.

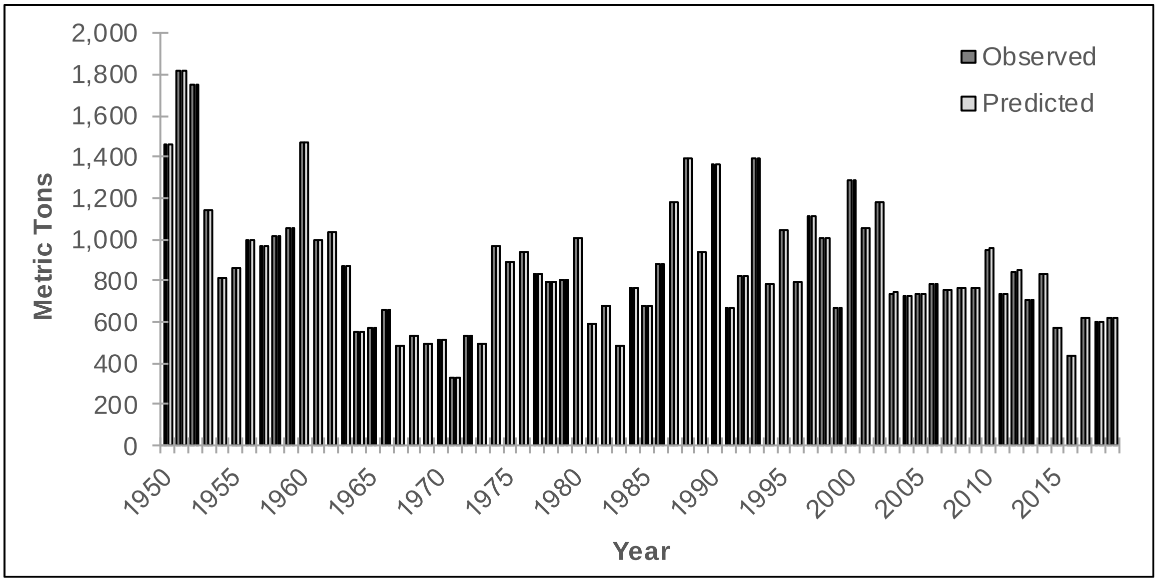


Figure 3.5. Observed and predicted commercial landings from the base run of the stock assessment model, 1950–2019.

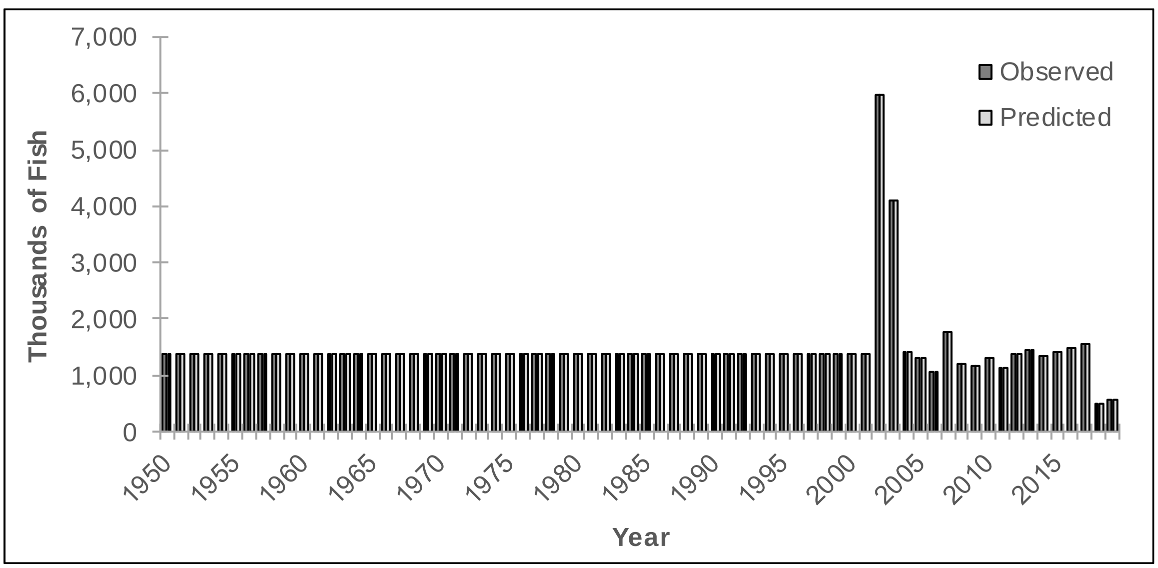
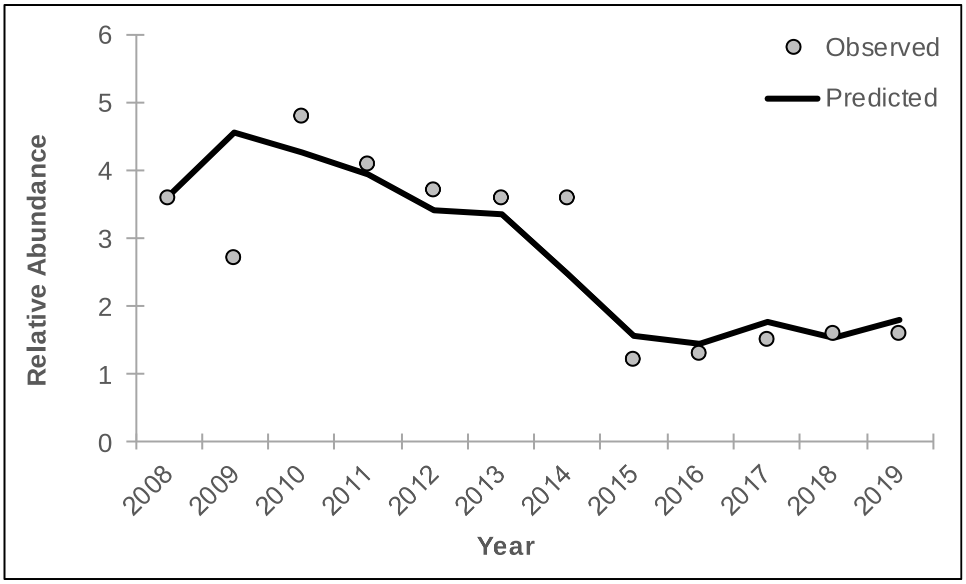


Figure 3.6. Observed and predicted recreational harvest from the base run of the stock assessment model, 1950–2019.



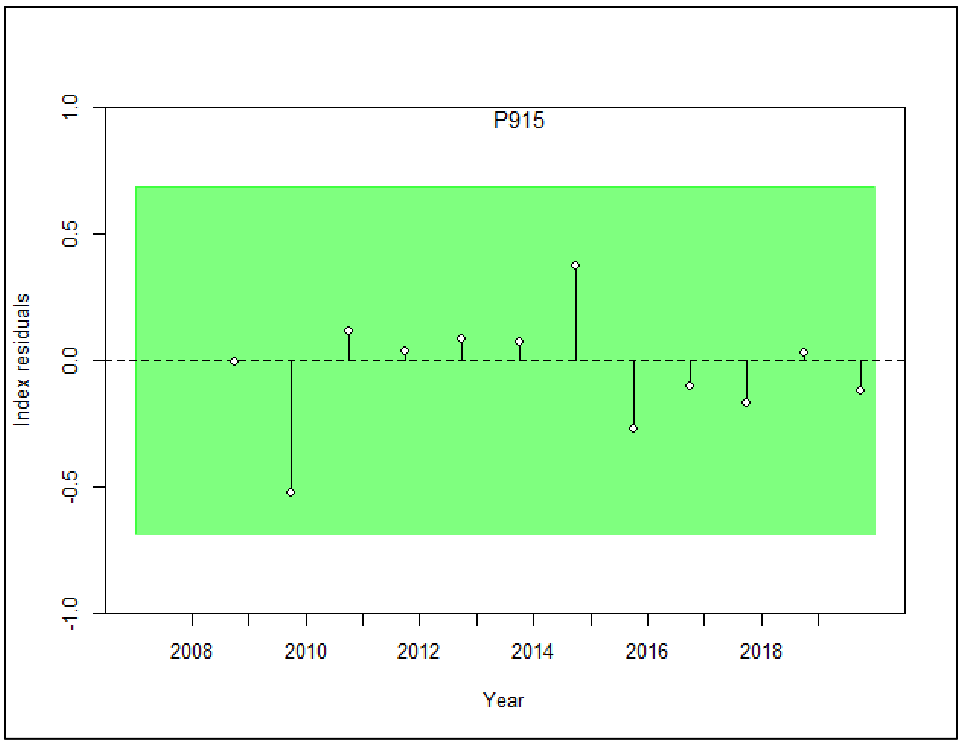


Figure 3.7. Observed and predicted relative abundance (top graph) and associated runs test plot (bottom graph) for the P915 Survey index from the base run of the stock assessment model, 2008–2019. In the runs test plot, green shading indicates no evidence ($\alpha = 0.05$) and red shading evidence ($p < 0.05$) to reject the hypothesis of a randomly distributed time series of residuals, respectively. The shaded (green/red) area spans three residual standard deviations to either side from zero and the red points outside the shading violate the 'three-sigma limit' for that series.

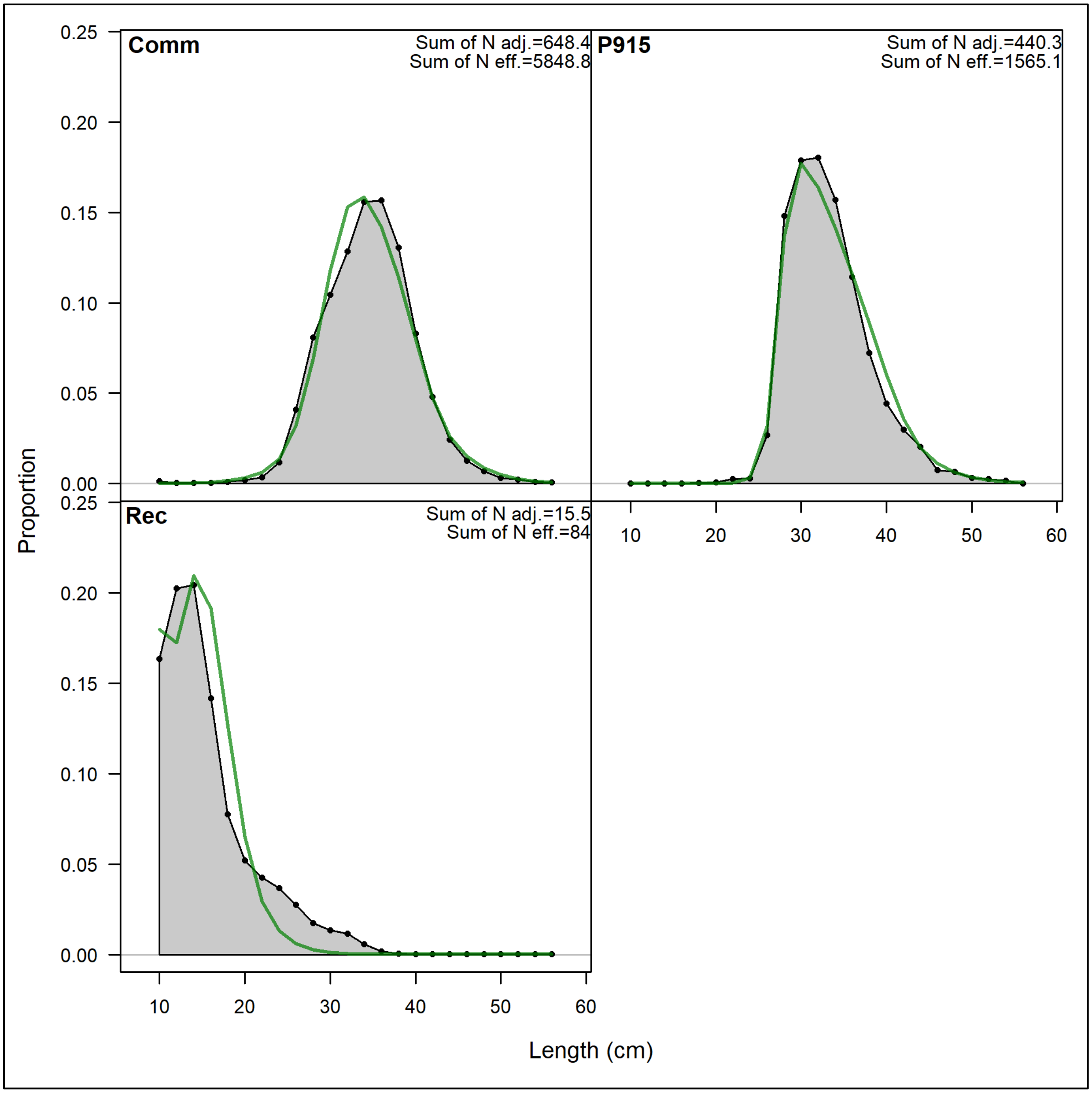


Figure 3.8. Observed and predicted length compositions for each data source from the base run of the stock assessment model aggregated across time. N adj. represents the input effective sample size (number of trips sampled) and N eff. represents the model estimate of effective sample size.

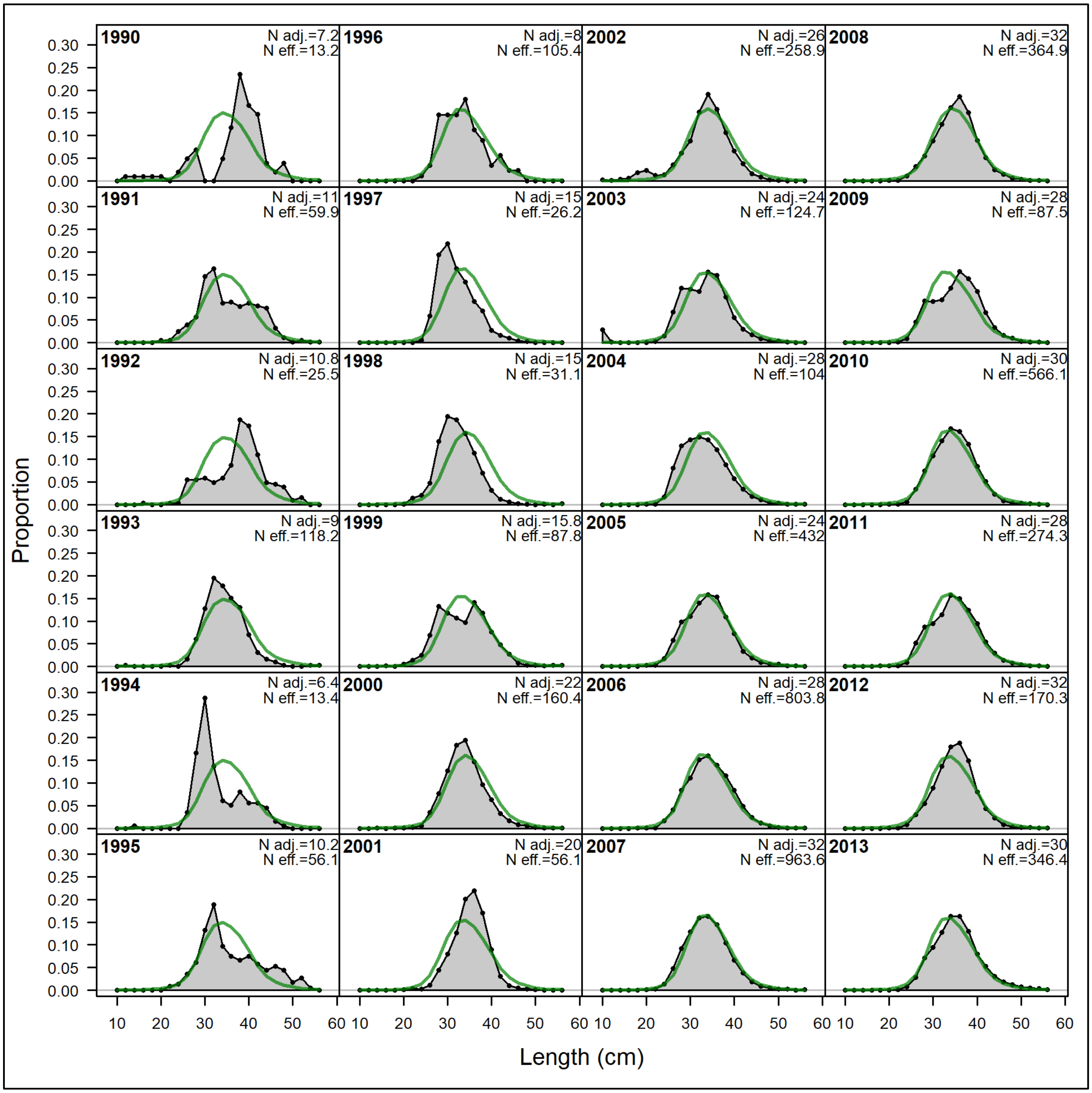


Figure 3.9. Observed and predicted length compositions for the commercial fishery from the base run of the stock assessment model, 1990–2013. N adj. represents the input effective sample size (number of trips sampled) and N eff. represents the model estimate of effective sample size.

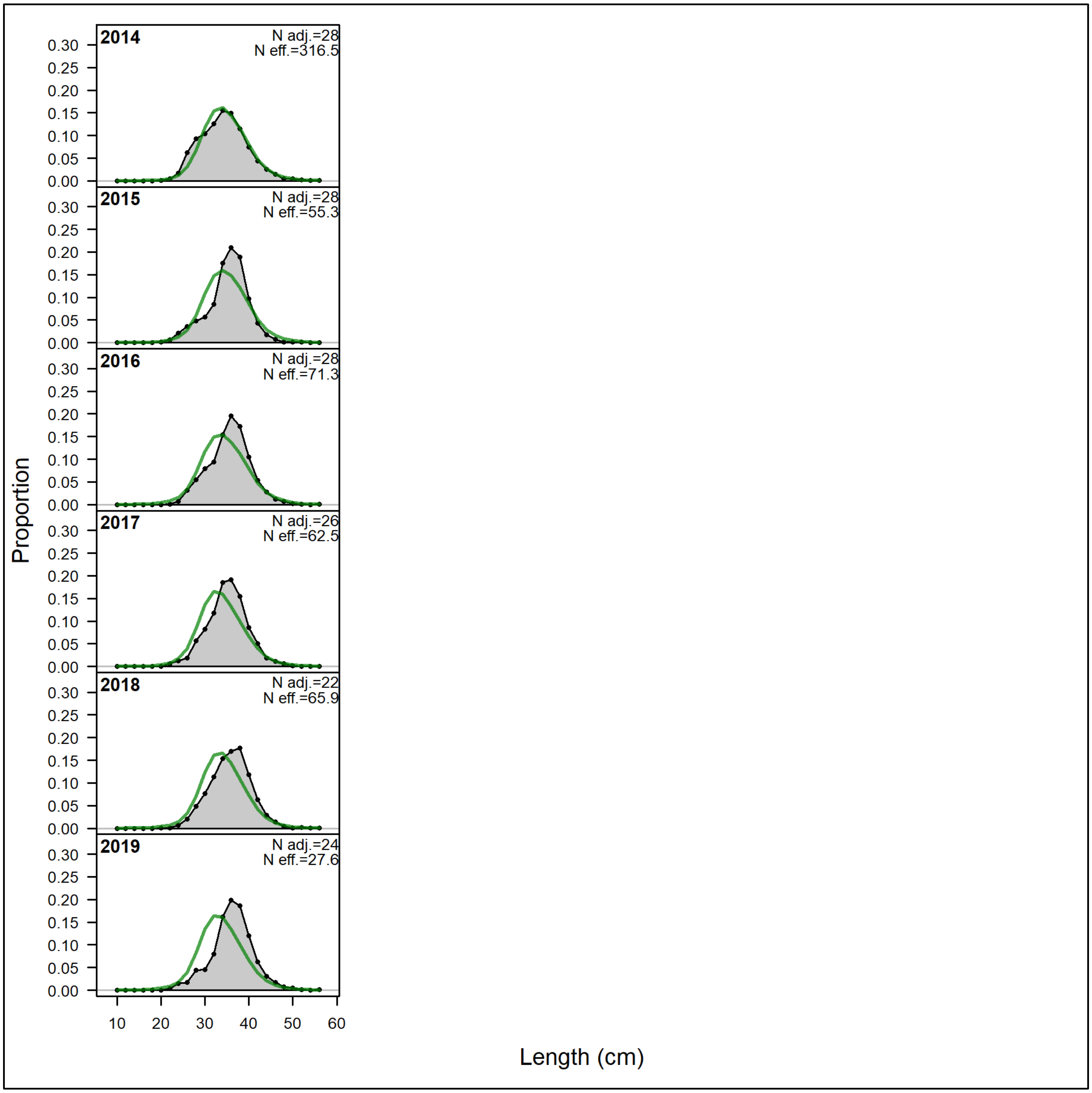


Figure 3.10. Observed and predicted length compositions for the commercial fishery from the base run of the stock assessment model, 2014–2019. N adj. represents the input effective sample size (number of trips sampled) and N eff. represents the model estimate of effective sample size.

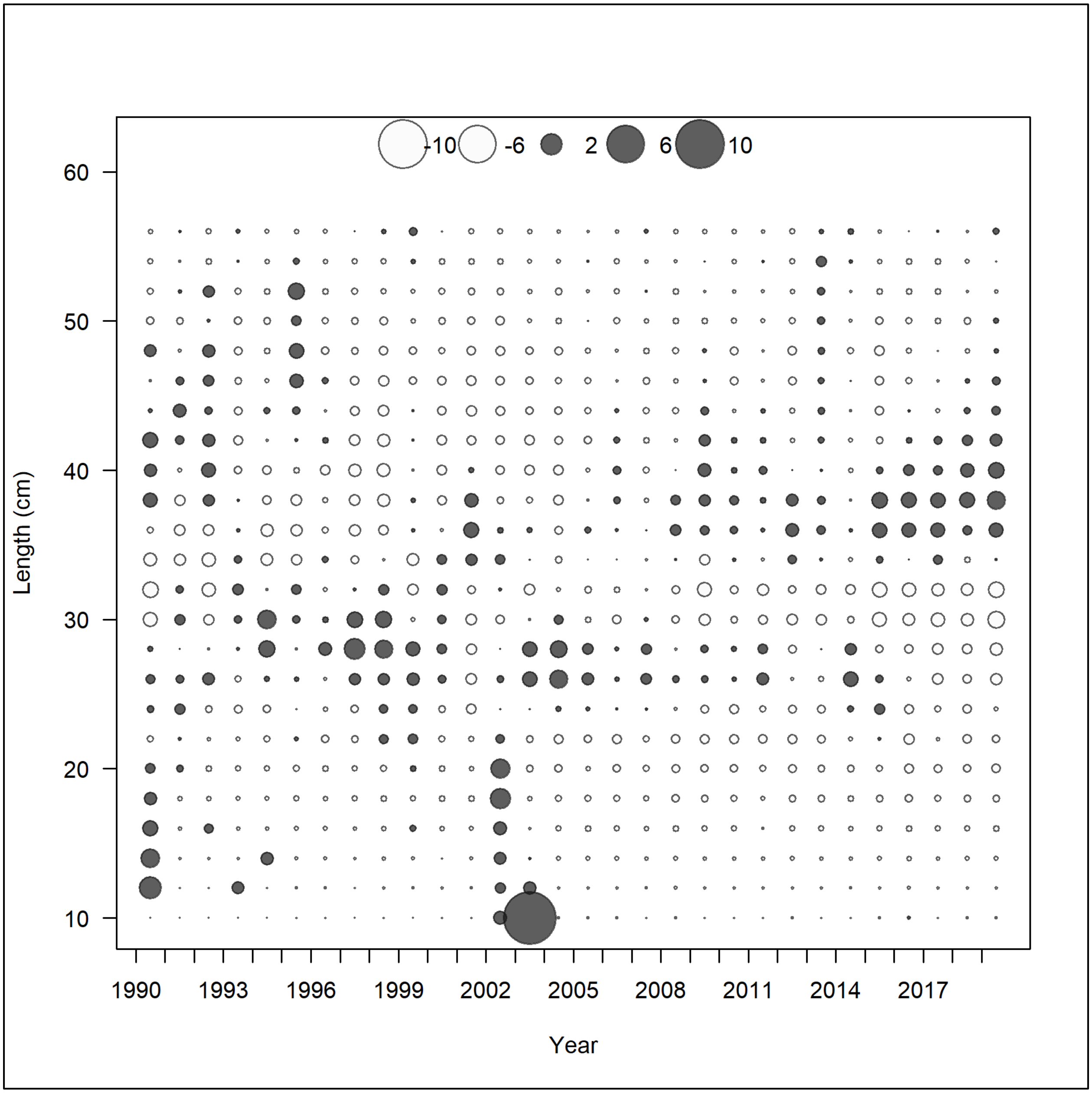


Figure 3.11. Standardized residuals for the commercial fishery length composition data from the base run of the stock assessment model, 1990–2019. Gray circles represent positive residuals (observed > expected) while white circles represent negative residuals (observed < expected). The area of the circles is proportional to the size of the residuals.

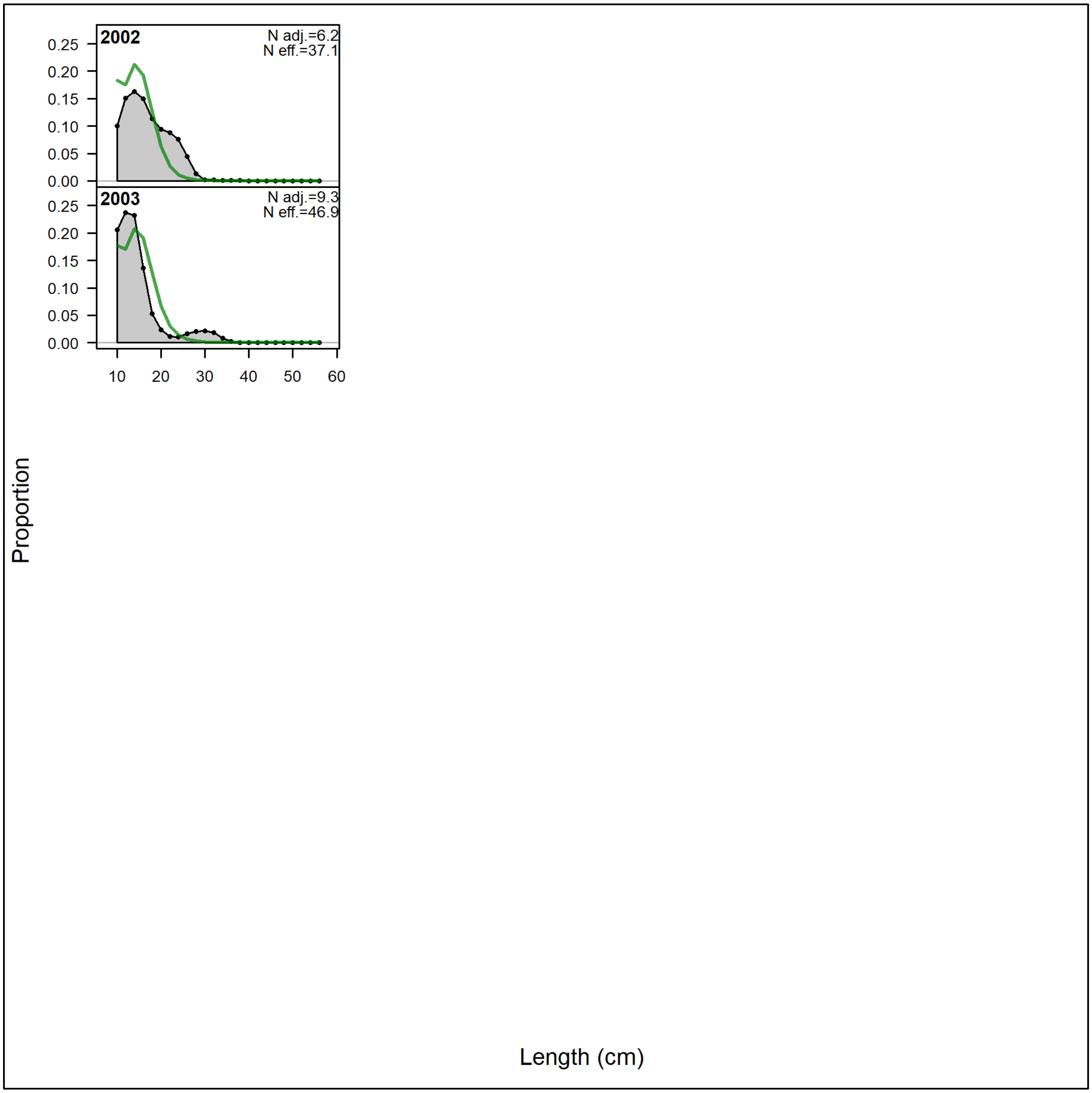


Figure 3.12. Observed and predicted length compositions for the recreational fishery from the base run of the stock assessment model, 2002–2003. N adj. represents the input effective sample size (number of trips sampled) and N eff. represents the model estimate of effective sample size.

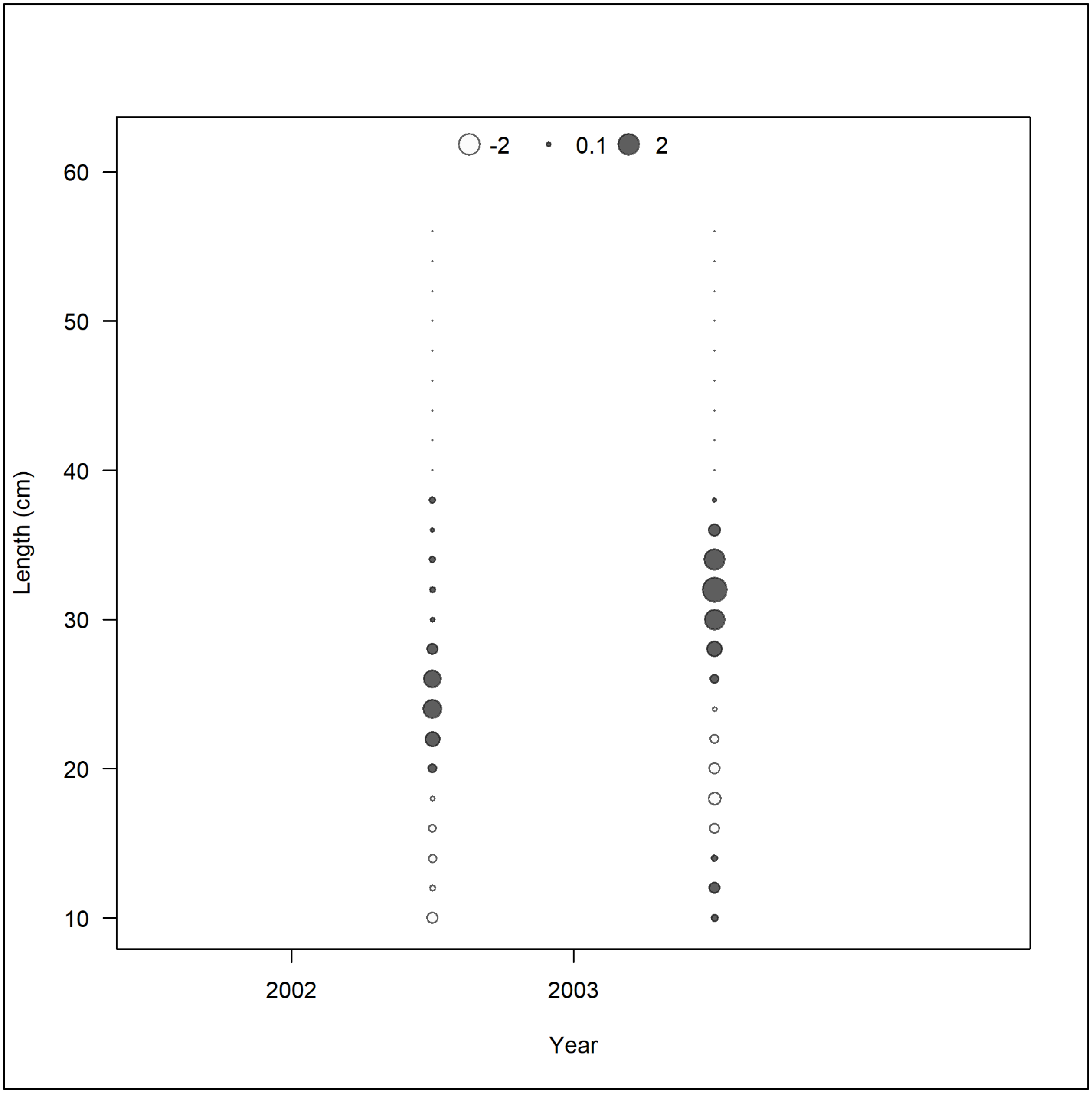


Figure 3.13. Standardized residuals for the recreational fishery length composition data from the base run of the stock assessment model, 2002–2003. Gray circles represent positive residuals (observed > expected) while white circles represent negative residuals (observed < expected). The area of the circles is proportional to the size of the residuals.

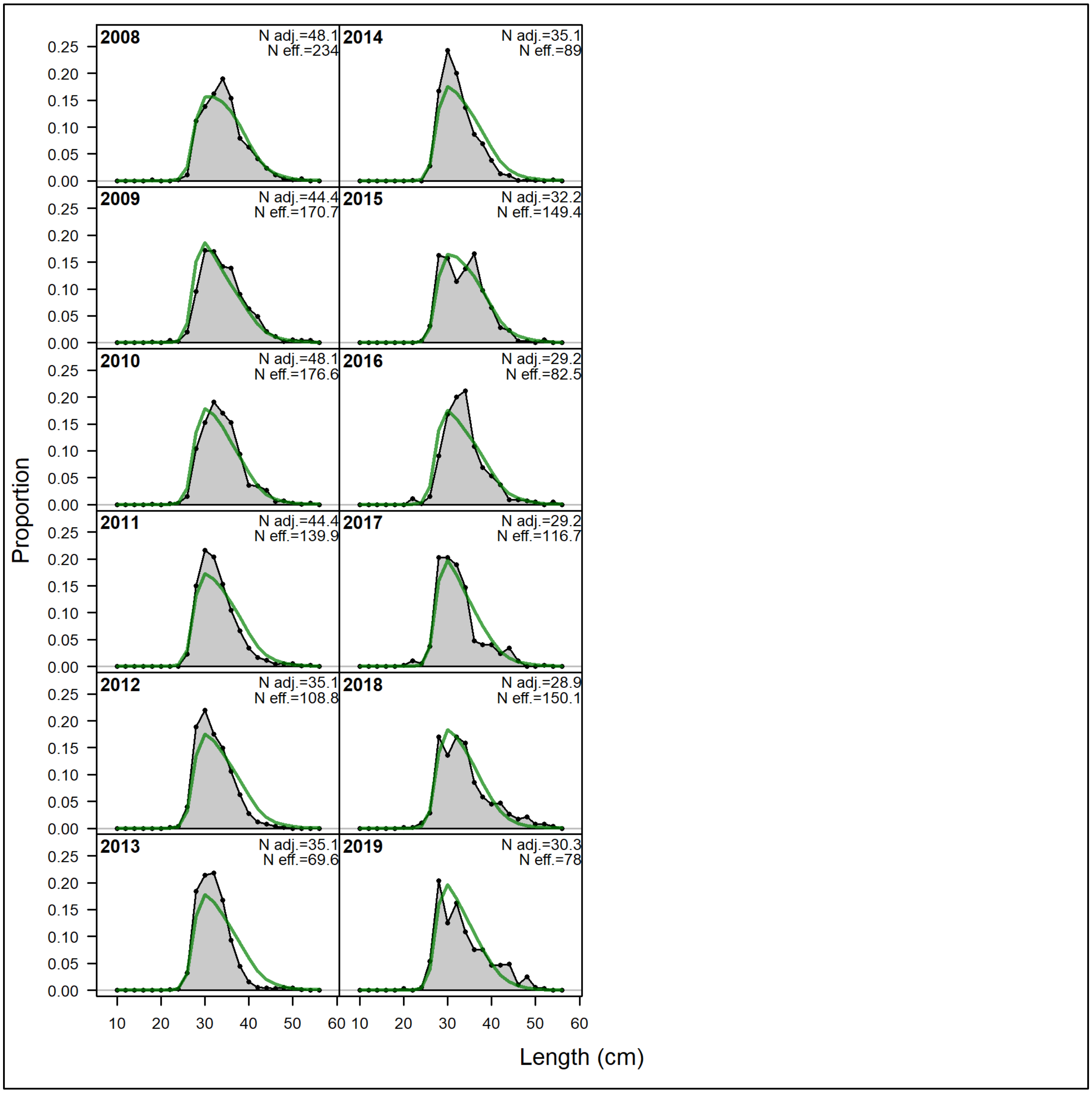


Figure 3.14. Observed and predicted length compositions for the P915 Survey from the base run of the stock assessment model, 2008–2019. N adj. represents the input effective sample size (number of trips sampled) and N eff. represents the model estimate of effective sample size.

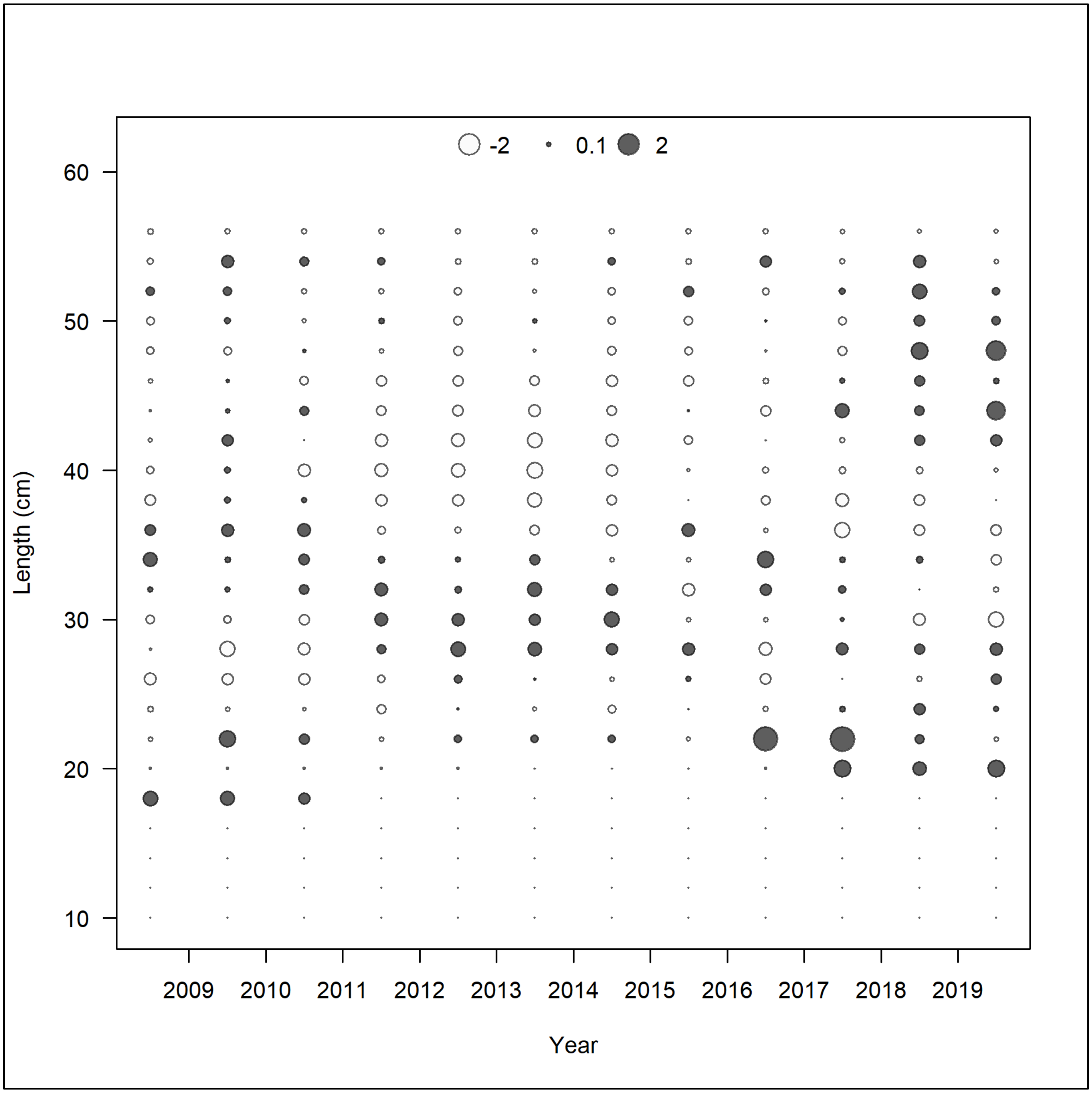


Figure 3.15. Standardized residuals for the P915 Survey length composition data from the base run of the stock assessment model, 2008–2019. Gray circles represent positive residuals (observed > expected) while white circles represent negative residuals (observed < expected). The area of the circles is proportional to the size of the residuals.

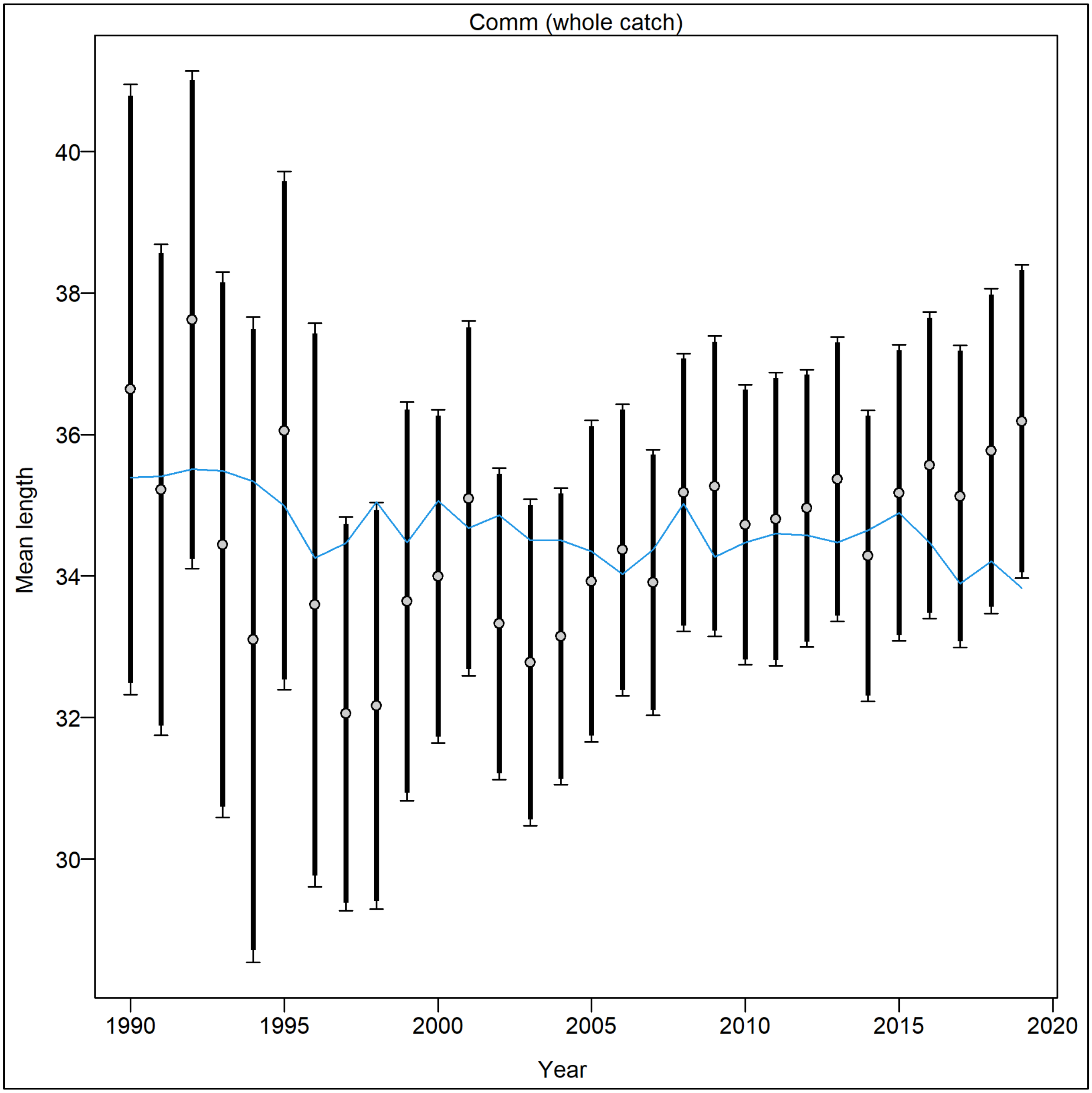


Figure 3.16. Observed mean lengths with 95% confidence intervals (grey dots with error bars) and predicted mean lengths (blue line) for the commercial fishery from the base run of the stock assessment model, 1990–2019.

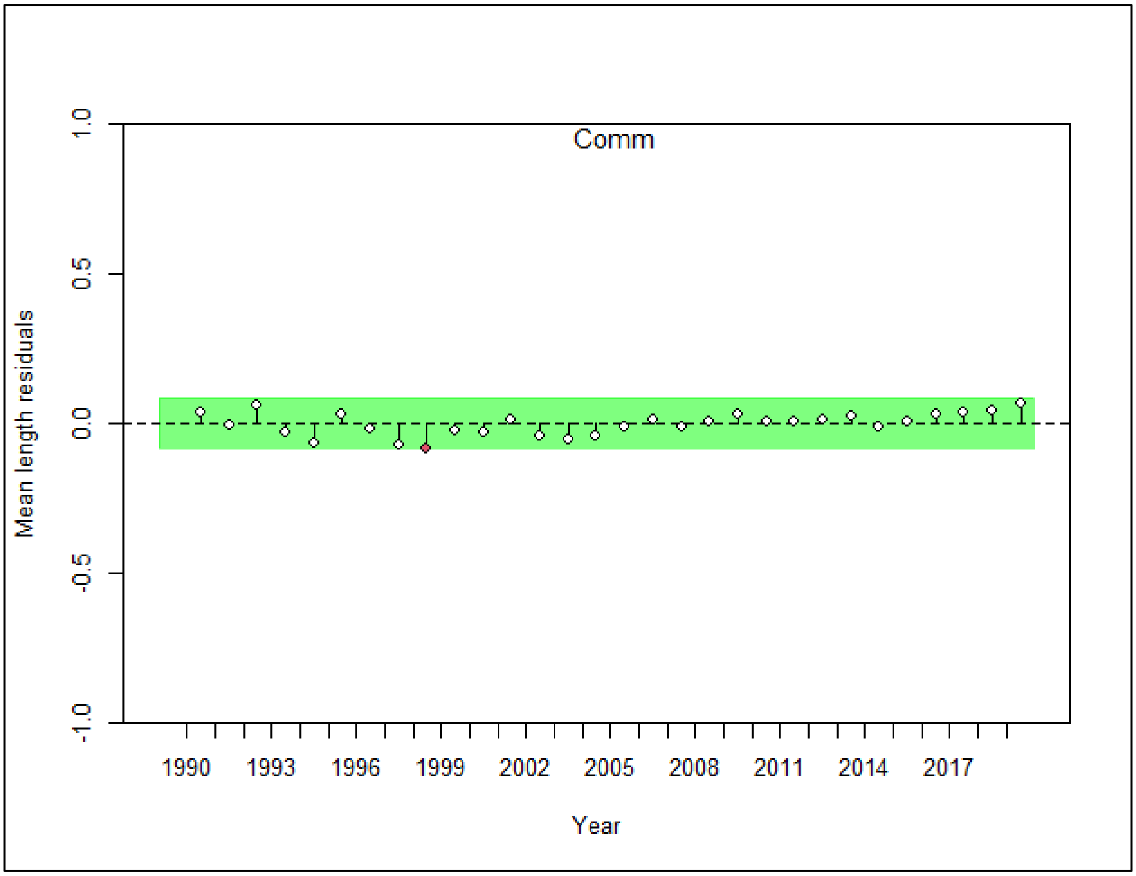


Figure 3.17. Results of the runs test for the commercial fishery mean lengths from the base run of the stock assessment model, 1990–2019. Green shading indicates no evidence (α = 0.05) and red shading evidence ($p < 0.05$) to reject the hypothesis of a randomly distributed time series of residuals, respectively. The shaded (green/red) area spans three residual standard deviations to either side from zero and the red points outside the shading violate the 'three-sigma limit' for that series.

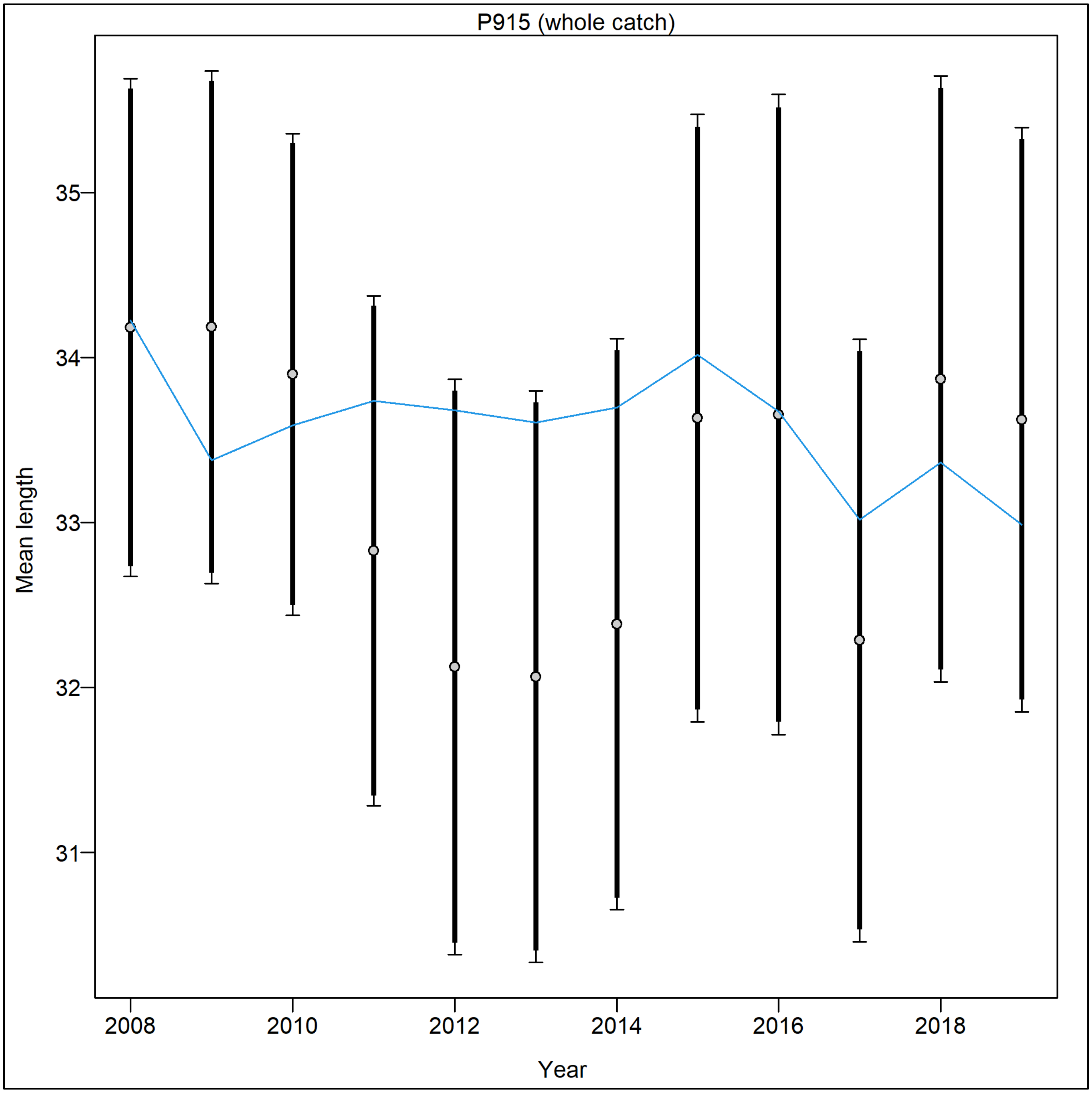


Figure 3.18. Observed mean lengths with 95% confidence intervals (grey dots with error bars) and predicted mean lengths (blue line) for the P915 Survey from the base run of the stock assessment model, 2008–2019.

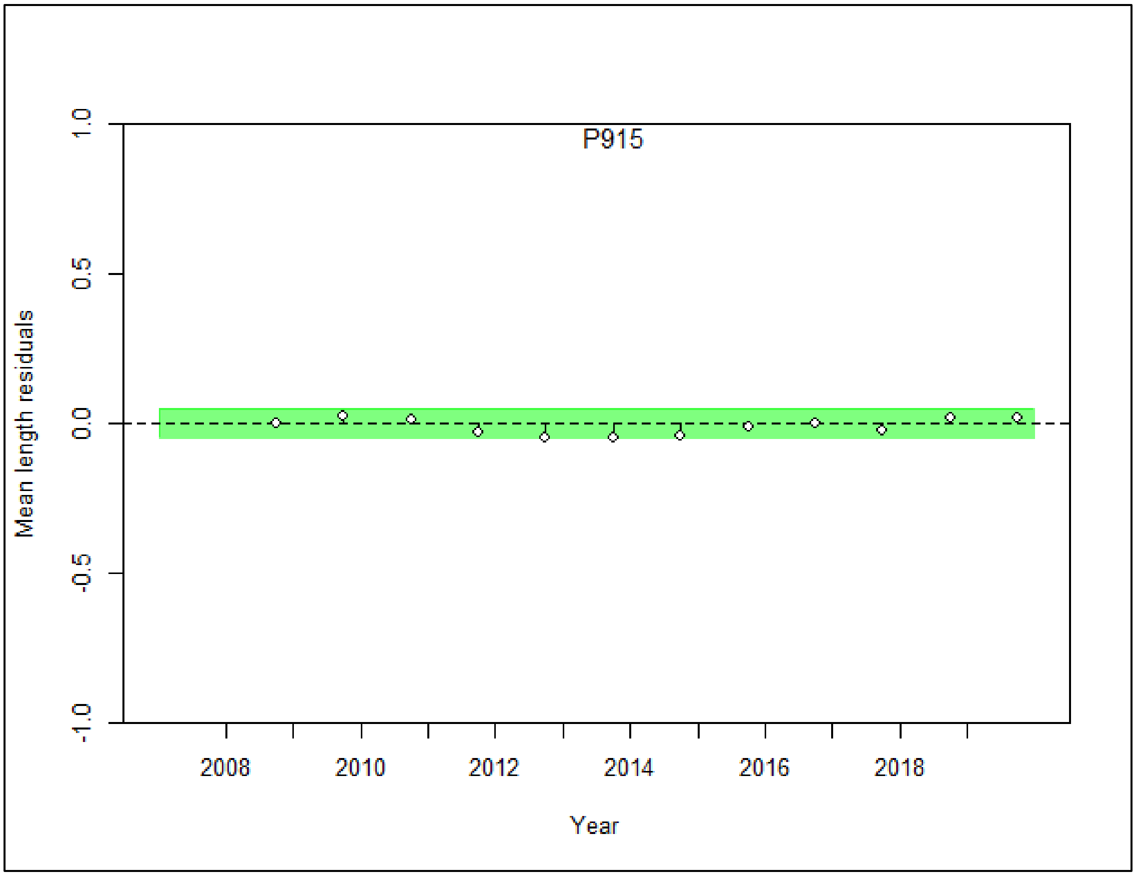


Figure 3.19. Results of the runs test for the P915 Survey mean lengths from the base run of the stock assessment model, 2008–2019. Green shading indicates no evidence (α = 0.05) and red shading evidence ($p < 0.05$) to reject the hypothesis of a randomly distributed time series of residuals, respectively. The shaded (green/red) area spans three residual standard deviations to either side from zero and the red points outside the shading violate the 'three-sigma limit' for that series.

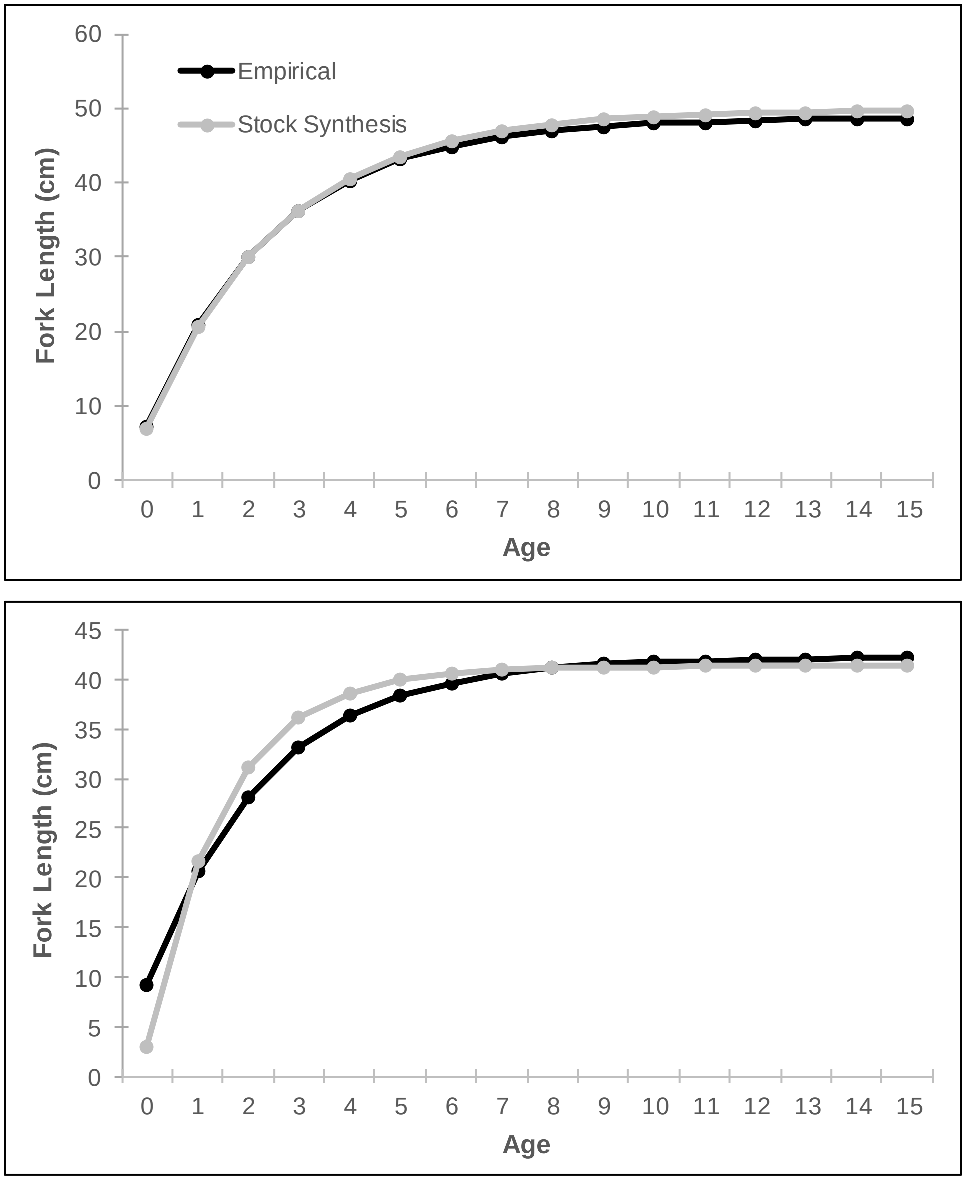


Figure 3.20. Comparison of von Bertalanffy age-length growth curve derived empirically to growth curve predicted by the base run of the Stock Synthesis model for females (top graph) and males (bottom graph).

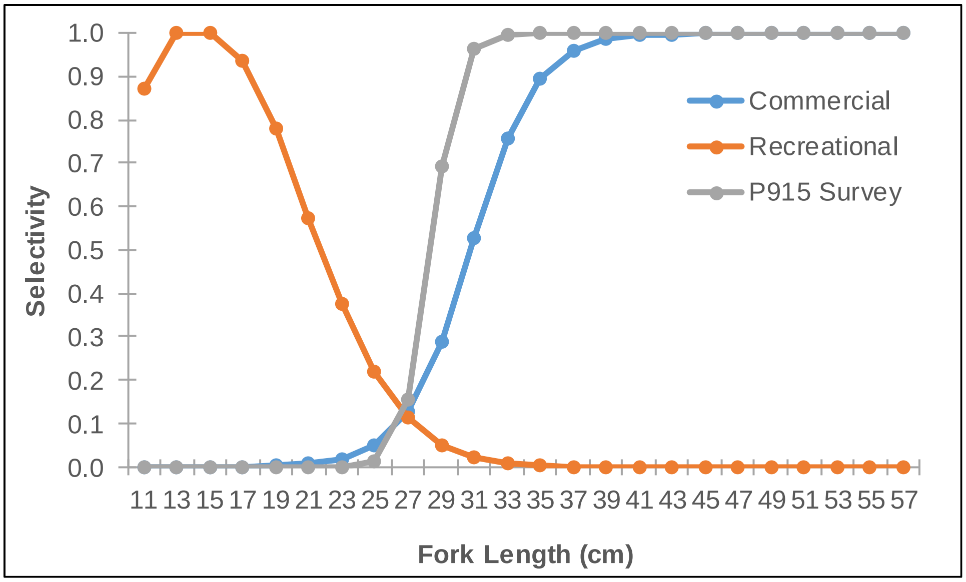


Figure 3.21. Predicted length-based selectivity for the commercial and recreational fleets and the P915 Survey from the base run of the stock assessment model.

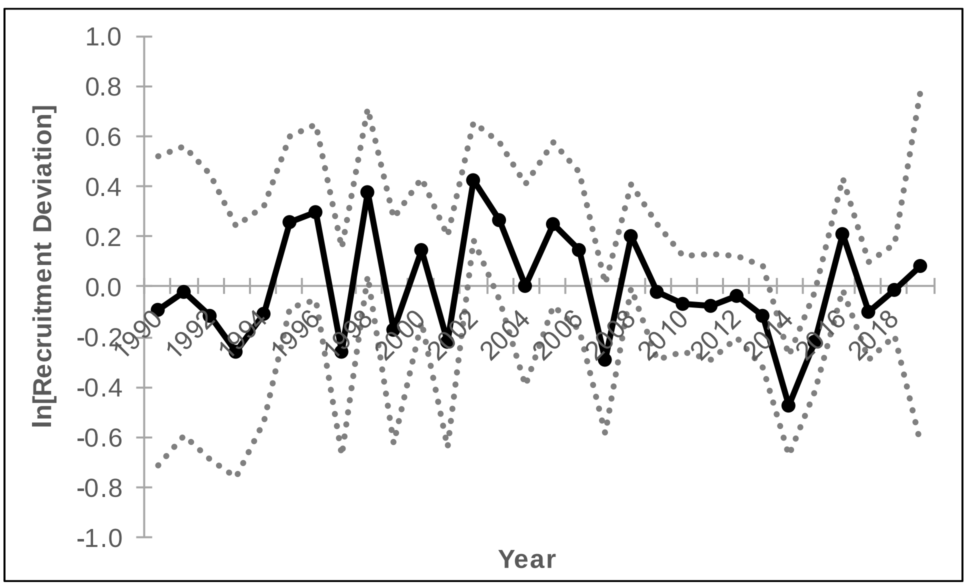


Figure 3.22. Annual recruitment deviations predicted from the base run of the stock assessment model, 1988–2019. Dotted lines represent ± 2 standard deviations.

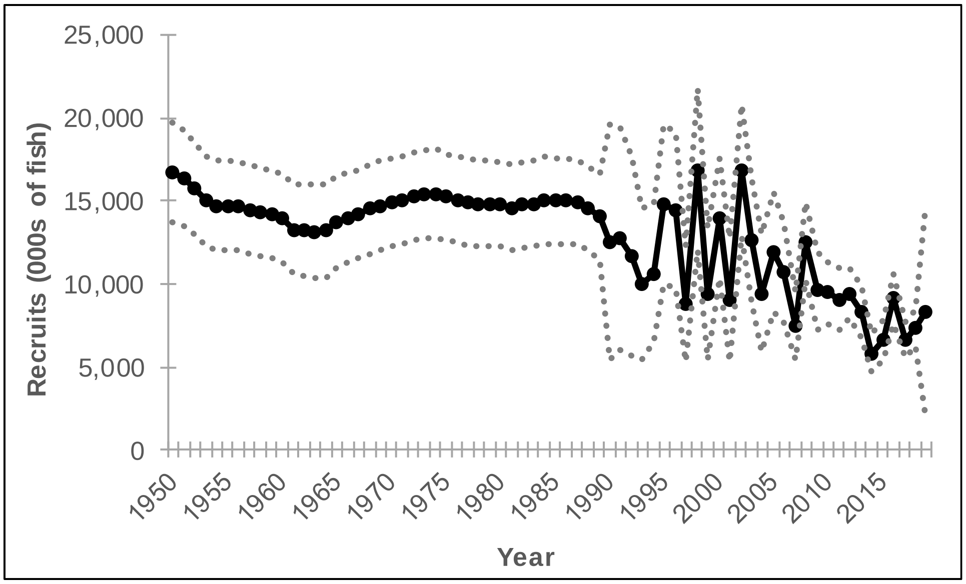


Figure 3.23. Annual predicted recruitment from the base run of the stock assessment model, 1950–2019. Dotted lines represent ± 2 standard deviations.

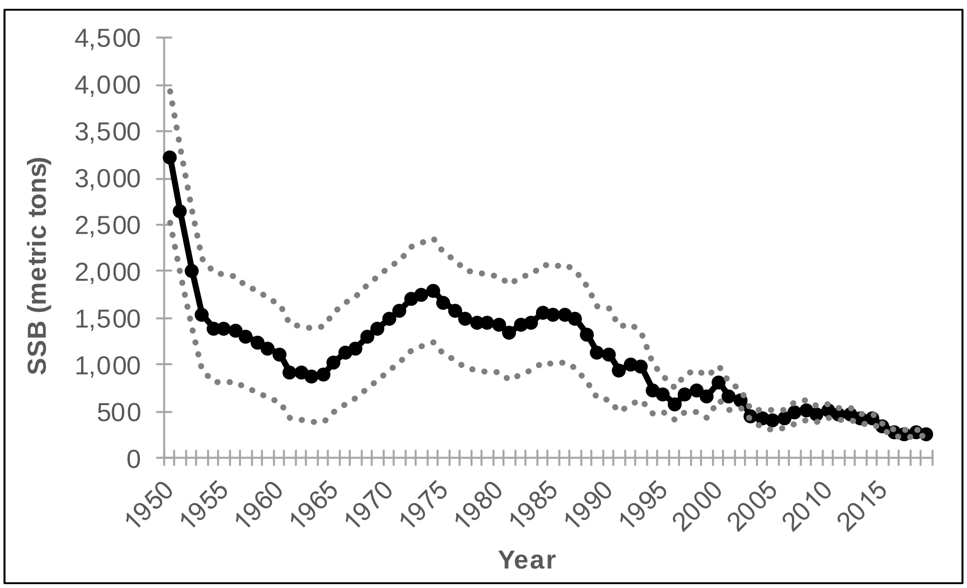


Figure 3.24. Annual predicted female spawning stock biomass from the base run of the stock assessment model, 1950–2019. Dotted lines represent ± 2 standard deviations.

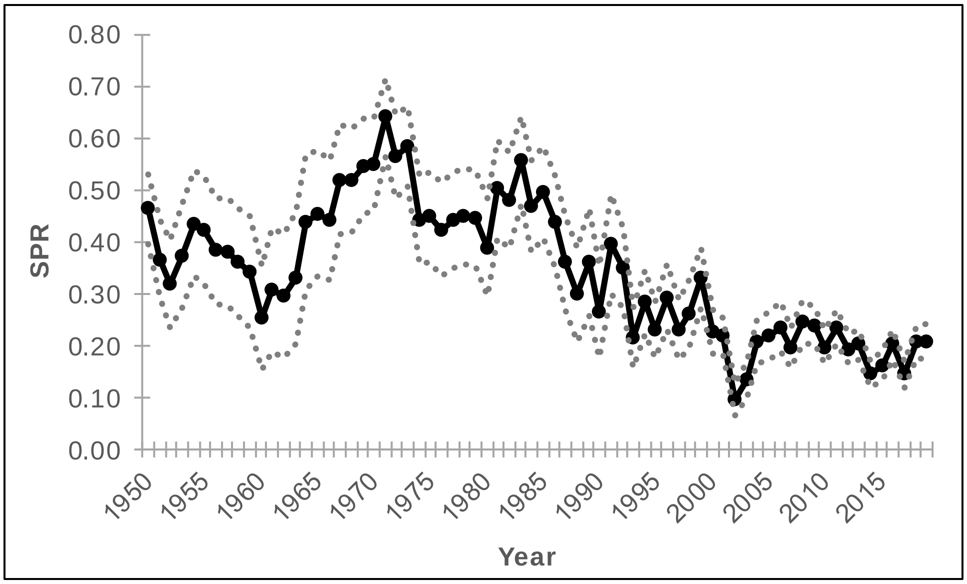


Figure 3.25. Annual predicted spawning potential ratio (SPR) from the base run of the stock assessment model, 1950–2019. Dotted lines represent ± 2 standard deviations.

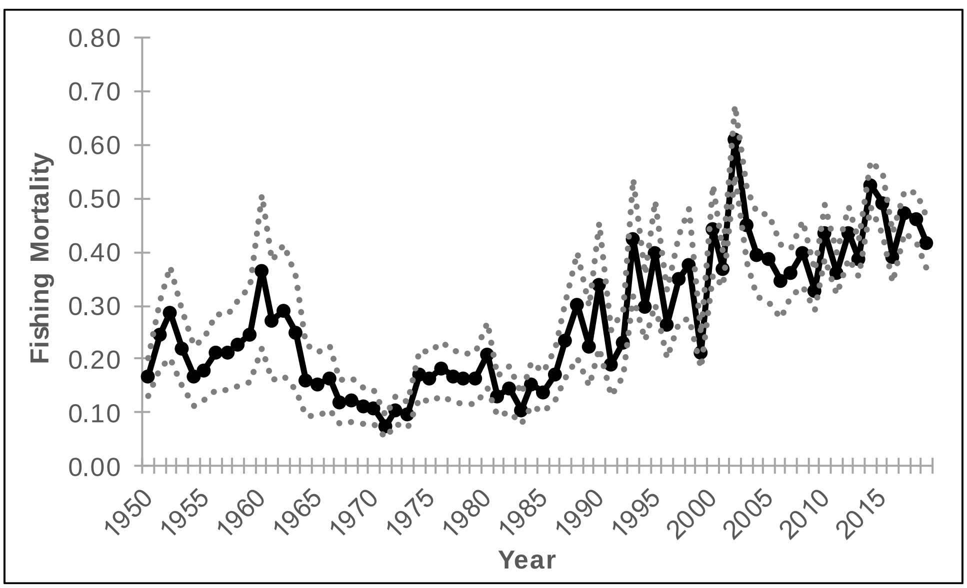


Figure 3.26. Annual estimates of fishing mortality (numbers-weighted, ages 1–5) from the base run of the stock assessment model, 1950–2019. Dotted lines represent ± 2 standard deviations.

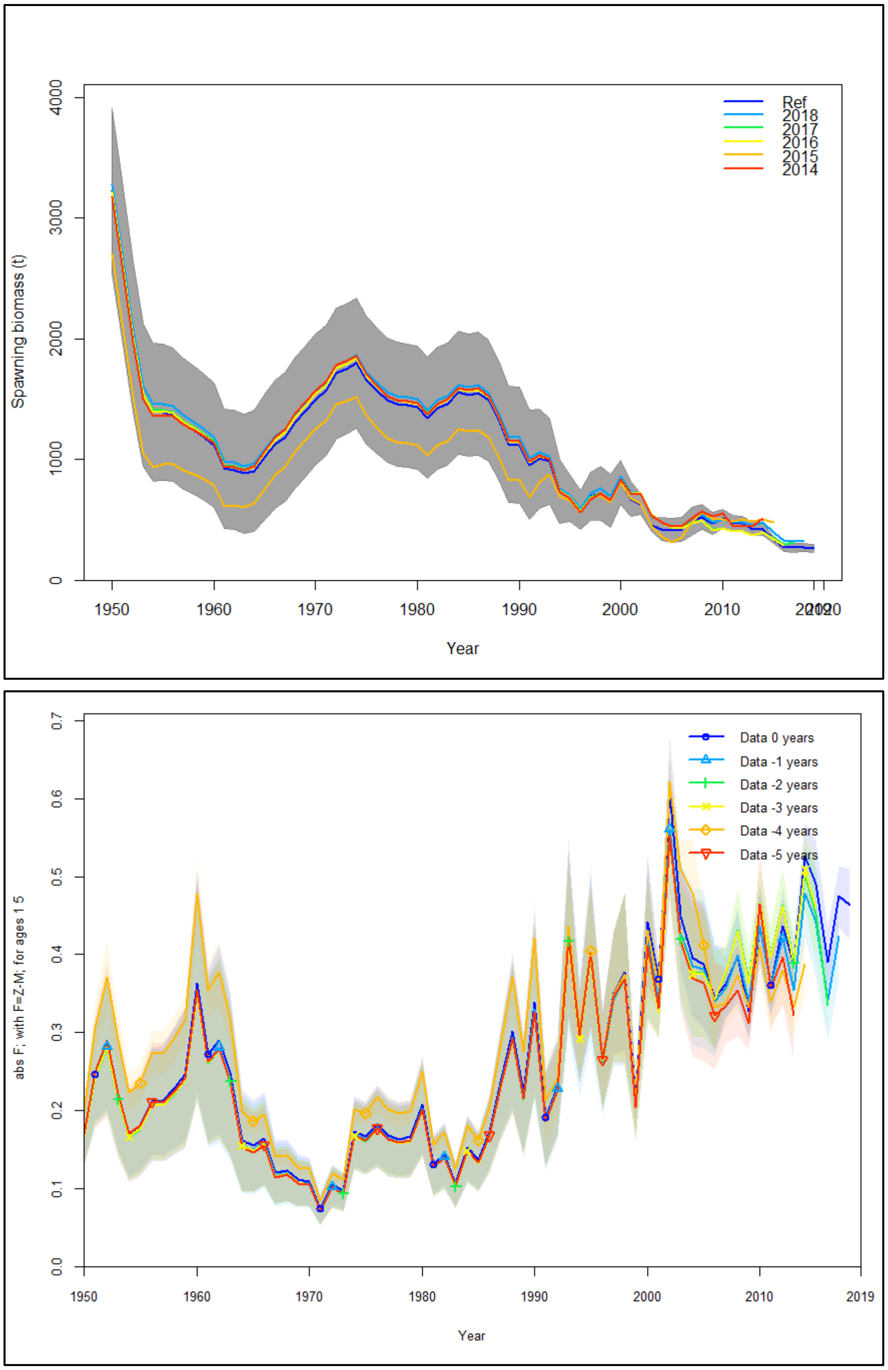
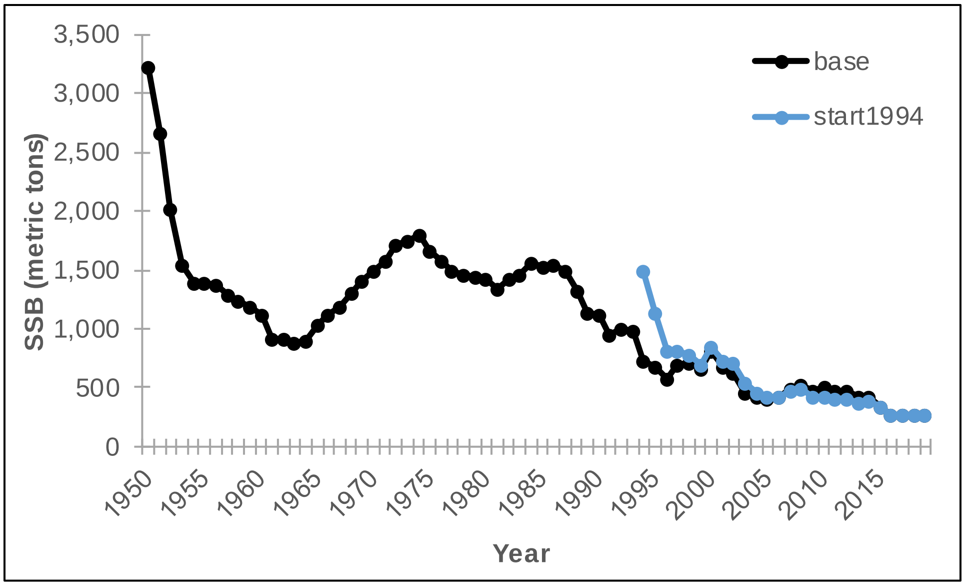


Figure 3.27. Predicted female spawning stock biomass (top graph) and fishing mortality (numbers-weighted, ages 1–5; bottom graph) from a retrospective analysis of the base run of the stock assessment model, 1950–2019.



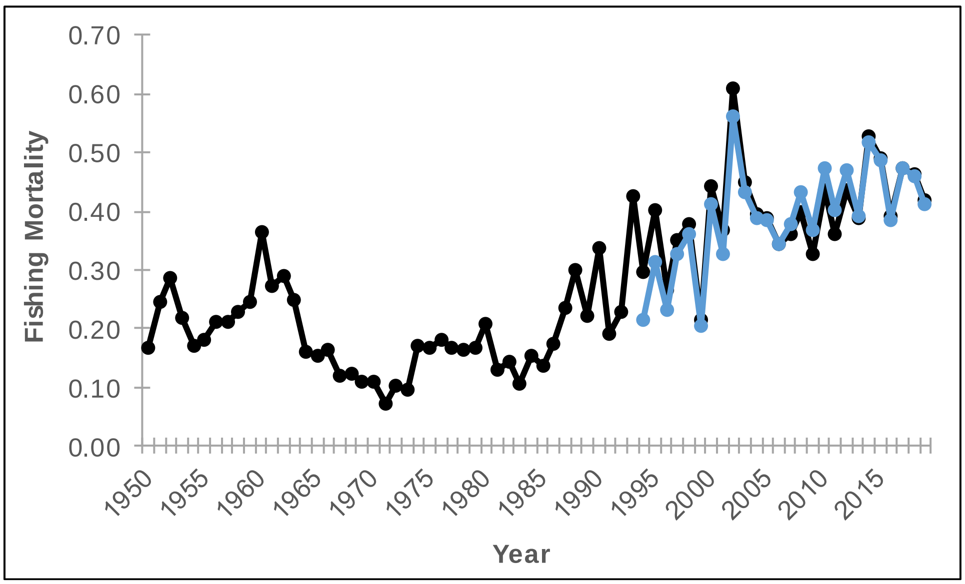


Figure 3.28. Sensitivity of model-predicted female spawning stock biomass (top graph) and fishing mortality (numbers-weighted, ages 1–5; bottom graph) to model start year.

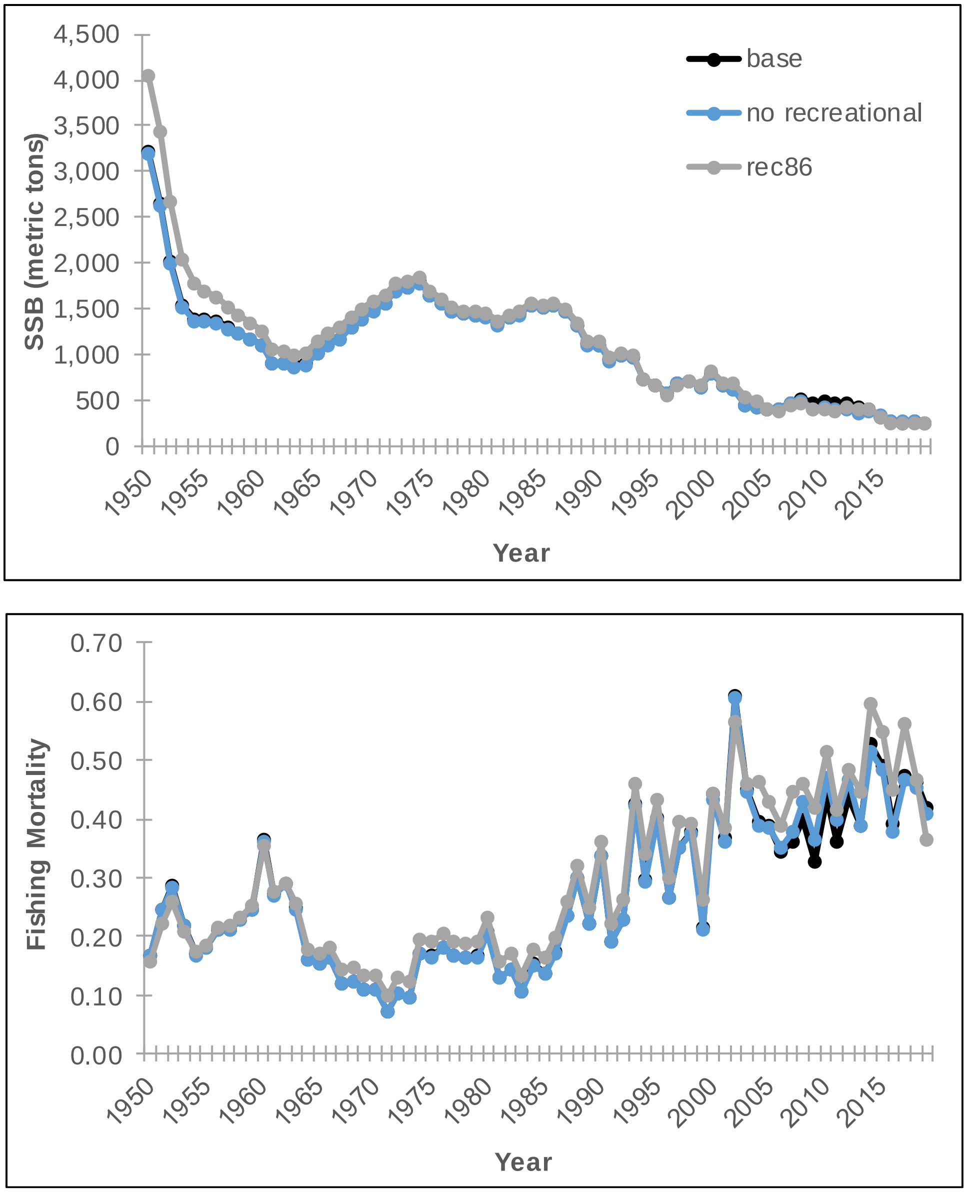


Figure 3.29. Sensitivity of model-predicted female spawning stock biomass (top graph) and fishing mortality (numbers-weighted, ages 1–5; bottom graph) to alternative assumptions regarding recreational removals, 1950–2019.

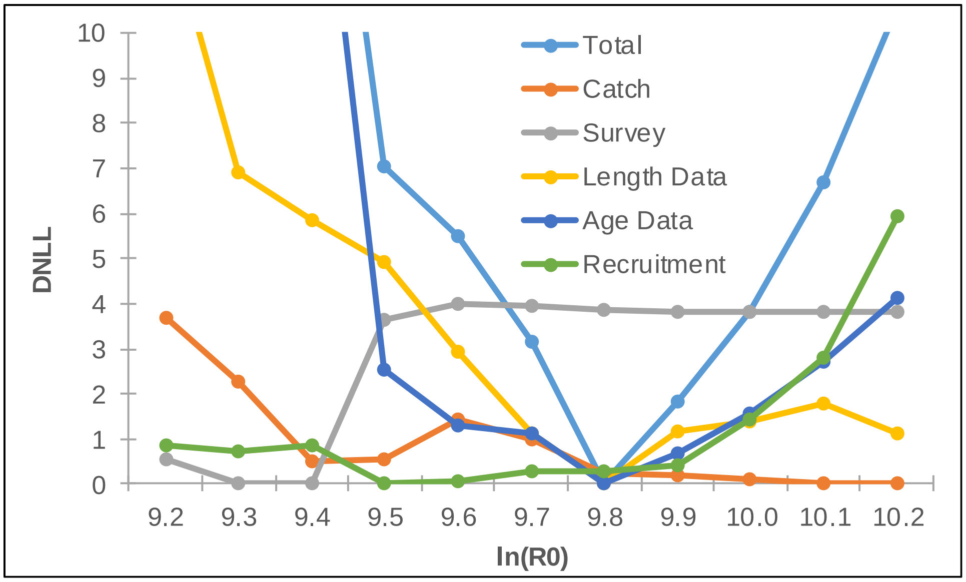
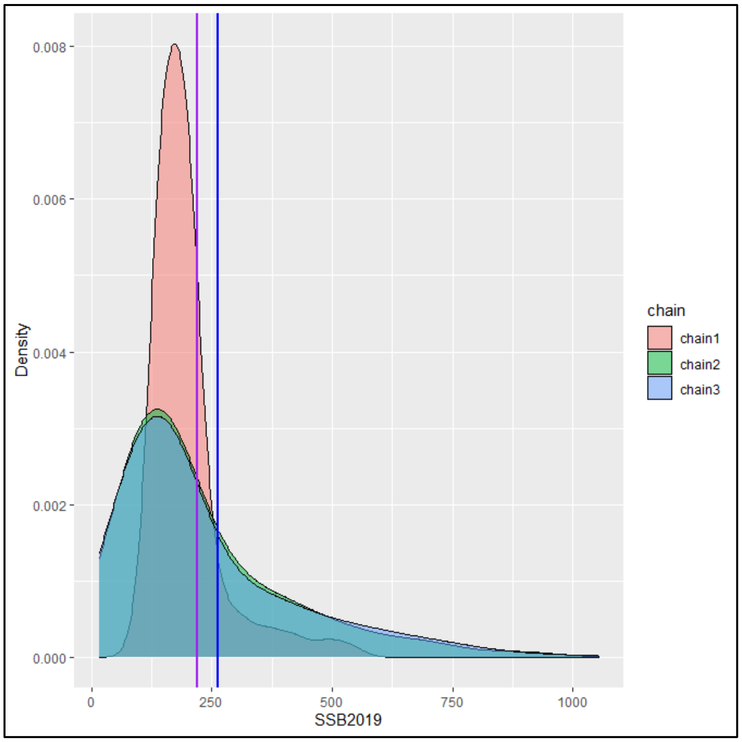


Figure 3.30. Likelihood profile on virgin recruitment, R_0, by data component.



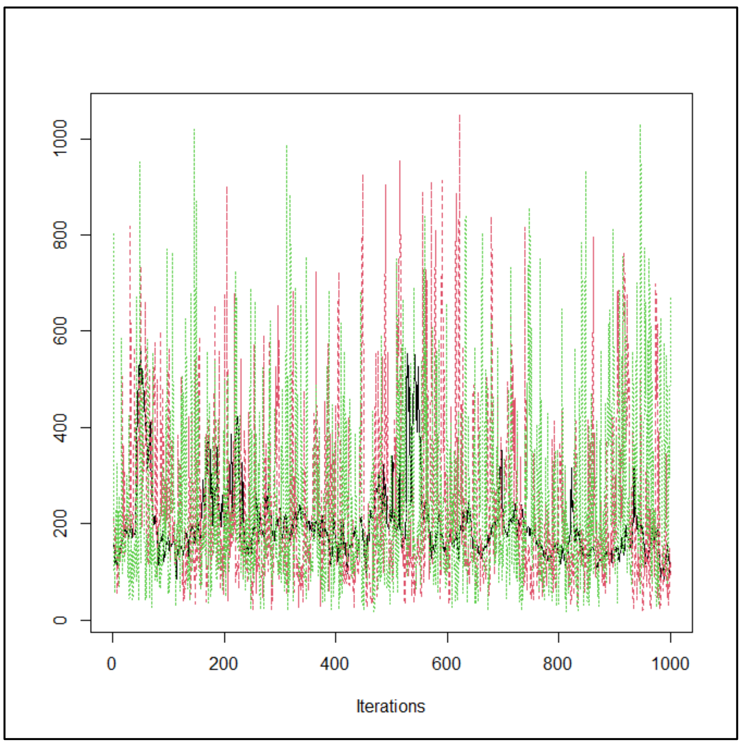


Figure 3.31. Density plot (top graph) and trace plot (bottom graph) for female SSB in 2019 from the MCMC chains. In the top graph, the vertical blue line represents the SS model estimate of female SSB in 2019 (263 mt) while the vertical purple line represents the mean of the posterior distribution for female SSB in 2019 (220 mt).

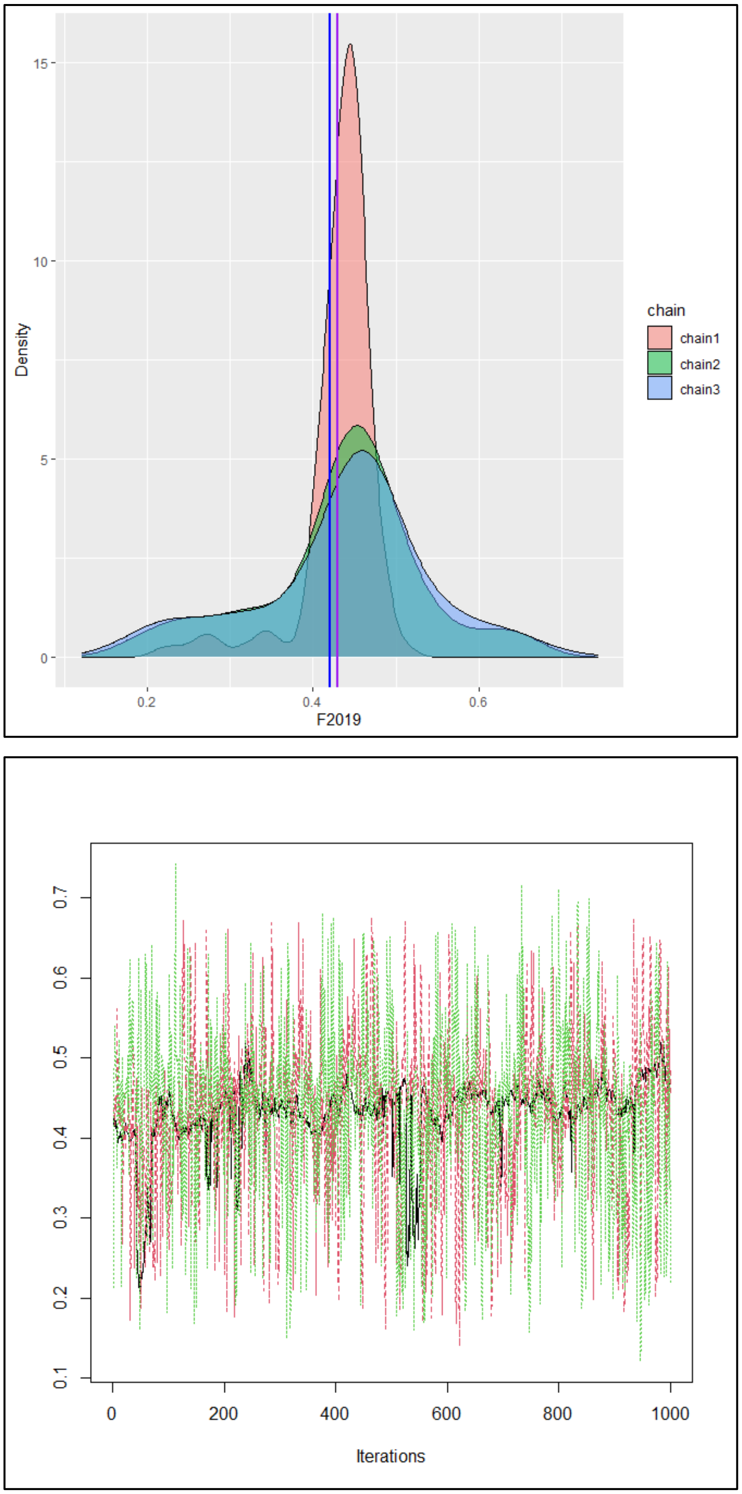


Figure 3.32. Density plot (top graph) and trace plot (bottom graph) for fishing mortality in 2019 from the MCMC chains. In the top graph, the vertical blue line represents the SS model estimate of fishing mortality in 2019 (0.42) while the vertical purple line represents the mean of the posterior distribution for fishing mortality in 2019 (0.43).

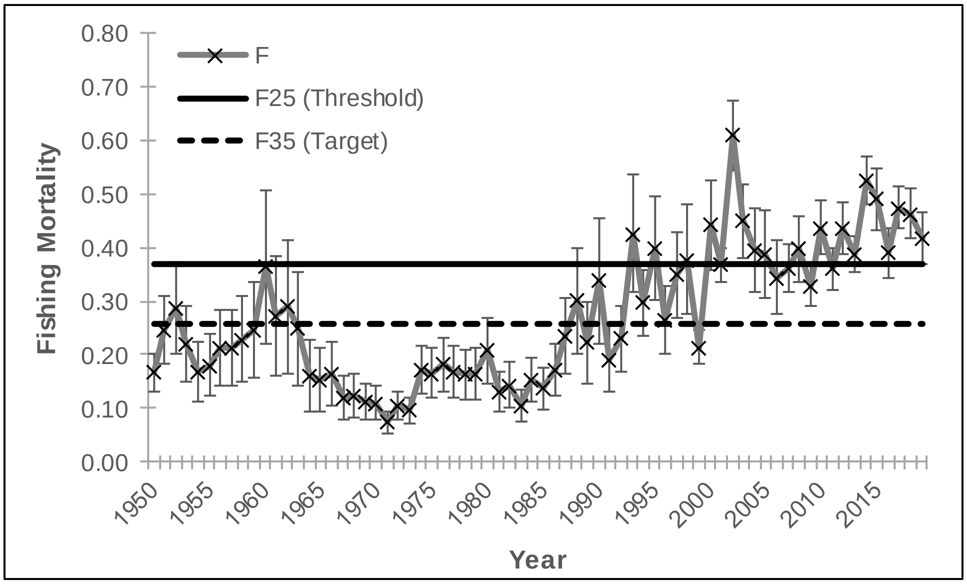


Figure 4.1. Comparison of annual estimates of fishing mortality (numbers weighted, ages 1–5) from the base run to estimates of the fishing mortality target ($F_{35\%}$) and threshold ($F_{25\%}$). Error bars represent ± 2 standard deviations.

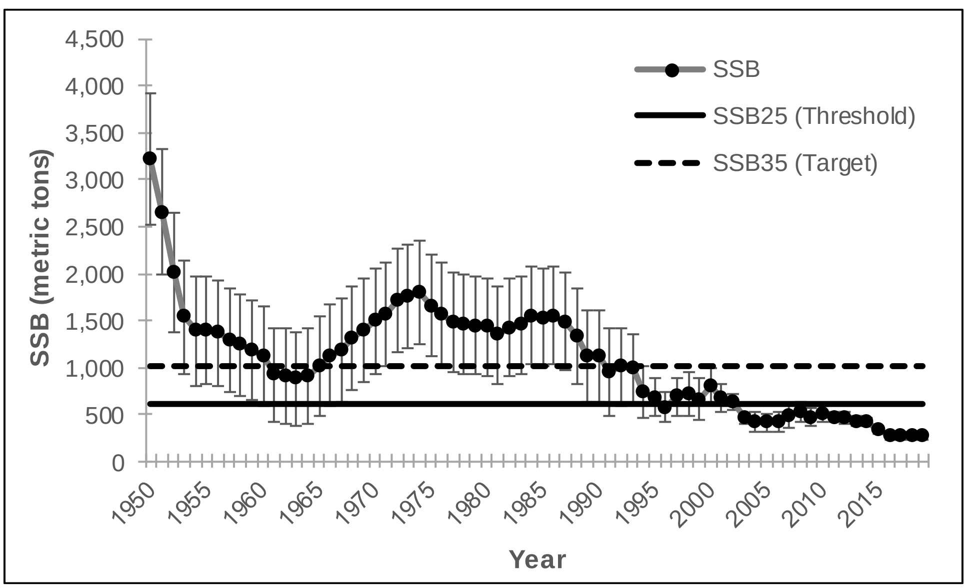


Figure 4.2. Comparison of annual estimates of female spawning stock biomass (SSB) from the base run to estimates of the SSB target ($SSB_{35\%}$) and threshold ($SSB_{25\%}$). Error bars represent ± 2 standard deviations.

External Peer Review Report
for the
2021 Stock Assessment
of
Striped Mullet in North Carolina

External peer review panel

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EXECUTIVE SUMMARY

The external peer review for North Carolina's Striped Mullet stock assessment, held in webinar workshops from November 8-10, 2021 and from February 8-9, 2022, was aimed to evaluate the stock assessment including input data, stock assessment model configuration, model outputs, model uncertainty, and to make recommendations for the improvement of the stock assessment and future research. As peer reviewers, we're charged with evaluating the North Carolina Striped Mullet stock assessment with respect to the Terms of Reference.

The Peer Review Panel (PRP) commends the Striped Mullet Plan Development Team for their concise and comprehensive presentation of the data inputs used in the stock assessment. The assessment report and summary presentations, as well as subsequent data and analysis requests made for the second workshop meeting, were complete and greatly facilitated evaluation of the assessment model.

The assessment team used fishery-dependent and fishery-independent data and an integrated statistical catch-at-age model (Stock Synthesis; v. 3.30) that was configured and parameterized prior to the review. However, the November 2021 review workshop revealed excluded data sources that were asked to be included by the peer review panel (PRP), existing data conflicts, and possible model misspecifications resulting in biased estimates of parameters and quantities derived from them. The assessment team accommodated all data and exploratory requests from the PRP and prepared a revised stock assessment model for the February 2022 workshop, which in turn was further developed in collaboration with the PRP to produce a base model.

The whole process was very open to alternative approaches and suggestions and allowed for constructive dialogue between the PRP and the assessment team, as conducting stock assessments are an iterative process that allows hypotheses to be tested to establish a stable base model by the reduction of data conflicts, model misspecifications, and uncertainty. We would like to commend the North Carolina Division of Marine Fisheries Striped Mullet Plan Development Team's efforts during the review for providing necessary information on the stock assessment model configuration and parameterization, control files, and input data including life history parameters, landings and discards, and indices of abundance.

Overall, based on the materials presented and additional runs conducted during the review, the PRP agrees the North Carolina Striped Mullet assessment provides stable and consistent results considering various uncertainties in data and model. The PRP agrees that this is the best scientific information available and is suitable for management advice.

Amendment 1 to the NCDMF FMP for Striped Mullet adopted a fishing mortality threshold of $F_{25\%SPR}$ and a fishing mortality target of $F_{35\%SPR}$, with corresponding spawning stock biomass reference points ($SSB_{25\%SPR}$, $SSB_{35\%SPR}$). The base model concludes that the North Carolina Striped Mullet is currently undergoing overfishing ($F_{2019} > F_{25\%SPR}$) and is currently overfished ($SSB_{2019} < SSB_{25\%SPR}$) in the terminal year.

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1 TERMS OF REFERENCE

1.1 Evaluate the adequacy of information used to justify definition of the unit stock.

The stock unit for NC was adequately defined with information from tagging studies, fishery dependent data and fishery independent surveys as all striped mullet inhabiting North Carolina coastal and inland waters. However, there are no recognized sub-populations or distinct genetic stocks of striped mullet in the Atlantic basin and the unit stock for NC is considered solely for the purpose of management in state jurisdictional waters. It is appropriate to consider the state management units as distinct due to the limited movement patterns between states observed in both juveniles and adults. The stock unit is adequately defined for management purposes. But given that the species spawns offshore and is continuously distributed along the Atlantic Coast, it is probably not reproductively isolated and not a completely closed population.

1.2 Evaluate the thoroughness of data evaluation and presentation including:

1.2.1 Justification for inclusion or elimination of available data sources

The 2021 NCDMF Striped Mullet assessment included several broad categories of data used to fit the model and characterize population dynamics: catch time series, indices of relative abundance time series, age compositions and length compositions. The review panel found that the data sets included in the final version of the model were all useful and provided valuable information to the model. However, the data sets included in the original version of the model described in the 2021 Striped Mullet Stock Assessment Report (SAR; NCDMF, 2021) were not all recommended for use, and additional data sources were recommended to be added. We will first focus on data sources included in the final model and then will comment on changes made during the review process.

Removals

The assessment included two sources of removals from the North Carolina Striped Mullet stock: commercial and recreational landings. While commercial landings make up the vast majority of the removals, recreational landings are important to account for, and tend to target smaller fish than the commercial fishery. As in many fisheries, data collection for the commercial fishery is more thorough, and catch is estimated more precisely than the recreational fishery. Due to the nature of the data collection process, the recreational landings are fairly uncertain. This is largely due to limited sampling of catches from anglers harvesting Striped Mullet and species identification issues between Striped Mullet and other mullet species. Recreational landings were not included in the original model run described in the 2021 report, due to the uncertainty in the data. However, substantial sources of removals are important to account for in a stock assessment even if they are uncertain because they characterize absolute losses (i.e. deaths) from the population, rather than providing a relative measure of some aspect of the population like other data sources (i.e. indices and compositions). Furthermore, despite the uncertainty of the recreational landings data, it was judged to be the best available.

Indices of abundance

The NCDMF conducts an annual fishery-independent gillnet survey (Program 915) that samples much of the stock area being assessed and uses gear with a selectivity pattern similar to that of the commercial landings. These attributes make it a relatively ideal source of relative abundance data for the stock. In the 2021 SAR, this survey was used to develop two separate indices. A north index included large areas of the Pamlico Sound in Hyde and Dare Counties, as well as the Neuse, Pamlico, and Pungo Rivers. A south index included the lower portion of the New River. Reviewers recommended combining these indices since the fish being encountered by these surveys are likely mixing substantially over the course of the year and their selectivity was already being described by the same function. Essentially, they were already indexing the same portion of the population despite small spatial differences, and it was judged to be preferable to combine them outside of the model than to include them both in the model and have to make some subjective decision about their relative weights in the model.

The SAR model also included indices from two other data sources which we did not recommend for use in this assessment: NCDMF electrofishing survey (Program 146) and the NOAA Beaufort Bridgenet Survey. Both surveys were excluded largely because they are conducted in areas that are very geographically limited. When included in the model both indices tended to conflict with the NCDMF gillnet survey. Indices from the electrofishing survey even conflicted with each other, even though they index the same location in different seasons. The Bridgenet Survey had the advantage of providing a recruitment index, but because the survey operates at only a single point in the dynamic estuarine waters of NC, we judged that it was not likely representative of the entire stock area.

Age and length compositions

The assessment included age composition data associated with the commercial catch and the gillnet survey. Length compositions were available for the commercial catch, recreational catch, and the gillnet survey. The annual sample sizes for the commercial catch and gillnet survey compositions were adequate, but were limited for the recreational fishery. Age and length composition data corresponding to the NCDMF electrofishing survey were included in the original model, but were not needed in the final model, since this survey index was also excluded.

1.2.2 Consideration of survey and data strengths and weaknesses (e.g., temporal and spatial scale, gear selectivities, sample size)

Based on the description in the SAR, the NCDMF gillnet survey seems to be pretty ideal for tracking abundance of this stock. First and foremost, it is a fishery independent index and using consistent sampling methods. It covers a broad spatial distribution over much of the stock area. It is executed with a gear type that is similar to that used by commercial fisheries that gather much of the harvest. The CVs associated with the index were sufficiently precise (<0.2) and quite consistent across years. Selectivity is estimated to be similar between the survey and the commercial fishery. Although it’s preferrable to have longer time series, this index is available for 12 years and exhibits only limited interannual variability between consecutive years while apparently tracking longer term trends.

A lot was made of the decrease in the index between 2014 and 2015, but the absolute change is only slightly larger than the increase in the index between 2009 and 2010. Considering the index standardized to a mean of 1 (I.e. dividing the index by its mean; see table below), a value of 1 in a year indicates the average population size and a value of 2 would suggest that the population was twice as large in that year. In fact, the range 0.43 - 1.73 is not much larger than one. According to the index, the size of the Striped Mullet population between 2008 and 2019 is not very variable but shows a clear decline in recent years.

Year	Program 915 index	Program 915 index standardized
2008	3.6	1.30
2009	2.7	0.97
2010	4.8	1.73
2011	4.1	1.48
2012	3.7	1.33
2013	3.6	1.3
2014	3.6	1.3
2015	1.2	0.43
2016	1.3	0.47
2017	1.5	0.54
2018	1.6	0.58
2019	1.6	0.58

1.2.3 Calculation and standardization of indices and other statistics (Nikolai)

The NCDMF gillnet survey index was standardized with generalized linear model (GLM) approach, that considered 13 environmental or temporal covariates, and ultimately retained six. Presentation of the method is relatively brief but the approach appears to be sound. A more detailed presentation of the methods would be preferable.

1.3 Evaluate the adequacy, appropriateness, and application of data used in the assessment.

The data and modeling framework selected by the analytic team were appropriate given the life history of the species and the history of data collection within the region. Pragmatically for this assessment and management, the decision was made to focus the assessment data collected on the unit stock within North Carolina waters. The approach in applying the data within the assessment is typical; which was to explore this through weighting likelihood components and by inclusion/rejection of individual data components in sensitivity analyses. However, this is not always the best approach by letting the model “decide” the base model. A better approach would be to understand the underlying data processes to allow for informed choices to be made prior to model construction.

The following data sources were applied within the model. Life history and biology parameters included growth, length-weight relationship, maturity and natural mortality. Growth was based on available otolith-based age data that were fit with a von Bertalanffy age-length model to estimate growth parameters by sex. The length-weight relationship used the relation of fork length in centimeters to weight in kilograms was modeled by sex using non-linear least squares. Maturity estimation utilized a logistic regression applied to the maturity samples from female striped mullet to estimate the length at 50% maturity (L_{50}) and slope. Based on the histological data, the value of L_{50} for females was estimated adequately. Natural mortality was estimated using the Lorenzen (1996) approach to produce estimates of *M* at age by sex.

Fishery dependent data utilized in the model include commercial landings and recreational harvest. Commercial landings in weight along with length and age compositions (NCDMF Trip Ticket Program) were considered. The commercial landings started in 1950, with length and age composition data available for 1990-2019. Recreational landings from the Marine Recreational Information Program (MRIP) included annual recreational observed (Type A) and reported (Type B1) harvest estimates for the mullet genus in North Carolina as estimated by the MRIP in units of numbers of fish, 1981-2019. Length composition data was available for 2002-2003. Fishery independent used in the model was the NCDMF Fisheries-Independent Gill-Net Survey (Program 915 survey) index, with length and age composition data available for 2008-2019.

The peer review panel asserted that long-term recreational landings are an important source of removals and should be included in the assessment model. The analytic team obliged and produced a fisheries-dependent reporting working paper. The recommendation from working paper stated for the base run of the stock assessment that the sum of recreational harvest for striped mullet and a proportion of the recreational harvest for mullet genus be used for removals by the recreational fleet. The proportion of mullet genus recreational harvest that was recommended was 29%, a value derived from a study by the NCDMF of cast net recreational harvest for striped mullet. Estimates of recreational harvest for mullet prior to 2002 were considered unreliable and estimates prior to 2002 (back to 1950) were assumed equal to the median of the 2002 to 2019 time series.

The Program 915 gill-net survey was deemed to be an adequate long-term fishery independent index of abundance that reflected a similar selectivity to that of the commercial fishery and had sufficient spatial coverage of North Carolina inshore waters (Pamlico Sound, Neuse River, Pamlico River, Pungo river, New River, Cape Fear River). Data uncertainties and potential biases were acknowledged and reported adequately within the assessment report.

Data limitations in this assessment exist both in terms of data quality and quantity. The assessment team were transparent and candid about problems with the data and with the model fitting process. After discussion, the review panel agreed that sensible and pragmatic decisions were made on how the data should be used in the final version of the assessment. There was a high amount of uncertainty from estimated MRIP recreational landings due to high annual coefficients of variation (CVs). Nonetheless, as a significant source of removals, recreational landings need to be accounted for in the model. Note that this was not the case with other data sources like indices of abundance which usually should not be used if they are very uncertain. The model uses these data sources in fundamentally different ways. There is also evidence of two distinct recreational fisheries in North Carolina, a live bait fishery and a fishery that targets adults for consumption or to be saved for use as cut bait. MRIP landings and length composition data may not adequately represent both of these fisheries, as those fishermen that catch mullet for live bait typically release them before visual inspection by creel clerks. Therefore, MRIP length composition predominately reflect retained adult lengths. Ideally, the assessment model would account for both recreational fisheries as separate fleets with associated length/age composition data and differing selectivities. However, there was a lack of sufficient data collection to support such a configuration.

Landings data (Commerical landings, NCDMF RCGL recreational survey landings) also did not differentiate between striped mullet and white mullet. Recreational angler misidentification between the two species can also be common, and bait mullet are usually released by anglers before visual inspection by creel clerks and therefore not identified to the species level in the MRIP data (Type B catch). Beginning in 2002, MRIP APAIS (Access Point Angler Intercept Survey) began deferring to mullet genus to classify unobserved type B1 and B2 catch. As a result, the magnitude of recreational harvest for mullet genus in units of numbers far exceeds that of both striped mullet and white mullet.

1.4 Evaluate the adequacy, appropriateness, and application of method(s) used to assess the stock.

The base model for the assessment was developed in Stock Synthesis (SS). Stock Synthesis is an age- and size-structured assessment model in the integrated analysis class of models. It's widely used, well documented, and further descriptions of SS options, equations, and algorithms can be found in the SS user's manual (Methot et al. 2019), the NOAA Fisheries Toolbox website (http://nft.nefsc.noaa.gov/), and Methot and Wetzel (2013). SS has 1) a population sub-model that simulates growth, maturity, fecundity, recruitment, movement, and mortality processes, 2) an observation sub-model which predicts values for the input data, 3) a statistical sub-model which characterizes goodness of fit and obtains best-fitting parameters and their associated variance, and 4) a forecast sub-model which projects various user-determined management quantities (Methot et al. 2019). The r4ss software (www.cran.r-project.org/web/packages/r4ss/index.html) was utilized extensively to develop various graphics for model outputs and summaries and was used to perform several diagnostic runs.

The methods were appropriate for the available data. SS is a very flexible model that can run in data poor or data rich situations. The differences in model outcomes are dependent on assumptions in implementing those data.

Specific notes on model configuration included the following. Variability in recruitment (SigmaR) was fixed at a value of 0.38. This value was estimated using the FishLife: Fisheries life-history database (http://github.com/james-thorson/FishLife/) which contains predictions of life history parameters for all marine fish and was estimated using a multivariate random-walk process. Recreational fleet selectivity (double normal pattern) was appropriately fixed in order for the model to fit the associated length composition data. Fixing selectivity can be helpful in cases where the fishery data were limited temporally, which was the case in this assessment with only two years of length composition data. However, fixing selectivity can also affect model fits and potentially compromise estimates of stock parameters (e.g. growth, natural mortality, and recruitment). All likelihood components, with the exception of the age data were assigned a lambda weight equal to 1.0 in the base run. The lambda for the age data was reduced to 0.25. This was a personal recommendation from Rick Methot (NOAA Fisheries), the model developer of Stock Synthesis. Despite being down-weighted, the fit to the age compositions was adequate. Francis reweighting was incorporated to improve model fits to the composition data by adjusting effective sample sizes of length and conditional age-at-length data so that variability of model inputs was consistent with the model fits to mean length or mean age (Francis 2011).

Model diagnostics used to assess model convergence, stability, and uncertainty in results:

- Hessian matrix inversion
- Model convergence level using the default criterion of 0.0001
- Presence of estimated parameters at a bound
- Examination of the correlation matrix identifying highly correlated parameter pairs
- Parameters examined for excessively high variance
- Jitter analysis (10% for a series of 100 trails)
- Evaluation of fits to commercial landings, survey indices, length compositions
- Evaluation of estimated growth vs empirical growth comparisons.
- Evaluation of residual fits to various data components
- Retrospective analysis (5-year peel)
- Jack-knife analysis
- Likelihood profile of R0
- Age Structured Production Model
- MCMC Analysis (3 chains, 7,500,000 iterations total, 1,000 posterior samples)
- Sensitivity runs of the base model included a start year of 1994 which corresponded to the data rich period (Base model start year is 1950) and characterizing 86% of recreational landings of mullet species to Striped Mullet (Base model characterizes 29% to Striped Mullet).

The base model was determined to be properly configured, and consistent with standard practices. Model diagnostics demonstrated that the base model converged successfully, reached a global solution, gave stable and consistent results, displayed minimal data conflicts, and showed little indication of model misspecification. Sensitivity runs showed that a differing start year and an alternative proportion of recreational landings of mullet species to Striped Mullet had very little effect on model outputs and stock status. After consideration of all sensitivity analyses, the PRP concluded that none of the cases considered made sufficient difference to the conclusions drawn from the analyses to warrant changing from the base case.

1.5 Evaluate the adequacy and appropriateness of recommended stock status determination criteria given available information regarding the ecological role of striped mullet. Evaluate the methods used to estimate values for stock status determination criteria.

Stock status was determined by comparing the estimated spawning stock biomass (SSB) in the terminal year of the assessment with the threshold value ($SSB_{threshold}$). The stock would be considered overfished if $SSB < SSB_{threshold}$. Similarly, fishery status was determined by comparing the estimated fishing mortality (F) in the terminal year of the assessment with the threshold value ($F_{threshold}$). The stock would be considered to be undergoing overfishing if $F > F_{threshold}$. Threshold values are commonly based on equilibrium values of F and SSB associated with the maximum sustainable yield (MSY). Alternatively, threshold reference points can be determined by estimating the F value that would maintain a proportion of the unfished spawning potential (e.g. $SSB_{F=0}$). The ratio of fished to unfished spawning potential is known as spawning potential ratio (SPR) can be used. For example, a value of $F_{40\%}$ represents the level of F that would maintain 40% of the spawning potential that would be present in the absence of fishing. It is commonly recommended that such reference points be set by determining the F that maintains at least 30-40% of the unfished spawning potential. In the current stock assessment, the threshold values are based on an F that is expected to maintain only 25% of the unfished spawner biomass. This criterion is based on Amendment 1 of the NCDMF FMP for striped mullet. While the general approach is appropriate, it should be noted that the use of F that maintains only 25% of the spawner biomass is relatively risky.

1.6 Do the results of the stock assessment provide a valid basis for management for at least the next five years given the available data and current knowledge of the species stock dynamics and fisheries? Please comment on response.

The base model of the striped mullet stock assessment identified as of March 2022 (results contained in STM_SSOutputData_2022_v3.xlsx file sent by Laura Lee to reviewers) should be considered the best scientific information available for management of this stock. The Stock Synthesis modelling software is used extensively throughout the United States and internationally, and has been widely tested. The fixed life history parameters provided to the model were based on high quality data from the NC stock and used sound approaches. The index of abundance and corresponding composition data are based on a fishery independent survey conducted by the NCDMF over much of the stock area using a gear that is very effective at catching Striped Mullet in the size range corresponding to much of the catch. Catch information for the commercial fleet, which harvests most of the removals, is high quality. Catch information for the recreational fleet is considered to be much less precise, but it appears that that fleet makes up a small proportion of the overall removals, and it is a merit of the current assessment that it is accounted for. The model fit the data fairly well, and once the range around parameters being estimated in the model was decreased to a reasonable range, the model proved to be quite stable. Other diagnostics such as jitter analysis, profile plots, sensitivity, and retrospective analysis also support the use of the model. The final model is fairly easy to interpret. The decline in the Program 915 index and age truncation indicated in the composition data show signs of a shrinking population. Recruitment is declining as the population declines, as expected from the stock-recruit relationship, but the good news is the recruitment residuals show no additional signs of recruitment problems (e.g. no decline in recruitment deviations). Though we were not presented with projection analyses, it seems likely that projections that apply an appropriate decrease in F will show that the population should rebound in a modest time frame. This situation can be monitored by observing trends in the Program 915 index and looking for expansion of age compositions between assessments.

It is worth noting that the results from this assessment are very different from the previous (2018) assessment, which found no overfishing and was unable to adequately quantify SSB. But we have reason to believe there may have been issues with the configuration of that model, and therefore the differences between the assessments may be partly due to problems with the 2018 assessment model. Although we did not review that assessment, we were given the impression that the configuration of the 2018 model was similar to the configuration of the version of the stock assessment model originally supplied to the current assessment, detailed in the November

2021 report. The main problem with the November 2021 model was that it contained several additional indices and sets of composition data that conflicted with each other and were not providing helpful information to the model. And by including these data sources, the model was required to estimate several more parameters (e.g. selectivity parameters) with poor information, leading to greater model instability. In addition, that model did not include any source of recreational landings data. If the 2018 model configuration was similar to that model, it may not have provided a reliable impression of the population dynamics of the Striped Mullet population. We consider the current model to be a substantial improvement from the November 2021 model, and likely the 2018 model and represents the best scientific information available.

1.7 Evaluate appropriateness of research recommendations. Suggest additional recommendations warranted, clearly denoting research and monitoring needs that may appreciably improve the reliability of future assessments.

The PRP thoroughly reviewed the research recommendations identified by the striped mullet working group, in addition to noting additional research and data collection needs. After review between the PRP and the assessment chair, the research recommendations were refined and prioritized into a final set of research recommendations, that were adapted from the stock assessment report and provided here as high, medium or low priorities. The order and priority of research recommendations address the needs and short-comings of current monitoring efforts as well as data that would make future assessments better.

The following research recommendations are offered to improve future stock assessments of the North Carolina striped mullet stock:

High

- Increasesampling of recreational mullet catches to determine the proportion of striped versus white mullet and improve estimates of recreational landings
- Improve characterization of the length and age structure of recreational fisheries removals by increasing the number of age samples and number of trips sampled for lengths and ages from fisheries-dependent sources
- Develop a reliable fisheries-independent abundance index for larger juveniles, to characterize trends in recruitment
- Consider expanding Program 915 to include the northern part of the state (Albemarle Sound and major tributaries).
-
- Evaluate the current sampling methodology of Program 146 and effectiveness for sampling striped mullet. Since this survey was not considered useful for the assessment of striped mullet, consider dropping this survey, and focusing effort elsewhere if it is not contributing to management of other species.
- Consider running a simpler, single-sex version of the stock assessment model.

Medium

- Consider a tagging program to provide estimates of stock size, *F*, and *M*
- Consider genetic and/or tagging studies to examine the extent of unit stock on a regional basis for the south Atlantic as well as the Gulf of Mexico.
- Expand ichthyoplankton survey to other inlets throughout the state

- Conduct an age validation study of known age fish to provide estimates of ageing error
- Consider alternative weighting of data sources in future stock assessments
- Develop estimates of fecundity for NC striped mullet

Low

- Perform an acoustic tagging study to evaluate spatial and temporal variation in habitat use to more effectively design and conduct fishery-independent surveys
- Investigate the predation impact on striped mullet; striped mullet is widely believed to be an important forage species but there is little evidence to support this claim in the North Carolina stock
- Investigate environmental factors that influence the spatial and temporal distribution of larval striped mullet

1.8 Recommend timing of next stock assessment for the species.

Next assessment should be able to stay on the current schedule used for the species (every ~ 5 years)

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