Central Southern Management Area Striped Bass Stocks in North Carolina, 2020

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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.

This report represents a joint effort between the North Carolina Division of Marine Fisheries (NCDMF) and the North Carolina Wildlife Resources Commission (NCWRC). A working group of modelers, university researchers, and fishery biologists were brought together to review available data and to develop analyses that would address current management and research interests of Central Southern Management Area (CSMA) striped bass. The CSMA includes three major river systems: the Cape Fear, the Neuse, and the Tar-Pamlico. No stock status determination was performed for CSMA striped bass in this report and biological reference points were not generated due to continuous stocking effort and lack of understanding on the abiotic factors that are hindering the successful natural recruitment given the large number of fish stocked every year. This report is intended to be a collection of (1) all data that have been collected, (2) all management effort, and (3) all major analyses that have been completed for CSMA stocks. This report serves as a record of completed research efforts with implications for fishery management, and as a guide for future research effort based on results and identified data gaps.

A demographic matrix model was developed for striped bass in the three river systems in the CSMA. The matrix model was parameterized by synthesizing existing knowledge and data regarding striped bass, particularly the striped bass in the CSMA, from a literature review, data review and expert opinions. The population growth rate and the relative importance of life history parameters of each age group was estimated and evaluated. The demographic matrix model does not provide population abundance or mortality estimates. Possible stocking and fishery management strategies were evaluated using this matrix model. A tagging model was developed for striped bass in the Cape Fear River using tagging data collected by the NCDMF from 2012 to 2018. The total mortality and annual abundance for age 3–7 striped bass in the Cape Fear River were estimated by the tagging model.

Results from the matrix model indicated that striped bass populations in the CSMA are depressed to an extent that sustainability is unlikely at any level of fishing mortality, especially the assumptions associated with longevity (7 years for Cape Fear River and 11 years for Neuse and Tar-Pamlico Rivers) and age-0 survival (0.000017). Population growth rate was more dependent on survival and fertility of young fish than old fish. Reproductive contribution was most influenced by older age-classes due to higher fertility. Fishing activities typically select larger fish; thus, increases in fishing mortality disproportionally impact the abundance of older fish, constrict the age structure of the population, and limit reproductive contribution. Simulation on stocking and fishing strategies showed that population would likely benefit more from stocking more fish. Among the fishing strategies tested, the 10-year closure was most effective in increasing adult (age 3+) abundance over the entire 15-year simulation time period, and was also most effective in increasing old adult (age 6+) abundance during the first 13 years of simulation. Abundance of older fish (age 6+); however, quickly declined after the 10-year closure ended, and the 10-year closure strategy became less effective than the combo strategy in no stocking scenario, and less effective than both the 26-inch size limit strategy and the combo strategy in stocking scenarios during the last two years of simulation.

Results of the tagging model showed a consistent decline in abundance estimates for striped bass in the Cape Fear River from 2012–2018. Abundance in 2018 was reduced to less than 20% of the abundance in 2012, even with a total no possession provision for striped bass in place in the Cape Fear River since 2008.

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1 INTRODUCTION

1.1 The Resource

The common and scientific names for the species are striped bass, *Morone saxatilis* (Walbaum; Robins et al. 1991). In North Carolina, it is also known as striper, rockfish, or rock. Striped bass naturally occur in fresh, brackish, and marine waters from Canada to the Gulf of Mexico. Due to their annual spawning migrations into freshwater, striped bass have been the focus of fisheries from North Carolina to New England for several centuries and have played an integral role in the development of numerous coastal communities. Striped bass regulations in the United States date to pre-Colonial times (circa 1640) when striped bass were prohibited from being used as fertilizer. Striped bass populations south of Cape Hatteras, North Carolina are considered to have a primarily endemic riverine life history, having limited or no adult oceanic migration (Setzler et al. 1980; Rulifson et al. 1982a; Callihan 2012).

Various levels of stocking have occurred in the Central Southern Management Area (CSMA; Tar-Pamlico, Neuse and Cape Fear rivers) since the 1940s (Bayless and Smith 1962; Woodroffe 2011), with the North Carolina Division of Marine Fisheries (NCDMF's) formal involvement beginning in 1980 as a result of a cooperative agreement with the United States Fish and Wildlife Service (Table1.1; NCDMF and NCWRC 2013). The North Carolina Wildlife Resources Commission (NCWRC) was added to the cooperative agreement in 1986 (NCDMF 2013) but has been involved in the CSMA striped bass stocking program since fry stocking began in Neuse River tributaries in 1949 (Bayless and Smith 1965). The practice of cross-stocking (stocking of striped bass from one drainage system to another, e.g., Roanoke River striped bass offspring being stocked throughout the southeastern United States) has introduced non-endemic genetic strains to many striped bass populations. The effects of this long-standing practice remain largely undocumented and unquantified (Rulifson and Laney 1999; Bergey et al. 2003).

A management strategy adopted in the North Carolina Estuarine Striped Bass Fisheries Management Plan (FMP) Amendment 1 continued the annual stocking program in the CSMA rivers. Specific objectives for stocking striped bass included attempts to increase spawning stock abundance while promoting self-sustaining population levels appropriate for various habitats (see Amendment 1, Section 11.2 Striped Bass Stocking in Coastal Rivers, NCDMF 2013). The management strategy from Amendment 1 increased the annual numbers stocked to a goal of 100,000 hatchery reared striped bass in each of the major river systems (Tar-Pamlico, Neuse, and Cape Fear rivers) to aid in recovery of the stocks. From 2004 to 2009, stocking occurred on a rotating basis where only two out of the three systems were stocked annually. Prior to 2004, stocking was focused on the Tar-Pamlico and Neuse rivers with sporadic stocking in the Cape Fear River (Table 1.1).

Prior to 2010, the otoliths of hatchery-reared striped bass were chemically marked with oxytetracycline to determine the percent contribution of hatchery fish to the wild population. Results from the chemical marking methodology suggested hatchery-reared striped bass contributed little to the spawning populations in the CSMA (0 to 31%; Barwick et al. 2008); however, since the adoption of Amendment 1, researchers have realized the chemical mark was not being retained in 100% of fish (73%; Barwick et al. 2008), which led to underestimation of the percent of hatchery reared fish in the striped bass populations in the CSMA (Barwick et al. 2008; NCDMF 2013).

In 2010, the NCWRC implemented parentage-based tagging (PBT) as a more accurate method to determine percent hatchery contribution of the striped bass spawning populations in the CSMA. This method utilizes genetic marking techniques and has proven to be greater than 99% accurate at determining if an individual fish was hatchery produced or not (Denson et al. 2012). In 2016, the NCDMF started collecting striped bass fin clip samples for PBT analysis from the commercial and recreational fisheries and from areas away from the spawning grounds in the lower portions of the rivers to gain additional spatial coverage of samples. Since 2011, PBT analysis of samples collected on the spawning grounds and in internal coastal fishing waters of the Tar-Pamlico, Neuse, and Cape Fear rivers has revealed hatchery-stocked striped bass can comprise up to 90% of the fish sampled in some years (O'Donnell and Farrae 2017); however, PBT results from fish sampled in 2017 revealed a noticeable decrease in contribution of hatchery-stocked fish (Farrae and Darden 2018). In 2017 and 2018, percentages of hatchery fish were much lower for the 2014 and 2015 year classes in NCDMF samples (63% and 41%, respectively) and NCWRC samples (76% and 77%, respectively).

While attempts have been made to use catch curves to assess the stock status of CSMA striped bass (NCDMF 2004, 2013) no peer-reviewed stock assessment has been conducted. The catch-curve analysis conducted in 2003 determined the stock was experiencing overfishing (NCDMF 2004), although it was not used for management; however, a repeat of that analysis in 2010, concluded stock status could not be determined due to uncertainty in the mortality estimates (NCDMF 2013). Therefore, striped bass in the Tar-Pamlico and Neuse rivers have an unknown stock status. The need for continued conservation management efforts has been supported by persistent low overall abundance, minimal natural recruitment, multiple sources of mortality, the absence of older fish on the spawning grounds, non-optimal environmental conditions on the spawning grounds in the spring, potential impacts from stocked juveniles and hybrid striped bass, and the high percentage of stocked fish in the population in most years.

1.1.1 Stock Definitions

There are two geographic management units (northern and southern) and four striped bass stocks inhabiting the estuarine and inland waters of North Carolina. The CSMA is located in the southern geographic management unit and includes all internal coastal, joint, and contiguous inland waters of North Carolina south of the Albemarle Sound Management Area (ASMA) to the South Carolina state line (Figure 1.1). There are spawning stocks in each of the major river systems within the CSMA (Tar-Pamlico River stock, Neuse River stock, and Cape Fear River stock). Spawning grounds are not clearly defined in these systems as access to spawning areas is influenced by river flows and impediments to migration. Management of striped bass within the CSMA is the sole responsibility of the North Carolina Marine Fisheries Commission (NCMFC; coastal and joint fishing waters) and the NCWRC (joint and inland waters) and is not subject to compliance with the ASMFC Interstate FMP for Atlantic Ocean striped bass.

This report focuses on the analyses performed for the striped bass in the CSMA. After reviewing available data, life history information, and stock assessment techniques, it was determined traditional stock assessment models would not be appropriate for CSMA stocks because of the high hatchery contribution and lack of natural recruitment in these systems.

1.2 Life History

1.2.1 Movements & Migration

Striped bass populations in the Tar-Pamlico, Neuse, and the Cape Fear rivers have been considered to have a primarily endemic riverine life history having limited or no adult oceanic migration (Setzler et al. 1980; Rulifson et al. 1982a). Tagging data have indicated there is some movement of striped bass from the Neuse and Pamlico rivers into other systems and the Atlantic Ocean, but this is at low levels (Callihan 2012; Callihan et al. 2014; Rock et al. 2018). Tag-return data from stocked striped bass (Phase II; 5–7 inch total length, TL) suggest that these fish contribute to the commercial and recreational fisheries as well as the spawning stock in the Neuse and Tar rivers but do not commonly migrate to other rivers (Winslow 2007). Acoustic tagging studies within the Cape Fear River Basin demonstrated adult fish making seasonal spawning migrations within the drainage; however, emigration out of the system was minimal (Rock et al. 2018; Prescott 2019). Many striped bass exhibited a pattern of residency in the lower portions of the Tar-Pamlico and Neuse rivers with some detected making multiple seasonal spawning runs with many moving as far upstream as Rocky Mount in the Tar River and Raleigh in the Neuse River (Rock et al. 2018).

1.2.2 Age & Size

Striped bass scales have been collected by the NCDMF since 1975, and otoliths have been collected since 2003. Striped bass otoliths have been documented to provide more accurate and precise age estimates than scales (Humphreys and Kornegay 1985; Boyd 2011; Liao et al. 2013) and that ageing error can bias results of stock assessments. In 2017, the NCDMF compared scale and otolith ages from multiple readers for known age striped bass and found age estimates from scales to be unreliable and commonly underage or overage CSMA striped bass; as a result, only otolith ages are considered in this assessment (see section 7). Additionally, in 2016 and 2017 genetic samples were collected by the NCDMF from striped bass that allowed for age determination of hatchery-produced fish that were used in this analysis. The NCWRC used scales to age Tar-Pamlico River striped bass from 1996–2012 and Neuse River striped bass from 1994–2012. Since the inception of the PBT program in 2010, the NCWRC has determined ages of hatchery-produced fish using PBT analysis and used scales when PBT ages were not available. The NCWRC does not routinely collect striped bass otoliths, and did not provide any otolith ages for this assessment. Based on otolith and PBT age data collected from 2004 to 2017 (Figure 1.2), a maximum age of 11 years has been observed for striped bass in the Tar-Pamlico and Neuse rivers and a maximum age of seven years has been observed for striped bass in the Cape Fear River. Fish older than age eight years are rare in all of the CSMA river systems; however, NCWRC scale-aged fish suggest greater maximum ages in all CSMA rivers (Homan et al. 2010; Fisk and Morgeson 2016). This report found that ageing biases from scale ages resulted in underestimates of population abundance (15%) and female spawning stock biomass (19%), while overestimating fishing mortality in the terminal year (19%) and made strong age-1 recruitment years appear weaker and weak ones stronger.

1.2.3 Growth

As a relatively long-lived species, striped bass (approaching 30 years) can attain a moderately large size. Females grow to a considerably larger size than males; striped bass over 30 pounds are almost exclusively female (Bigelow and Schroeder 1953; NCDMF, unpublished data). Growth occurs between April and October. During the spawning migration, striped bass stop feeding for a brief period just before and during spawning, however feeding continues during the upriver spawning migration and resumes soon after spawning (Trent and Hassler 1968). From November through March, striped bass growth is thought to be negligible.

Striped bass in the CSMA grow at a faster rate and have a greater total length at age compared to the A-R stock (Knight 2015) and Neuse River striped bass exhibit the fastest growth rate in the CSMA (NCDMF 2020). As an example, in 2017, mean length of age-5 female striped bass in the Roanoke River was 559 mm TL while Neuse River female mean length at age 5 was 634 mm TL (Ricks and Buckley 2018; Smith and Potoka 2018). Fast growth in CSMA rivers has been attributed to a lack of density-dependent forage limitations (Ricks and Buckley 2018). This is possibly attributed to superior growth in the initial year of life for hatchery fish compared to wild fish, abundant food availability, and relatively small population. In addition, a tagging study showed striped bass stocked in the Neuse and Tar-Pamlico rivers had a higher growth rate (growth coefficient of 0.54–0.61 per year) than in their natal habitat (Roanoke River; Callihan et al. 2014).

1.2.4 Reproduction

Striped bass spawn in freshwater or nearly freshwater portions of North Carolina’s coastal rivers from late March to June depending upon water temperatures (Hill et al. 1989). Spawning behavior is characterized by brief peaks of surface activity when a mature female is surrounded by up to 50 males as eggs are broadcast into the surrounding water and males release sperm, termed “rock fights” by locals (Setzler et al. 1980). Spawning by a given female is probably completed within a few hours (Lewis and Bonner 1966).

Based on data collected on the Tar-Pamlico River in 2004 and 2005, the peak spawning activity was observed in April through mid-May (Smith and Rulifson 2015) and acoustic detection data in the Neuse River shows striped bass were only in the upper portions of the river from March through May (Rock et al. 2018). Despite an apparent spawning migration, and NCWRC surveys that have documented limited numbers of striped bass eggs in various stages of development in the Tar-Pamlico and Neuse rivers (Jones and Collart 1997; Smith and Rulifson 2015), the stocks remain comprised of predominantly hatchery origin fish (Farrae 2019; Table 1.2).

Studies have collected eggs, larvae, juveniles (Winslow et al. 1983; Smith 2009; Smith and Hightower 2012; Morgeson and Fisk 2018), or adult fish (Ashley and Rachels 2006) to show evidence of spawning and/or spawning migrations in the main stem of the Cape Fear River.

1.2.4.1 **Eggs**

Mature eggs are 1.0–1.5 mm (0.039 to 0.059 inch) in diameter when spawned and remain viable for about one hour before fertilization (Stevens 1966). Fertilized eggs are spherical, non-adhesive, semi-buoyant, and nearly transparent. Fertilized eggs need to drift downstream with currents to hatch into larvae. If the egg sinks to the bottom, the chances of hatching are reduced because the sediments reduce oxygen exchange between the egg and the surrounding water. After hatching, larvae are carried by the current to the downstream nursery areas.

There is some discrepancy over temperature tolerance for striped bass eggs. Morgan and Rasin (1973) and Rogers et al. (1977) indicated that egg survival gradually declines as temperature drops below 17°C and rapidly declines as water temperature approaches 23°C. In general, lower temperatures lead to longer incubation periods (Hardy 1978). Bain and Bain (1982) documented hatching at approximately 48 hours after fertilization at a temperature of 18°C, and other studies have shown that hatching time varied from 29 hours at 22°C to 80 hours at 11°C (Mansueti 1958; Hardy 1978). Hassler et al. (1981) found that A-R striped bass eggs hatch in 38 hours. Sampling by the NCWRC in 1965 and 1975 indicated striped bass spawning occurs in the Tar-Pamlico River from mid-April to mid-May with peak egg production occurring from 18 to 21° C (Humphries 1965; Kornegay and Humphries 1975).

Smith and Rulifson (2015) collected striped bass in the Tar-Pamlico River from early March through mid-April in 2004 and 2005. The NCWRC surveyed striped bass eggs in the Tar-Pamlico River in 1996 and collected 1,366 striped bass eggs with 77.3% being identified as viable during sampling from April through May (Jones and Collart 1997). The NCWRC also collected 188 striped bass eggs from Fishing Creek, a tributary of the Tar-Pamlico River, of which 79% were identified as viable.

Numerous studies employing differing methodology have investigated the presence and viability of striped bass eggs in the Neuse River (Baker 1968; Hawkins 1980; Nelson and Little 1991; Burdick and Hightower 2006; Buckley et al. 2019). Eggs have been collected throughout the Neuse River and its tributaries, generally above Kinston, from the end of March through May. Eggs have been collected at all developmental stages with up to 65% viable eggs (Buckley et al. 2019).

A number of studies have examined the presence of striped bass eggs in the Cape Fear River using variable methodology (Smith 2009; Dial Cordy and Associates 2017; Morgeson and Fisk 2018). Eggs were generally collected from April and May despite sampling occurring in March, though there is generally low abundance of eggs in the river and very few eggs are captured above Lock and Dam 3. Most eggs have been collected below Lock and Dam 1, and collected eggs have been identified as being at multiple developmental stages, although Smith and Hightower (2012) found that the river section between Lock and Dam 2 and Lock and Dam 3 had the highest egg collections and highest predicted proportion of the run.

Research suggests the egg buoyancy of certain strains (e.g., Roanoke River and Chesapeake Bay) are adapted to specific flow conditions. Chesapeake Bay strain eggs are lighter and maintain their position in the water column of calmer tidal waters through neutral buoyancy, whereas Roanoke River strain eggs are heavier and use the more turbulent, high energy system of the Roanoke River to maintain their position in the water column (Bergey et al. 2003).

In 2017, North Carolina State University (CRFL# 2017-F-046) initiated research to provide insight into the current striped bass recruitment status by evaluating genetic and environmental influences on egg development. Preliminary results suggest that the heaviest eggs collected in 2018 and 2019 were from striped bass in the Tar-Pamlico and Neuse rivers (Cara Kowalchyk, NCSU, personal communication). It is interesting to note that the heaviest eggs in the study came from the shallowest river systems; the upper Tar-Pamlico River has an average width of 15 m and an average depth of 0.6 m in the upper reaches and an average width of 49 m and average depth of 4.6 m in the lower reaches (NCWRC 2006).

1.2.4.2 **Larvae**

The larval development of striped bass is dependent upon water temperature and is usually regarded as having three stages: (1) yolk-sac larvae are 5–8 mm (0.20 to 0.31 inch) in total length and depend on yolk material as an energy source for 7 to 14 days; (2) fin-fold larvae (8–12 mm;

0.31-0.47 inch TL) having fully developed mouth parts and persist about 10 to 13 days; and (3) post fin-fold larvae attain lengths up to 30 mm (1.18 inches) in 20 to 30 days (Hill et al. 1989). Researchers of North Carolina stocks of striped bass (primarily the A-R stock) divide larval development into yolk-sac and post yolk-sac larvae.

Over the past several decades, very few striped bass larvae have been collected in CSMA systems. In 2004 and 2005, Smith and Rulifson (2015) first collected striped bass larvae on the Tar-Pamlico River in early March, and collections continued through mid-May with peak spawning periods detected in April through mid-May. In the Neuse River, only one striped bass larva was collected during each sampling conducted in 1978, 1989, and 2017 (Hawkins 1980; Nelson and Little 1991; Buckley et al. 2019). Larvae (n=32) were collected by Burdick and Hightower (2006) between 8 April–28 May in 2003 and 19 April–12 May in 2004 when water temperatures ranged from 14°C to 28°C in the main stem of the Neuse River and its tributaries. In the Cape Fear River, larval striped bass have generally been captured between April and mid-May with water temperatures ranging 18.6°C–22.5°C. In 2006, larval sampling coincided with the egg collections described in section 1.2.4.1. Larvae were collected at sites downstream of LD-1 (n=1), upstream of LD-1 (n=2), and upstream of LD-2 (n=4). No larval striped bass were captured in 2007, however in 2008 larvae were captured at LD-1 (n=3), LD-3 (n=1), and at the Fayetteville site (n=1). Dial Cordy and Associates Inc. (2017) captured one newly hatched larva below LD-2 on 29 March 2017 when the water temperature was 17.6°C, and two larvae were captured at LD-2 in May. An additional survey for larval fish using quatrefoil light traps was completed May–June 2017 in the Cape Fear, Northeast Cape Fear, and Black Rivers (NCWRC, unpublished data). Although 70 trap nights (1 trap night=1 light trap fished overnight) occurred and over 18 species (155 individuals) were collected, no striped bass larvae or juveniles were collected.

1.2.4.3 **Juveniles**

Most striped bass enter the juvenile stage at about 30 mm (1.18 inches) TL; the fins are then fully formed, and the external morphology of the young is similar to that of the adults. For the A-R stocks, juveniles are often found in schools and associate with clean sandy bottoms (Hill et al. 1989) and there is evidence of density dependent habitat utilization, with juveniles being collected in the Alligator River and Stumpy Point, Pamlico Sound in late June when large year classes are produced by the A-R stock (NCDMF, unpublished data).

Little is known about juvenile striped bass within the CSMA. Historically, very few juveniles have been captured during NCDMF and NCWRC sampling. Seine and trawl surveys conducted by the NCDMF from 1977 to 1983 collected 37 juveniles in Tar-Pamlico River and 14 juveniles in the Neuse River (Hawkins 1980). The Cape Fear River was only sampled from July–December 1977 and June–September 1978; two striped bass were collected in July 1977.

The NCWRC conducted exploratory juvenile sampling in the Neuse River during 2006 and 2007. No juvenile striped bass were collected in 2006, and five juvenile striped bass were collected in 2007. Evaluation of oxytetracycline (OTC) tagging determined that three of these fish were of hatchery origin and the other two had no OTC mark and could have been wild produced fish (Barwick et al. 2008).

In 2017, exploratory juvenile abundance surveys were developed for the Tar-Pamlico, Neuse, and Cape Fear rivers using trawl and seine nets based on historical sampling locations. No striped bass have been collected in the Tar-Pamlico and Neuse rivers; however, a total of 24 juvenile striped bass were collected in the Northeast Cape Fear River in 2018 and an additional four were collected in 2019 (Program 100 Juvenile Abundance Survey).

Results from these sampling efforts support the hypothesis of very limited natural reproduction occurring in the CSMA for several decades (Hawkins 1979; Judy and Hawkins 1982; NCDMF 2005; Barwick et al. 2008; NCDMF 2013; Darsee et al. 2019). The existence of limited natural reproduction in the CSMA is supported by results of otolith microchemistry work suggesting 53% of striped bass sampled in the Neuse River in 2010 were not of hatchery origin (Rulifson 2014).

1.2.4.4 **Maturation & Fecundity**

There is a strong positive correlation between the length, weight, and age of a female striped bass and the number of eggs produced (Monteleone and Houde 1990; Olsen and Rulifson 1992; Boyd 2011; Knight 2015).

In the Tar-Pamlico and Neuse rivers, 50% of female striped bass are mature at 2.7 years and 98% are mature by age-3 (Knight 2015). Length at 50% maturity (L50) in the CSMA was estimated at 467.8 mm TL (18.4 inches TL) and fish were estimated to be 100% mature at 537.3 mm TL (21.1 inches TL). Female striped bass produce large quantities of eggs which are broadcast into riverine spawning areas and fertilized by mature males, typically age-2 and older. In the Tar-Pamlico and Neuse rivers, fecundity ranged from 223,110 eggs for an age-3 female to 3,273,206 eggs for an age 10 female.

1.2.5 Mortality

A telemetry tagging study on the Neuse River estimated a discrete annual total mortality of 66.3% for phase II stocked juveniles (202–227 mm TL), a discrete annual total mortality of 54.0% for adults (349–923 mm TL), and a discrete natural mortality of 20.1% for adults (Bradley et al. 2018b). A tagging study showed that striped bass stocked in the Neuse and Tar-Pamlico rivers experienced higher mortality (instantaneous total mortality of 0.48–0.51) than in their natal habitat (instantaneous total mortality of 0.33; Callihan et al. 2014).

Instantaneous total mortality of striped bass in the Neuse River varied considerably from 1997–2011, ranging from 0.36 to 1.08 (Rachels and Ricks 2018). Mortality was generally lowest during the period 1997–2007 and highest during the period 2008–2011. Instantaneous fishing mortality ranged from 0.12–0.84 assuming the instantaneous natural mortality rate given by Bradley (2016) remained constant throughout the time series.

1.2.6 Food & Feeding Habits

Striped bass are opportunistic feeders; specific food types depend upon the size of the fish, habitat, and the season (Rulifson et al. 1982b). Striped bass undergo an ontogenetic shift in diet with larvae feeding primarily on mobile planktonic invertebrates (Doroshev 1970; Markle and Grant 1970; Bason 1971). As they grow, juvenile striped bass diets include larger aquatic invertebrates and small fish (Shapovalov 1936; Ware 1971). Adult striped bass are piscivorous and primarily feed on fish in the Family Clupeidae, including Atlantic menhaden (*Brevoortia tyrannus*), alewife (*Alosa pseudoharengus*), blueback herring (*Alosa aestivalis*), and gizzard shad (*Dorosoma cepedianum*; Manooch 1973).

Binion-Rock (2018) conducted a multispecies food habits study for 25 finfish species in Pamlico Sound, North Carolina and its tributaries and found that Atlantic menhaden, spot (*Leiostomus* *xanthurus*), and Atlantic croaker (*Micropogonias undulatus*) were the most commonly consumed fish for larger predators, such as striped bass. Atlantic menhaden contributed the most to bluefish (*Pomatomus saltatrix*), longnose gar (*Lepisosteus osseus*), spotted seatrout (*Cynoscion nebulosus*), and striped bass diets. Striped bass diets also consisted of forage species including anchovies, silversides, mollusks, and polychaetes. Striped bass were also reported as prey items consumed by bluefish, longnose gar, and spotted seatrout.

1.3 Habitat

Striped bass use a variety of habitats with variations in preference due to location, season, and ontogenetic stage. Although primarily estuarine, striped bass use habitats throughout the estuaries and the coastal ocean. Striped bass are found in most habitats identified by the North Carolina Coastal Habitat Protection Plan (CHPP) including water column, wetlands, submerged aquatic vegetation (SAV), soft bottom, hard bottom, and shell bottom (NCDEQ 2016).

The loss of habitat has contributed to the decline in anadromous fish stocks throughout the world (Limburg and Waldman 2009). Numerous documents have been devoted entirely to habitat issues and concerns, including the North Carolina Coastal Habitat Improvement Plan (Street et al. 2005) and ASMFC's "Atlantic Coast Diadromous Fish Habitat: A review of Utilization, Threats, Recommendations for Conservation, and Research Needs" (Greene et al. 2009).

1.3.1 Spawning Habitat

Spawning grounds are not clearly defined in CSMA systems as access to spawning areas is influenced by river flows as well as impediments to migration. In the Tar-Pamlico River, the main spawning habitat for striped bass occurs from the Rocky Mount Mills Dam downstream approximately 72 km to the vicinity of the town of Tarboro (Kornegay and Humphries 1975; Rock et al. 2018). Acoustic tagging data indicate spawning areas in the Tar-Pamlico River likely occur from the area around Dunbar Road downstream to Tarboro (Rock et al. 2018).

During NCWRC striped bass surveys on the Neuse River, spawning aggregates have been observed from Raleigh, North Carolina to Kinston, North Carolina and acoustic detection data indicate striped bass move upriver as far as Raleigh during the spawning season (Rock et al. 2018). During high flows fish are more likely to spawn near Raleigh, North Carolina (approximately river kilometer (rkm) 350), and when flows are lower fish tend to spawn further downstream around Smithfield, North Carolina (approximately rkm 300; Burdick and Hightower 2006). Striped bass spawning has also been observed further downriver near Goldsboro, North Carolina (rkm 240) and was correlated with higher water velocities and larger substrates (Beasley and Hightower 2000).

In a study conducted by the NCWRC in 2016 and 2017, Neuse River water velocities appeared to be sufficient to keep striped bass eggs suspended until hatching (Buckley et al. 2019). Although water velocities were more variable in 2017, mean velocity for all sites in both years was above the minimum water velocity (30 cm/s) recommended by Albrecht (1964). Additionally, Neuse River velocities were comparable to those observed in the Roanoke River (USGS Oak City, NC 02081022, USGS Williamston, NC 02081054, and Barnhill's Landing from Rulifson and Isely, 1995; Buckley et al., 2019). A study in the Roanoke River indicated that river flow during the pre-spawn and post-spawn periods was the most important factor contributing to survival of larval fish (Hassler 1981); however, comparisons between systems may not be appropriate because of differences in river depth.

In the Cape Fear River, historic anadromous fish spawning areas have been identified from below the mouth of Town Creek, North Carolina to upstream as far as Lillington, North Carolina (Sholar 1977). Three locks and dams were constructed on the main stem of the Cape Fear River between Riegelwood, North Carolina and Tar Heel, North Carolina and the lowermost was completed in 1915 and the uppermost in 1935. These impediments to passage limit the ability of striped bass to reach known historic spawning areas near Smiley Falls at the fall line in Lillington, North Carolina (Nichols and Louder 1970). Several studies in the Cape Fear River have tracked adult striped bass to show evidence of spawning and/or spawning migrations in the main stem river to and above the locks and dams (Ashley and Rachels 2006; Smith 2009; Smith and Hightower 2012). Rock et al. (2018) found that striped bass in the Cape Fear River were generally detected at a core region near downtown Wilmington during all seasons and that many striped bass in the Cape Fear system showed fidelity to and made repeated spring migrations each year up the Northeast and Cape Fear rivers, suggesting spawning migrations or behavioral contingents.

In the Northeast Cape Fear River, Winslow et al. (1983) documented striped bass spawning areas to be located from Croomsbridge Road (rkm 130) to Ness Creek (rkm 47) in the lower Northeast Cape Fear River, and stated that peak spawning occurred in the area downstream of Lanes Ferry (rkm 93); however, Rock et al. (2018) determined that during the spawning season, striped bass migrate to at least near Hallsville, North Carolina (rkm 183), and mature fish were captured between White Stocking, North Carolina (rkm 118) and Chinquapin, North Carolina (rkm 168), thus it is likely that the extent of the upriver spawning habitat in the Northeast Cape Fear River has been underestimated.

1.3.2 Nursery & Juvenile Habitat

Neuse River juvenile striped bass captured in 1979 appeared to show no preference for fresh or brackish water areas but were associated with sandy bottom areas near grass beds (Hawkins 1979).

1.3.3 Adult Habitat

In the Tar-Pamlico river, striped bass are able to migrate as far as Rocky Mount, North Carolina, where Rocky Mount Mills Dam prevents further upstream migration. In the Neuse River, Quaker Neck Dam was removed near Goldsboro, North Carolina in 1998 and Milburnie Dam, in Raleigh, North Carolina, was removed in 2017. Currently, striped bass can access habitats from Falls Dam at Raleigh, North Carolina downstream to the Pamlico Sound. Striped bass are primarily found in these upriver locations during the spawning season from March through May. During the summer and fall, striped bass in the Neuse River concentrate in an area from New Bern downstream to Slocum and Hancock Creeks, and in the Tar-Pamlico River striped bass concentrate in an area from Washington to South Creek (Rock et al. 2018). In the Cape Fear River, adult fish distribution is centered in the upper estuary at the confluence of Cape Fear and Northeast Cape Fear rivers (Wilmington, North Carolina; Stewart and Li 2019).

1.3.4 Habitat Issues & & Concerns

There are many contaminants known to adversely affect striped bass at various life stages, particularly at the egg and larvae stages (Setzler et al. 1980; see Richards and Rago 1999 for review), but little is known about current contaminants in the CSMA. Adequate river flows during the spawning season are also needed to keep eggs suspended for proper development (Manooch and Ru1ifson 1989). Hassler (1981) indicated that river flow during the pre-spawn and post-spawn periods was the most important factor contributing to survival of fish larvae.

Between 1915 and 1935, three locks and dams were constructed on the Cape Fear River. These structures inhibit access to the historical striped bass spawning grounds. A rock arch rapids fishway was constructed at Lock and Dam 1 in 2012 to provide improved volitional passage for anadromous fish; however, Raabe et al. (2019) determined the structure was not effective for striped bass. Consequently, striped bass reproduction is limited because migration to traditional spawning grounds on the Cape Fear River is restricted.

1.4 Description of Fisheries

1.4.1 Commercial Fishery

Commercial landings in the CSMA have been constrained by an annual Total Allowable Landings (TAL) of 25,000 pounds since 1994. Most commercial landings come from the Pamlico and Pungo rivers and the Neuse and Bay riversand the remainder come from Pamlico Sound. Since 2004, there has only been a spring harvest season, recently opening March 1 each year and closing when the TAL is reached. In 2008 due to continued concerns over low abundance levels, a no-harvest provision was implemented in the Cape Fear River. Due to the no possession measure for the remainder of the CSMA approved in Supplement A to Amendment 1 to the N.C. Estuarine Striped Bass FMP (NCDMF 2019a), the commercial striped bass fishery was closed in 2019 while Amendment 2 to the N.C. Striped Bass FMP is developed (refer to Figure 2.1).

1.4.2 Recreational Fishery

Coastal striped bass populations have continuously provided a popular and economically important recreational fishery in North Carolina. Despite past surveys covering a considerable area, recreational fisheries data were lacking for the CSMA when the stock was listed as overfished in 2003. A comprehensive creel survey was initiated in January 2004 to identify and estimate recreational striped bass effort and catch in the CSMA, particularly the Tar-Pamlico and Neuse river systems. Due to the recreational no possession measure implemented by the NCMFC and the NCWRC in Supplement A to Amendment 1 to the N.C. Estuarine Striped Bass FMP (NCDMF 2019a), the recreational striped bass fishery was closed in 2019 while Amendment 2 to the N.C. Striped Bass FMP is developed (refer to Figure 2.4).

1.5 Fisheries Management

1.5.1 Management Authority

Fisheries management includes all activities associated with maintenance, improvement, and utilization of the fisheries resources of the coastal area including research, development, regulation, enhancement, and enforcement. North Carolina’s existing fisheries management system is powerful and flexible and rulemaking (and proclamation) authority is vested in the NCMFC and the NCWRC within their respective jurisdictions.

The North Carolina Department of Environmental Quality (NCDEQ) is the parent agency of the NCMFC and the NCDMF. The NCMFC is responsible for managing, protecting, preserving, and enhancing the marine and estuarine resources under its jurisdiction, which includes all state coastal fishing waters extending to three miles offshore. In support of these responsibilities, the NCDMF conducts management, enforcement, research, monitoring statistics, and licensing programs to provide information on which to base these decisions. The NCDMF presents information to the NCMFC and NCDEQ in the form of fisheries management and coastal habitat protections plans and proposed rules. The NCDMF also administers and enforces the NCMFC's adopted rules.

The NCWRC is a state government agency authorized by the General Assembly to conserve and sustain the state's fish and wildlife resources through research, scientific management, wise use, and public input. The NCWRC is the regulatory agency responsible for the creation and enforcement of hunting, trapping, and boating laws statewide and fishing laws within its jurisdictional boundaries including all designated inland fishing waters. The NCWRC and NCDMF share authority for regulating recreational fishing activity in joint fishing waters.

1.5.2 Management Unit Definition

There are three geographic management units defined in the Estuarine Striped Bass FMP and the fisheries throughout the coastal systems of North Carolina (NCDMF 2004). The management unit for this evaluation is the CSMA and is defined as:

The CSMA includes all internal coastal, joint and contiguous inland waters of North Carolina south of the ASMA to the South Carolina state line. There are spawning stocks in each of the major river systems within the CSMA; the Tar-Pamlico, the Neuse, and the Cape Fear. These stocks are collectively referred to as the CSMA stocks. Spawning grounds are not clearly defined in these systems as access to spawning areas is influenced by river flows as well as impediments to migration. Management of striped bass within the CSMA is the sole responsibility of the NCMFC and the NCWRC and is not subject to compliance with the ASMFC Interstate FMP for Atlantic Striped Bass (Figure 1.1).

1.5.3 Regulatory History

Estuarine striped bass in North Carolina are managed jointly by the NCMFC and the NCWRC under Amendment 1 (NCDMF 2013), Revision 1 to Amendment 1 (NCDMF 2014), and Supplement A to Amendment 1 (NCDMF 2019a) to the N.C. Estuarine Striped Bass FMP (NCDMF 2004). Amendment 1, adopted in 2013, lays out separate management strategies for the A-R stock in the ASMA and the RRMA and the CSMA stocks in the Tar-Pamlico, Neuse, and Cape Fear rivers. Management measures in Amendment 1 consist of daily possession limits, open and closed harvest seasons, seasonal gill-net attendance and other gill-net requirements, minimum size limits, and slot limits to maintain sustainable harvest and reduce regulatory discard mortality in all sectors. Amendment 1 also maintained the stocking measures in the major CSMA river systems and the harvest moratorium on striped bass in the Cape Fear River and its tributaries, including Snow's Cut (NCDMF 2013).

The following regulations were initially contained in the jointly adopted Amendment 1 to the N.C. Estuarine Striped Bass FMP. Both commercial and recreational fisheries are subject to an 18-inch TL minimum size limit for striped bass within the CSMA. As an additional protective measure in joint and inland CSMA waters, it is unlawful for recreational fishermen to possess striped bass between 22 and 27 inches TL. The recreational harvest season for striped bass within the CSMA is October 1 through April 30. Recreational fishermen are constrained to a two fish per person per day possession limit.

The striped bass commercial fishery in the CSMA is a directed fishery, except in Pamlico Sound where bycatch restrictions are in place and primarily uses anchored large mesh (≥5 inches stretched mesh (ISM) gill nets. There is a commercial daily possession limit of 10 fish per person per day with a maximum of two limits per commercial operation issued by proclamation. Daily reporting of the number and pounds of striped bass landed from all licensed striped bass dealers helps ensure the 25,000 pound total allowable landings (TAL) is not exceeded. The commercial harvest season opens by proclamation and may occur between January 1 and April 30 and is closed by proclamation once the annual 25,000 pound TAL is reached or on April 30, whichever occurs first. After closure of the commercial harvest season and continuing through December 31, commercial fishermen are required to use three-foot tie downs in gill nets with a stretch mesh length ≥5 inches in internal coastal fishing waters west of the 76 28.0000' W longitude line. They must also maintain a minimum distance from shore (DFS) of 50 yards for these nets upstream of the existing DFS line.

In recreational and commercial fisheries, it has been unlawful to possess striped bass taken from the internal coastal and joint waters of the Cape Fear River and its tributaries since 2008 per MFC Rules 15A NCAC 03M .0202 and 03Q .0107, and in the inland fishing waters of the Cape Fear River and its tributaries downstream of Buckhorn Dam per NCWRC rules 15A NCAC 10C .0314 (h).

The following management change was implemented solely under the purview of the NCWRC and was not developed through the NCDMF FMP process. The NCWRC has jurisdiction in the inland waters of the CSMA, and on February 16, 2016, the NCWRC voted to modify the exception to the general statewide size regulation for striped bass in inland waters of the Tar-Pamlico, Pungo, and Neuse rivers and their tributaries by increasing the minimum size limit from 18 inches to 26 inches TL. The no-possession prohibition on fish between 22 and 27 inches TL was removed. The daily creel limit (two fish per person per day) and harvest season (October 1–April 30) were not changed. The new rule was scheduled to go into effect August 1, 2017, but ten letters of objection requesting legislative review of the rule were received in March 2017. No action was taken during the mandatory legislative review period, and the rule 15A NCAC 10C .0314 became effective on June 1, 2018.

Supplement A to Amendment 1 to the N.C. Estuarine Striped Bass FMP was adopted by the NCMFC at their February 2019 business meeting and by the NCWRC in March 2019 (NCDMF 2019a). Supplement actions in the FMP implemented March 29, 2019 consisted of a recreational no possession measure for striped bass (including hybrids) in coastal and inland fishing waters of the CSMA (NCDMF Proclamation FF-6-2019). The NCWRC hook-and-line closure proclamation had the effect of suspending rules 15A NCAC 10C .0107 (l) and 10C .0314 (g). A no-possession requirement has been in place for the Cape Fear River by rule since 2008.

In March 2019, the NCMFC held an emergency meeting that directed the NCDMF to issue a proclamation regarding gill nets, beyond what was contained in Supplement A to Amendment 1 to the N.C. Estuarine Striped Bass FMP. Proclamation (M-6-2019) prohibits the use of all gill nets upstream of the ferry lines from the Bayview Ferry to Aurora Ferry on the Pamlico River and the Minnesott Beach Ferry to Cherry Branch Ferry on the Neuse River. It also maintains tie-down (vertical net height restrictions) and distance from shore restrictions for gill nets with a stretched mesh length 5 inches and greater in the western Pamlico Sound and rivers.

An emergency meeting called under North Carolina General Statute section 113-221.1(d), authorizes the NCMFC to review the desirability of directing the fisheries director to issue a proclamation. Once the NCMFC votes under this provision to direct issuance of a proclamation, the NCDMF fisheries director has no discretion to choose another management option and is bound by law to follow the NCMFC decision. In these cases, under existing law, the decision of the NCMFC to direct the director to issue a proclamation is final and can only be overruled by the courts.

1.5.4 Current Regulations

Commercial and recreational harvest of striped bass in the CSMA is prohibited. Supplement A to the N.C. Estuarine Striped Bass FMP was adopted by the NCMFC at their February 2019 business meeting (NCDMF Proclamation FF-6-2019) and by the NCWRC in March 2019. The NCWRC hook-and-line closure proclamation had the effect of suspending rules 15A NCAC 10C .0107 (l) and 10C .0314 (g). NCDMF proclamation (M-6-2019) prohibits the use of all gill nets upstream of the ferry lines from the Bayview Ferry to Aurora Ferry on the Pamlico River and the Minnesott Beach Ferry to Cherry Branch Ferry on the Neuse River. It also maintains tie-down (vertical net height restrictions) and distance from shore restrictions for gill nets with a stretched mesh length 5 inches and greater in the western Pamlico Sound and rivers.

As a response to low numbers of documented spawning adults and limited evidence of juvenile recruitment, the NCDMF and NCWRC implemented, by separate rule making, a moratorium on both the commercial and recreational harvest of striped bass in the Cape Fear River in 2008, which is still in effect.

1.5.5 Management Performance

Stocking appears to have maintained striped bass populations in the Tar-Pamlico and Neuse rivers during recent history, in the absence of stocking, population declines likely would have occurred given the absence of natural recruitment and evidence that populations remain almost entirely composed of hatchery fish. The slot limit imposed on the joint and inland waters portions of the Tar-Pamlico and Neuse rivers does not seem to have protected spawning females to older age classes as intended. In an effort to reduce discards in the commercial fishery, tie-downs and distance from shore measures adopted in the 2004 Estuarine Striped Bass FMP (NCDMF 2004) were implemented in 2008. Rock et al. (2016) investigated the effectiveness of these management measures by collecting effort, catch, and bycatch data for striped bass in the commercial estuarine large mesh gill-net fishery. Due to the persistence of striped bass in nearshore waters and the comparatively low number of discarded striped bass observed in commercial gill nets, it appears as though the distance from shore and tie-down requirements enacted in 2008 have been successful in reducing the number of striped bass discards in the commercial gill-net fishery in the Tar-Pamlico and Neuse rivers. Overall, this study indicated approximately an 82% reduction in striped bass discards from previous levels estimated in Amendment 1 to the Estuarine Striped Bass FMP (NCDMF 2014); however, Rachels and Ricks (2018) observed that gill-net effort (number of nets set annually) had greater impact on Neuse River striped bass mortality rates than commercial harvest and theorized that discard mortality continues to significantly impact the population. The work of Rachels and Ricks (2018) was expanded as part of this assessment to include removals from all sectors (recreational and commercial) that could influence discrete annual mortality. Results from additional analysis showed, along with the relative annual variation in commercial effort and in commercial harvest, the relative annual variation in recreational effort and in recreational discards were also significant factors contributing to the relative annual variation in total mortality of striped bass in the Neuse River (see section 5).

1.6 Assessment History

No formal peer-reviewed stock assessments have been conducted for the CSMA striped bass.

1.6.1 Review of Previous Methods & Results

No peer-reviewed stock assessments have been conducted for the CSMA striped bass; however, an index-based method of catch curve analysis was used to assess the status of striped bass populations in the CSMA (Appendix 14.7 in NCDMF 2013). The large confidence intervals and lack of precision in the catch curve Z estimates (total instantaneous mortality rate) made them unsuitable for making a stock status determination (NCDMF 2013).

1.6.2 Progress on Research Recommendations

No peer reviewed stock assessment has been conducted for CSMA striped bass stocks. However, many of the research recommendations from the FMP focused on collection of data and life history information needed for completion of a stock assessment.

- Increase surveys of stocked systems to determine percent contribution of hatchery stocked fish (ongoing through NCWRC and NCDMF genetics survey)

- Conduct egg abundance and egg viability studies

  The NCWRC and the NCDMF continue to collect genetic data throughout the range of striped bass to evaluate the percent contribution of hatchery stocked fish. In 2016 and 2017, the NCWRC sampled anadromous ichthyoplankton to investigate striped bass egg and larval abundance and egg viability (Buckley and Ricks 2018). In 2017, North Carolina State University began research designed to investigate striped bass egg yolk composition, egg buoyancy, and recruitment.

- Acquire life history information: maturity, fecundity, size and weight at age, egg and larval survival

  Knight (2015) conducted research on striped bass maturation and fecundity in the Neuse and Tar-Pamlico rivers and additional work is ongoing through the NCDMF ageing program. In 2017, to adequately capture all life stages of striped bass, Program 100 was expanded into the CSMA to evaluate juvenile striped bass recruitment.

- Improve tagging program, conduct a mark-recapture study utilizing conventional tags and telemetry approaches to estimate fishing mortality and abundance

  Conventional tagging and deployment of acoustic tagged striped bass has continued in the CSMA to improve estimates of fishing mortality and abundance. Rock et al. (2018) assessed critical habitat, movement patterns, and spawning grounds of anadromous fishes in the Tar-Pamlico, Neuse, and Cape Fear rivers using telemetry tagging techniques.

- Develop better estimates of life-history parameters, especially growth and natural mortality

In an effort to improve discard estimates in the commercial gill-net fishery, Rock et al. (2016) evaluated discard estimates through the NCDMF creel survey and an expanded NCDMF observer program. Bradley et al. (2018a and 2018b) conducted research in the Neuse River to estimate mortality rates of juvenile and adult striped bass, determine distribution and migration patterns of adults, and built an age-structured population model to explore the effects of observed mortality rates on the adult population.

2 DATA

2.1 Fisheries-Dependent

2.1.1 Commercial Landings

Prior to 1978, North Carolina's commercial landings data were collected by the National Marine Fisheries Service (NMFS). Between 1978 and 1993, landings information was gathered through the NMFS/North Carolina Cooperative Statistics program. Reporting was voluntary during this period and North Carolina and NMFS port agents sampled the state's major dealers (Lupton and Phalen 1996).

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

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

2.1.1.1 **Sampling Intensity**

North Carolina dealers are required to record the transaction at the time of the transactions and report trip-level data to the NCDMF (see NCDMF 2019).

2.1.1.2 **Biological Sampling**

Historically, biological sampling occurred during the spring and fall fishery; however, since 2004 there has only been a spring harvest season. This is a directed fishery (except Pamlico Sound) for striped bass primarily using anchored gill nets. Commercial fish houses are sampled throughout the CSMA, during each open harvest season. Fish are measured to the nearest mm for fork length (FL) and TL and weighed to the nearest 0.01 kg. Striped bass scales and otoliths have been collected sporadically by the NCDMF since 1975, although since 2003 both scales and otoliths have been collected routinely. Scales are removed from the left side of the fish, above the lateral line and between the posterior of the first dorsal fin and the insertion of the second dorsal fin. Scales are cleaned and pressed on acetate sheets using a Carver heated hydraulic press. NCDMF staff read scales using a microfiche reader set on 24x or 33x magnification. Otoliths are collected from the left and right sides, but only one side (left) is typically sectioned and mounted for ageing. To prepare otoliths for ageing, thin sections of whole otoliths were cut, mounted to a slide, ground down, and covered with a top coat. Starting in 2016, although limited in number, PBT samples were also collected by taking a partial pelvic fin clip and preserving in 95% ethyl alcohol.

2.1.1.3 **Potential Biases & Uncertainties**

All fish that are caught are not required to be landed and sold so some fish may be taken for personal consumption and not reported in the landings under this program authority. Hadley (2015) found that 28% of commercial license holders maintained a license for personal consumption or donation of harvest. Another potential bias relates to the reporting of multiple gears on a single trip ticket because the order in which gears are reported is not indicative of the primary method of capture.

2.1.1.4 **Development of Estimates**

Commercial landings were summarized by year using the NCDMF TTP data. Length data collected from the commercial fish house sampling program were used to compute annual length-frequency distributions.

2.1.1.5 **Estimates of Commercial Landings Statistics**

Commercial landings in the CSMA have been constrained by an annual TAL of 25,000 pounds since 1994. Over the past ten years, landings have closely followed the annual TAL, except for 2008 when less than half of the TAL was landed. Since 2004, striped bass commercial landings in the CSMA have averaged 24,179 pounds and ranged from a low of 10,115 pounds in 2008 to a high of 32,479 pounds in 2004 (Figure 2.1). Most commercial landings come from the Pamlico and Pungo rivers and the Neuse and Bay rivers and the remainder come from the Pamlico Sound (Figure 2.2).

Length data from the commercial harvest shows that on average striped bass in the Neuse and Bay rivers are slightly larger than fish harvested in the Pamlico and Pungo rivers (Table 2.1). Additionally, maximum lengths are generally larger in the Neuse and Bay rivers compared to the Pamlico and Pungo rivers. CSMA commercial length frequencies show that striped bass are routinely harvested up to 30 inches total length and that few fish under the 18 inch total length minimum size limit are harvested (Figures 2.3, 2.4).

2.1.2 Commercial Gill-Net Discards

2.1.2.1 **Survey Design & Methods**

NCDMF's Program 466 (Onboard Observer Monitoring) was designed to monitor fisheries for protected species interactions in the gill-net fishery by providing onboard observations. Additionally, this program monitors finfish bycatch and characterizes effort in the fishery. The onboard observer program requires the observer to ride onboard the commercial fishermen's vessel and record detailed gill-net catch, bycatch, and discard information for all species encountered. Observers contact licensed commercial gill-net fishermen holding an Estuarine Gill-Net Permit (EGNP) throughout the state to coordinate observed fishing trips. Observers may also observe fishing trips from NCDMF vessels under Program 467 (Alternative Platform Observer Program), but these data were not used in this analysis due to the lack of biological data collected through the program.

2.1.2.2 **Sampling Intensity**

Commercial fishing trips targeting striped bass are observed during the open season (March–April); however, most observed trips occur outside of that time period when striped bass are discarded as bycatch in other gill-net fisheries.

2.1.2.3 **Biological Sampling**

Data recorded includes species, weight, length, and fate (landed, live discard, or dead discard).

2.1.2.4 **Potential Biases & Uncertainties**

Program 466 began sampling statewide in May 2010. To provide optimal coverage throughout the state, management units were created to maintain proper coverage of the fisheries. Management units were delineated based on four primary factors: (1) similarity of fisheries and management, (2) extent of known protected species interactions in commercial gill-net fisheries, (3) unit size, and (4) the ability of the NCDMF to monitor fishing effort. Total effort for each management unit can vary annually based on fishery closures due to protected species interactions or other regulatory actions. Therefore, the number of trips and effort sampled each year by management unit varies both spatially and temporally.

Program 466 data do not span the entire time series for this analysis (no data are available for 1991–2000) and statewide sampling began in May 2010 decreasing the variability of observed trips with better spatial and temporal sampling beginning in 2012.

Striped bass discard data were not available in sufficient quantities to estimate discards or post-release mortality from other fisheries; however, other gears, like pound nets, are known to have discards of striped bass.

It is also important to note that this survey was designed to target trips that occur in times and areas where protected species interactions are highest; the program does not target striped bass trips. For this reason, a high number of zero-catch trips relative to striped bass occur in the data.

2.1.2.5 **Development of Estimates**

A generalized linear model (GLM) framework was used to estimate striped bass discards in the North Carolina commercial gill-net fishery based on data collected from the mandatory observer program (initiated 2012) during 2013 through 2018. The presence or absence of striped bass from on-board observer trips in the Tar-Pamlico and Neuse rivers (Figure 2.5) was used to more accurately estimate striped bass discards from the commercial gill-net fisheries (Figure 2.6). Only those variables available in all data sources were considered as potential covariates in the model. Available variables were year, season, mesh category (small: <5 inches and large: ≥5 inches), and area (Figure 2.6), which were all treated as categorical variables in the model. Year is based on the calendar year. Season is based on the calendar year such that January through February, and December equates to winter, March through May equates to spring, June through August equates to summer, and September through November equates to fall. Discards were assigned to one of four areas: (1) Albemarle-Roanoke, (2) Neuse, (3) Tar-Pamlico, or (4) Cape Fear. Though estimates for the Albemarle-Roanoke were produced, they are not presented in this report. Due to the overall low gill-net activity and observed striped bass in the Cape Fear River during the 2013 to 2018-time period, commercial discards could not be estimated for this area.

All available covariates were included in the initial model and assessed for significance using likelihood ratio tests (Zuur 2012). Non-significant covariates were removed using backwards selection to find the best-fitting predictive model. An offset term was included in the model to account for differences in fishing effort among observations (Zuur et al. 2009, 2012). Effort was measured as soak time (days) multiplied by net length (yards). Using effort as an offset term in the model assumes the number of striped bass discards is proportional to fishing effort (A. Zuur, Highland Statistics Ltd., personal communication).

Live and dead discards were modeled separately. Examination of the data indicated both the live and dead discard data were zero inflated. There are two types of models 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 initially considered though were unable to converge. For this reason, zero-altered models were pursued.

The best-fitting models for live discards and for dead discards were applied to available effort data from the NCDMF TTP to estimate the total number of live discards and dead discards for the North Carolina commercial gill-net fishery. Because not all live discards survive, an estimate of post-release mortality was applied to the predicted number of live discards to estimate the number of live discards that did not survive. Live discards are multiplied by an estimated discard mortality rate for gill nets of 43% (ASMFC 2007). This estimate was added to the number of dead discards to produce an estimate of the total number of dead discards for the North Carolina commercial gill-net fishery.

2.1.2.6 **Estimates of Commercial Gill-Net Discard Statistics**

The best-fitting GLM for the commercial gill-net live discards assumed a zero-altered Poisson distribution (dispersion=3.3). The significant covariates for the count part of the model were year and mesh category and the significant covariates for the binomial part of the model were year, season, mesh category, and management area. The best-fitting GLM for the dead discards assumed a zero-altered Poisson distribution as well (dispersion=2.5). The significant covariates for the count part of the model were year, and season, and the significant covariate for the binomial part of the model was season.

In both the Neuse and Tar-Pamlico rivers, dead discards were higher in large mesh (≥5 inches) gill nets than in small mesh (<5 inches) gill nets, though in some years estimates between the two years were similar. Estimates of total dead discards in the Neuse River ranged from a low of 140 striped bass in 2017 to a high of 342 in 2013 (Table 2.2). Estimates of total dead discards in the Tar-Pamlico River were higher than in the Neuse River and ranged from a low of 306 striped bass in 2017 to a high of 709 in 2013 (Table 2.3). Relatively low estimates of dead discards are potentially an indicator that the distance from shore and tie-down requirements enacted in 2008 have been successful in reducing the number of striped bass discards in the commercial gill net fishery in the Tar-Pamlico and Neuse rivers (Rock et al. 2016).

2.1.3 Recreational Fishery Monitoring

A comprehensive angler creel survey was initiated in January 2004 to identify and estimate recreational striped bass effort and catch in the CSMA.

2.1.3.1 Survey Design & Methods

Survey points in the Neuse River included 45 boat ramps and fishing access points from Milburnie Park in East Raleigh to Lee's Landing on Broad Creek. The river was divided into three segments and all access points in Goldsboro and above classified as the upper zone, sites on Contentnea Creek and downstream from Goldsboro to Core Creek were considered the middle zone, and those downstream from Core Creek, the lower zone. Prior to 2012, the Neuse River was comprised of only two zones and all sites above Contentnea Creek considered the upper.

Access points surveyed on the Tar-Pamlico River include 19 boat ramps and access sites from Battle Park in Rocky Mount to the Quarterdeck Marina in Bath, North Carolina. This system was divided into upper and lower zones and sites upstream of Greenville, North Carolina are considered the upper zone. The Pungo River was surveyed at the Leechville ramp (NC-264 bridge), the Belhaven NCWRC ramp, Wrights Creek (NCWRC) ramp, and Cee Bee Marina on Pungo Creek.

2.1.3.2 Sampling Intensity

Recreational fishing statistics from the CSMA are calculated through a non-uniform stratified access-point creel survey (Pollock et al. 1994) on the Neuse, Pamlico, and Pungo rivers from January–December. Site probabilities were set in proportion to the likely use of the site according to time of day, day of the week, and season. Probabilities for this survey were assigned based on observed effort from past years and direct observation by creel clerks. Morning and afternoon periods were assigned unequal probabilities of conducting interviews and each period represents half a fishing day. A fishing day was defined as the period from one hour after sunrise until one hour after sunset. This is slightly different than in years prior to 2012 when the fishing day was defined as beginning 1.5 hours after sunrise. Monthly sampling periods for each river and zone were stratified accordingly, and all weekend and holiday dates along with two randomly selected weekdays were chosen from each week for sampling.

Tar-Pamlico River anglers in the upper zone were interviewed throughout the spring months (January–May), while anglers in the lower zone were interviewed year round based on the evidence of a year-round fishery and no seasonal closures. Two creel clerks were assigned to this river, with one surveying the upper zone January through May and one clerk surveying the lower zone from January through December. The three zones within the Neuse River were covered with one creel clerk per zone. The lower zone was surveyed from January to December while middle zone surveys were conducted January–May and the upper zone surveys from February–May. The Pungo River was surveyed throughout the year with one creel clerk.

Returning fishing parties are interviewed by a creel clerk at the selected access point to obtain information regarding party size, effort, total number of fish harvested and/or released, primary fishing method, and location.

Creel clerks also obtained socioeconomic information from the angler, including age, state and county of residence, sex, ethnic background, marital status, number of individuals within household, and trip information and expenditures.

2.1.3.3 **Biological Sampling**

Harvested fish are identified, counted, measured to the nearest mm fork length (converted to centerline length and total length for appropriate species), and weighed to the nearest 0.1 kg, while information on discarded fish was obtained from the angler to acquire the number and status of discarded individuals. Scale collections were taken from available fish to determine age of catch. Since 2015, additional biological sampling has included the collection of striped bass fin clips for genetic analysis.

2.1.3.4 **Potential Biases & Uncertainties**

The current dockside sampling methodology only intercepts those individuals accessing inland, joint, and coastal waters via public boating access sites thereby excluding those individuals using private access such as residences, marinas, and community boat ramps. Given the substantial human footprint within the CSMA, it is certain that estimates of effort and catch currently being produced by the NCDMF are under-representative of the actual fishing pressure and associated catch occurring in these systems.

2.1.3.5 **Development of Estimates**

Effort and Catch Estimations

Only striped bass effort and catch data were used to produce estimates. Results were stratified by river, access point, and time of day. Catch was defined as the sum of harvested fish and discarded fish. Discarded fish equaled the sum of fish caught in excess of creel limits (over-creel), legal-sized fish caught and released, and sub-legal fish returned to the water. Daily effort and catch for each river were calculated by expanding observed numbers by the sample unit probability (time of day probability multiplied by access area probability). Total catch estimates for the CSMA and catch estimates for each zone and type of day were calculated based on the Horvitz-Thompson estimator for non-uniform probability sampling (NCDMF 2019b; Pollock et al. 1994). Total effort, in number of trips, over the CSMA and each individual zone and type of day were estimated in the same fashion, as were other extrapolated data. Targeted trips refer to trips where the angler explicitly identified their target species during the sampling interview. If multiple species were targeted, then a primary target species was designated (1st target; see Appendix IV.1 in NCDMF 2017). Approximate standard errors (SE) of the catch and effort estimates within zone and type of day were calculated based on the variance of the observations, the number of days sampled, and the number of days of that type available for sampling (Pollock et al. 1994). Percent standard errors (PSE) for the year are presented by river system and zone. Monthly PSEs within river system and zone are available upon request. Estimated catch-per-unit-effort (CPUE) values were obtained by dividing estimated catch by estimated striped bass trips as well as angler hours (angler-h) in order to identify trends in fishing pressure and angler success. Size structure of striped bass in harvests was described for each zone using length-frequency distributions of observed samples. Fishing party characteristics and methods used during striped bass trips reported by anglers were documented by river and day type. Beginning in 2012, the NCWRC Portal Access to Wildlife Systems (PAWS) was used to house these data and estimate effort and catch. NCDMF and NCWRC staff have been verifying calculations to ensure consistency with the previous work. Please note that estimates of catch and effort are expanded averages presented as whole numbers. Any inconsistency in the total catch and/or effort due to adding across rows or columns presented in this chapter is due to rounding.

2.1.3.6 **Estimates of Recreational Fishery Statistics**

In 2018, recreational landings were 10,844 pounds; however, recreational landings have fluctuated since 2004 and have ranged from lows in 2008 and 2009 to a high of 26,973 pounds most recently in 2017 (Table 2.4). In recent years, both the number of trips and the hours spent targeting striped bass within the CSMA have increased, although recreational harvest dropped sharply by more than half of the 2016 and 2017 values in 2018 (Table 2.4; Figure 2.7). Harvest on the Pungo River has remained consistent at a relatively low level compared to fluctuations in the Tar-Pamlico and Neuse rivers. Since 2011, harvest in the Tar-Pamlico and Neuse rivers has been similar, ranging from 4,000 pounds to 9,000 pounds; however, in 2016 and 2017 there was a sharp increase in recreational harvest (25,260 and 26,973 pounds, respectively; Figure 2.8).

Legal-sized striped bass discards have increased over the past six years, more than doubling in 2017 but returning to more normal levels in 2018 (12,232 legal sized discarded fish; Table 2.4). Fish released that were within the slot limit, have fluctuated since 2004 and have ranged from a low in 2004, 2006, and 2007 of zero fish to a high of 6,779 fish in 2016. In 2018, there were approximately 1,890 discarded striped bass that were within the slot limit. In 2017, mainly due to the large number of undersized striped bass available, there was more than a fivefold increase in the number of discards occurring in the fishery since 2015; however, in 2018 there was a sizeable decline back to more normal levels (34,128 under sized discarded fish; Table 2.4; Figure 2.9). Within the CSMA, there is a significant catch-and-release fishery during the summer in the middle reaches of the Tar-Pamlico and Neuse rivers. Releases during the last ten years have averaged 43,255 fish per year (Table 2.4). CSMA recreational length frequencies show that striped bass are routinely harvested up to 25 inches TL and that few fish under the 18 inch total length minimum size limit are harvested (Figures 2.10, 2.11).

2.2 Fisheries-Independent

2.2.1 Juvenile Abundance Survey (Program 100)

2.2.1.1 **Survey Design & Methods**

In 2017, exploratory juvenile abundance sampling was initiated in the Tar-Pamlico, Neuse, and Cape Fear rivers using trawl and seine nets replicating methods used in the ASMA. The fixed station survey uses an 18-foot semi-balloon trawl with a body mesh size of 0.75-inch and a 0.25-inch mesh tail bag with ten-minute tow times. Beach seines are 60-ft long by 6-ft tall, with a 6 ft by 6 ft by 6 ft bag constructed of 0.25-inch stretch mesh (ISM) in the body and 0.125 ISM in the bag. Seine nets are stretched parallel to shore approximately 30 feet from shore and pulled directly to the beach. NCDMF staff continue to develop and refine these abundance surveys in order to standardize sampling methods and locations. In the Tar-Pamlico River, sampling occurs from Washington, North Carolina to South Creek and in the Neuse River sampling occurs from New Bern to Slocum Creek (Figure 2.12). In the Cape Fear River, sampling occurs in the mainstem as well as in the Northeast Cape Fear, and between Lock and Dams 1 and 2 (Figure 2.13).

2.2.1.2 **Sampling Intensity**

Sampling in the Tar-Pamlico and Neuse rivers occurs during early June and continues through late October. Beach seines are conducted weekly at six locations in the Tar-Pamlico River and at six locations in the Neuse River. Sampling using seines starts the first week of June and continues weekly until the second week of July, for a total of six rounds of sampling and 72 total combined samples. Bi-weekly trawl samples are conducted at six locations in the Tar-Pamlico and at six locations in the Neuse River with ten-minute tow times. Sampling occurs from the third week of July through late October, for a total of eight rounds of sampling and 96 total combined samples.

Sampling in the Cape Fear River occurs during early June and continues through late October. Beach seines are conducted weekly from June through mid-July. Due to the hydrological features of the Cape Fear and tidal nature of the system, distance from shore is at maximum 30 feet. Several sites are unable to be sampled occasionally due to environmental conditions (i.e., high flow/flood conditions, low tide line at the drop-off to 60 feet).

Bi-weekly trawl samples are conducted at fixed locations in the Cape Fear River with ten-minute tow times starting the third week of July and ending in late October.

2.2.1.3 **Biological Sampling**

All striped bass captured are counted and a subsample (maximum of 30) is measured (mm; FL and TL). Genetic samples (fin clips) are collected from all juvenile striped bass captured in the CSMA surveys.

Surface and bottom water temperature (°C), dissolved oxygen (mg/L), secchi depth (cm), and salinity (ppt) are recorded at each station. Submerged aquatic vegetation (SAV) is identified to species and/or genus level.

2.2.1.4 **Potential Biases & Uncertainties**

The Juvenile Abundance Survey employs a fixed-station survey design that is currently exploratory in nature. A fixed-station survey can run the risk of bias if the sites selected do not adequately represent the sampling frame. Additionally, even if the sites adequately cover the sampling frame, the increased variation that would come about from sampling randomly is not accounted for and is therefore at risk of being neglected.

Indices derived from fixed-station surveys such as P100 may not accurately reflect changes in population abundance (Warren 1994, 1995); however, Blanchard et al. (2008) found that fixed-stratified survey design provided the greatest power to identify abundance trends in depleted stocks compared to random or random stratified. The accuracy of the estimates is tied to the degree of spatial persistence in catch data of the species (Lee and Rock 2018). The persistence of the P100 data in the CSMA has not been evaluated.

2.2.1.5 **Development of Estimates**

Because of the exploratory nature of the survey and the short time series and low catches, estimates of juvenile striped bass abundance cannot be developed at this time.

2.2.1.6 **Estimates of Survey Statistics**

In three years of sampling, no juvenile striped bass have been captured in the Tar-Pamlico or Neuse rivers. In the Cape Fear River (Northeast Cape Fear River), a total of 24 young-of-year (YOY) striped bass were captured in 2018 and four were captured in 2019. The YOY striped bass surveys in the CSMA were implemented to have sampling programs in place to monitor natural recruitment in these systems and measure the success of management strategies developed in Amendment 2 to the Striped Bass Fishery Management Plan. If natural recruitment does occur in the CSMA river systems, data from this survey will be valuable for estimating year-class strength and as an index of juvenile abundance in stock assessment models.

2.2.2 Independent Gill-Net Survey (Program 915)

The Fisheries-Independent Gill-Net Survey, also known as Program 915 (P915), employs a random survey design stratified by area and depth that has sampled in Hyde and Dare counties (Pamlico Sound) since 2001 and in the Tar-Pamlico, Pungo, and Neuse rivers since 2003. Sampling in the Cape Fear and New rivers was added in 2008, and sampling in the Central Region (Bogue Sound, Core Sound, White Oak River, etc.) has occurred since 2018.

The goal of the survey is to maintain long-term fisheries-independent surveys that will provide data on catch composition, relative abundance, size, and age for key species taken in the survey. The survey occurs over much of the habitat commonly utilized by striped bass and is used to calculate annual indices of abundance in major North Carolina estuaries for key estuarine species including striped bass.

2.2.2.1 **Survey Design & Methods**

The Independent Gill-Net Survey employs a stratified-random sampling design based on area and water depth for each region. Sampling in the Pamlico Sound is divided into two regions: Region 1 includes areas of eastern Pamlico Sound adjacent to the Outer Banks from southern Roanoke Island to the northern end of Portsmouth Island; Region 2 includes Hyde County bays from Stumpy Point Bay to Abel's Bay and adjacent areas of western Pamlico Sound (Figure 2.14). After grid delineation, each region is further segregated into four similar sized areas to ensure that samples are evenly distributed throughout each region.

Sampling in CSMA rivers is divided into three regions: the Pamlico Region includes areas of the Pamlico River from Washington, North Carolina to the mouth of the Pamlico River (south of Wade Point) and the Pungo River from Haystack Point and west to Belhaven and south to Jordan Creek; and the Neuse River from New Bern to Oriental, North Carolina (from Old House Point south to Sandy Point; Figure 2.15). The Central Region includes coastal waters from West Bay to the White Oak River, including parts of Core and Bogue Sounds (Figure 2.16). The area that includes the North River, Back Sound, southern Core Sound, lower portions of Jarrett Bay, and Barden Inlet (estuarine gill net management unit D-1) were removed from the study area to mitigate concerns over interactions with endangered sea turtles; and the Southern Region includes the New and Cape Fear rivers (Figure 2.17).

Each region is overlaid with a one-minute by one-minute grid system (equivalent to one square nautical mile) and delineated into shallow (<6 ft) and deep (>6 ft) strata using bathymetric data from NOAA navigational charts and field observations. NCDMF staff also considered factors such as obstructions to fishing, safety, and accessibility when evaluating each grid for inclusion in the sampling universe. After grid delineation, the Pamlico Sound and Pamlico/Pungo and Neuse rivers (Pamlico Region) are each segregated into four similar size areas to ensure samples are evenly distributed throughout each region. In the Pamlico/Pungo rivers, areas are assigned as follows: upper Pamlico (Washington, North Carolina to Ragged Point), middle Pamlico (Ragged Point to Gum Point), lower Pamlico (Gum Point to Wades Point), and Pungo (Haystack Point south to Sandy Point). In the Neuse River, areas are assigned as follows: upper Neuse (New Bern to Bay Point), upper-middle Neuse (Bay Point to Kennel Beach), lower-middle Neuse (Kennel Beach to Wilkinson Point), and lower Neuse (Wilkinson Point to Gum Thicket Shoal; Figure 2.15).

The Central region is divided into four areas of roughly equal geographic size (Figure 2.16). Area 1 includes West, Long, Cedar Island, and West Thorofare bays, as well as the northernmost part of Core Sound. Area 2 includes Core Sound and all adjoining waters south of area 1 to a line running west from the Clubhouse in Core Sound through the northernmost section of Jarrett Bay. This is the same line that separates the D-1 and B estuarine gill net management areas. Area 3 includes Newport River and adjoining waters, and eastern Bogue Sound to its midpoint. Area 4 includes western Bogue Sound and the White Oak River. The Central Region utilizes only shallow water sets due to depth limitations.

In the Southern region areas are assigned as follows: upper New (from Wilson Bay to Hines Point line extending eastward to French's Creek), lower New (Hines Point to the intersection of the New River and the Intracoastal Waterway), and the Cape Fear River is considered one area (the northern end of US Army Corps of Engineer's Island 13 south to the mouth of the river; Figure 2.17).

SAS/STAT® software procedure PLAN is used to select random sampling grids within each area (SAS Institute 2004). Sampling gear for the Pamlico, Central, and Southern regions consists of an array of gill nets (30-yard segments of 3, 3½, 4, 4½, 5, 5½, 6, and 6½-ISM webbing, 240 yards of gill net per sample). Catches from this array of gill nets comprised a single sample, while two samples (one shallow, one deep), totaling 480 yards of gill net fished, are completed in a sampling trip. In the Cape Fear River and Central Region, only shallow water samples are completed. If adverse weather conditions or other factors prevented the primary grid in an area from being sampled, alternative grids for that area are randomly selected to increase flexibility and ensure completion of sampling requirements each month.

Nets are deployed parallel or perpendicular to shore based on the strata and common fishing techniques for each area. Gear is deployed within an hour of sunset from February 15 to April 30 and September 1 to December 30 and within an hour and a half of sunset from May 1 to August 31. Gear is fished the following morning to keep soak times at a standard 12 hours. In the Southern Region, soak times are reduced to four hours from April 1 through September 30 and deployed within two hours of sunset and fished in the dark (sampling was modified in July 2008). This action was taken to minimize interactions with endangered and threatened sea turtles. Twine size is based on the twine size most frequently used by local commercial fishermen in the corresponding region (Pamlico, Central, and Southern: #177 or 0.47mm). All gill nets are constructed with a hanging ratio of 2:1. Nets constructed for shallow strata have a vertical height between six and seven feet. All deep water nets are constructed with a vertical height between ten and eleven feet. With this configuration, all gill nets fished the entire water column.

Physical and environmental conditions including surface and bottom water temperature (ºC), salinity (ppt), dissolved oxygen (mg/L), bottom composition, and a qualitative assessment of sediment size are recorded upon retrieval of the nets on each sampling trip. Reported water temperature, salinity, and dissolved oxygen values are the mean of surface and bottom values at deployment and retrieval of nets. All attached submerged aquatic vegetation (SAV) in the immediate sample area was identified to species and density of coverage is estimated visually when possible. Additional habitat data recorded include distance from shore, presence/absence of sea grass or shell, and substrate type.

Each sampling area within each region is sampled twice a month. For the Pamlico/Pungo and Neuse rivers, a total of 32 samples are completed (eight areas x twice a month x two samples; shallow and deep) each full month. For the Southern Region, a total of 12 samples are completed (New River: two areas x twice a month x two samples; Cape Fear River: one area x four times a month x one shallow sample) each month. Samples are collected from February 15 through December 15 each year. The period of December 16 through February 14 is not sampled due to low catch rates and safety concerns associated with fewer daylight hours and cold water and air temperatures during this period.

2.2.2.3 **Biological Sampling**

Each collection of fish (30-yard net) is sorted into individual species groups. All species groups are enumerated and an aggregate weight (nearest 0.01 kilogram, kg) is obtained for most species. Individuals are measured to the nearest millimeter FL or TL according to morphology of the species. Selected species, such as striped bass, are retained and taken to the lab where data on weight, lengths (FL and TL), age structures (otoliths, scales, and/or fin clips), sex, and maturity stage are collected.

2.2.2.4 **Potential Biases & Uncertainties**

Although this program was not designed to specifically target striped bass, striped bass occur in large enough numbers to make this survey a valuable data source to help manage this species. Though this survey does not sample the many shallow creeks and tributaries off the main river stems, habitats frequently used by striped bass, the stratified random design of the survey, and the broad area of habitats sampled in the main estuarine system should be sufficient to detect trends in striped bass relative abundance. The range of gill-net mesh sizes used in this survey would exclude the availability of the smallest and largest individuals to the sample gear.

Many factors affect gill-net catch efficiency including net visibility and turbidity (Berst 1961; Hansson and Rudstam 1995), though setting nets overnight may offset some concerns of net visibility. Efficiency can also decrease if nets become tangled or fouled with debris. In Program 915, performance of individual net panels is evaluated and recorded and catch is evaluated at the sample level (catch from a gang of nets is a sample), so performance of individual net panels may not have a large impact on catch from a sample.

2.2.2.5 **Development of Estimates**

The relative index is defined as the number of striped bass captured per sample (240 yards of gill net). P915 index precision appears to be good for most strata, months, and years, with some exceptions (Southern Region). The deep strata do not track well with the shallow strata after 2011 (Pamlico Region) and prior to 2005 (Pamlico Sound). Overall, the percent frequency of occurrence is lower and PSE values are typically higher in the deep stratum; thus, the deep stratum was dropped from index calculations. The months of April and October to November are used in index calculation because striped bass are most available to the survey during these months. The Pamlico Sound data were not used due to low catch numbers and concerns about stock assignment. Pungo River data were also excluded due to mixed stock concerns. Central Region data were not used due to the very short time series. In the Southern Region, although striped bass catch rates were very low, data from the Cape Fear River data were used to calculate an index. New River data were not used in index calculations because striped bass were seldom captured there.

2.2.2.6 **Estimates of Survey Statistics**

Samples collected from P915 on the Pamlico, Pungo, and Neuse rivers show most striped bass were captured in the upper and middle portions of the rivers. Over the past twelve years, striped bass indices show relative abundance has been higher in the Pamlico/Pungo and Neuse rivers when compared to the Cape Fear River (Table 2.5; Figure 2.18–2.20). Since 2004, striped bass relative abundance in the Pamlico/Pungo and Neuse rivers ranged from 0.84 to 2.66 fish per sample, whereas relative abundance in the Cape Fear River ranged from 0 to 0.14 fish per sample (Table 2.5). Length frequencies from P915 are represented in Figures 2.21 and 2.22. Length frequency distributions generally follow a normal bell-shaped patterns; however, in 2016 and 2017 in the Pamlico/Pungo and 2015–2017 in the Neuse rivers, there was a higher percentage of small fish that could represent the two year classes of striped bass thought to be the result of successful natural reproduction in 2014 and 2015. Due to a commercial and recreational no possession measure implemented in March 2019, fishery-independent programs like P915 will be the only source CSMA striped bass data while Amendment 2 to the N.C. Estuarine Striped Bass Fishery Management Plan is being developed and adopted.

2.2.3 Electrofishing Surveys

2.2.3.1 **Survey Design & Methods**

The objectives of the NCWRC spawning ground surveys are to monitor and quantify population metrics of striped bass migrating to the spawning grounds during spring of each year. Sampling in all rivers normally begins in March and continues into May when water temperatures consistently exceed optimal temperatures for spawning (18–22ºC) and striped bass spawning appears complete. The NCWRC uses a boat mounted electrofishing unit (Smith-Root 7.5 GPP; 5000–7000 W; 120 Hz) and either one or two dip netters to collect striped bass as they are observed. To minimize size selection during sampling, striped bass are netted as they are encountered regardless of size. Electrofishing time (seconds) is recorded for each sample site, and relative abundance of striped bass for each sample is indexed by the number of fish caught per hour (fish/h). Water temperature (°C) and other water quality measurements are recorded at each sample site.

In the Tar-Pamlico River, the electrofishing on the spawning grounds began in 1996. The survey uses a stratified random design, although the sampling design was less rigid in early years of the time series. The sample area extends from Battle Park in Rocky Mount to Tarboro, North Carolina and is divided into three approximately 20 km strata (Tar 1 Battle Park = Battle Park to Dunbar; Tar 2 Dunbar = Dunbar to Bell's Bridge; Tar 3 Bell's Bridge = Bell's Bridge to Tarboro town ramp; Figure 2.23). Weekly sampling events consist of boat electrofishing for approximately 1,800 seconds followed by maneuvering downstream several kilometers and sampling again for another 1,800 seconds within a stratum. The starting location of each sample site is randomly chosen within a stratum on a sample day. Sampling within each stratum is attempted each week, but low flow conditions can prohibit sampling in the upper stratum and flood conditions can prevent sampling all strata.

In the Neuse River, striped bass electrofishing surveys began in 1994. Sampling design has varied throughout the time series, but the survey has typically employed a stratified random design.

During some years, opportunistic sample sites were added if catches were low at random sites. Four strata were developed based on observation of striped bass spawning activity near Kinston, Goldsboro, Smithfield, and Raleigh, North Carolina (Figure 2.24). Only the Kinston and Goldsboro strata were sampled from 1994–1997, but Smithfield and Raleigh strata were added after removal of Quaker Neck Dam in 1998. Additionally, the Kinston stratum was only sampled after 1998 during drought conditions. The two primary sampling strata are located near Goldsboro, North Carolina, which is attempted weekly, but ability to sample the Smithfield, North Carolina and Raleigh, North Carolina strata is highly dependent upon accessibility due to low streamflow. Sample sites approximately 1 km in length are randomly selected within strata in most years; however, longer sites were sampled once per week in 2005, 2008, and 2014.

The Cape Fear River striped bass electrofishing survey was initiated in 2003. The survey is a fixed station design with four fixed sites: Buckhorn Dam (rkm 316) near Moncure, Lock and Dam 3 (rkm 186) near Tar Heel, Lock and Dam 2 (rkm 149) near Elizabethtown and Lock and Dam 1 (rkm 97) near Riegelwood (Figure 2.25). Fixed sites are sampled once weekly for 30 minutes of electrofishing time at each site. Sampling occurs immediately downstream of each dam with lock chambers sampled opportunistically during 2014–2016. Lock chamber sampling contributed little to striped bass catches. The number of sampling events per year ranged from eight to 43. Striped bass abundance during March sampling for American shad is typically low; therefore, March samples were excluded from analysis. The Buckhorn Dam site, added in 2014, was also excluded from final analyses because boating access is limited by low flows, the short time series is inconsistent with other sites, and catch rates are typically low at the site.

2.2.3.2 **Sampling Intensity**

In the Tar-Pamlico River, NCWRC personnel normally begin striped bass sampling in March and continue into May when water temperatures consistently exceed optimal temperatures for spawning (18–22°C) and striped bass spawning appears complete.

NCWRC sampling on the Neuse River is conducted a minimum of once at each stratum per week during spawning season (dependent on adequate streamflow) and generally occurs April–May.

NCWRC personnel collect striped bass on the Cape Fear River weekly in April and May at each of three sample sites (Lock and Dam 1, Lock and Dam 2, Lock and Dam 3). Sampling continues through May until water temperatures exceed 22°C, or until a decline in CPUE signifies spawning completion. In 2009, sampling effort was standardized to approximately 30 minutes at each sample site. Sampling is typically not conducted when streamflow exceeds 20,000 cubic feet per second (cfs), which creates dangerous sampling conditions.

2.2.3.3 **Biological Sampling**

Individual striped bass are measured for TL (mm) and weighed (g). Sex is determined by applying directional pressure to the abdomen toward the vent and observing the presence of milt (male) or eggs (female). Typically, scales are removed from a subsample of fish in the field (target maximum of 15 fish for each sex and 25-mm size-class) on the left side of the fish between the lateral line and the dorsal fin. Before release, untagged striped bass are tagged with an individually numbered internal anchor tag as a cooperative effort with the NCWRC as part of the ongoing NCDMF Multi-Species Tagging Program. A partial pelvic fin clip is collected (approximately 200) and preserved in 95% ethyl alcohol to estimate contribution of hatchery fish to the spawning stock using parentage-based tagging. Striped bass scales are examined at 24X and 36X magnification using a microfiche reader, and annuli are counted to estimate age in accordance with standard protocols (NCWRC and NCDMF 2011). A subsample of 15 scales per 25-mm size-class per sex (as available) was aged by one reader, and a 20% verification subsample by size class was aged by a second reader. Differences between readers were resolved to establish 100% reader agreement. Subsample ages of the primary reader are compared to the secondary reader to determine ageing precision, and the entire sample is re-aged if bias patterns are detected.

2.2.3.4 **Potential Biases & Uncertainties**

Sample stations are often not accessible due to low river levels. This could bias the abundance estimates either by concentrating striped bass in the accessible areas or allowing striped bass to go undetected because of boating obstacles. Biases can also occur due to variation in river discharge; catch rates can be greatly influenced during high and low flows years by making fish less available. Additionally, it is possible that fish may be missed by the dip netter, or that using different numbers of dip netters could impact index calculations. If striped bass are not universally available to the dip netter at all population densities (full range of sizes and ages) during the spawning run, it could bias abundance estimates.

In the Tar-Pamlico River, an attempt is made to distribute sampling evenly among each of the sampling strata; yet, due to low river levels on some sampling days, the lower segment (closer to Tarboro) often receives a slightly greater proportion of the sampling effort. Spring streamflow and associated navigability significantly affect our ability to access spawning areas and may inflate or underestimate striped bass abundance within and among seasons. Analyses of relative abundance indices are further deterred by the lack of well-defined, concentrated spawning grounds such as those found on the Roanoke River.

In the Neuse River, striped bass catch rates can be influenced by streamflow conditions and obstructions to upstream migration. Quaker Neck Dam was removed in 1998, and sample sites further upstream were added thereafter. Upstream strata in Raleigh, North Carolina and Smithfield, North Carolina were added because striped bass had access to the upstream habitats after dam removal. In some years (e.g., 2005, 2008, 2014), entire strata were sampled rather than randomly selecting sites within the strata. Sampling upstream strata is highly dependent upon accessibility due to streamflow, with low flow conditions causing sampling to only occur in lower river strata. In these instances, striped bass potentially utilizing upper river habitats would not be sampled; however, striped bass access to upper river habitats is also limited during low water levels.

In the Cape Fear River, striped bass catch rates are influenced by abundance, habitat below each dam structure, and upstream passage rates through each lock and dam. Since the 1960s, the U.S. Army Corps of Engineers has operated the lock structures each spring for anadromous fish passage. In 2012, a rock arch rapids fishway was completed at Lock and Dam 1 and anadromous fish locking operations ceased at that location. It is likely that this operational change has influenced striped bass catch at each lock and dam due to habitat modification at Lock and Dam 1 and altered passage rates. The number of dip netters has varied (1 or 2) among and within years; however, the number of striped bass encountered on the Cape Fear River never approaches gear saturation with one dip netter; therefore, it is unlikely that catch rates are influenced by a second dip netter.

Other biases could be due to the gear itself. Striped bass of abnormal size may not be as vulnerable to the stunning effects of the electrofishing gear and could escape capture. Electrofishing tends to select for larger fish as they are more visible to the dip netters and have a lower immobilization threshold (Sullivan 1956; Reynolds 1996; Dolan and Miranda 2003; Ruetz et al. 2007). For this reason, the relative abundance of smaller fish is likely biased too low (Reynolds 1996). Collection of fish by netting may be associated with bias. Daugherty and Sutton (2005) demonstrated that capture efficiency was affected by moderate flow rates due to movement of fish out of range of the netters. Schoenebeck and Hansen (2005) indicated how gear saturation caused electrofishing catch rate to be non-linearly related to abundance. Some fish may be less likely to be immobilized by electrofishing gear. Dolan and Miranda (2003) demonstrated how immobilization thresholds were inversely proportional to body size. Conductivity, water temperature, water transparency, dissolved oxygen, depth, flow, and electric current are some of the factors that can impact the efficiency of electrofishing gear (Reynolds 1996; McInerny and Cross 2000; Speas et al. 2004; Buckmeier and Schlechte 2009).

2.2.3.5 **Development of Estimates**

Relative abundance of striped bass for each sample was computed as the number of striped bass collected per hour of pedal time of electrofishing (fish/h). For the Tar and Neuse rivers, relative abundance indices and associated standard errors were calculated for all samples each year. For the Cape Fear River, relative abundance and associated standard errors were calculated for each of the three sample sites and for all sites combined. Annual length-frequency distributions were graphically examined using density ridgeline plots (R packages ggplot2 and ggridges; Wickham 2009; Wilke 2019). Fish age and the proportion of non-hatchery fish were determined using PBT when possible. Ages derived using PBT were used in the matrix model.

2.2.3.6 **Estimates of Survey Statistics**

Tar River

Electrofishing surveys in the Tar River yielded 10,933 individual striped bass from 1996–2018. Total catch ranged from 180 fish in 2017 to 1,429 fish in 2005, and relative abundance ranged between 18.2 and 99.8 fish/h (Table 2.6). Other than peaks in 2005 and 2010, relative abundance was consistently between 25 and 50 fish/h throughout the time series, and an obvious temporal trend was not apparent (Figure 2.26). However, abundance declined during the 2016 to 2018-time period, with the lowest mean CPUE of the survey (18.2 fish/h) occurring in 2018. Striped bass ranged in size from 155–1,190 mm. Length distribution of the Tar River striped bass population was typically unimodal, and the modes progressed in size for several years, suggesting persistence of periodic, strong year classes (Figure 2.27). A high percentage of hatchery fish (83–93%) contributed to Tar River striped bass samples between 2013 and 2016, but the proportion of non-hatchery fish increased in 2017 (30%) and 2018 (59%; Table 1.2)

Neuse River

A total of 4,866 striped bass were collected in the Neuse River electrofishing survey from 1994–2018. Total catch ranged from 58 fish in 2006 to 401 in 2003, and the relative abundance index ranged between 4.4 and 20.4 fish/h (Table 2.7). No trend in relative abundance was apparent since 1994, despite the removal of Quaker Neck dam in 1998 and implementation of conservative harvest limits in 2008 (Figure 2.28). Striped bass have ranged in length from 185–1,140 mm. Length distributions of Neuse River electrofishing samples were typically unimodal and the peak of the distributions occurred around 500 mm or 600 mm (Figure 2.29). Analysis of hatchery contribution indicated the Neuse River striped bass population is mostly composed of stocked fish (Table 1.2). The fish of unknown origin in most years were all large enough to be fish stocked prior to 2010 and therefore not eligible for identification by PBT. In 2018, however, 17% of fish less than 550 mm were non-hatchery.

Cape Fear River

Total catch of striped bass ranged from a low of five fish in 2006 to a high of 202 fish in 2016 (Table 2.8). Striped bass ranged in length from 158–891 mm. The oldest PBT-aged fish was an age-8 male collected in 2018 and age 8 was the maximum possible PBT age in that survey year. There was little trend in relative abundance for all sites combined throughout the time series; however, the relative abundance index increased at Lock and Dam 1 after the construction of the rock arch rapids in 2012 but has been followed by a declining trend since 2016 (Figure 2.30). Relative abundance has remained low at lock and dams 2 and 3, indicating few fish are migrating above Lock and Dam 1. Length distribution increased between 2007 and 2012 as the stock expanded following the initiation of annual stocking in 1998; however, length distributions are truncated throughout the time series, with few larger (e.g., ≥ 700 mm) fish occurring in the survey (Figure 2.31). Additionally, PBT analysis indicates the stock is overwhelmingly hatchery-origin fish (e.g., 93% in 2018; Table 1.2).

2.2.4 Cape Fear Tagging Program

2.2.4.1 **Survey Design & Methods**

In 2011, the NCDMF and NCWRC initiated a fishery-independent mark-recapture study to estimate the total mortality and population size of Cape Fear River striped bass using a tag return model. All healthy striped bass were tagged using internal anchor tag and passive integrated transponder (PIT) tags; only data from PIT tagged fish were used for the model. A combination of electrofishing and hook-and-line gears are used to capture fish throughout the Cape Fear River and its tributaries (Figure 2.32). A boat-mounted electrofishing unit (Smith-Root 7.5 GPP) is the primary gear used (2 dip netters) to catch and tag striped bass. A combination of continuous and ambush (intermittent) electrofishing was used during daylight hours. Continuous shocking assures that all habitat types are sampled and particular habitat types are not preferentially selected. To minimize size selection during sampling, striped bass were netted as they were encountered regardless of size.

Striped bass were also tagged using hook-and-line gear during the Cape Fear River Watch Striped Bass Tournament and by a volunteer recreational fisherman trained by NCDMF staff. Additional fish were tagged using run-around gill nets by NCDMF staff to supplement tagging when environmental conditions were not conducive for electrofishing and as part of targeted sampling for the NCDMF Multispecies Tagging Program. Striped bass captured in the Cape Fear River in NCDMF Independent Gill-Net Surveys (Program 915) were also tagged and released if in good condition.

2.2.4.2 **Sampling Intensity**

Sampling within the Cape Fear River and its tributaries (Brunswick, Black, and Northeast Cape Fear rivers) was conducted by the NCDMF from January to April 2011–2018 (Figure 2.32). Sampling on the Cape Fear River spawning grounds was conducted by the NCWRC at the base of the three lock and dams from April–June; however, additional samples were collected as part of NCDMF P366 (Multi-Species Tagging Program) throughout the year.

2.2.4.3 **Biological Sampling**

All striped bass were scanned for existing PIT tags by NCDMF and NCWRC staff prior to being tagged with an internal anchor tag and an PIT tag. Tagged fish were measured to the nearest millimeter for FL and TL and weighed to the nearest 0.01 kilogram (kg).

2.2.4.4 **Potential Biases & Uncertainties**

PIT tag retention was assumed to be 100% and the tag reporting rate was assumed to be 100% because the tag can only be returned by the NCDMF and NCWRC staff through fishery-independent surveys. No angling fishing effort was involved, so the tagging data cannot inform fishing mortality and cannot separate fishing and natural mortalities. Striped bass with estimated ages of 3–7 were tagged in the study, so the estimates only apply to age 3–7 striped bass.

2.2.4.5 **Development of Estimates**

Prior to October 1, 2014 all data on striped bass tagged and recaptured as part the Cape Fear River Striped Bass Mark Recapture Study were entered in the NCDMF Biological Database (BDB) according to the Program 311 documentation. As of October 1, 2014, all data are entered into the BDB under the Program 366 documentation (Multi-Species Tagging Program). Following the transition period between tagging programs, data collected in Program 311 was reformatted to match the Program 366 documentation to allow recaptured fish to be linked back to the original tagging event in Program 311 and to be accounted for in the new multi-species tagging program (P366) upon re-release.

Data were extracted from the NCDMF Biological Database (BDB) and transformed into a PIT tag matrix. Only fish that were PIT tagged using electro-fishing and hook-and-line gears within the selected time period of 2012–2018 were included as releases. To minimize bias associated with higher post-release mortality, fish tagged using gill nets were excluded from the analysis. Data from the 2011 field season were excluded from the analysis due to low sample size (n=265) and to limit the chance of selection bias. Only tagged fish that were recaptured after seven days at large were included as recapture events. In addition, only the fishery-independent PIT tags recaptures by NCDMF and NCWRC staff were included in the analysis. Recreational anglers were not provided PIT tag readers. Multiple recapture events of the same individual were also removed from the analysis. Also, for ease of analysis, all tagging and recapture events were merged into a single recapture category for the matrix. Missing FL and TL were estimated using: $FL = (TL * 0.945673822) - 5.277089838$ or $TL = 6.206909513 + (1.055954699 * FL$; see Appendix 1).

2.2.4.6 **Estimates of Survey Statistics**

A total of 3,760 striped bass were tagged and released with PIT tags using all gears from 2011 to 2018 (Table 2.9); however, only 3,450 striped bass were included in the tagging model from 2012 to 2018 (Table 2.10). The majority (88%) of the striped bass included in the model were captured using electrofishing gear. Of the fish included in the model, NCDMF tagged 2,507 striped bass in the mainstem of the Cape Fear River and its tributaries (Figure 2.32). The NCWRC tagged 585 striped bass included in the model on the spawning grounds at lock and dams 1, 2, and 3. Volunteer anglers tagged 358 of the striped bass included in the model using hook-and-line gear at various locations in the Cape Fear River and its tributaries as well as the Northeast Cape Fear River.

Mean length of striped bass that were included in the model ranged from 508.5 mm TL in 2015 to a high of 569.0 mm TL in 2018 (Table 2.11). Minimum TL of tagged striped bass ranged from 192 to 337 mm. Maximum TL of tagged striped bass ranged from 800 to 891 mm. The length-frequency distribution of fish included in the model had bimodal peaks at 375 and 500 mm TL length classes (Figure 2.33). Volunteer anglers using hook-and-line gear primarily tagged larger striped bass, while NCDMF and NCWRC staff tagged fish over a wider range of sizes (Table 2.11; Figure 2.33). Using the results of the 2016 and 2017 genotyping and parentage analyses of Cape Fear River striped bass (Figure 2.34), the length-frequency distribution of striped bass included in the tagging model are thought to represent age three to seven striped bass.

A total of 259 striped bass were recaptured from all gears from 2011 to 2018 (Table 2.12). Two-hundred and twenty-one tag returns (6.4% return rate) from electrofishing gear were included in the tagging model from 2012 to 2018 (Table 2.13). Annual return rates ranged from 1.3% (2018) to 11.8% (2013). Striped bass were recaptured in all sampling areas (Brunswick River, Cape Fear River, Northeast Cape Fear River, and at lock and dams 1, 2, and 3); however, most of the recaptures occurred near downtown Wilmington, North Carolina (Figure 2.35). Distance between release and recapture sites ranged from 0 to 65.0 miles with an average of 6.5 miles and a median distance traveled of 1 mile (Table 2.14). Time at large ranged from 8 to 2,232 days with a mean time at large of 457.5 days (Table 2.15).

Mean length of recaptured striped bass included in the model ranged from 481.2 mm TL in 2018 to 611.6 mm TL in 2012 (Table 2.16). Minimum TL of recaptured striped bass ranged from 359 to 469 mm. Maximum TL of recaptured striped bass ranged from 534 to 845 mm. The length-frequency distribution of recaptured striped bass included in the model had had bimodal peaks at 550 and 650 TL size classes and had a similar distribution as those tagged (Figures 2.33, 2.35). Growth varied by time at large, ranging from 0 to 367 mm (Table 2.17). Twenty negative growth values were removed from the growth estimates and were the result of measuring errors. The mean annual growth rate for all recaptured fish included in the tagging model was 0.190 mm/day and ranged from 0.162 to 0.243 mm/day (Table 2.18).

3 DEMOGRAPHIC MATRIX MODEL

3.1 Objectives

Objectives of this analysis were to (1) estimate the growth of striped bass in each of the three CSMA rivers (Tar-Pamlico, Neuse, and Cape Fear rivers) using von Bertalanffy growth (VB) model; (2) estimate age-specific natural mortality using the Lorenzen method and growth parameters; (3) develop a demographic matrix model for each system; (4) conduct sensitivity and elasticity analyses to identify critical age classes and demographic parameters for sustaining population growth; (5) evaluate efficacy of hypothetical restoration strategies to aid in management of striped bass and to prioritize recovery efforts in these three rivers. Objectives (1) and (2) provide information on demographic parameters used in the matrix model. The demographic matrix model does not provide population abundance or mortality estimates.

3.2 Methods

3.2.1 Demographic Matrix Model

An age-structured demographic matrix model was developed to forward project population dynamics for striped bass (Quinn and Deriso 1999; Caswell 2001). In the matrix model, the population vector of abundance N_y in year y is multiplied by the projection matrix A to obtain the population vector of abundance in year y+1. The top row of the projection matrix specifies the fertility for each age group, which serves as the renewal part of the model. The sub-diagonal of the projection matrix specifies the survival for each age group. The matrix model takes the form as below:

$$N_{y+1} = AN_y,$$

where $N_y = [N_{y,1}, N_{y,2}, \ldots, N_{y,T}]$ is a vector of age-specific population size (i.e., number of individuals) from age one to age T in year y, where T is the maximum observed age for striped bass. In this study, $T = 7$ for Cape Fear River and $T = 11$ for Neuse and Tam-Pamlico Rivers based on survey data (previously described programs, with the exception of Program 100) with striped bass otolith and PBT ages (. Notation A represents the projection matrix with a size of $T \times T$:

$$A = \begin{bmatrix} f_1 & f_2 & \cdots & f_{T-1} & f_T \\ S_1 & 0 & \cdots & 0 & 0 \\ 0 & S_2 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & S_{T-1} & 0 \end{bmatrix},$$

where f_t, $t = 1, 2, \ldots, T$ is the fertility (i.e., number of actual recruitment produced per individual) for age t, and S_t is the probability of individuals surviving from age t to the next age class (or from one year to the next year) and can be calculated as:

$\boldsymbol{S_t = \exp(-M_t)}$ for non-harvested population, and

$\boldsymbol{S_t = \exp(-M_t - F_t)}$ for harvested population,

where M and F are instantaneous natural and fishing mortality (per year). Values for f and S are non-negative by definition. In this study, the age-specific natural mortality M_t was estimated using growth information (Section 3.2.2).

The age-specific population abundance can be forward projected by using the projection matrix, which will eventually become stationary. The dominant eigenvalue of this projection matrix (A) equals the population growth rate (λ); the right and left eigenvectors of the projection matrix give the stable size structure of the population and the reproductive contribution of each age class, respectively (Caswell 2001).

3.2.2 Growth

In this study, the von Bertlanffy growth (VB) model was used to describe individual growth (von Bertalanffy 1938):

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

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

where j indexes the jth population, L_∞ is the asymptotic length (mm), K is the Brody growth coefficient (yr^{-1}), t_0 is the age at which fish has a length of zero, L_i and t_i are the length and age of each individual i, respectively. The observed individual length $L_{i,j}$ was assumed to follow a lognormal distribution.

In this study, a Bayesian hierarchical approach was used to estimate parameters, in which priors for the growth parameters ($L_{\infty,j}$, K_j, and $t_{0,j}$) in the VB model were hierarchically structured. The growth parameters were assumed to vary across populations but were constant over time. Specifically, logarithm of population-specific parameters $L_{\infty,j}$, and K_j were assumed to follow a multivariate normal distribution (*MVN*), and $t_{0,j}$ to follow a normal distribution which were further governed by population-average parameters:

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

$$t_{0,j} \sim N\left(\bar{t}_0, \sigma^2_{t0}\right),$$

where $\bar{L}_\infty$, $\bar{K}$ and $\bar{t}_0$ are population-average parameters describing the growth across populations, and they further follow a uniform distribution. The standard deviation σ_{t0} was also uniformly distributed. The $\sum$ denotes the variance-covariance matrix that was modeled with an inverse-Wishart distribution (Gelman and Hill 2007):

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

where $\sigma_{L\infty}$ and σ_K are standard deviations of lnL_∞ and ln$K$ across populations, and represent spatial variability in growth; φ is the covariance of lnL_∞ and ln$K$ across populations. To improve model convergence given highly negatively correlated L_∞ and K in VB model, these two parameters were jointly modeled with a negative correlation (Kimura 2008; Midway et al. 2015).

The posterior distribution was obtained through the Metropolis-Hasting algorithm using Markov Chain Monte Carlo (MCMC) 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 4.0.1) was used to run the Bayesian analysis. The data collected from the above fishery-independent surveys during 2004 to 2017 were used to fit the VB growth model.

3.2.3 Mortality

The Lorenzen method (Lorenzen 2000; Lorenzen 2005) was used to estimate age-specific natural mortality (M_t) for striped bass, which assumes M_t is inversely proportional to the length at age t (L_t):

$$M_t = M_0 L_t^d,$$

where $M_0 > 0$ and $d < 0$ are constants. The constant M_0 can be determined by setting the integral of M_t equal to the integral of a constant natural mortality M_c:

$$\int_{t_{\min}}^{t_{\max}} M_t \, dt = M_c \left(t_{\max} - t_{\min} \right),$$

where t_{max} and t_{min} are the maximum and minimum ages for calculating M_t. In this study, $t_{max} = 7$ for Cape Fear River, $t_{max} = 11$ for Neuse and Tar-Pamlico Rivers, and $t_{min} = 1$ was fixed for all three rivers. Let $d = -1$ and L_t following the VB growth model, i.e., $L_t = L_\infty \left(1 - \exp\left(-K\left(t - t_0\right)\right)\right)$, then M_0 can be solved as:

$$M_0 = \frac{M_c \left(t_{\max} - t_{\min} \right) L_\infty K}{K\left(t_{\max} - t_{\min} \right) + \ln\left(\dfrac{1 - \exp\left(-K\left(t_{\max} - t_0\right)\right)}{1 - \exp\left(-K\left(t_{\min} - t_0\right)\right)} \right)}.$$

In this study, L_∞ and K were set to be the posterior medians estimated from the above growth analysis (Section 3.2.2; Table 3.1). Because natural mortality is one of the most uncertain and difficult-to-estimate parameters in stock assessments (Vetter 1988; Clark 1999), M_c was modeled using a hierarchical structure in this study. Compared with a non-hierarchical model where the projection matrix is further governed by parameters, in a hierarchical model, both parameters and hyper-parameters determine values in the projection matrix (Caswell 2001; Jiao et al. 2009; Li and Jiao 2015). In the hierarchical model, the M_c followed a normal distribution $N\left(\bar{M}, \sigma_M^2\right)$ with a mean natural mortality $\bar{M}$ and a standard deviation σ_M, and the mean was further governed by hyper-parameters m_1 and m_2 in a uniform distribution $U(m_1, m_2)$:

$$M_c \sim N\left(\bar{M}, \sigma_M^2\right),$$

$$\bar{M} \sim U\left(m_1, m_2\right).$$

In this study, the standard deviation of natural mortality (σ_M) was calculated as:

$$\sigma_m = CV \times \bar{M},$$

where CV is the coefficient of variation and was randomly assigned a value between 20 and 40%, which has been used as a reasonable uncertainty level in fisheries data analyses (Jiao et al. 2009; Li and Jiao 2015). In this study, $m_1 = 0.6$ and $m_2 = 1$ for age 1–3, and $m_1 = 0.1$ and $m_2 = 0.5$ was fixed for age 4+. Such parameter values resulted in a natural mortality pattern (Figure 3.1) that approximates previous estimates for striped bass in Neuse River (Bradley et al. 2018b).

The fishing mortality (F) can be scaled by the age-specific fishery selectivity (g_t) to obtain the age-specific fishing mortality (F_t):

$$F_t = Fg_t \, .$$

In North Carolina, no striped bass harvest is allowed in the Cape Fear River whereas both commercial and recreational harvest occurred in Neuse and Tar-Pamlico rivers prior to spring 2019. In this study, fishery selectivity was estimated (Table 3.1) using 2017 fishery-dependent data for Neuse and Tar-Pamlico rivers and using 2017 fishery-independent data for the Cape Fear River (see section 6). The previous estimates for fishing mortality in the Neuse River ranges from 0.53 to 0.71 (Rachels and Ricks 2015; Bradley et al. 2018b). Therefore, in this study, the matrix model was tested at six fishing intensities (i.e., $F = 0, 0.2, 0.4, 0.6, 0.8, 1$) to represent possible fishing intensities in these three systems.

3.2.4 Reproduction

In this study, a pre-breeding population was assumed and thus, the age-specific fertility (f_t) is a product of the age-specific fecundity (E_t, the number of eggs produced per mature female), the proportion of viable eggs (x), the survival of offspring from birth to next census (S_0, i.e., the survival of offspring through the first year), and the age-specific maturity (w_t):

$$f_t = E_t \times x \times S_0 \times w_t \times 0.5,$$

where the value of 0.5 was multiplied because a 1:1 sex ratio was assumed. In this study, $x = 0.64$ based on a study for the Neuse River (Buckley et al., 2019), and $S_0 = 0.000017$ based on a single field study that measured the survival of eggs, yolk-sac larvae (from hatching to complete absorption of yolk-sac), and postlarvae (from yolk-sac absorption to demersal or fully developed juvenile) for striped bass (Table 1 in Dahlberg 1979).

In this study, the age-specific fecundity (E_t)) was derived from the survey data collected from the Neuse River and Tar-Pamlico River during 2013–2014 (Knight 2015):

Cape Fear: $\ln(E_t) = 12.484 + 0.205t$,

Neuse: $\ln(E_t) = 12.52 + 0.214t$,

Tar-Pamlico: $\ln(E_t) = 12.429 + 0.203t$,

where t is age, and the relationship for Cape Fear River was developed by pooling all data from the Neuse River and Tar-Pamlico River because no fecundity data are available for the Cape Fear River.

In the survey data for Neuse and Tar-Pamlico rivers, striped bass older than three years old are 100% mature (Knight 2015); however, striped bass in the Roanoke River may reach 100% maturity at age five or six (Olsen and Rulifson 1992; Boyd 2011). Therefore, in this study, $w_i = 0$ for age ≤ 2 and $w_i = 1$ for age ≥ 5. Due to uncertainty in maturity estimates for ages 3–4, similar to natural mortality, a hierarchical structure was developed to describe the maturity for these two ages:

$$w_i \sim N\left(\bar{w}, \sigma_w^2\right),$$

$$\bar{w} \sim U\left(w_1, w_2\right),$$

$$\sigma_w = CV \times \bar{w},$$

where CV = 20-40%, $w_1 = 0.29$ and $w_2 = 1$ for age 3, and $w_1 = 0.94$ and $w_2 = 1$ for age 4.

3.2.5 Elasticity and Sensitivity

In a demographic matrix model, elasticity analysis can help compare the relative influence of different age classes to the population growth rate (λ), and therefore identify critical age classes to focus on in management. The elasticity is defined as the proportional change in population growth rate in response to the proportional change in matrix parameters θ (Caswell 2001). The definition of sensitivity is similar to elasticity except that sensitivity is defined using the absolute change in growth rate and in matrix parameters. In this study, elasticity was calculated through Monte Carlo simulation (Jiao et al. 2009; Li and Jiao 2015):

Elasticity $\frac{\theta}{\lambda}\frac{d\lambda}{d\theta} = \frac{\theta}{\lambda}\frac{\Delta\lambda}{\Delta\theta}$,

Sensitivity $\frac{d\lambda}{d\theta} = \frac{\Delta\lambda}{\Delta\theta}$,

where θ can be survival or fertility for each age class.

3.2.6 Evaluation of Fishery Management Strategies

In this study, five stocking strategies were evaluated and under each stocking strategy, six fishing strategies were tested. Simulations were run for the Neuse River only because the conclusions would be consistent across rivers given the similar life history characteristics among populations. In the stocking scenarios stocked fish were assumed to be age 1; Phase II fish are hatched in the spring and released in the winter near the end of their first year of life. The five stocking strategies included: (1) no stocking; (2) stocking 100,000 fish per year with 2-years stocking and 2-years no stocking alternating for 15 years (8 years of stocking in total); (3) stocking 500,000 fish per year with 2-years stocking and 2-years no stocking alternating for 15 years (8 years of stocking in total); (4) stocking 100,000 fish per year with 8-years continuous stocking; (5) stocking 500,000 fish per year with eight-years continuous stocking.

The six fishing strategies included: (1) baseline scenario in which the fishing mortality was set at $F = 0.53$ based on the estimates for Neuse River (Bradley et al., 2018b); the fishery selectivity in Table 3.1 was used; the fishery selectivity in Table 3.1 was used; (2) 26-inch (approximately five years old) minimum size limit scenario in which fishery selectivity $g_t = 1$ for fish of five years and older and $g_t = 0$ for fish younger than five years; (3) 2-year closure scenario in which $F = 0$ for the first two years; (4) 5-year closure scenario in which $F = 0$ for the first five years; (5) 10-year closure scenario in which $F = 0$ for the first 10 years; (6) a scenario with 5-year closure, followed by 26-inch minimum size limit.

A 15-year time period was used according to Morris and Doak (2004) who suggests a minimum number of ten years to examine the population trend in the population viability analysis. Additionally, a 15-year time period is relatively sufficient given the observed maximum age of striped bass (11 years) in our study systems. The initial population size was set at 5,000 fish. The initial size structure was constructed based on information from the most recent surveys on the Neuse River (North Carolina Wildlife Resources Commission, personal communication; Table

3.2). The adult abundance (age ≥ 3 year) and old adult (age ≥ 6 year) abundance over time was tracked for each scenario. Results were obtained from 10,000 Monte Carlo simulation runs. For each run, parameter values in the projection matrix were randomly drawn from corresponding statistical distributions. Extreme values (i.e., within 2.5% of the lower and upper bounds of the distribution) were discarded to avoid unrealistic combinations of parameter values.

3.2.7 Results

The Neuse River had the largest population growth rate estimates with medians ranging from 0.87 to 1.13, followed by Tar-Pamlico (medians ranging from 0.86 to 1.1) and Cape Fear rivers (medians ranging from 0.75–1.01; Table 3.3). Estimated population growth rates and the probability of population increasing (i.e., Pr ($\lambda > 1$)) declined with increased fishing intensity. Even without fishing allowed, the striped bass in these three rivers would barely sustain, with the medians of population growth rate being slightly above one, and the probability of population growing ranging from 0.52 to 0.8. At fishing mortality rates ≥ 0.4, median population growth rates for all three populations dropped below one, and there was less than 50% probability that the population would grow.

Elasticity of population growth rate to survival and fertility and age-specific reproductive contribution showed similar patterns across three rivers (Figure 3.2). Regardless of fishing intensity, survival and fertility of younger fish influenced population growth rate more than older-age fish, whereas older fish contributed more than younger fish to reproduction due to higher fecundity. As fishing mortality increased, the influence of older fish survival and fertility on the population growth rate decreased, while the influence of younger fish increased. Population growth rate was sensitive to the proportion of viable egg, and age-0 survival but not to the asymptotic length parameter in the growth model (Figure 3.3). As the viable egg proportion and age-0 survival increased, population growth rate estimates increased.

Stocking scenarios produced greater abundance than the scenario with no stocking, and stocking more fish resulted in greater abundance than stocking fewer fish (Figures 3.4 and 3.5). Regardless of stocking strategy, the fishing strategy with 10-year closure was most effective to increase abundance for adults (age 3+), followed by the strategy with 5-year closure combined with 26-inch size limit after closure. The 26-inch size limit strategy was competitive with the closure-size limit combo strategy to increase adult and older adult abundance in stocking scenarios. However, in the no stocking scenario, it was far less effective than the combo strategy. Although 10-year closure was the most effective for age-3+ adults during the first 13 years of simulation, its effectiveness to increase old adult abundance was reduced dramatically once the closure ended and fishing selectivity reverted to the 18-inch size limit, and it became less effective than the combo strategy in no stocking scenario, and less effective than both the 26-inch size limit strategy and the combo strategy in stocking scenarios during the last two years of simulation (Figure 3.5).

3.3 Discussion

Fishing activities driven by fishery selectivity that targets older and larger fish not only reduce fish abundance but also alter age structure of the population. As fishing intensity increased, the influence of older fish survival and fertility to population growth rate decreased in response to massive reduction in their abundance due to fishing. The influence of younger fish survival and fertility increased as fishing mortality increased due to their increased proportion in population abundance. Reproductive contribution by each age group depends on both abundance and fertility of the age group. Although fishing reduces abundance of older fish faster than younger fish, older fish have far greater fertility than younger fish. Thus, the fertility of young fish is too low to offset the reduction in its abundance, and its reproductive contribution became smaller as fishing mortality increased. As the reproductive contribution of younger fish declined with increased fishing mortality, the contribution of older fish rose. This is congruent with Secor (2000), who found that older striped bass contribute far more to reproduction than young age classes, even in populations experiencing fishing mortality. Given that fishing mortality typically impacts older age-classes more than younger age-classes, it is apparent that even relatively moderate levels of fishing mortality can substantially reduce the reproductive potential of a population.

Sensitivity analysis suggests the demographic matrix model is very sensitive to several assumed values. Choice of age-0 survival (S_0) has the greatest influence on model results, with relatively small parameter changes resulting in dramatic changes to the population growth rate (see Table 3.3). In fact, the modeled variability in S_0 was likely minimal compared to realized S_0 in systems with natural striped bass recruitment, which regularly experience order-of-magnitude changes (e.g., Cowan et al. 1993; Martino and Houde 2010). Regardless, the choice of any S_0 is arbitrary as PBT analyses and NCDMF juvenile surveys have demonstrated little age-0 survival in all three systems. This prevents interpretation of the estimated level of the population growth rates; rather, the demographic matrix model best serves as a comparison of the relative efficacy of the several management scenarios investigated.

Finally, the maximum age in each river system was based on the oldest observed fish aged using either PBT or otoliths. NCWRC scale-aged fish have demonstrated longevity greater than the modeled maximum age in each system, and striped bass are known to reach ages in excess of 20 years throughout their range including stocks in other regions. Research has found, however, that scales underestimated ages of older fish when compared to otoliths (Welch et al. 1993; Secor et al. 1995; Liao et al. 2013). Additionally, results of the Age Comparison study (see section 7) show that otoliths provide a more precise and accurate age estimate for CSMA striped bass when compared to scales. Nevertheless, the demographic matrix model results as evaluated with a maximum age of 7 years in the Cape Fear River and 11 years in the Neuse and Tar-Pamlico rivers are likely conservative; models that allow survival to older age classes will likely result in greater divergence in model results among the fishing mortalities investigated.

4 TAGGING MODEL

4.1 Objectives

Objectives of this analysis were to (1) estimate total mortality of striped bass (*Morone saxatilis*) in Cape Fear River using a tagging model; (2) estimate abundance of striped bass in Cape Fear River based on Jolly-Seber method.

4.2 Methods

4.2.1 Tagging Data

PIT tagging data from 2012 to 2018 were used in this analysis. No recreational fishing effort was involved in this study; PIT tags could only be returned by NCDMF or NCWRC staff through fishery-independent surveys. The tagging data cannot inform fishing mortality and cannot separate fishing and natural mortalities, and thus only total mortality was estimated in this study. Striped bass ages were estimated to range from 3–7 years old based off of length frequency data, so the estimated total mortality only applies to striped bass ages 3–7.

4.2.2 Tagging Model

In the tagging model (e.g., Jiang et al. 2007; Bacheler et al. 2009; Ellis et al. 2018), the observed number of tags returned from fish tagged and released in period i and captured in period j ($j \geq i$), X_{ij}, follows a multinomial distribution with parameters R_i and P_{ij}. The parameter R_i is the total number of tags from fish tagged and released in period i, P_{ij} is the probability of a tag returned from a fish tagged and released in period i being captured in period j. In the model, $\sum_j X_{ij} = R_i - X_{i,\ unknown}$ and $\sum_j P_{ij} = 1 - P_{i,\ unknown}$ where $X_{i,\ unknown}$ and $P_{i,\ unknown}$ are the total number of tags and the probability of a tag returned from fish tagged and released in period i with unknown destiny (i.e., have never been captured) by the end of the study period. The parameter P_{ij} can be estimated as follows:

$$P_{ij} = \phi\lambda\rho S_c \left(1 - S_{ij}\right)\frac{U_j}{U_j + Z_j + \Omega},$$

$$S_{ij} = \begin{cases} \exp\left(-U_j - Z_j - \Omega\right) & \textit{when survey occurs in period } j \\ \exp\left(-Z_j - \Omega\right) & \textit{otherwise} \end{cases},$$

where S_{ij} is the survival of tags in period j from fish tagged and released in period i, ϕ is survival from tagging procedure, ρ is immediate tag retention probability, λ is tag reporting rate, and Ω is tag loss. In this study, PIT tags were used and only NCDMF and NCWRC staff can return the tags through a fishery-independent survey, and thus it was assumed that $\phi = 1$, $\rho = 1$, $\lambda = 1$ and $\Omega = 0$. The parameter S_c is cumulative survival of tags from fish tagged and released in period i before being captured in period j and can be calculated as:

$$S_c = \begin{cases} 1 & \textit{when } j = i \\ \prod_{v=i}^{j-1} S_{iv} & \textit{when } j > i \end{cases}.$$

Major assumptions for the tagging model in this study include: (1) tagged individuals mix completely with untagged population given that there were 7 days allowed for mixing before starting to recapture fish; (2) all tagged individuals have the same survival and recapture probabilities; (3) tagged individuals have independent fates; (4) a monthly time-step is assumed (i.e., j represents jth month); however, the total mortality was estimated on a yearly basis and was assumed constant over months within the year (i.e., $Z_j = Z_y / 12$), where y is the year that month j corresponds to; (5) tags from the fish that were caught and released with tag intact were treated as though tags were cut off; the new subsequent captures of those fish were ignored (Bacheler et al. 2009).

4.2.3 Bayesian Estimator

In this study, the Bayesian approach was used to estimate parameters. The posterior probability of a parameter set (θ) given the observed data (X), $p(\theta|X)$ can be calculated as follows:

$$p(\theta|X)=\frac{f(X|\theta)\pi(\theta)}{\int_{\theta} f(X|\theta)\pi(\theta)d\theta},$$

where $f(X|\theta)$ is the probability density function of the observed data X given the parameter set θ, and $\pi(\theta)$ is the prior probability, i.e., the probability density function of θ. In the tagging model, the observed data X include the number of tags returned from each time period (X_{ij}), and the parameter set θ includes the total number of tags from fish tagged and released (R_i) and the probability of a tag returned (P_{ij}). With multinomial distribution, the density function $f(X|\theta)$ is:

$$f\left(X_{11},\ldots,X_{IJ}\,\middle|\,P_{11},\ldots,P_{IJ},\, R_1,\ldots,R_I\right)=\prod_i\left(\frac{R_i!}{X_{i1}!\cdots X_{iJ}!X_{i,\,unknown}!}P_{i1}^{X_{i1}}\cdots P_{iJ}^{X_{iJ}}P_{i,\,unknown}^{X_{i,\,unknown}}\right),$$

where J is the end return time period and I is the end release time period. The posterior distribution was obtained through the Metropolis-Hasting algorithm using Markov Chain Monte Carlo (MCMC) simulation (Hilborn et al. 1994; Hoff 2009). Three concurrent chains were run with a total of 50,000 iterations for each chain. The first 20,000 iterations were discarded as burn-in and every 10th of the remaining samples from each chain were saved for analysis. The software JAGS (version 4.0.1) was used to run the Bayesian analysis.

4.2.4 Model Priors

Non-informative priors (i.e., uniform priors) were used for parameters in the tagging model, except for total mortality Zy (Table 4.1). In this study, a hierarchical prior was used for *Zy* where *Zy* follows an unknown lognormal distribution centering around $\bar{Z}$ that is further governed by a uniform distribution bounded by z_1 and z_2:

$$Z=\bar{Z}\exp(\varepsilon_Z)$$
$$\bar{Z}\sim Uniform(z_1,\, z_2),$$

where $\varepsilon_Z\sim Normal(0,\,\sigma_Z^2)$ is a random error representing the variation in total mortality. Based on previous studies, $z_1 = 0.1$ and $z_2 = 1.5$ (Bradley et al. 2018b).

4.2.5 Abundance Estimate

The Jolly-Seber method (Seber 1982) was used to estimate abundance of age 3–7 striped bass in the Cape Fear River:

$$N_y=\frac{R_y}{\alpha_y},$$

where N is abundance, y indexes year, R is the total number of tags from fish tagged and released, and α is the capture probability, i.e., the probability that a tagged fish is captured. The tag recovery probability can be calculated as:

$$\alpha_y = \left(1 - \exp\left(-U_y - Z_y - \Omega\right)\right)\frac{U_y}{U_y + Z_y + \Omega}.$$

4.3 Results

Median estimates of instantaneous total mortality (Z) for age 3 to 7 striped bass ranged from 0.53 (2017) to 1.13 (2014; Table 4.2; Figure 4.1). Total mortality estimates were high in 2012 (median = 0.96; 95% credible interval (CI) = 0.53–1.43) and 2014 (median = 1.13; 95% credible interval (CI) = 0.71–1.47). In 2013, total mortality was low (median = 0.58; 95% credible interval (CI) = 0.21–1.00), and declined in 2015, until another increasing in 2018. Early years (2012–2014) were associated with less uncertainty than the later in the time period (2015–2018).

Abundance estimates ranged from 1,578 (2017) to 10,983 (2012) (Table 4.2; Figure 4.1). Abundance estimates consistently declined over the study period (2012–2018). Abundance in 2018 (median = 1,914; 95% CI = 1,415–,765), was reduced to less than 20% of the abundance in 2012 (median = 10,893; 95% CI = 5,418–23,479). Abundance estimates had greater uncertainty in earlier years of the study period. Median capture probability estimates ranged from 0.04 (2012) to 0.22 (2017; Table 4.2).

4.4 Discussion

Previous estimates of total mortality for adult striped bass in Neuse River, Tar-Pamlico River, and Albemarle Sound-Roanoke River ranged from 0.33 to 1.52 on average (Callihan et al. 2014; Harris and Hightower 2015; Rachels and Ricks 2015; Bradley et al. 2018b). These systems are more intensively subject to fishing than Cape Fear River, which would result in higher total mortality in these systems if assuming similar natural mortality. Total mortality estimates for the Cape Fear River fell within the range from previous studies on North Carolina striped bass.

Collier et al. (2013) estimated total mortality and abundance for adult striped bass in the Cape Fear River using tagging data from 2011 to 2013. The study estimated an average total mortality of 0.24 per year (95% CI = 0.02–0.59), a median annual abundance of 15,209 with a 95% CI between 5,000 and 25,000 (Figure 4.1). The authors reported a capture probability ranging from 0.01 to 0.03. Compared to estimates from Collier et al. (2013), total mortality estimates for 2012 and 2013 had a median of 0.96 and 0.58 respectively, which is three times and 1.4 times greater than their estimates. Estimates of abundance for 2012 was not significantly different from the Collier et al. (2013), and estimates of capture probability for 2012 (median = 0.04; 95% CI = 0.02–0.07) were close to the range reported by Collier et al. (2013); however, abundance estimates for 2013 (median = 4,535; 95% CI = 3,024–6,921) were 70% lower, and capture probability estimates were 3 to 4 times higher than the Collier et al. (2013) estimates (Figure 4.2). Collier et al. (2013) accounted for fish movement between four locations within the Cape Fear River, emigration and immigration, which may have contributed to their lower total mortality estimates, lower capture probability estimates and higher abundance estimates compared to this study. While striped bass in the Cape Fear River are thought to remain in the river year around, Raabe et al. (2019) detected a fish leaving the telemetry array at the river mouth and in 2017 a fish tagged with an anchor tag at Lock and Dam 1 was recaptured by a recreational angler on the Roanoke River.

Estimates of striped bass recreational fishing effort and discards reported by the NCDMF recreational creel survey were substantially higher in 2014 compared to other years (2013, 2015–2018) surveyed (Table 4.3; Figure 4.3), although survey probabilities may be imprecise because they are not set up for striped bass and the estimates have high PSEs. The estimated recreational fishing effort (number of hours fished) was approximately 1.5 times the effort reported in 2016 and three times those in 2013 and 2015; the estimated discards in 2014 were 3 to 64 times higher than other years in the survey. Thus, the high total mortality estimates in 2014 in this study may be caused by high fishing and discard mortalities. In September of 2018, Hurricane Florence made landfall at Wrightsville Beach, North Carolina, causing extensive damage and extreme flooding along the Cape Fear River and its tributaries. Heavy flooding after the storm led to large fish kills due extended periods of hypoxic conditions along the Cape Fear River, likely contributing to the increased mortality estimates observed in 2018. NCDMF staff observed 574 dead striped bass at Battleship Park over the course of two days following the storm (Figure 4.4). Twenty-three anchor tags were recovered from fish tagged with both anchor and PIT tags. NCDMF staff could not access the Wilmington Regional Office due to the hurricane, thus these fish were not scanned to determine if PIT tags were present. If these fish were included in the model, the 2018 total mortality estimates would likely be much higher than those reported for just PIT tag returns alone. The small number of tag returns during 2015–2018 may have also contributed to the high uncertainty of total mortality estimates in this time period. An average of 46 tags were returned per year during 2012–2014, whereas an average of 21 tags were returned during 2015–2018. The low uncertainty in capture probability estimates in early years numerically led to the large variation in abundance estimates given the total number of fish released annually was a known constant.

The use of PIT tags has proven to be an effective means to collect biological data for a variety of species (Gibbons and Andrews 2004; Marvin 2012). While the cost of PIT tags exceeds that of traditional anchor tags, their high retention rate, low mortality associated with tagging, and their ability to retain a fish's identity after multiple recapture events makes them ideal in systems such as the Cape Fear River. In 2019, additional money was secured through the NCDMF's Multi-Species Tagging Program (P366) to continue PIT tagging striped bass in the Cape Fear River. Models used to estimate parameters such as mortality and abundance often have the highest amount of uncertainty for the terminal year. Thus, adding additional years of data to the model should lower the variation in abundance and uncertainty of the total mortality estimates observed during 2015–2018. This additional data should also give managers a better understanding of the true impact of Hurricane Florence on striped bass in the Cape Fear River.

5 GLM ANALYSIS ON COMMERCIAL & RECREATIONAL FISHERIES DATA

5.1 Objectives

The linear regression analysis was extended in Rachels and Ricks (2018) by adding recreational data for the striped bass population in the Neuse River. The goal of this analysis was to identify important factors that influence the response variable (i.e., the relative annual variation in spawning stock mortality). The details of Rachels and Ricks (2018) analysis can be found in Appendix 2.

5.2 Methods

The time period of the analysis was confined to 2004–2015 because recreational data are only available since 2004. Along with the four predictor variables that were used in Rachels and Ricks (2018), namely commercial gill-net effort (number of trips), commercial harvest (kg), summer temperature (ºC) and summer dissolved oxygen (DO, mg/L), five predictor variables were added to represent recreational fishing activities in this analysis. These five recreational variables included recreational effort (number of trips), recreational harvest (kg), recreational discard (number), recreational total catch (number) and recreational total removal (number, catch + dead discard). The same exact assumptions and procedures were followed as in Rachels and Ricks (2018). These assumptions included: (1) a simple linear regression was applied; (2) original data (both response and predictor variables) were transformed by taking the difference between every two years, i.e., the variation relative to previous year (relative annual variation) and the transformed data were then used in the regression; (3) a one-year delay was applied to all predictor variables except commercial harvest. The one-year delay for commercial gill-net and environmental factors were based on Rachels and Ricks (2018), and the one-year delay for recreational variables was based on the same rationale that the recreational fishing occurs in fall, after the survey sampling season for the current year.

The sensitivity of model outcomes to a series of scenarios was explored further (Figure 5.1). These scenarios included a combination of (1) how long time series of data to use, i.e., a time period of 1994–2015 as in Rachels and Ricks (2018) or a shorter time period of 2004–2015 when recreational data are available; (2) whether or not to apply one-year delay to the variable commercial gillnet effort; fishing effort and fishery harvest are generally considered to occur simultaneously and to associate together; (3) whether or not to transform data, i.e., using relative annual variation or using original data; (4) what error distribution to assume when using original data, i.e., normal error as in Rachels and Ricks (2018) or lognormal error that can describe the possible nonlinear relationship between response and predictor variables; lognormal error cannot be applied when using transformed data due to negative values in response variable that are generated during transformation, and thus only normal error was applied. A stepwise variable selection procedure was used to select the most important factors based on Akaike information criterion, AIC (e.g., Li et al. 2016). This procedure starts with a model only including an intercept. At each step, the variable that reduces the AIC value most or shows the most significant effects (i.e., the smallest P-value) on the response variable will be selected into the model. This step is repeated until including an additional variable will not lead to substantial improvement to model goodness-of-fit.

5.3 Results

A total of 31 candidate models were tested, of which eight models had ΔAIC_c values less than two (Table 5.1). In this analysis, the eight candidate models with a ΔAIC_c value less than two are considered equally plausible in terms of goodness-of-fit and parsimony. The variables contained in these eight models included commercial effort, commercial harvest, recreational effort, recreational discard, recreational total catch and recreational harvest. The model with commercial effort had the highest weight (w_i=0.15), followed by the model with commercial effort and commercial harvest (w_i=0.086), the model with recreational effort (w_i=0.081), and the model with recreational discard (w_i=0.071). This result suggested the relative annual variation in both commercial and recreational fisheries related factors such as fishing effort and removal (including harvest and discard) could play an important role in driving the relative annual variation in total mortality of striped bass in Neuse River.

Sensitivity results showed that model outcomes could be very sensitive to the assumptions that were tested (Figures 5.1 A–C). First, commercial gill–net effort being one-year lagged had a great impact on the outcomes, especially when using data from 2004–2015. For example, using transformed data from 2004–2015, when commercial gill–net effort was not one-year lagged, none of the predictor variables were significant, regardless of including recreational information; however, when commercial gill–net effort was one-year lagged, the variables commercial gill–net effort, commercial harvest, and DO were significant (Figures 5.1 B and C). Second, use of transformed data versus non-transformed data greatly influenced the model outcomes, especially for data from 2004–2015. For example, using non-transformed data from 2004–2015 with recreational information considered and no one-year lag being applied to commercial gill–net effort, the variable commercial gill–net effort was selected as the most significant factor, followed by recreational effort and summer temperature; by contrast, none of the variables showed significant impacts when using transformed data (Figure 5.1 C). Third, whether to include recreational information was critical to determine the model outcomes. For example, using non-transformed data from 2004–2015 with commercial gill-net effort being lagged by one year, none of the variables were selected (Figure 5.1 B) whereas the variables recreational effort and summer temperature were significant when adding recreational information, regardless of the model error distribution (Figure 5.1 C). Model error distribution showed little impacts on model outcomes.

5.1 Discussion

Although using different time series of data due to the availability of recreational data, both this analysis and Rachels and Ricks (2018) documented commercial effort as an important predictor of striped bass mortality in the Neuse River. Model averaging analysis by Rachels and Ricks (2018) indicated commercial gill-net effort was far more influential than the other parameters that were examined. Although Rachels and Ricks (2018) did not include recreational effort or harvest due to benefits of the longer available time series for commercial data, the study also acknowledged the potential importance of recreational angling on total mortality of Neuse River striped bass. Results from this analysis indicated recreational effort and recreational discards may indeed be as influential on annual striped bass mortality as commercial effort and commercial harvest.

6 YIELD-PER-RECRUIT

6.1 Objectives

Yield-per-recruit analysis can be used to evaluate the impacts of fishing mortality and selectivity on fishery yield. The analysis can be extended to estimate the spawning potential in a stock under different conditions. The results of these analyses can be used to balance management and biological objectives for the population of interest.

In this report, several per-recruit analyses are applied to data characterizing striped bass collected from the Neuse River during 2017. Yield-per-recruit analysis is used to examine the impacts of various minimum length limits and fishing mortality rates on fishery yield in terms of numbers and weight. Spawning stock biomass- and eggs-per-recruit models were also applied to estimate the spawning potential ratio based on conditions in 2017 and to evaluate how the spawning potential ratio varied under different management scenarios.

Traditional per-recruit analyses have been modified here to allow for age-varying natural mortality and logistic selectivity and to account for both non-hatchery and hatchery-origin fish. Due to low spawning stock sizes and limited recruitment, an annual stocking program has occurred in the Neuse River since 1981 (Table 1.1).

6.2 Methods

6.2.1 Data

6.2.1.1 **Description**

The primary source of data characterizing striped bass in the Neuse River comes from the North Carolina Wildlife Resource Commission's (NCWRC) Spawning Stock Survey (Figure 6.1). The goal is to monitor striped bass migrating to the spawning grounds. The survey occurs in the spring and is conducted using boat-mounted electrofishing gear. Sampling is contingent on adequate streamflow to allow boat access to sites. Effort on any one individual sampling event varied from 11 to 58 minutes during 2017 (Figure 6.2). The median sampling time on an individual trip was 19 minutes. The survey began in 1994. Scales were collected for ageing from 1994 through 2015. Beginning in 2015, genetic ages have been taken. Only genetic ages were used in the analyses in this report.

6.2.2 Initialization

6.2.2.1 **Initial Number of Recruits**

The analyses applied here (see section 6.2.2) track the development of a fixed number of recruits over time. That initial number is simply used for scaling and all final calculations are computed on a per-recruit basis. Here, the initial number of recruits was set at 1,000 individuals.

6.2.2.2 **Age Range**

The minimum age was set at 1 and the maximum age was set at 11. A plus group was set at age 7. The maximum age of 11 was selected based on the maximum (scale) age observed in the NCWRC Spawning Stock Survey since it started in 1994. The plus group was selected based on the maximum age observed in 2017.

6.2.2.3 **Sex Ratio**

In the absence of compelling evidence to the contrary, a sex ratio of 50:50 was assumed in the analyses.

6.2.3 Hatchery Fish

6.2.3.1 **Proportion of Hatchery Fish in Population**

Data on origin (hatchery versus non-hatchery) were collected from 266 striped bass in the Neuse River during 2016 and 2017. Of those individuals, a total of 207 (78%) were of hatchery origin. The per-recruit models assumed that 78% of the population was hatchery-origin fish.

6.2.3.2 **Initial Number of Recruits**

The length of stocked hatchery fish ranges from 152 millimeters (6 inches) to 203 millimeters (8 inches). The length of stocked hatchery fish assumed in the analyses was 178 millimeters (7 inches). Because the assumed length of stocked hatchery fish is less than the length at age 1 (252 millimeters or 10 inches; section 6.2.4.1), the minimum age used in the analyses, changing this value will not have an impact on any of the results presented.

6.2.4 Growth

Biological data collected from the NCWRC Spawning Stock Survey during 2017 were used in the estimation of growth parameters described below.

6.2.4.1 **Age-Length**

The relationship of age to length was modeled using the von Bertalanffy function:

$$L_t = L_\infty\left(1 - e^{-K(t-t_0)}\right)$$

where L_t is total length in millimeters at age t, L_∞ is the theoretical asymptotic average length (if $K > 0$), K is growth rate at which the asymptote is approached, and t_0 is the hypothetical age at which length is zero.

It was necessary to fit the age-length model using inverse weighting (based on sample size at age) to ensure reasonable parameter estimates due to the low sample sizes at the youngest and oldest ages. The estimated parameters of the von Bertalanffy age-length function are given in Table 6.1 and a graph of the observed and predicted values is shown in Figure 6.3.

6.2.4.2 **Length-Weight**

The relation of length to weight as modeled using:

$$W = aL^b$$

where W is weight in grams, L is total length in millimeters, and a and b are the parameters that are estimated.

The estimated length-weight parameters are given in Table 6.2 and a graph of the observed and predicted values is shown in Figure 6.4.

6.2.5 Mortality

6.2.5.1 **Fully-Recruited Fishing Mortality**

The value assumed for fully-recruited fishing mortality was 0.33 and was derived from a catch curve analysis, which is described in section 6.2.2.1 of this report.

6.2.5.2 **Discard Mortality**

Bradley et al. (2018b) used telemetry and tag reporting data collected from December 2013 through September 2015 to estimate mortality rates of striped bass in the Neuse River. Their estimate of discard mortality was 0.0% so discard mortality was assumed negligible in the per-recruit analyses.

6.2.5.3 **First Length at Capture**

The length at first capture was assumed equal to the current minimum length limit, 457 millimeters (18 inches).

6.2.5.4 **Pre-Spawning Mortality**

Peak spawning in the Neuse River is assumed to occur the second week of April. If natural mortality is assumed to occur equally throughout the year, the proportion of natural mortality that occurs before spawning is 0.35 (4.25/12).

The proportion of fishing mortality that occurs before spawning was estimated by calculating the amount of total catch (commercial plus recreational) that occurs before April. Estimates of commercial landings, commercial discards, recreational harvest, and recreational discards were available by season for 2017. The total catch was computed by season and then the proportion of the total was calculated for each season. The proportion of the total catch occurring in the winter season (January through March) was 0.28. This value (0.28) was assumed for the proportion of fishing mortality that occurs before spawning.

6.2.5.5 **Natural Mortality**

The idea that natural mortality of fishery resources changes with body weight or length is supported by both ecological theory and empirical evidence. For a given species, the youngest life stages tend to experience higher natural mortality than older life stages.

Lorenzen's (1996) approach was used to estimate age-specific natural mortality for striped bass in the Neuse River. This approach requires parameter estimates from the von Bertalanffy age-length growth model (to translate age to length), parameter estimates from the length-weight function (to translate length to weight), and the range of ages for which natural mortality will be estimated.

The growth parameter values reported in section 6.2.1.4 of this report were used to compute natural mortality at ages 1 through 7+, using Lorenzen's (1996) equation. The estimates of natural mortality at age used in the per-recruit modeling are given in Table 2.3 and the relationship is shown in Figure 6.5.

6.2.6 Spawning

6.2.6.1 **Maturity**

A logistic model was used to describe the relationship between total length and maturity based on data collected from the Tar and Neuse rivers in 2013 and 2014 (Knight 2015). Data from the Tar and Neuse rivers were combined because too few immature fish were observed in the Neuse River alone to support modeling. The logistic model used was:

$$mat = \frac{e^{a+bL}}{1+e^{a+bL}}$$

where *mat* is the proportion mature, L is total length in millimeters, and *a* and *b* are the parameters that are estimated.

The estimated length-maturity parameter values are given in Table 6.4 and a graph of the observed and predicted values is shown in Figure 6.6. The estimated length at 50% maturity is 471 millimeters total length.

Because no immature fish of non-hatchery origin were observed, it was not possible to consider separate models for non-hatchery and hatchery-origin fish.

6.2.6.2 **Fecundity**

As with the maturity data, fecundity data collected from the Tar and Neuse rivers in the Knight (2015) study were combined to ensure adequate sample sizes for modeling. There were sufficient numbers to model fecundity relationships separately for non-hatchery and hatchery-origin fish. Linear models were used to describe the relationship between total length and fecundity for fish of each origin type. The relationship for non-hatchery origin fish (Figure 6.7) was estimated as:

$$Fecundity = -3{,}222{,}798 + 6{,}365.4622L$$

where Fecundity is the number of eggs produced per female and L is total length in millimeters.

The linear relationship for hatchery-origin fish (Figure 2.8) was estimated as:

$$Fecundity = -1{,}875{,}954 + 4{,}429.5759L$$

An analysis of covariance (ANCOVA) was used to compare the two linear regressions (Zar 1999). The ANCOVA can test whether the slopes and/or intercepts are significantly different from each other. Here, the ANCOVA found the slopes and intercepts to be significantly different, suggesting it was appropriate to use different fecundity models for fish of different origin.

6.2.2 Analyses

A table of symbols, their definitions, and measurement units used in the equations in this section is given in Table 6.5.

6.2.2.1 Catch Curve & Selectivity

A catch curve approach was used to estimate total mortality and selectivity for striped bass. The method developed by Thorson and Prager (2011) estimates logistic selectivity (to avoid the need to choose an age at full selection) in addition to estimating total mortality and incorporates age-varying natural mortality. Traditional per-recruit analyses assume knife-edge selection in which selectivity transitions from 0 at the length (or age) before length (or age) at full recruitment to 1 at the length (or age) at full recruitment. In the analyses here, this assumption was modified to allow for a logistic-shaped selection curve. Selectivity at lengths smaller than the minimum length limit (section 6.2.5.3) was assumed equal to 0 and selectivity at lengths greater than or equal to the minimum length limit was equal to the selectivity predicted by the logistic model (Figure 6.9).

Because the sampling time varied among sampling events (section 6.2.1), the frequency at age was standardized to 19 minutes (Table 6.6). The values assumed for natural mortality at age were those values estimated in section 6.2.5.5 of this report.

Natural mortality at age was subtracted from the estimated total mortality at age for each year to produce annual estimates of fishing mortality at age (Table 6.7). The apical fishing mortality from this vector ($F_{2017} = 0.33$) was assumed for the fully-recruited fishing mortality (section 6.2.5.1) in the per-recruit analyses.

6.2.7 Yield-per-Recruit

Yield-per-recruit models follow a fixed number of recruits and track their growth and mortality over time and evaluate the impacts of various factors on fishery yield. The methods of Thompson and Bell (1934) and Ricker (1975) have been modified to allow for more realistic conditions in that the modifications allow for age-varying natural mortality and logistic selectivity (in contrast to knife-edge selectivity). The modified approach also allows for contributions to the stock from both non-hatchery and hatchery-origin fish. Note that the model assumes no migration.

6.2.7.1 **Fishing & Total Mortality**

Fishing mortality, *F*, at age *t* was computed as:

$$F_t = F_{full} S_t$$

where F_{full} is the assumed value for the fully-recruited fishing mortality (section 6.2.5.1) and S_t is the vector of selectivity at age (section 6.2.2.1).

Total mortality, *Z*, at age *t* was calculated as the sum of natural mortality at age, M_t, and fishing mortality at age:

$$Z_t = M_t + F_t$$

6.2.7.2 **Population Size**

The total population size (in numbers) at the minimum age used in the analyses, age 1, was set equal to 1,000 individuals (see section 6.2.3.2):

$$N_1 = 1{,}000$$

Total population size at ages older than age 1 (in numbers) was calculated using;

$$N_t = N_{t-1} e^{-Z_{t-1}}$$

The weight (kilograms) of the total population at age, B_t, was calculated as:

$$B_t = N_t \left(\frac{w_t}{1{,}000} \right)$$

where w_t is the individual weight at age in grams.

The number of individuals in the population at age of non-hatchery origin, U_t, was computed as:

$$U_t = N_t (1 - h)$$

where *h* is the assumed proportion of hatchery fish in the population (section 6.2.3.1).

The number of individuals in the population at age that are of hatchery origin, H_t, was calculated as:

$$H_t = N_t h$$

The weights of non-hatchery and hatchery individuals at age were calculated the same way as the total population weight at age.

6.2.7.3 **Catch**

The total number of individuals in the catch at age, C_t, was computed as:

$$C_t = N_t \frac{F_t}{Z_t} (1 - e^{-Z_t})$$

The yield per recruit for the entire population, YPR, in numbers was calculated as:

$$\mathrm{YPR} = \frac{\sum_t C_t}{N_1}$$

The weight (kilograms) of the total catch at age, W_t, was calculated as:

$$W_t = C_t\left(\frac{w_t}{1{,}000}\right)$$

The yield per recruit in weight (kilograms) for the entire population, WPR, was calculated as:

$$\mathrm{WPR} = \frac{\sum_t W_t}{N_1}$$

6.2.8 Spawning Stock Biomass-per-Recruit

The yield-per-recruit analysis can be extended to evaluate the effects of fishing mortality and minimum length limit on spawning potential. The method of Gabriel et al. (1989) has been modified to incorporate age-varying natural mortality.

SSB at age for non-hatchery female fish, SSU_t, in weight (kilograms) was calculated as:

$$\mathrm{SSU}_t = pU_t\left(\frac{w_t}{1{,}000}\right)mat_t e^{-(fF_t+mM_t)}$$

where p is the proportion of individuals in the population that are female (section 6.2.2.3), U_t is the number of individuals in the population that are non- hatchery origin, mat is maturity at age t (section 6.2.6.1), f is proportion of fishing mortality that occurs before spawning (section 6.2.5.4), and m is the proportion of natural mortality that occurs before spawning (section 6.2.5.4).

SSB per recruit for the non-hatchery female fish, SSU/R, in weight (kilograms) was calculated as:

$$\mathrm{SSU/R} = \frac{\sum_t \mathrm{SSU}_t}{N_1}$$

SSB at age for hatchery-origin female fish, SSH_t, in weight (kilograms) was calculated as:

$$\mathrm{SSH}_t = pH_t\left(\frac{w_t}{1{,}000}\right)mat_t e^{-(fF_t+mM_t)}$$

where H_t is the number of individuals in the population that are of hatchery origin.

SSB per recruit for hatchery-origin female fish, SSH/R, in weight (kilograms) was calculated as:

$$\mathrm{SSH/R} = \frac{\sum_t \mathrm{SSH}_t}{N_1}$$

SSB per recruit for the entire population, SSB/R, was computed as:

$$\mathrm{SSB/R} = \mathrm{SSU/R} + \mathrm{SSH/R}$$

6.2.9 Eggs-per-Recruit

Eggs-per-recruit models estimate the number of eggs, on average, that a single female produces in a lifetime. By comparing the current estimate of eggs per recruit to an estimate computed assuming no fishing, one can calculate the spawning potential ratio, which is a measure of the reproductive health of the stock (see below). Goodyear's (1993) approach has been modified to allow for different assumed fecundity relationships for non-hatchery and hatchery-origin fish.

The total number of eggs at age for the non-hatchery female fish, EU_t, was computed as:

$$\mathrm{EU}_t = \left[pU_t mat_t e^{-(fF_t+mM_t)}\right][-3{,}222{,}798 + 6{,}365.4622L_t]$$

Eggs per recruit for the non-hatchery female fish, EU/R, in numbers of eggs was calculated as:

$$\mathrm{EU/R} = \frac{\sum_t \mathrm{EU}_t}{N_1}$$

The total number of eggs at age for hatchery-origin female fish, EH_t, was computed as:

$$\mathrm{EH}_t = \left[pH_t mat_t e^{-(fF_t+mM_t)}\right][-1{,}875{,}954 + 4{,}429.5759L_t]$$

Eggs per recruit for hatchery-origin female fish, EH/R, in numbers of eggs was calculated as:

$$\mathrm{EH/R} = \frac{\sum_t \mathrm{EH}_t}{N_1}$$

Eggs per recruit for the entire population, E/R, was computed as:

$$\mathrm{E/R} = \mathrm{EU/R} + \mathrm{EH/R}$$

The spawning potential ratio (SPR) is a measure of the reproductive health of the stock based on fecundity that is calculated relative to the virgin stock condition (i.e., unfished stock; Goodyear 1993). SPR was computed as:

$$\%\mathrm{SPR} = \frac{\mathrm{E/R}_{F=F_{full}}}{\mathrm{E/R}_{F=0}}$$

6.3 Approach

The per-recruit analyses were used to estimate SPR based on conditions in 2017 using the values indicated in the descriptions above. Additionally, yield per recruit in both numbers and weight as well as SPR were calculated for combinations of minimum length limits and fully-recruited fishing mortality values. The minimum length limits evaluated ranged from 406 millimeters (16 inches) to 673 millimeters (26.5 inches) at increments of 13 millimeters (0.5 inches). The range of fully-recruited fishing mortality values evaluated was 0.0 to 2.0 at increments of 0.1.

6.4 Results

The per-recruit analyses indicated that SPR based on conditions in 2017 was 44%.

In terms of weight, yield per recruit is maximum at minimum length limits ranging from 508 millimeters (20 inches) to 559 millimeters (22 inches) when fishing mortality rates are at the highest levels evaluated ($F > 1.6$; Figure 6.10). Yield per recruit in terms of numbers is maximized at smaller minimum length limits (<500 millimeters or 20 inches) and fishing mortality rates greater than 0.60 (Figure 6.11). SPR is maximum when fully-recruited fishing mortality is equal to 0.0 (Figure 6.12), which is expected. In the presence of fishing mortality, SPR increases with decreasing fishing mortality and increasing minimum size.

Over the range of fishing mortality rates evaluated, there is not much difference in terms of yield per recruit in weight among minimum size limits less than 610 millimeters (24 inches; Figure 6.13). A different pattern emerges when evaluating yield per recruit in terms of numbers. Regardless of fishing mortality, yield in numbers generally decreases as the minimum size limit increases (Figure 6.14). SPR generally increases as the minimum length increases (Figure 6.15).

At the current size limit, yield per recruit in terms of both weight and numbers is maximized when fully-recruited fishing mortality is 2.0, possibly higher as this was the largest value evaluated (Figures 6.13, 6.14). At a fully-recruited fishing mortality rate equal to 2.0, SPR would be reduced to 10% (Figure 6.15).

6.5 Discussion

Balancing management objectives against biological objectives is often challenging. Increasing the harvest rate (i.e., fully-recruited fishing mortality rate) will result in increased yield per recruit (in weight and numbers) but the spawning potential of the stock will be reduced. Increasing the minimum size limit could increase SPR but would result in increased discards, though the mortality of these discards is currently assumed negligible (section 6.2.5.2; Bradley et al. 2018b).

There are a number of uncertainties in the analyses that affect the interpretation of the results. One important issue is that the estimate of fully-recruited fishing mortality assumed in the analyses is likely inaccurate. The estimate was derived from catch curves based on data collected from spawning fish, which are likely not representative of fish in the catch. Bradley et al. (2018b) estimated mortality rates of striped bass in the Neuse River using telemetry and tag reporting data collected from December 2013 through September 2015. Their estimate of harvest mortality of adult striped bass was 0.131. Assuming this value in the per-recruit analyses results in a SPR value of 69%.

Bradley et al. (2018a, 2018b) estimated a fishing mortality of 0.53 and suggested their reported mortality levels were lower than those outside the study area because fishing practices differed between the study area and the entire area used by the population. Bradley et al. (2018b) also estimated an adult natural mortality rate of 0.24. Bradley et al.'s (2018b) estimates of both fishing and natural mortality were not sex- or age-specific and applied to a range of ages (ages 3 to 9 based on length). The average Lorenzen estimate of M over ages 3 to 9 used in this study is 0.31, which is only slightly higher than 0.24.

Rachels and Ricks (2015) conducted a yield-per-recruit analysis for Neuse River striped bass assuming a fishing mortality rate equal to 0.69 and a natural mortality rate equal to 0.16. They estimated SPR equal to 3% assuming the same minimum size limit as modeled in this analysis (457 mm). The disparity in SPR (3% vs. 44%) and length limits producing maximum yield per recruit between Rachels and Ricks (2015) and this analysis are due to different underlying assumptions regarding Neuse River striped bass growth, longevity, natural mortality, fishing mortality, selectivity, and the contribution of non-hatchery versus hatchery-origin fish.

Rachels and Ricks (2015) assumed a maximum age of 30 years, which has not been observed in the Neuse River stock and so is not reflective of current conditions. Although selection of the maximum age considered can be arbitrary (Ricker 1975), the maximum age used in a YPR analysis, whether 11 years as used here or 30 years as in Rachels and Ricks (2015), can alter model results and should be realistic for the modeled species and system at the time of the analysis.

Assuming an older maximum age in the yield-per-recruit analysis will result in a lower estimate of SPR.

In the yield-per-recruit analysis performed here, selectivity was assumed to follow a logistic curve (i.e., changing with age) as opposed to knife-edge selection assumed in the Rachels and Ricks (2015) analysis, which assumes selectivity equivalent to zero until a pre-defined age at which selectivity is equal to one for that age and all older ages.

Per-recruit analyses do have the advantage of considering both growth overfishing and recruitment overfishing; however, another source of error and a disadvantage to using per-recruit approaches is that they do not account for differences in recruitment at varying stock abundance.

7 AGE COMPARISON

7.1 Introduction

Accurate age determination of fish is one of the most important elements to consider when conducting age structured stock assessments and is crucial information in estimating population parameters including recruitment, natural mortality, and growth.

Striped bass (*Morone saxatilis*) scales and otoliths have been collected sporadically by the North Carolina Division of Marine Fisheries (NCDMF) since 1975, although since 2003 both scales and otoliths have been collected routinely (Table 7.1). Since 1975, a total of 8,949 scale samples have been collected (primary ageing structure for striped bass), with roughly 8,518 collected between 2002 and 2018 (Table 7.1). Very few striped bass otoliths were collected before 2003, however since 2003, 2,122 otoliths have been collected by NCDMF (Table 7.1).

Beginning in 2010, a new genetics technique, termed parental based tagging (PBT), was implemented by the North Carolina Wildlife Resources Commission (NCWRC) to more accurately determine the percent hatchery contribution to striped bass populations in the Central Southern Management Area (CSMA). This method has proven to be greater than 99% accurate in determining if a fish was hatchery produced (Denson et al. 2012). In addition to determining hatchery contribution, PBT samples from hatchery produced fish identify the cohort or year class the striped bass was produced and consequently its age as each parent group is only used once. In 2016, the NCDMF started collecting striped bass fin clip samples for PBT analysis to determine percent hatchery contribution, and age of hatchery reared striped bass collected in the lower portions of CSMA rivers.

Though scale samples were collected by NCDMF from 1975 to 2001, very few striped bass were aged, and no striped bass were aged using scales from 2002–2017. To address the backlog of scale samples in anticipation of the 2017 stock assessment, all striped bass scales from 2002–2017 were processed to be aged.

In 2016, NCDMF began ageing the striped bass scales collected from 2002 to 2017, however concerns were quickly raised about the difficulty in interpreting CSMA striped bass scale annuli and disagreement between readers was high. Additionally, beginning in 2016 exact ages of stocked striped bass through PBT analysis became available.

7.2 Objectives

The objectives of this study were to: 1) determine and compare the accuracy and precision of scale ageing versus otolith ageing for CSMA striped bass, assuming genetic ages are true ages, and 2) to determine the difference in ageing-bias at each age and determine the precision among readers for each method using ages from scales and otoliths.

7.3 Methods

7.3.1 Preparation

7.3.1.1 **Scale Preparation**

To prepare scales for ageing, scale impressions were made on acetate sheets with a Carver© heated hydraulic laboratory press and annuli were counted by examination at 24x and 33x magnification on a microfiche reader. For a more detailed explanation of North Carolina Estuarine Striped Bass scale preparation and ageing protocol see the cooperative scale ageing document developed by NCWRC and NCDMF staff (NCWRC and NCDMF 2011).

7.3.1.2 **Otolith Preparation**

To prepare otoliths for ageing, a thin sectioning machine was used to section whole otoliths. The water-cooled, thin sectioning machine is equipped with two individual tools; a diamond blade cut-off saw and a precision diamond grinder. The precision grinder is fitted with a dial indicator gauge to control thickness and allows for varied section thicknesses. Both have guide arms for feeding slides to the blades.

Although left and right otoliths are collected, only one side is typically sectioned for ageing. Alternating between left and right otoliths for a species could lead to inconsistencies in the ageing process. The Ageing Lab at the NC Division of Marine Fisheries typically uses the left otolith for sectioning unless the left otolith was not collected or is of lower quality (e.g., crystalized, broken) than the right.

Otoliths are hand held and ground on the transverse plane adjacent to the focus. The purpose of sectioning is to remove both ends of the otolith leaving the transverse section containing the focus. The otolith is then mounted cut side down with the sulcal groove upward onto a frosted microscope slide using an ultra-violet (UV) cure adhesive, Loctite AA 349. After curing, the slides are placed on the guide-arm of the cut-off saw and guided past the saw to remove the bulk of the otolith. Slides are then placed onto the guide arm of the precision grinder and ground down by turning the guide arm adjuster gradually, starting at 1.0 mm thick and stopping at 0.5 mm thick for striped bass, and passing the sample on the guide-arm across the precision grinder.

Once the slides have been ground down, striped bass otolith sections are covered with a top coat. The top coat fills in the rough ground surface of the otolith section providing a clearer view of annuli. In a fume hood, a disposable pipette is used to apply enough Flo-Texx to entirely cover the sample. Adding this cover eliminates the need for polishing most samples.

7.3.1.3 **Genetic Sample Collection and Preparation**

A small piece of the pelvic fin was clipped from an individual striped bass and preserved in 95% ethyl alcohol for use in PBT analysis. The South Carolina Department of Natural Resources

(SCDNR) Population Genetics lab conducted microsatellite genotyping for individual fin clips, using a suite of 12 microsatellite markers for striped bass.

7.3.2 Age Determination

7.3.2.1 **Scale & Otolith Age Determination**

Scale and otolith annuli were counted to estimate age and assign a year-class. A minimum of two independent reads were required to age a fish and determine estimates of precision and accuracy. If both readers agreed on an age, that age was assigned to the fish. Discrepancies were resolved by readers sitting together and re-ageing the fish to assign a final age. If an agreement could not be reached, the sample was excluded from further analysis and not used in calculating the age agreement rate with known PBT ages.

7.3.2.2 **PBT Age Determination**

Since 2010, all broodstock used at the hatcheries to produce the stocked striped bass each year are genotyped (makeup of specific genes as passed on from ancestors). This is done each year, so a genetic record now exists of all the broodstock fish since 2010 used to produce striped bass that are stocked in CSMA rivers each year. This technique can only be applied to striped bass produced in the hatcheries since 2010. Therefore, year-classes produced before 2010 are of unknown origin via PBT. As of 2018, hatchery origin can be determined for all fish that are eight years of age and younger.

7.3.3 Comparison Analysis

7.3.3.1 **Objective 1**

In this analysis, a generalized linear mixed model (GLMM) was used to compare scale ageing versus the otolith ageing. In the model, ageing method was set as a fixed effect. The data included ages from scales (n=445; 2016–2017)), otoliths (n=126; 2016–2018), and genetics (PBT ages; n=513; 2016–2018) for the years 2016 through 2018 from 513 total striped bass. PBT ages ranged from one to seven. A total of five readers participated in ageing, among which all five readers read scale ages whereas only two readers read otolith ages. The response variable (Y) was the percentage ageing-bias relative to the genetic age (%):

$$Y = (\text{observed age} - \text{genetic age})/\text{genetic age} * 100,$$

where observed age is either scale age or otolith age. During the ageing process, the same reader aged multiple fish. Thus, in the model, the reader was set as a random effect that assumed the percentage ageing-bias from the same reader was dependent while those from different readers were independent. This random effect represents the variability in percentage ageing-bias among readers, and thus it contributes to explaining the part of the variation that cannot be explained by the fixed effects. The GLMM was developed as follows:

$$Y_{gij} \sim Normal(\mu + \gamma_j + \alpha_i + \gamma_j * \alpha_i, \sigma_e^2)$$

where Y_{gij} is the percentage ageing-bias from fish $g = 1, \dots, n$, reader $i = 1, \dots, m$, and ageing method $j = \{\text{otolith ageing, scale ageing}\}$; γ_j is the ageing method fixed effect, α_i is the reader random effect. An interaction term between reader and ageing method was included because a reader may be more proficient at one ageing method than the other. The fixed and random effects were modeled as:

$$\alpha_i \sim Normal(0, \sigma_r^2)$$

with priors;

$\mu \sim Normal(0, 100), \qquad \gamma_j \sim Normal(0, 100),$

$\sigma_r^2 \sim Gamma(0.1, 0.1), \qquad \sigma_e^2 \sim Gamma(0.1, 0.1)$

The total variance was $Var(Y_{ij}) = \sigma_e^2 + \sigma_r^2$. The relative contribution of reader and error variance are given as the posterior summaries for random error and reader random effects is as follows:

$p_e = \frac{\sigma_e^2}{\sigma_e^2+\sigma_r^2} \qquad p_r = \frac{\sigma_r^2}{\sigma_e^2+\sigma_r^2}$

The analysis was modeled in a Bayesian framework using JAGS version 4.30 (Plummer 2003) in RStudio version 3.6.0 (R Core Team 2013) with 200,000 iterations, three separate chains, a 20,000 iteration burn-in, and thinning set to ten. Convergence was verified by visual inspection of chain trace plots and Rhat values of 1.03 or less.

7.3.3.2 **Objective 2**

Statistical analyses were done using a symmetric test (Hoenig et al. 1995) and coefficient of variation (CV) analysis to determine bias and precision. The data included ages from scales (n=3,611; 2002–2017) and otoliths (n=1,890; 2003–2018) for the years 2002 through 2018 for 4,604 striped bass. Ages ranged from one through 16. Ages were read by seven readers in total and scales were read by all seven readers whereas otoliths were read by only two of the readers. Tests were done for the following comparisons: (1) between otolith and scale ages; (2) between scale readers; and (3) between otolith readers.

7.4 Results

7.4.1 Objective 1

Preliminary investigation to understand the underlying relationships that explain the variability in the data indicated that the reader identification (ID) might be an important variable (Figure 7.1, Table 7.2) as well as method type (Figure 7.2). The summary statistics from the raw data (Table 7.2) indicated that readers 1 and 2 demonstrated differences in accuracy and precision dependent on the method type. Reader 1 had similar accuracy for both method types but with higher variability for scale ages with mean age bias for otolith ages of -0.899% (sd=8.45) and for scale ages of -0.0935% (sd=15.2); however, reader 2 had very different levels of accuracy and precision between methods with a mean age bias for otolith ages of -1.81% (sd=7.25) and for scale ages of 23.1% (sd=22.3). This demonstrates a need to account for the interaction between reader and method type.

Some ages may be more likely to be underestimated or overestimated than other ages thus, the genetic age of the fish was also initially considered as a possible variable that may affect ageing accuracy and precision (Figure 7.3). However, since the genetic ages were used in the calculation of the response variable, there was an inherent correlation between these values and thus, genetic age was not used in the analysis.

The results demonstrated differences in accuracy and precision due to reader ID (Table 7.3, Figure 7.4) with readers 1, 3, and 4 tending to slightly underestimate age with low variability indicated by the posterior medians of -0.858% (sd=0.274), -0.931% (sd=0.291), and -1.00% (sd=0.302), respectively. Readers 2 and 5 tended to overestimate with higher variability as shown by the posterior medians of 2.47% (sd=2.48) and 0.280% (sd=0.916), respectively. The posterior median of standard deviation from reader effects was 1.67 (sd=1.46). Reader effects explained 1.7% (sd=4.0) of the total variability in data. The ageing method results (Table 7.3, Figure 7.4) showed that ages from scales tended to overestimate age with a posterior median of 7.90% (sd=3.90, 95% conf. interval=1.37 to 16.6) and ages from otoliths were unbiased with much higher precision than scales demonstrated by the posterior median of -1.19% (sd=0.82, 95% conf. interval=-2.88 to 0.51). The random error standard deviation posterior median was 15.5 (sd=0.261) and accounted for the remaining 98.3% (sd=4.0) of the total variability.

7.4.2 Objective 2

The comparison between scales and otoliths (Figure 7.5) indicate agreement of 50.7% with a CV of 5.4% (χ^2=1373.2, *df*=64, P<0.01). The percentage age-bias plot (Figure 7.6) demonstrates that scales compared to otoliths tended to overestimate ages less than 5 and underestimate ages greater than 5. There was no difference between otolith readers with a CV of 2.2% (χ^2=35.6, *df*=34, P=0.392); however, the results from the between reader comparisons for scale ages (Table 7.4) indicate that 11 out of the 13 unique reader combinations were significantly different with CVs ranging from 2.5% to 7.0% and percent agreements ranging from 19% to 88%.

7.5 Discussion

7.5.1 Objective 1

This analysis demonstrates the importance of understanding and accounting for differences among readers and the interaction between the method type and reader ID to accurately assess the potential bias and level of precision in ageing striped bass. The results from this analysis indicate that scale ageing was biased with comparatively low precision whereas, otolith ageing was unbiased with a higher level of precision. These results are in agreement with previous research where ages from otoliths were significantly different than ages from scales (Secor et al. 1995; Liao et al. 2009). Furthermore, they agree with results from Liao et al. (2013) where known ages were compared with ages from both otoliths and scales and otoliths were found to have much smaller error than scales.

7.5.2 Objective 2

The results from this analysis agree with the Bayesian GLMM analysis demonstrating significant differences in ages from otoliths compared to ages from scales. In both analyses, the precision between otolith readers was much higher than for scale readers indicating scale ages have higher uncertainty associated with them. Moreover, the results from this analysis also agree with prior research where scale ages from older fish tend to be underestimated and younger fish tend to be overestimated (Secor et al. 1995; Liao et al. 2009; Liao et al. 2013). The reason for the overestimation of younger ages is likely due to false annuli being mistaken for true annuli and older ages are underestimated due to the slenderness of tightly packed annuli on the periphery of the scales (Secor et al. 1995; Liao et al. 2013).

7.6 Conclusion

Estimating striped bass age with scales is a common practice and the preferred method for anadromous striped bass on the Atlantic Coast (ASMFC 2003). Scales are relatively easy to collect in the field and striped bass may be released alive after structure collection. In addition, scales may be collected with negligible effect on striped bass intended for market. However, Liao et al. (2013) found that scales overestimated ages of young fish and underestimated ages of old fish. Studies by Welch et al. (1993) and Secor et al. (1995) also indicate scales tend to underestimate the actual age of older fish beginning at age 10 when compared to otoliths. Biases in age estimates impact catch-at-age data and estimates of recruitment, natural mortality and growth.

Unlike most studies, due to PBT analysis, known-age samples from striped bass are now available and allow for validation of scale and otolith ages. A comparison of scale and otolith ages collected from striped bass in the Chesapeake Bay found otoliths provided more accurate and precise estimates of ages than scales when compared to known age fish (Liao et al. 2013). The current study similarly shows otoliths provide a more precise and accurate age estimate for CSMA striped bass when compared to scales.

This research has important implications regarding the use of ages from scales and otoliths for the management of striped bass populations. Age bias and imprecision can have significant effects on estimates of growth parameters used in stock assessment modeling (either estimated outside of the assessment model or within an integrated assessment model). Previous research has demonstrated that population dynamics estimates and biological reference points used for management are sensitive to the misspecification (bias) in growth parameter estimates (Zhu et al. 2016). Liao et al. (2013) demonstrated that age bias can adversely affect catch-at-age models by reducing the ability to track the progression of year classes caused by incorrectly assigning fish to appropriate cohorts resulting in strong recruitment events appearing weaker thus resulting in a subsequent reduction in recruitment variability. Liao et al. (2013) suggest the inability to track recruitment signals would prolong recovery of a depleted stock and result in an unnecessarily restricted harvest after recovery had occurred.

7.7 Recommendation

The NCDMF recommends that otoliths should be used by both agencies to age CSMA striped bass if PBT ages are not available, and a power analysis should be conducted to determine sample sizes needed for determining the representative age structure. Another recommendation is conduct a similar study across NCDMF and NCWRC biologists to determine and compare the accuracy and precision of scale ageing versus otolith ageing for the Albemarle Sound and Roanoke River striped bass management areas.

8 RESEARCH RECOMMENDATIONS

The research recommendations listed below (in no particular order) are intended to improve future assessments of the CSMA striped bass stocks. The bulleted items outline the specific issue and are organized by priority ranking.

High

- Acquire life history information: maturity, fecundity, size and weight at age, egg and larval survival (ongoing through CRFL funded projects and NCDMF P930 data collection; see Knight, 2015, for recent work on maturation and fecundity in the Neuse and Tar-Pamlico rivers)
- Conduct delayed mortality studies for recreational and commercial gear during all seasons factoring in relationships between salinity, dissolved oxygen, and water temperature
- Develop better estimates of life-history parameters, especially growth and factors influencing rates of natural mortality for all striped bass life stages (growth is ongoing through NCDMF P930 data collection; for natural mortality, see recent publications Bradley 2016 and Bradley et al. 2018b)

Medium

- Determine factors impacting survivability of stocked fish in each system (Bradley et al. 2018b)
- Implement a random component to NCDMF program 100 juvenile sampling in the CSMA
- Conduct a power analysis to determine minimum sample sizes needed for determining the representative age structure

Low

- Determine if contaminants are present in striped bass habitats and identify those that are potentially detrimental to various life history stages (ongoing through N.C. Division of Water Quality but could be expanded; in 2017, NCSU was awarded a CRFL grant to conduct research on striped bass eggs, including evaluating for Gen X)
- Identify minimum flow requirements in the Tar-Pamlico, Neuse, and Cape Fear rivers necessary for successful spawning, egg development, and larval transport to nursery grounds
- Evaluate factors influencing catchability of striped bass, particularly larger striped bass, in electrofishing surveys conducted on the spawning grounds
- Obtain improved commercial discard estimates from the estuarine gill-net fisheries (i.e., anchored, runaround, and strike gill nets) in the CSMA systems to better characterize harvest and discards
- Investigate factors influencing mixing rates between A-R and CSMA striped bass stocks
- Identify water quality parameters that impact spawning, hatching, and survival of striped bass in CSMA systems
- Develop a consistent ageing approach across agency sampling programs
- Continue PIT tagging striped bass in the Cape Fear River and expand PIT tagging to the Tar-Pamlico and Neuse rivers to estimates of spawning population size
- Investigate factors influencing rates of natural mortality for all striped bass life stages in the CSMA systems

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10 TABLES

Table 1.1. Stocking numbers of Phase II (5–7 inches total length) striped bass by system and year for the Tar-Pamlico, Neuse, and Cape Fear rivers, 1980–2018.

Year Class	Tar-Pamlico River	Neuse River	Cape Fear River
1980			14,874
1981		47,648	
1982	76,674		
1983			
1984	26,000		56,437
1985		39,769	
1986			
1987	17,993		
1988		71,092	
1989			77,242
1990		61,877	
1991	30,801		
1992		116,820	
1993	118,600		
1994	183,254	79,933	
1995	140,972		
1996		100,760	
1997	24,031		
1998		83,195	
1999	17,954		
2000		108,000	
2001	37,000		
2002		147,654	
2003	159,996		
2004		168,011	172,055
2005	267,376		
2006		99,595	102,283
2007	69,871	69,953	
2008	91,962		92,580
2009	61,054	104,061	112,674

Table 1.1. **(*continued*)** Stocking numbers of Phase II (5–7 inches total length) striped bass by system and year for the Tar-Pamlico, Neuse, and Cape Fear rivers, 1980–2018.

Year Class	Tar-Pamlico River	Neuse River	Cape Fear River
2010[1]	114,012	107,142	210,105
2011	107,767	102,089	130,665
2012[2]	45,667	90,178	127,078
2013	123,416	113,834	195,882
2014	92,727	78,899	141,752
2015	52,922	109,146	116,011
2016	121,190	134,559	63,914
2017	101,987	14,203[3]	154,024
2018	186,609	149,076	152,593

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[1] First year of *in situ* broodstock collection from the Cape Fear River

[2] First year of *in situ* broodstock collection form the Tar-Pamlico and Neuse rivers

[3] Poor spawning of broodstock led to low stocking numbers

Table 1.2. Percent hatchery contribution from striped bass genetic samples collected in the Tar-Pamlico, Neuse, and Cape Fear rivers by NCDMF and NCWRC staff, 2013–2018. (Source: South Carolina Department of Natural Resources)

Year	Agency	System	n Total	n Hatchery	n Unknown	% Hatchery	% Unknown
2013	NCWRC	Upper Tar-Pamlico	196	162	34	83	17
		Upper Neuse	195	130	65	67	33
		Cape Fear	219	138	81	63	37
2014	NCWRC	Upper Tar-Pamlico	205	174	31	85	15
		Upper Neuse	299	247	52	83	17
		Cape Fear	292	223	71	76	24
2015	NCWRC	Upper Tar-Pamlico	208	194	14	93	7
		Upper Neuse	241	176	65	73	27
		Cape Fear	233	166	67	71	29
2016	NCDMF	Tar-Pamlico	190	164	26	86	14
		Neuse	150	142	8	95	5
		Cape Fear					
	NCWRC	Upper Tar-Pamlico	195	171	24	88	12
		Upper Neuse	61	44	17	72	28
		Cape Fear	213	196	17	92	8
2017	NCDMF	Tar-Pamlico	147	102	45	70	31
		Neuse	118	66	52	56	44
		Cape Fear	110	93	17	85	15
	NCWRC	Upper Tar-Pamlico	137	96	41	70	30
		Upper Neuse	233	198	35	85	15
		Cape Fear	119	106	13	89	11
2018	NCDMF	Tar-Pamlico	206	74	132	36	64
		Neuse	86	46	40	54	47
		Cape Fear	96	81	15	84	16
	NCWRC	Upper Tar-Pamlico	166	67	99	41	59
		Upper Neuse	322	250	72	78	12
		Cape Fear	119	110	9	93	7

Table 2.1. Summary (mean, minimum, maximum and number of samples) striped bass length data (TL in inches) from CSMA commercial harvest, 2000–2018.

	Tar-Pamlico R. / Pungo R.				Neuse / Bay R.			
Year	**Mean**	**Min**	**Max**	**n**	**Mean**	**Min**	**Max**	**n**
2000	23	20	35	126	25	22	31	5
2001	23	21	26	116	25	23	31	12
2002	24	19	39	96	25	19	29	31
2003	23	18	37	173	24	19	37	19
2004	24	20	42	131	25	19	37	74
2005	23	20	37	127	24	20	36	70
2006	22	18	37	119	24	19	36	144
2007	22	19	33	112	22	19	27	63
2008	22	18	43	84	23	19	44	39
2009	22	19	31	99	22	18	31	85
2010	22	19	26	194	23	19	32	263
2011	23	18	27	284	23	19	42	195
2012	24	15	30	254	24	19	29	96
2013	25	18	40	225	25	18	39	301
2014	22	18	39	52	24	20	38	56
2015	24	19	40	97	24	19	44	97
2016	24	17	29	257	23	19	28	78
2017	24	19	31	151	24	19	50	97
2018	23	19	32	76	24	18	38	163

Table 2.2. Commercial estimates of striped bass discards (standard error in parentheses) in the Tar-Pamlico/Pungo rivers by mesh size, 2013–2018.

Year	Live Releases			Dead			Release Mortalities		Total Dead	
	Small Mesh	Large Mesh	Combined	Small Mesh	Large Mesh	Combined	Small Mesh	Large Mesh	Small Mesh	Large Mesh
2013	484 (123)	490 (150)	975 (244)	59 (13)	230 (73)	289 (85)	208	211	267	442
2014	258 (83)	490 (133)	749 (143)	33 (11)	233 (80)	266 (91)	112	212	145	445
2015	149 (46)	145 (51)	296 (87)	41 (15)	184 (75)	224 (90)	65	63	106	246
2016	421 (97)	470 (171)	891 (242)	30 (11)	131 (36)	161 (46)	181	203	210	333
2017	269 (104)	143 (64)	411 (159)	37 (13)	93 (38)	130 (51)	115	60	152	154
2018	416 (214)	346 (145)	762 (344)	25 (7)	86 (30)	111 (36)	179	148	204	234

Table 2.3. Commercial estimates of striped bass discards (standard error in parentheses) in the Neuse/Bay rivers by mesh size, 2013–2018.

Year	Live Releases			Dead			Release Mortalities		Total Dead	
	Small Mesh	Large Mesh	Combined	Small Mesh	Large Mesh	Combined	Small Mesh	Large Mesh	Small Mesh	Large Mesh
2013	110 (32)	132 (45)	243 (69)	34 (8)	204 (53)	237 (61)	47	58	81	261
2014	182 (61)	74 (22)	256 (76)	54 (20)	108 (35)	162 (54)	78	32	133	139
2015	56 (20)	14 (6)	71 (25)	45 (17)	68 (27)	112 (43)	23	7	68	74
2016	57 (14)	91 (36)	149 (47)	10 (3)	88 (25)	98 (28)	25	39	36	127
2017	51 (22)	35 (17)	86 (37)	20 (7)	81 (31)	101 (38)	21	15	44	96
2018	180 (96)	117 (48)	297 (138)	29 (8)	96 (29)	124 (37)	78	51	107	145

Table 2.4. Recreational effort, harvest, and discards estimates for striped bass in the Tar-Pamlico, Pungo, Neuse, and Cape Fear rivers and tributaries.

		Recreational Fishing Effort				**Recreational Harvest**		**Striped Bass Discards**				
Zone	**Year**	**Total Angler Fishing Trips**	**Total Fishing Effort (Angler Hours)**	**Striped Bass Angler Trips**	**Striped Bass Effort (Angler Hours)**	**numbers**	**pounds**	**n over creel**	**n undersized**	**n legal sized**	**n slot sized**	**Total**
Neuse River	**2004**	26,663	162,424	7,445	39,942	3,985	14,845	29	5,721	1,221	0	6,971
	2005	64,301	249,396	9,678	42,107	1,641	6,540	13	6,473	630	77	7,193
	2006	39,181	162,559	6,260	24,053	1,244	4,079		7,797	1979	0	9,776
	2007	31,052	142,093	4,965	20,966	2,616	7,115	140	4,858	1,484	0	6,482
	2008	28,134	136,575	3,174	12,954	405	1,510	2,838	4,801	2,450	51	10,140
	2009	17,519	77,634	2,474	12,995	249	868		443	704	138	1,285
	2010	19,540	83,108	2,340	9,177	109	361		699	1,440	13	2,152
	2011	24,407	97,302	5,657	21,393	1,080	3,809		7,426	2,434	913	10,773
	2012	70,649	210,197	8,703	34,652	1,508	5,742	334	13,660	9,741	664	24,400
	2013	62,013	201,924	10,433	45,068	2,563	9,604	312	6,709	3,286	1,191	11,498
	2014	56,805	213,867	7,840	35,829	1,230	5,603	0	5,810	3,050	1,044	9,903
	2015	56,636	250,634	6,515	27,747	1,373	4,804	0	4,904	3,184	387	8,476
	2016	49,869	210,111	7,107	30,422	1,506	5,619	0	10,788	3,599	2,189	16,575
	2017	60,899	270,485	10,450	50,648	3,188	12,337	519	27,870	16,343	1,479	46,210
	2018	45,237	160,827	6,076	26,228	965	3,090	17	3,459	7,296	986	11,758
	Total	**652,905**	**2,629,136**	**99,117**	**434,181**	**23,661**	**85,926**	**4,202**	**111,419**	**58,841**	**9,132**	**183,593**

Table 2.4. (***continued***) Recreational effort, harvest, and discards estimates for striped bass in the Tar-Pamlico, Pungo, Neuse, and Cape Fear rivers and tributaries.

		Recreational Fishing Effort				**Recreational Harvest**		**Striped Bass Discards**				
Zone	**Year**	**Total Angler Fishing Trips**	**Total Fishing Effort (Angler Hours)**	**Striped Bass Angler Trips**	**Striped Bass Effort (Angler Hours)**	**numbers**	**pounds**	**n over creel**	**n undersized**	**n legal sized**	**n slot sized**	**Total**
Tar-Pamlico River	**2004**	13,880	74,984	3,427	13,666	663	2,886	0	3,465	263	0	3,728
	2005	18,334	68,588	4,662	17,668	572	2,511	0	8,423	310	0	8,733
	2006	15,012	72,475	2,964	12,297	675	1,442	0	2,588	278	0	2,866
	2007	21,623	102,968	4,144	17,001	346	1,655	0	12,393	114	0	12,507
	2008	11,521	59,030	2,899	13,283	175	647	0	5,138	295	37	5,470
	2009	15,298	68,715	2,412	10,474	233	794	0	2,347	512	288	3,147
	2010	12,008	52,227	3,913	15,102	1,510	4,696	22	3,925	843	338	5,128
	2011	15,260	60,509	6,209	26,258	1,234	4,253	9	8,062	2,687	1,124	11,882
	2012	30,626	109,560	8,936	34,027	2,049	8,221	17	10,298	3,480	2,246	16,040
	2013	39,446	137,943	8,811	35,645	2,108	7,289	134	10,311	6,401	1,090	17,937
	2014	22,514	89,749	6,945	30,131	1,898	7,163	728	12,793	2,052	531	16,105
	2015	38,513	147,296	10,724	47,305	2,147	8,082	40	12,329	4,566	426	17,361
	2016	46,700	199,478	14,909	72,897	4,861	18,502	203	29,089	5,844	4,544	39,680
	2017	48,876	182,534	14,636	63,843	3,495	12,566	0	51,334	9,522	803	61,659
	2018	34,648	130,200	9,274	38,548	2,046	6,403	854	22,366	4,028	904	28,151
	Total	**384,259**	**1,556,255**	**104,865**	**448,144**	**24,011**	**87,110**	**2,008**	**194,861**	**41,195**	**12,331**	**250,395**
Pungo River	**2004**	5,532	40,573	1,910	10,183	1,493	5,227	56	2,543	259	0	2,858
	2005	7,029	34,386	2,074	9,595	1,619	5,914	139	713	76	0	928
	2006	8,470	44,599	1,387	5,716	562	1,831	33	2,163	57	0	2,253
	2007	13,089	64,273	1,862	8,688	635	2,024	7	4,422	109	0	4,538
	2008	13,232	71,210	548	2,176	263	833	0	1,782	571	3	2,356

Table 2.4. (***continued***) Recreational effort, harvest, and discards estimates for striped bass in the Tar-Pamlico, Pungo, Neuse, and Cape Fear rivers and tributaries.

		Recreational Fishing Effort				**Recreational Harvest**		**Striped Bass Discards**				
Zone	**Year**	**Total Angler Fishing Trips**	**Total Fishing Effort (Angler Hours)**	**Striped Bass Angler Trips**	**Striped Bass Effort (Angler Hours)**	**numbers**	**pounds**	**n over creel**	**n undersized**	**n legal sized**	**n slot sized**	**Total**
Pungo River	**2009**	13,090	67,410	756	3,142	413	1,399	7	1,681	553	292	2,533
	2010	5,970	29,308	306	1,075	138	480	7	576	118	9	710
	2011	5,579	27,996	740	3,889	414	1,412	0	1,171	276	86	1,533
	2012	9,415	50,264	700	3,285	365	1,277	88	2,385	400	0	2,873
	2013	12,665	69,902	892	5,336	796	2,644	0	2,282	669	75	3,026
	2014	7,440	44,458	459	2,192	173	602	0	582	2,002	66	2,650
	2015	5,767	32,743	711	3,644	414	1,383	0	5,038	279	0	5,317
	2016	8,806	46,520	1,268	5,670	330	1,139	0	17,997	534	46	18,578
	2017	14,534	81,889	1,013	5,031	652	2,070	31	22,582	622	11	23,246
	2018	10,785	66,683	1,019	5,080	360	1,391	0	8,304	768	0	9,072
	Total	**141,401**	**772,215**	**15,645**	**74,703**	**8,627**	**29,626**	**368**	**74,221**	**7,293**	**589**	**82,471**
Cape Fear River	**2013**	22,251	103,412	257	870	0	0	92	0	263	0	355
	2014	6,931	28,622	438	2,164	0	0	721	0	830	0	1,551
	2015	9,056	55,463	209	702	0	0	176	0	22	0	199
	2016	9,936	43,226	391	1,464	0	0	12	0	616	0	628
	2017	2,159	11,057	26	159	0	0	0	0	14	0	14
	2018	6,062	24,568	24	61	0	0	0	0	140	0	140
	Total	**50,332**	**241,780**	**1,345**	**5,419**	**0**	**0**	**1,001**	**0**	**1,885**	**0**	**2,886**

Table 2.4. (***continued***) Recreational effort, harvest, and discards estimates for striped bass in the Tar-Pamlico, Pungo, Neuse, and Cape Fear rivers and tributaries.

		Recreational Fishing Effort				**Recreational Harvest**		**Striped Bass Discards**				
Zone	**Year**	**Total Angler Fishing Trips**	**Total Fishing Effort (Angler Hours)**	**Striped Bass Angler Trips**	**Striped Bass Effort (Angler Hours)**	**numbers**	**pounds**	**n over creel**	**n undersized**	**n legal sized**	**n slot sized**	**Total**
All CSMA	**2004**	46,075	277,981	12,782	63,791	6,141	22,958	85	11,729	1,743	0	13,557
	2005	89,664	352,370	16,414	69,370	3,832	14,965	152	15,609	1,016	77	16,854
	2006	62,663	279,633	10,611	42,066	2,481	7,352	33	12,548	2,314	0	14,895
	2007	65,764	309,334	10,971	46,655	3,597	10,794	147	21,673	1,707	0	23,527
	2008	52,887	266,815	6,621	28,413	843	2,990	2,838	11,721	3,316	91	17,966
	2009	45,907	213,759	5,642	26,611	895	3,061	7	4,471	1,769	718	6,965
	2010	37,518	164,643	6,559	25,354	1,757	5,537	29	5,200	2,401	360	7,990
	2011	45,246	185,807	12,606	51,540	2,728	9,474	9	16,659	5,397	2,123	24,188
	2012	110,689	370,021	18,338	71,964	3,922	15,240	439	26,343	13,621	2,910	43,313
	2013	136,374	513,181	20,394	86,918	5,467	19,537	539	19,302	10,619	2,357	32,816
	2014	93,690	376,696	15,682	70,316	3,301	13,368	1,449	19,185	7,934	1,641	30,209
	2015	109,972	486,136	18,159	79,398	3,934	14,269	217	22,272	8,052	813	31,353
	2016	115,311	499,335	23,675	110,453	6,697	25,260	215	57,874	10,593	6,779	75,461
	2017	126,467	545,965	26,125	119,680	7,334	26,973	549	101,787	26,501	2,293	131,129
	2018	96,732	382,278	16,393	69,917	3,371	10,884	871	34,128	12,232	1,890	49,122
	Total	**1,228,898**	**5,199,385**	**220,972**	**962,447**	**56,299**	**202,662**	**7,579**	**380,500**	**109,215**	**22,052**	**519,345**

Table 2.5. Annual weighted relative abundance index of striped bass (number of individuals per sample), total number of striped bass collected, and the number of gill net samples (n) in the Tar-Pamlico, Pungo, and Neuse rivers (2004–2018) and the Cape Fear and New rivers (2008–2018). The Percent Standard Error (PSE) represents a measure of precision of the index.

	Tar-Pamlico and Pungo rivers				Neuse River				Cape Fear and New rivers[4]			
Year	Index	n Striped Bass	n samples	PSE [Index]	Index	n Striped Bass	n samples	PSE [Index]	Index	n Striped Bass	n samples	PSE [Index]
2004	1.2	184	160	16	1.04	158	160	26				
2005	2.66	396	152*	14	1.37	200	152[5]	23				
2006	2.38	371	160	17	1.74	268	160	17				
2007	1.57	241	160	22	1.16	177	160	19				
2008	1.61	249	160	21	1.25	193	161	23	0.04	3	84	100
2009	1.18	182	160	16	0.9	142	160	26	0.03	3	119	67
2010	2.11	329	160	17	2.02	311	160	23	0.01	1	120	100
2011	2.15	328	160	20	2.14	325	160	18	0.04	4	120	50
2012	0.94	143	160	20	0.84	127	160	20	0.03	3	120	67
2013	1.41	215	160	18	0.98	149	160	24	0.02	2	120	50
2014	1.43	217	160	16	1.82	273	160	20	0	0	120	
2015	1.14	173	160	18	1.65	251	160	18	0.14	15	120	36
2016	1.16	178	160	14	1.17	178	160	14	0.11	12	120	45
2017	1.21	186	160	17	1.41	218	160	16	0.08	9	120	50
2018	2.26	346	160	21	1.34	204	160	19	0.03	3	113	67

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[4] Sampling in the Cape Fear and New rivers began in 2008

[5] In 2005, fewer stations were sampled due to high gasoline prices

Table 2.6. NCWRC annual catch summary for the Tar River striped bass electrofishing survey, 1996–2018.

Year	n Sample Events	Total Catch	Males	Females	Effort	Mean Index	SD [Index]	SE [Index]	Peak Index
1996	3	535	373	162	98,640	19.5	0.6	0.4	20.3
1997	3	1,275	1,045	230	103,572	44.3	13.7	7.9	53.1
1998	14	1,061	897	164	91,263	41.6	30.8	8.2	97.3
1999	8	561	334	227	50,793	36.7	28.7	10.1	93.7
2000	9	547	348	199	41,443	51.8	37.7	12.6	132.1
2001	6	326	240	86	24,814	46.8	15	6.1	68
2002	7	369	260	109	40,798	35.2	23.4	8.8	68.4
2003	6	211	169	42	23,862	31.1	13.8	5.6	51.7
2004	7	318	225	93	32,401	36.3	11.6	4.4	51
2005	13	1,429	1,390	39	63,456	86.9	53.1	14.7	184.9
2006	7	530	437	93	35,300	55.1	18.6	7	82.2
2007	8	317	264	53	41,019	29	12.2	4.3	43.5
2008	10	505	469	36	42,564	43.4	35.3	11.2	116.8
2009	6	347	265	82	23,532	48.1	33.6	13.7	98.3
2010	4	392	313	79	12,600	99.8	81.1	40.6	200
2011	4	202	100	102	18,800	37.1	19.8	9.9	54.7
2012	7	249	195	54	33,630	29.7	24.6	9.3	71.6
2013	7	315	241	74	32,400	34.2	13.5	5.1	44.7
2014	9	339	243	96	43,200	27	15.9	5.3	58.7
2015	11	418	354	64	46,800	35.1	21.9	6.6	90
2016	12	286	247	39	36,000	27.3	14.7	4.2	52
2017	5	180	128	49	23,400	25.5	9.9	4.4	34.7
2018	16	221	166	48	45,000	18.2	20.1	5	80

Table 2.7. NCWRC annual catch summary for the Neuse River striped bass electrofishing survey, 1994–2018.

Year	n Sample Events	Total Catch	Males	Females	Effort	Mean Index	SD [Index]	SE [Index]	Peak Index
1994	5	121	92	28	26,452	18.7	10.5	4.7	29.7
1995	5	125	107	18	26,381	15.3	13.2	6.6	33.2
1996	24	226	168	58	69,489	10	16.1	3.3	48
1997	26	143	114	29	76,537	6	7.1	1.4	20.8
1998	21	219	176	43	61,125	11.9	15.6	3.4	44
1999	15	292	242	50	49,562	20.4	15.6	4	62
2000	24	352	241	111	67,449	18.4	19.2	3.9	66.7
2001	22	155	132	23	57,680	8.6	11.2	2.4	46.6
2002	22	100	82	18	68,340	5.1	4.9	1	21
2003	40	401	303	98	112,305	11.8	17.6	2.8	90.5
2004	14	73	54	19	40,858	6.5	3.6	1	12.6
2005	14	65	56	9	51,094	4.5	6.6	1.8	24
2006	15	58	53	5	36,528	6.8	12.2	3.1	43.7
2007	23	170	138	32	62,372	9.8	11	2.3	51.2
2008	23	138	107	31	81,116	4.4	4.4	0.9	16.6
2009	18	360	328	31	59,094	14.1	18.1	4.3	57.3
2010	17	141	122	19	52,116	10	12.6	3.1	44.4
2011	19	176	115	60	54,129	13.9	12.4	2.8	38.4
2012	28	144	116	27	63,468	8.9	15.5	2.9	66.6
2013	29	322	265	56	71,490	15	12.4	2.3	53.7
2014	39	284	201	83	91,120	10.1	14.7	2.3	71.6
2015	42	226	198	28	47,560	15.5	27.6	4.3	137.4
2016	42	93	71	22	45,579	7.4	6.6	1	29.5
2017	61	200	155	45	81,692	6.7	11.2	1.4	55.8
2018	56	282	236	46	77,132	12.5	11.5	1.5	44.1

Table 2.8. NCWRC annual catch summary for the Cape Fear River striped bass electrofishing survey, 2003–2018.

Year	n Sample Events	Effort	n Females	n Males	Total Catch	Mean Index	SD [Index]	SE [Index]	Peak Index
2003	11	18,562	12	4	16	4.5	5.5	1.7	14
2004	8	8,843	20	17	42	25.4	20.1	7.1	57.8
2005	20	61,200	35	42	103	6.5	7.3	1.6	26
2006	12	25,429	2	2	5	1	1.9	0.5	5.8
2007	22	46,557	28	30	120	10.8	15.6	3.3	60
2008	21	45,900	35	64	100	8.8	11.2	2.5	38
2009	21	44,677	27	57	103	9.2	8.3	1.8	24
2010	24	43,200	110	62	182	15.2	13.7	2.8	56
2011	24	42,300	59	37	105	9	12.3	2.5	54
2012	26	45,521	64	55	119	9.2	10	2	30
2013	23	41,400	28	65	99	8.6	14.7	3.1	52
2014	24	43,123	30	71	154	12.9	15.7	3.2	55.6
2015	20	36,259	78	102	193	19.1	27.9	6.2	104
2016	25	45,408	45	145	202	15.9	28.7	5.7	102
2017	19	34,036	47	59	107	11.3	24.7	5.7	86
2018	15	27,315	20	28	58	7.7	6.8	1.7	23.8

Table 1.9. Total number of striped bass PIT tagged by all gears and tagger affiliation in the Cape Fear River, 2011–2018.

Tagger	Gear	2011	2012	2013	2014	2015	2016	2017	2018	All
NCDMF	Electrofisher	133	235	336	410	484	388	262	342	2,590
	Gill Net (P915)	11			2	4	3	4		24
	Gill Net (run-around)	9				3	2	6		20
	Hook and line	23	8		8	9	14	11		73
	Trotline			1						1
NCWRC	Electrofisher	72	88	50	99	154	128	33	33	657
Tournament	Hook and line	16	21	38	31	20	33	34	17	210
Volunteer	Hook and line	21	42	34	45	10	24	9		185
All	All	285	394	459	595	684	592	359	392	3,760

Table 2.10. Total number of striped bass PIT tagged by gear and tagger affiliation included in the tagging model in the Cape Fear River, 2012–2018.

Tagger	Gear	2012	2013	2014	2015	2016	2017	2018	All
NCDMF	Electrofisher	235	336	410	484	388	262	342	2,457
	Hook and line	8		8	9	14	11		50
NCWRC	Electrofisher	88	50	99	154	128	33	33	585
Tournament	Hook and line	21	38	31	20	33	34	17	194
Volunteer	Hook and line	42	34	45	10	24	9		164
All	All	394	458	593	677	587	349	392	3,450

Table 2.11. Mean, standard deviation (SD), minimum, and maximum total length (TL) of striped bass tagged by year, gear, and tagger affiliation included in the tagging model for the Cape Fear River, 2012–2018.

Group	Level	n	Mean TL (mm)	SD [Mean TL]	Minimum TL (mm)	Maximum TL (mm)
Year	2012	394	544.6	118.2	219	846
	2013	458	534.3	109	192	835
	2014	593	540.8	119.2	212	800
	2015	677	508.5	128.9	284	891
	2016	586	525.7	101.8	329	889
	2017	349	540.4	103.4	298	867
	2018	392	569	101.4	337	809
Gear	Hook and line	408	557.8	115.4	330	838
	Electrofishing	3,041	531.5	114.4	192	891
Tagger	NCDMF	2,507	525.2	114.5	219	867
	NCWRC	584	558.7	109.1	192	891
	Tournament	194	537	110.7	330	823
	Volunteer	164	590.7	116.3	355	838

Table 2.12. Total number of striped bass PIT tag recaptures by all gears in the Cape Fear River, 2011–2018.

Year	Tagged	Recapture Year								Total Recaptured	Percent Recaptured
		2011	2012	2013	2014	2015	2016	2017	2018		
2011	285	6	8	10	3	2	4	.	.	33	11.6
2012	394	.	4	14	12	6	.	.	1	37	9.4
2013	459	.	.	18	14	9	8	3	3	55	12
2014	595	.	.	.	14	23	5	3	4	49	8.2
2015	684	.	.	.	.	9	8	11	2	30	4.4
2016	592	.	.	.	.	.	10	15	7	32	5.4
2017	359	.	.	.	.	.	.	7	11	18	5
2018	392	.	.	.	.	.	.	.	5	5	1.3
All	3,760	6	12	42	43	49	35	39	33	259	6.9

Table 2.13. Total number of striped bass PIT tag recaptures, from electrofishing gear, included in the tagging model for the Cape Fear River, 2012–2018.

Year	Tagged	Recapture Year							Total Recaptured	Percent Recaptured
		2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**		
2012	394	4	14	12	5	.	.	1	36	9.1
2013	458	.	18	14	8	8	3	3	54	11.8
2014	593	.	.	14	21	5	3	4	47	7.9
2015	677	.	.	.	9	7	11	2	29	4.3
2016	587	.		.	.	10	15	7	32	5.5
2017	349	.	.	.	.	.	7	11	18	5.2
2018	392	.	.	.	.	.	.	5	5	1.3
All	3,450	4	32	40	43	30	39	33	221	6.4

Table 2.14. Distance (miles) between release and recapture sites of striped bass included in the tagging model by days at large in the Cape Fear River, 2012–2018.

Days at Large	n	Median	Mean	SD[Mean]	Minimum	Maximum
8 to 20	15	1	2.7	5	0	20
21 to 100	37	1	6.2	11.4	0	54
101 to 200	5	20	14.4	11.5	1	25
201 to 300	25	3	11.2	15	0	65
301 to 400	49	1	4.4	9.9	0	43
401 to 500	23	1	4.8	8.2	0	25
501 to 1,000	40	1	7.2	14.3	0	62
1,001 to 1,500	20	1	7	15.1	0	65
1,501 to 2,000	6	1	1.5	0.8	1	3
2,001 to 2,500+	1	56	56		56	56
All	221	1	6.5	12.3	0	65

Table 2.15. Mean, standard deviation (SD), minimum, and maximum number of days at large of striped bass recaptured by year, 2012–2018.

Year	n	Mean	SD[Mean]	Minimum	Maximum
2012	36	594.4	418.5	14	2,232
2013	54	559.8	485.3	12	1,870
2014	47	434.9	443.9	8	1,695
2015	29	412.6	348.7	21	1,371
2016	32	398.9	217.1	8	826
2017	18	231.6	189	12	467
2018	5	28.6	22.5	12	57
All	221	457.5	406.9	8	2,232

Table 2.16. Mean, standard deviation (SD), minimum, and maximum total length (TL) of striped bass recaptured by year in the Cape Fear River, 2012–2018.

Year	n	Mean TL (mm)	SE[Mean TL]	Minimum TL (mm)	Maximum TL (mm)
2012	36	611.6	94	456	845
2013	54	592.5	69.9	469	747
2014	47	600.2	89.1	380	814
2015	29	560.5	104.1	359	760
2016	32	570.7	83.5	382	766
2017	18	577.2	96.4	397	766
2018	5	481.2	51.3	402	534
All	221	586.7	89.1	359	845

Table 2.17. Mean, standard deviation (SD), minimum, and maximum growth (mm) of recaptured striped bass by days at large in the Cape Fear River, 2012–2018.

Days at Large	n	Mean (mm)	SD[Mean]	Minimum (mm)[6]	Maximum (mm)
8 to 20	11	2.7	2.8	0	9
21 to 100	29	11.8	13.6	0	69
101 to 200	4	29.5	24.4	3	62
201 to 300	22	64.5	45.8	4	192
301 to 400	49	67.6	45.3	7	255
401 to 500	21	80.5	43.10	19	154
501 to 1,000	41	126.9	63.5	15	221
1,001 to 1,500	21	133.3	73.4	29	306
1,501 to 2,000	6	242.8	55.9	181	332
2,001 to 2,500+	1	367.0		367	367

Table 2.18. Mean, standard deviation (SD), minimum, and maximum growth (mm) of striped bass recaptured by year in the Cape Fear River, 2012–2018.

Year	n	Mean (mm/day)	SD[Mean]	Minimum (mm/day)[6]	Maximum (mm/day)
2012	33	0.18	0.10	0.02	0.39
2013	52	0.16	0.14	0.01	0.78
2014	47	0.19	0.15	0.00	0.77
2015	24	0.20	0.12	0.04	0.57
2016	30	0.21	0.13	0.04	0.54
2017	16	0.24	0.18	0.08	0.75
2018	3	0.23	0.20	0.11	0.46
All	205	0.19	0.14	0.00	0.78

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[6] Negative values were removed

Table 3.1. Summary of parameter values used to develop the demographic matrix model.

Parameter	Notation	Cape Fear	Neuse	Tar-Pamlico	Reference
Maximum age (yr)	T	7	11	11	Age-length data from three rivers 2004–2017
Asymtotic length (mm)	L_∞	759.7	874.4	838.7	Posterior median estimated using age-length data from three rivers 2004–2017
Growth coefficient (yr^{-1})	K	0.35	0.185	0.197	
Age at which fish has a length of zero (yr)	t_0	-0.003	-1.914	-1.696	
Maximum age for calculating M (yr)	t_{max}	7	11	11	Maximum age assumed for matrix model
Minimum age for calculating M (yr)	t_{min}	1			Minimum age assumed for matrix model
Mean constant natural mortality lower bound (yr^{-1})	m_1	0.6 for age 1-3; 0.1 for age 4+			Harris and Hightower 2017; Bradley et al. 2018
Mean constant natural mortality upper bound (yr^{-1})	m_2	1 for age 1-3; 0.5 for age 4+			
Coefficient of variation	CV	U(20%, 40%)			Jiao et al. 2009; Li and Jiao 2015
Fishery selectivity	g	0.014 for age 1; 0.13 for age 2; 0.6 for age 3; 0.94 for age 4; 0.99 for age 5; 1 for age > 5	0 for age < 3; 0.28 for age 3; 1 for age > 3	0 for age < 3; 0.12 for age 3; 1 for age > 3	Estimated from a catch-curve analysis using 2017 fishery-dependent data for Neuse and Tar-Pamlico Rivers, and 2017 fishery-independent data for Cape Fear River
Fishing mortality (yr^{-1})	F	0, 0.2, 0.4, 0.6, 0.8, 1			Hypothetical scenarios based on Rachels and Ricks 2015, Bradley et al. 2018
Sex ratio		1:1			
Proportion of viable eggs	x	0.64			Bradley et al. 2018b
Survival of offspring from birth to next census	S_0	0.000017			Estimated using Table 1 in Dahlberg 1979
Fecundity (number of eggs per mature female)	E	$\ln(E_t)=12.484+0.205t$	$\ln(E_t)=12.52+0.214t$	$\ln(E_t)=12.429+0.203t$	Estimated using survey data from Neuse River and Tar-Pamlico River 2013–2014

Table 3.1. (***continued***) Summary of parameter values used to develop the demographic matrix model.

Parameter	**Notation**	**Cape Fear**	**Neuse**	**Tar-Pamlico**	**Reference**
Maturity	w	0 for age ≤ 2, 1 for age ≥ 5			Survey data from Neuse River and Tar-Pamlico River 2013–2014; Olsen and Rulifson 1992; Boyd 2011
Maturity lower bound	w_1	0.29 for age 3, 0.94 for age 4			
Maturity upper bound	w_2	1 for ages 3 and 4			

Table 3.2. Initial year age structure for fishery management strategy evaluation.

Age	Proportion
1	0.35
2	0.16
3	0.12
4	0.1
5	0.08
6	0.08
7	0.06
8	0.05
9	0
10	0
11	0

Table 3.3. Population growth rate estimates from the matrix model. Pr is the probability of population growth rate greater than one.

	Cape Fear				**Neuse**				**Tar-Pamlico**			
F	**Median**	**Lower**	**Upper**	**Pr**	**Median**	**Lower**	**Upper**	**Pr**	**Median**	**Lower**	**Upper**	**Pr**
0	1.01	0.70	1.39	0.52	1.13	0.83	1.48	0.80	1.10	0.81	1.44	0.74
0.2	0.94	0.64	1.30	0.36	1.05	0.76	1.39	0.63	1.02	0.74	1.36	0.56
0.4	0.88	0.60	1.24	0.24	0.99	0.71	1.34	0.47	0.97	0.69	1.31	0.41
0.6	0.83	0.56	1.20	0.15	0.94	0.66	1.30	0.35	0.92	0.65	1.28	0.32
0.8	0.79	0.52	1.14	0.10	0.90	0.62	1.26	0.27	0.89	0.61	1.24	0.24
1	0.75	0.49	1.10	0.07	0.87	0.59	1.24	0.23	0.86	0.59	1.22	0.20

Table 4.1. Cape Fear River tagging model parameters and priors. *U* denotes the uniform distribution.

Parameters	**Values**	**Reference**
Constant parameters		
Survival from tagging procedure	ϕ=1	
Immediate tag retention probability	ρ =1	
Tag reporting rate	λ =1	
Tag loss	Ω =0	
Priors		
Instantaneous total mortality (yr^{-1})	$\bar{Z}$~ U(0.1, 1.5)	Bradley et al. 2018; Harris and Hightower 2017
Instantaneous survey mortality (month^{-1})	U ~ U(0, 0.1)	
Standard deviation of log-total mortality	σ_Z ~ U(0.001, 1)	

Table 4.2. Estimated instantaneous total mortality (*Z*, yr^{-1}) due to natural causes and fishing, estimated abundance (number) and estimated capture probability (α) from the tagging model in the Cape Fear River. Median—posterior median; Lower and Upper—lower and upper 95% credible intervals.

	***Z* (yr^{-1})**			***N* (number)**			**α**		
Year	**Median**	**Lower**	**Upper**	**Median**	**Lower**	**Upper**	**Median**	**Lower**	**Upper**
2012	0.96	0.53	1.43	10,983	5,418	23,479	0.036	0.017	0.073
2013	0.58	0.21	1.00	4,532	3,024	6,921	0.101	0.066	0.151
2014	1.13	0.71	1.47	7,372	4,623	11,708	0.080	0.051	0.128
2015	0.81	0.37	1.29	3,778	2,655	5,825	0.179	0.116	0.255
2016	0.63	0.24	1.09	3,335	2,191	5,573	0.176	0.105	0.268
2017	0.53	0.18	0.97	1,578	1,168	2,293	0.221	0.152	0.299
2018	0.73	0.21	1.41	1,914	1,415	2,765	0.205	0.142	0.277

Table 4.3. Estimated striped bass effort and catch in the Cape Fear River. (Source: Costal Angling Program (CAP) Central Southern Management Area (CSMA) recreational striped bass creel survey)

Year	Month	n Striped Bass Trips	n Striped Bass Hours	Harvest		Discard (numbers)				Total Catch (n fish)
				numbers	pounds	legal sized	over creel	undersized	slot	
2013	Jan									
	Feb									
	Mar									
	Apr	92	399					81		81
	May	165	470			263		11		274
	Total	257	870			263		92		355
	PSE	48.6	63.1			90.8		55.6		
2014	Jan									
	Feb									
	Mar	134	558							
	Apr	138	833			708		703		1,412
	May	161	748			122		17		139
	Total	433	2,140			830		721		1,551
	PSE	42.9	45.9			72.7		77.5		
2015	Jan									
	Feb									
	Mar	110	422			22				
	Apr	19	181					162		162
	May	79	100					15		15
	Total	209	702			22		176		199
	PSE	50.1	53			100		57.4		
2016	Jan									
	Feb									
	Mar	179	750			10		12		22
	Apr	87	315			17				17
	May	126	399			588				588
	Total	391	1,464			616		12		628
	PSE	46.4	44.4			95.8		100		

Table 4.3. (***continued***) Estimated striped bass effort and catch in the Cape Fear River. (Source: Costal Angling Program (CAP) Central Southern Management Area (CSMA) recreational striped bass creel survey)

Year	Month	n Striped Bass Trips	n Striped Bass Hours	Harvest		Discard (numbers)				Total Catch (n fish)
				numbers	pounds	legal sized	over creel	undersized	slot	
2017	**Jan**									
	Feb	26	159			14				14
	Mar									
	Apr									
	May									
	Total	26	159			14				14
	PSE	100..0	100			100				
2018	**Jan**									
	Feb									
	Mar	18	35							
	Apr									
	May	7	26			140				140
	Total	24	61			140				140
	PSE	77.1	71.5			70.8				

Table 5.1. Fit of the candidate models. Com = commercial; Rec = recreational; DO = dissolved oxygen (mg/L); K = the number of parameters; AIC_c = Akaike's information criterion corrected for small sample size; Δ_i = Akaike difference; w_i = Akaike weight. The candidate models from Rachels and Ricks (2018) are formatted in **bold**.

Model	***K***	**AIC_c**	**Δ_i**	**w_i**	**R^2**
Com effort	**2**	**-20.41**	**0**	**0.152**	**0.21**
Com effort, Com harvest	**3**	**-19.27**	**1.14**	**0.086**	**0.43**
Rec effort	2	-19.15	1.26	0.081	0.11
Rec discard	2	-18.89	1.52	0.071	0.09
Com harvest	**2**	**-18.88**	**1.53**	**0.071**	**0.08**
Rec total catch	2	-18.77	1.64	0.067	0.075
Rec effort, Com effort	3	-18.68	1.73	0.064	0.39
Rec harvest, Rec effort	3	-18.5	1.91	0.058	0.38
DO	**2**	**-18**	**2.41**	**0.045**	**0.001**
Rec harvest	2	-17.99	2.42	0.045	0
Rec total removal	2	-17.99	2.42	0.045	0
Com effort, Temperature	**3**	**-17.61**	**2.8**	**0.037**	**0.32**
Com effort, DO	**3**	**-16.62**	**3.79**	**0.023**	**0.25**
Rec harvest, Com effort	3	-16.57	3.84	0.022	0.25
Rec effort, Temperature	3	-16.1	4.31	0.018	0.21
Rec effort, DO	3	-15.69	4.72	0.014	0.18
Rec discard, Rec effort	3	-15.36	5.05	0.012	0.15
Rec effort, Com harvest	3	-15.26	5.15	0.012	0.14
Com harvest, Temperature	**3**	**-14.94**	**5.47**	**0.010**	**0.12**
Rec harvest, Com harvest	3	-14.86	5.55	0.009	0.11
Rec discard, Temperature	3	-14.76	5.65	0.009	0.1
Rec discard, DO	3	-14.65	5.76	0.009	0.09
Rec discard, Rec harvest	3	-14.61	5.8	0.008	0.09
Com harvest, DO	**3**	**-14.59**	**5.82**	**0.008**	**0.08**
DO, Temperature	**3**	**-13.86**	**6.55**	**0.006**	**0.015**
Rec harvest, Temperature	3	-13.82	6.59	0.006	0.01
Rec harvest, DO	3	-13.72	6.69	0.005	0.002
Rec discard, Rec effort, Rec harvest	4	-12.82	7.59	0.003	0.4
Com effort, DO, Temperature	**4**	**-11.88**	**8.53**	**0.002**	**0.34**
Com harvest, DO, Temperature	**4**	**-10.51**	**9.9**	**0.001**	**0.24**
Rec discard, Rec harvest, Com harvest	4	-10.37	10.04	0.001	0.23
Com effort, Com harvest, DO, Temperature	**5**	**-6.55**	**13.86**	**0.000**	**0.54**

Table 6.1. Estimated parameter values of the von Bertalanffy age-length relationship and their associated standard errors (SE) where total length was measured in millimeters (n=166).

Parameter	Value	SE
L_∞	787	65
K	0.26	0.084
t_0	-0.94	0.72

Table 6.2. Estimated parameter values of the length-weight relationship and their associated standard errors (SE) where total length was measured in millimeters and weight was measured in grams (n=198).

Parameter	Value	SE
a	2.4E-06	9.5E-07
b	3.2	6.2E-02

Table 6.3. Estimated natural mortality (M) at age based on Lorenzen's (1996) approach. The values given represent instantaneous rates.

Age	M
1	0.60
2	0.45
3	0.38
4	0.34
5	0.31
6	0.30
7	0.29

Table 6.4. Estimated parameter values of the logistic length-maturity relationship and their associated standard errors (SE) where total length was measured in millimeters (n=170).

Parameter	Value	SE
a	-49	18
b	0.10	0.037

Table 6.5. Definitions of symbols used in the per-recruit equations.

Symbol	Definition	Units
t	age	years
F_t	fishing mortality at age t	year^{-1}
F_{full}	fully-recruited fishing mortality	year^{-1}
S_t	selectivity at age t	proportion
Z_t	total mortality at age t	year^{-1}
M_t	natural mortality at age t	year^{-1}
N_1	number of fish at age 1	numbers of fish
N_t	number of fish at age t	numbers of fish
B_t	population biomass at age t	kilograms
w_t	individual weight at age t	grams
U_t	population size at age t for non-hatchery origin fish	numbers of fish
h	assumed proportion of hatchery fish in the population	proportion
H_t	population size at age t for hatchery-origin fish	numbers of fish
C_t	catch at age t	numbers of fish
YPR	yield per recruit	numbers of fish
W_t	weight of catch at age t	kilograms
WPR	weight per recruit	kilograms
SSB	spawning stock biomass	kilograms
SSU_t	SSB at age t for non-hatchery female fish	kilograms
p	proportion of individuals in the population that are female	proportion
mat_t	maturity at age t	proportion
f	proportion of fishing mortality that occurs before spawning	proportion
m	proportion of natural mortality that occurs before spawning	proportion
SSU/R	SSB per recruit for the non-hatchery female fish	kilograms
SSH_t	SSB at age t for hatchery-origin female fish	kilograms
SSH/R	SSB per recruit for hatchery-origin female fish	kilograms
SSB/R	SSB per recruit for the entire population	kilograms
EU_t	total number of eggs at age t for the non-hatchery female fish	numbers of eggs
EU/R	eggs per recruit for the non-hatchery female fish	numbers of eggs
EH_t	total number of eggs at age t for hatchery-origin female fish	numbers of eggs
EH/R	eggs per recruit for hatchery-origin female fish	numbers of eggs
E/R	eggs per recruit for the entire population	numbers of eggs
%SPR	spawning potential ratio	percentage

Table 6.6. Sample frequency at (genetic) age of striped bass collected in the Neuse River by the NCWRC's Spawning Stock Survey in 2017. Catches have been standardized to a collection time of 19 minutes.

Age	Frequency
1	0
2	8
3	123
4	88
5	37
6	36
7	7

Table 6.7. Estimates of fishing mortality (*F*) at age derived from the catch curve analysis.

Age	*F*
1	0
2	0.0092
3	0.25
4	0.33
5	0.33
6	0.33
7+	0.33

Table 7.1. Number of scales, otoliths, and genetic (PBT) structures collected by NCDMF available for CSMA striped bass age determination, 1975–2018. Genetic (PBT) structures are only available from 2016–2018.

Year	Scale	Otolith	PBT		Year	Scale	Otolith	PBT
1975	77	0			**1997**	0	0	
1976	4	0			**1998**	1	8	
1977	2	0			**1999**	18	0	
1978	32	0			**2000**	57	0	
1979	29	0			**2001**	50	0	
1980	105	0			**2002**	204	0	
1981	0	0			**2003**	334	64	
1982	0	0			**2004**	254	66	
1983	16	0			**2005**	532	86	
1984	18	0			**2006**	484	115	
1985	9	0			**2007**	335	87	
1986	0	0			**2008**	242	114	
1987	2	0			**2009**	316	39	
1988	4	0			**2010**	671	156	
1989	7	0			**2011**	688	196	
1990	0	0			**2012**	766	248	
1991	0	0			**2013**	993	189	
1992	0	0			**2014**	376	181	
1993	0	0			**2015**	413	107	
1994	0	0			**2016**	592	123	322
1995	0	0			**2017**	599	132	261
1996	0	0			**2018**	719	219	201
					Total	8,949	2,130	784

Table 7.2. Mean percentage age bias (bias compared to genetic age) for each reader for overall age bias and age bias by method type (standard deviation in parentheses). Cells with no values indicate the reader performed no readings for that method type.

Reader ID	Overall % Age Bias	Otolith % Age Bias	Scale % Age Bias
1	-0.274 (14.0)	-0.899 (8.5)	-0.0935 (15.2)
2	15.3 (22.2)	-1.81 (7.3)	23.1 (22.3)
3	-0.603 (13.3)		-0.603 (13.3)
4	-1.12 (12.4)		-1.12 (12.4)
5	7.81 (17.3)		7.81 (17.3)

Table 7.3. Parameter estimates from Bayesian generalized linear mixed effects model for scale ages and otolith ages compared to genetic ages. Estimates are median of posterior distributions with confidence interval in parentheses.

Parameter		Estimates
Reader ID random effects		
	α_1	-0.858 (-1.31, -0.304)
	α_2	2.47 (0.373, 8.96)
	α_3	-0.931 (-1.47, -0.399)
	α_4	-1.01 (-1.61, -0.505)
	α_5	0.280 (-0.527, 2.63)
	p_r	1.70 (0.1, 10.7)
	σ_r	1.67 (0.589, 5.34)
Ageing method fixed effects		
Otolith:	γ_1	-1.19 (-2.88, 0.507)
Scale:	γ_2	7.90 (1.37, 16.6)
Random error		
	p_e	98.3 (89.3, 99.9)
	σ_e	15.5 (15.0, 16.0)

Table 7.4. Coefficient of variation (%) analyses results for between readers for scale ages. Values in parentheses are percent agreement. Values in **bold** are significant ($P < 0.01$). Between reader coefficients of variation differ depending on which reader is the reference reader.

		Reader						
		1	2	3	4	5	6	7
	1		**6.1 (31)**	**4.7 (65)**	**3.2 (59)**	3.8 (72)	**5.4 (24)**	**4.4 (19)**
	2	**5.2 (31)**		**4.3 (38)**	**3.8 (46)**	**5.5 (30)**		
	3	**5.1 (65)**	**6.3 (38)**		**3.2 (67)**	2.5 (88)		
Reader	4	**5.8 (59)**	**5.4 (46)**	**4.9 (67)**		**6.0 (66)**		
	5	3.6 (72)	**7.0 (30)**	2.8 (88)	**3.1 (66)**			**4.3 (22)**
	6	**5.2 (24)**						
	7	**4.0 (19)**				**3.6 (22)**		

11 FIGURES

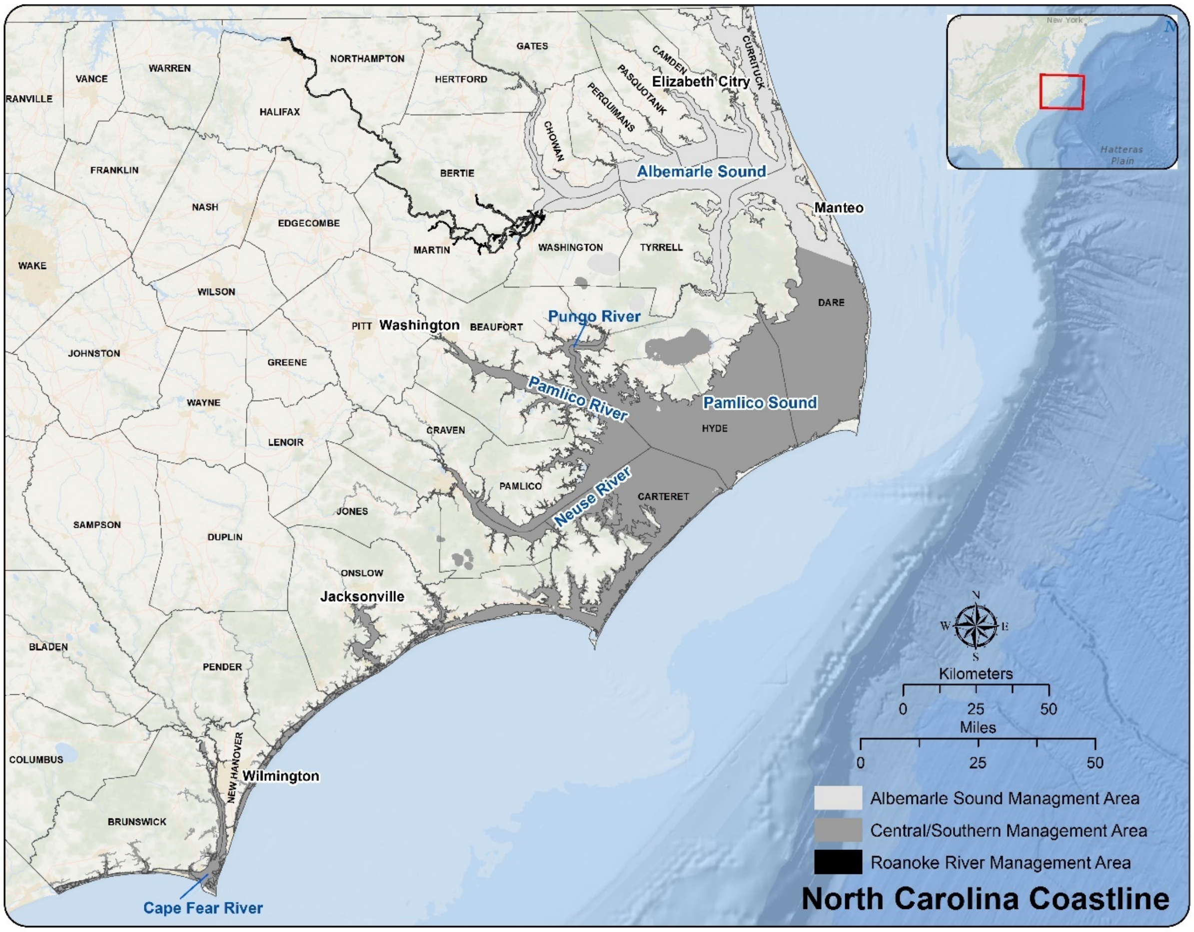


Figure 1.1. Boundary lines between the Albemarle Sound Management Area, Central Southern Management Area, and the Roanoke River Management Area.

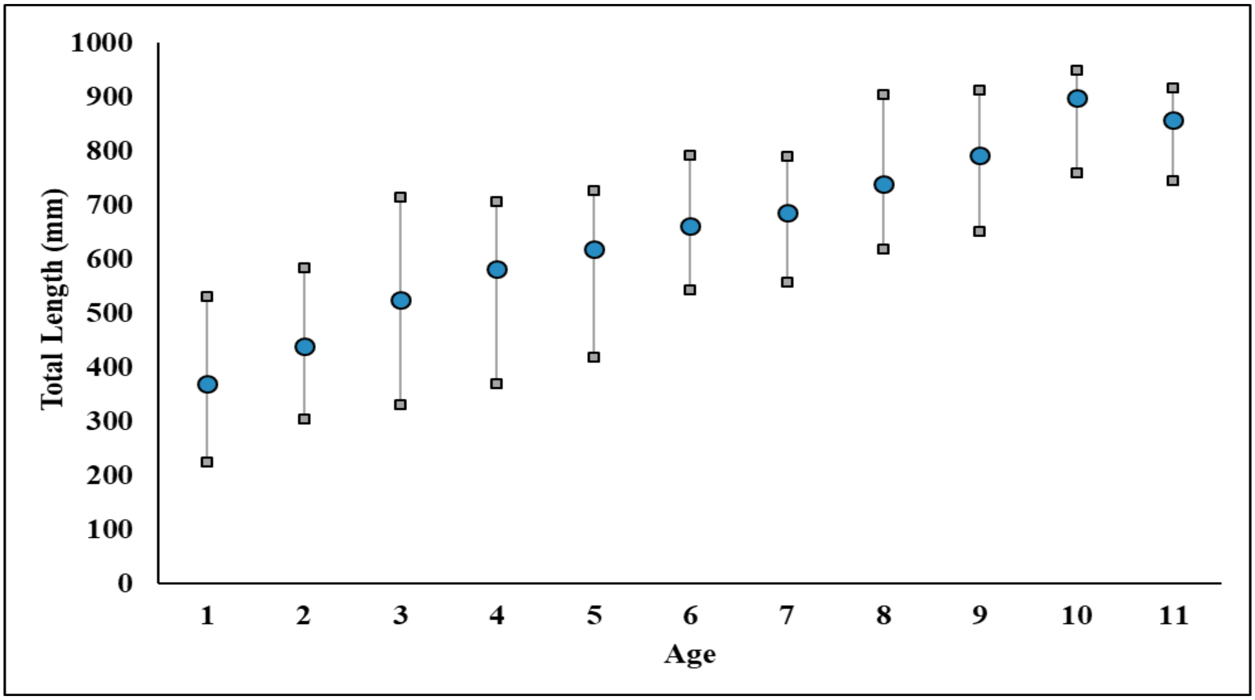


Figure 1.2. CSMA striped bass length at age based on otolith and genetic age samples collected by NCDMF, 2004–2018. Blue circles represent the mean size at a given age while the grey squares represent the minimum and maximum observed size for each age.

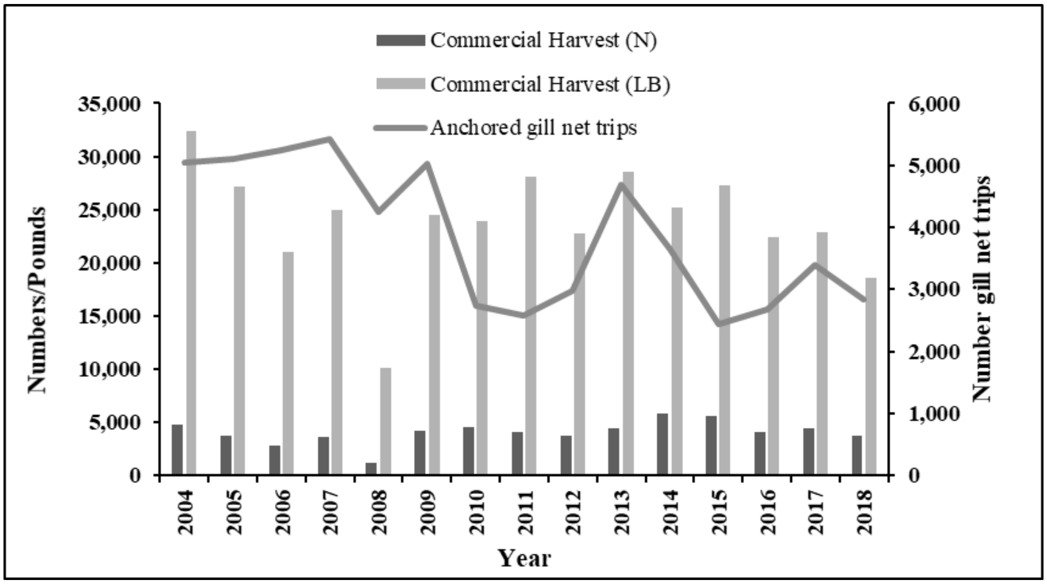


Figure 2.1. Commercial striped bass harvest in numbers and pounds and anchored gill-net trips in the Tar-Pamlico, Pungo, Neuse, and Bay rivers, 2004–2018.

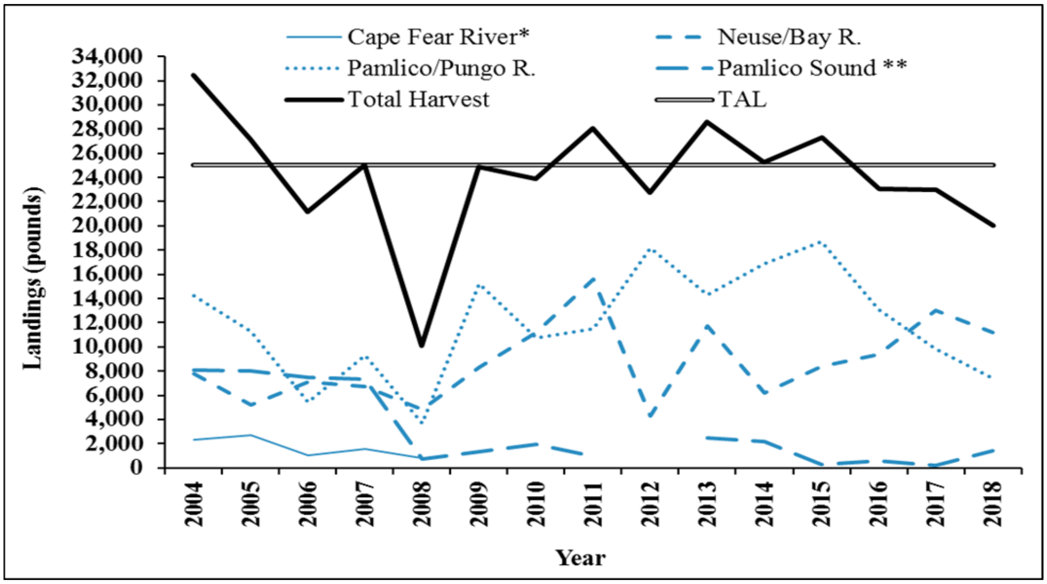


Figure 2.2. Commercial striped bass harvest by system, and the TAL in the CSMA, 2004–2018. *There has been a harvest moratorium in the Cape Fear River since 2008. **Landings data for the Pamlico Sound in 2012 are confidential.

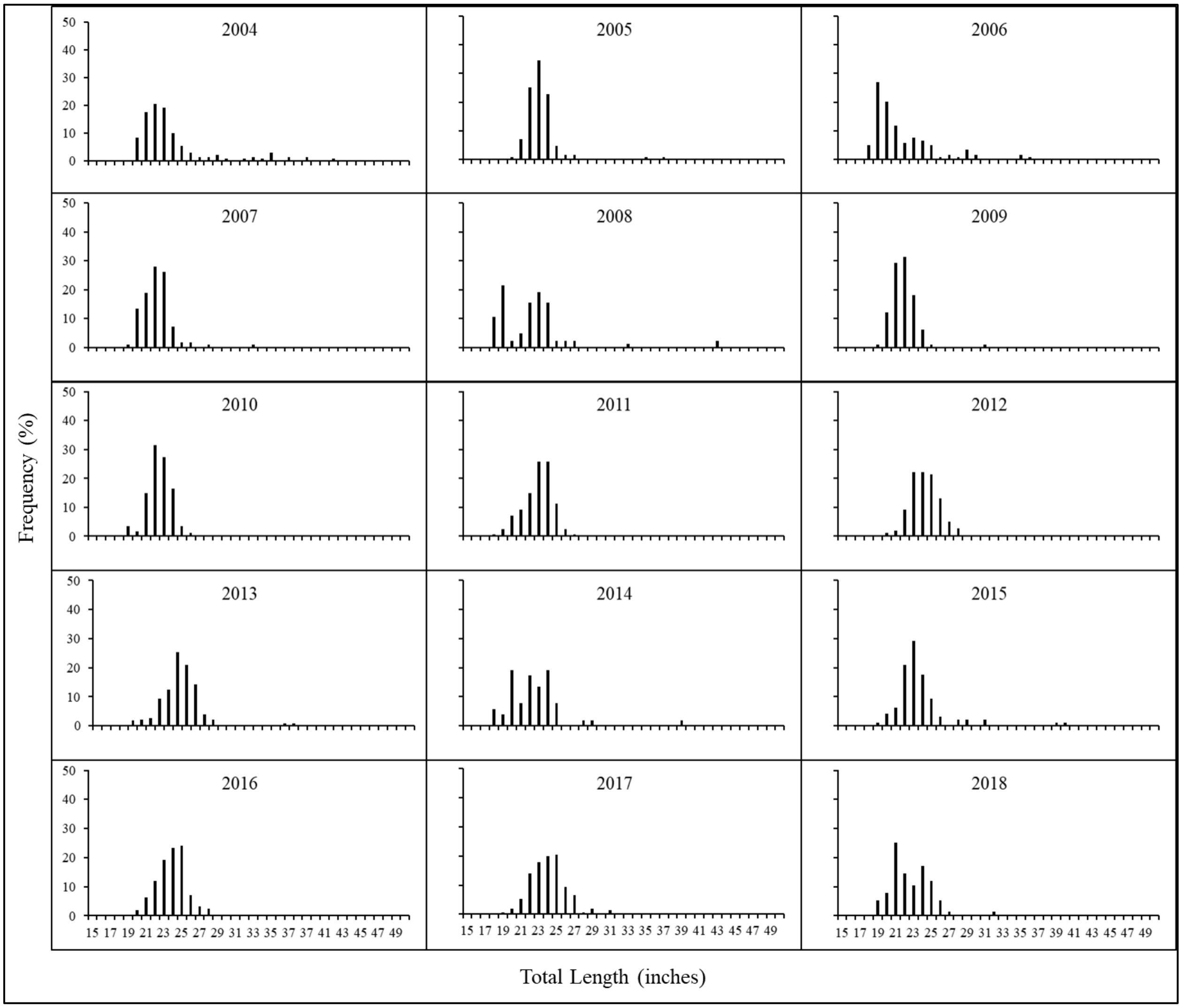


Figure 2.3. Length frequency of CSMA striped bass landed commercially in the Tar-Pamlico and Pungo rivers, 2004–2018.

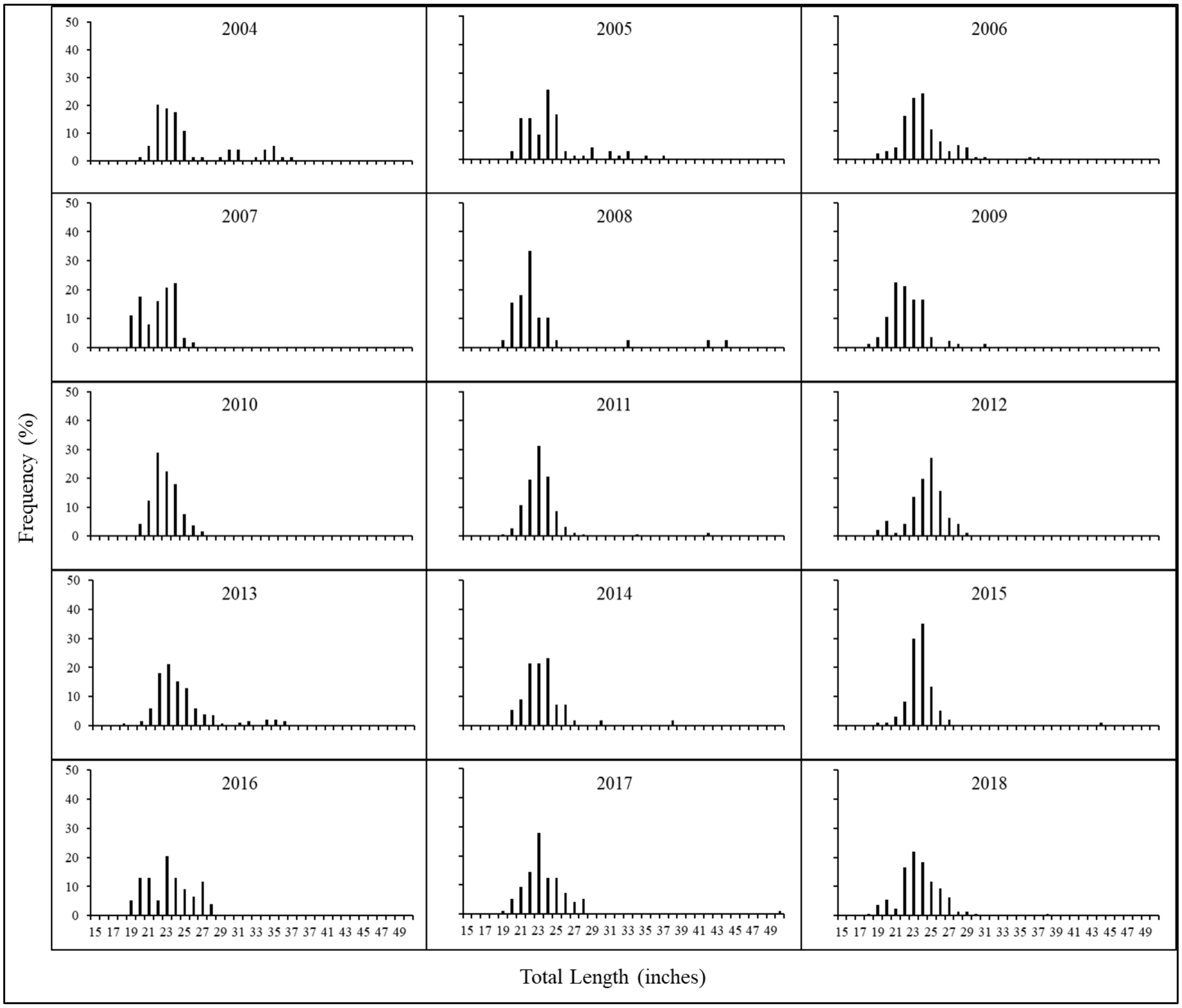


Figure 2.4. Length frequency of CSMA striped bass landed commercially in the Neuse and Bay rivers, 2004–2018.

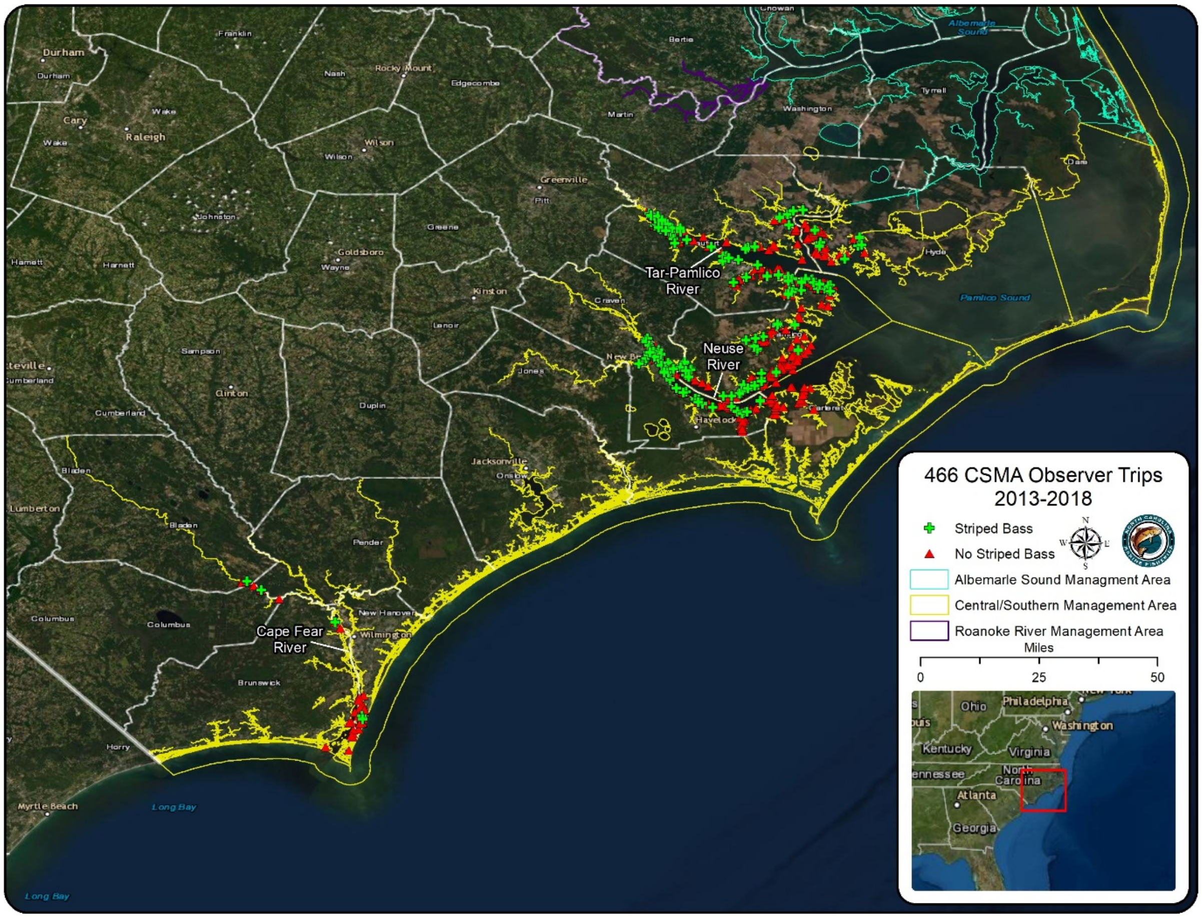


Figure 2.5. Program 466 CSMA observer trips by the presence or absence of striped bass, 2013–2018. The cross sign is an observer trip that encountered a striped bass (n=284), and the triangle is an observer trip that did not encounter striped bass (n=789).

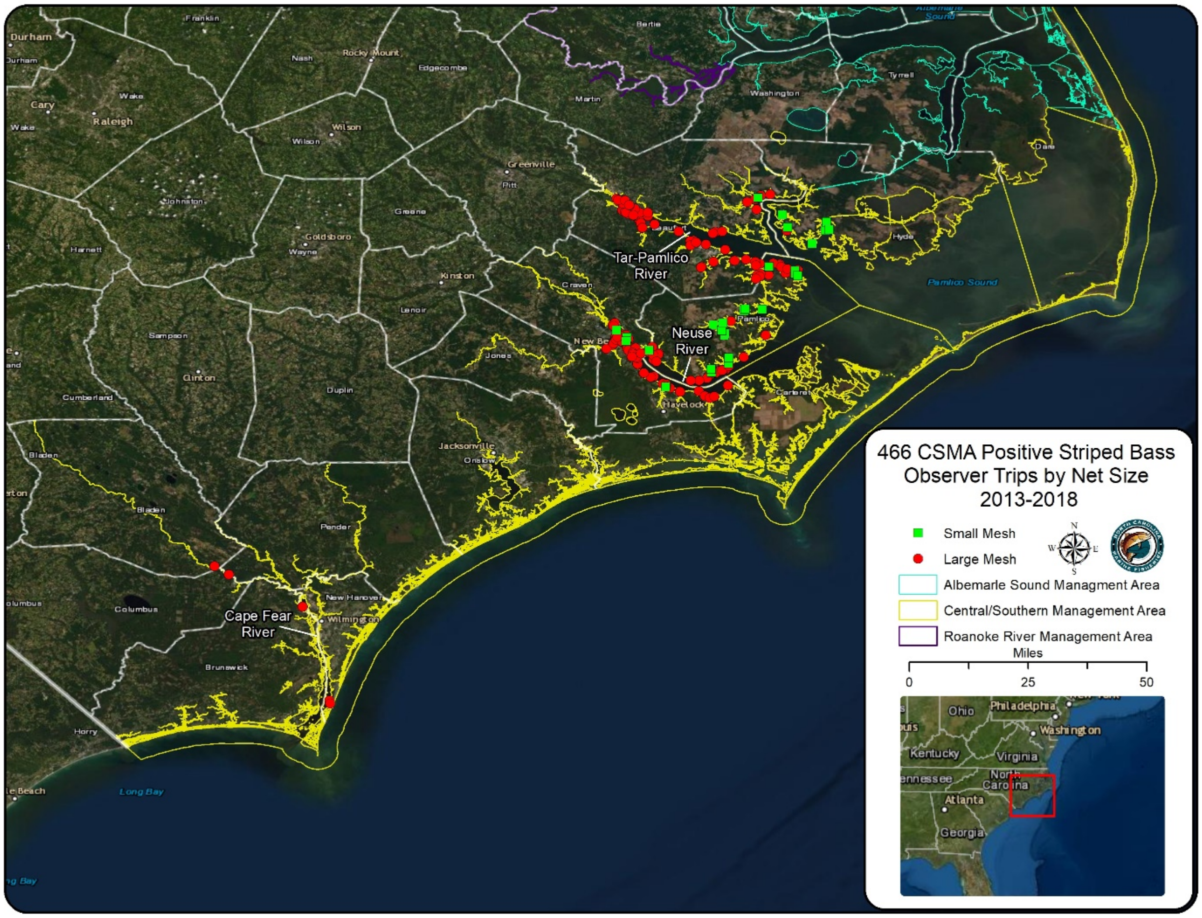


Figure 2.6. Program 466 CSMA observer trips by mesh size, 2013–2018. The square is a small mesh observer trip that encountered striped bass (n=38), and the circle is a large mesh observer trip that encountered striped bass (n=246). Eight large mesh observer trips accounted for 37 striped bass that are not presented on the map due the absence of coordinates.

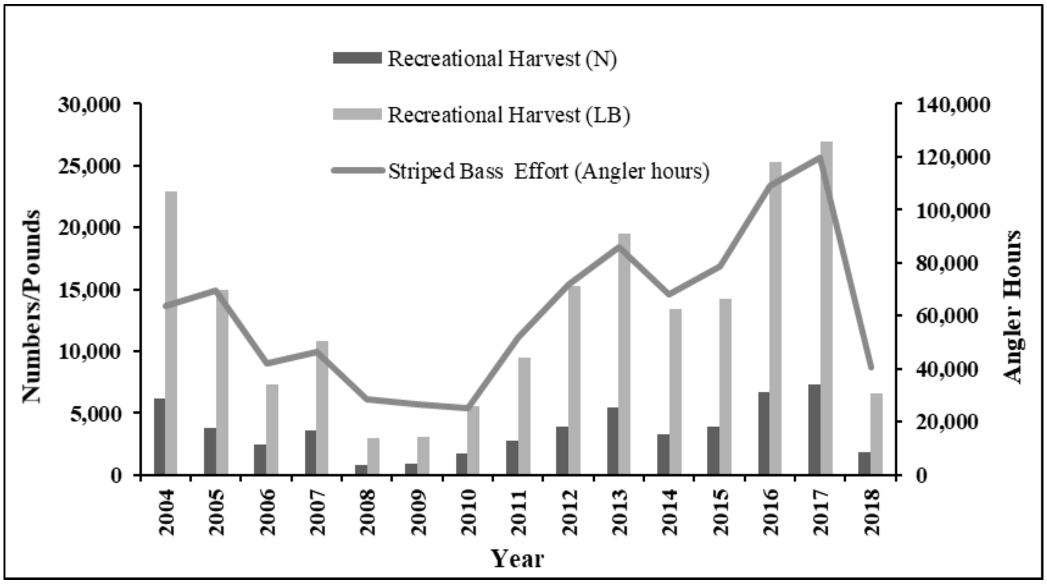


Figure 2.7. Recreational striped bass harvest in numbers and pounds and effort in angler hours for the Tar-Pamlico and Neuse rivers and tributaries, 2004–2018.

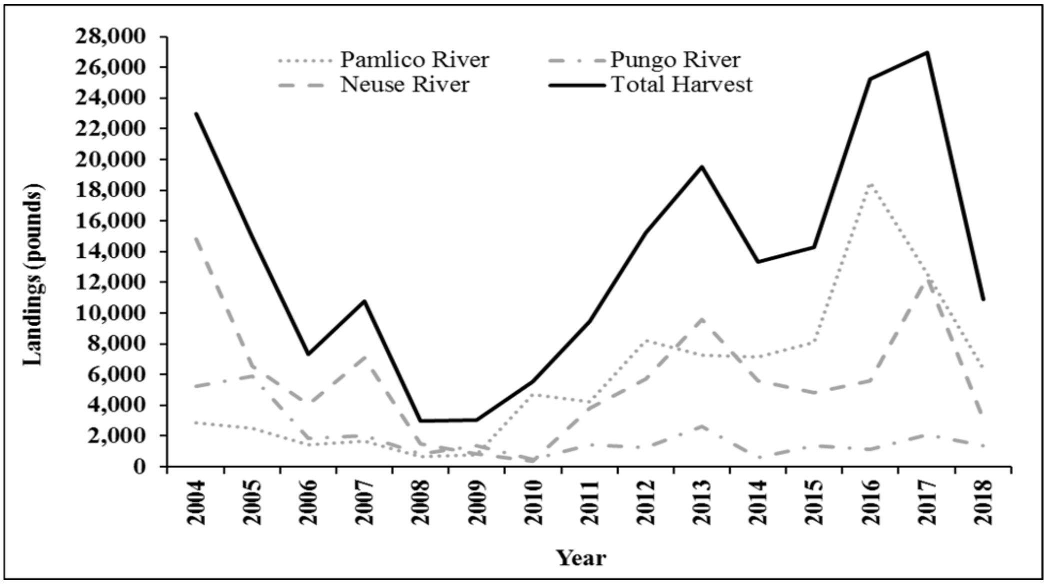


Figure 2.8. Recreational striped bass harvest in the Tar-Pamlico, Pungo, and Neuse rivers, 2004–2018.

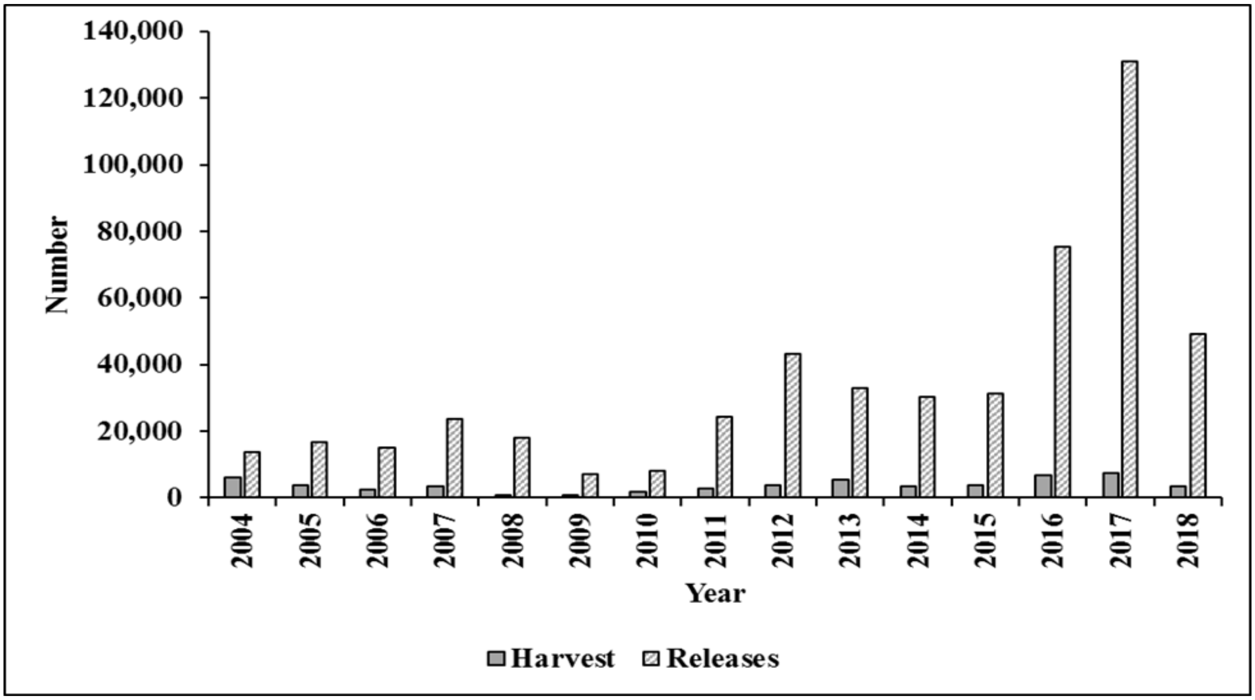


Figure 2.9. Annual recreational catch (released and/or harvested) of striped bass in the CSMA, 2004–2018.

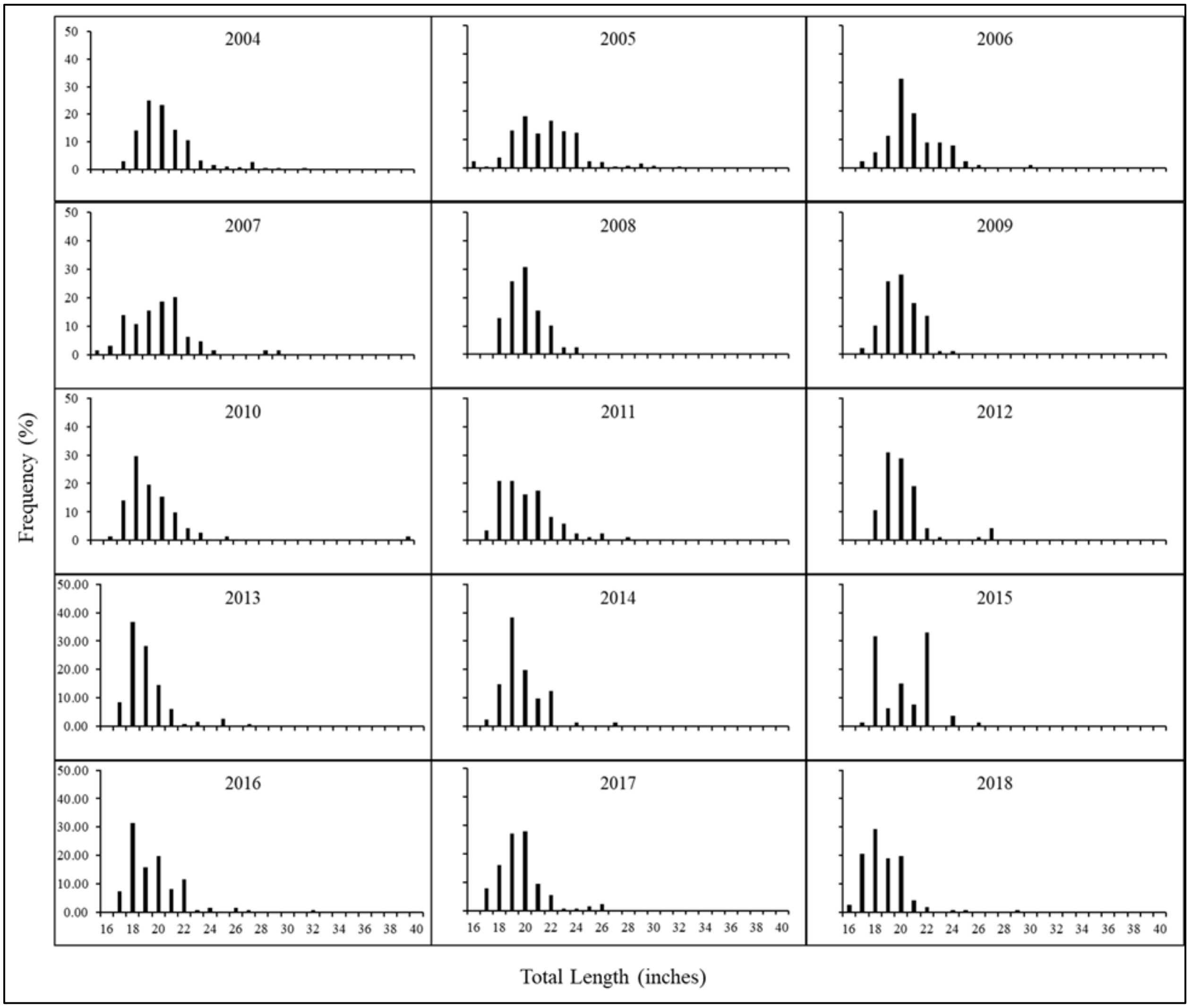


Figure 2.10. Length frequency of CSMA striped bass recreationally harvested in the Tar-Pamlico and Pungo rivers, 2004–2018.

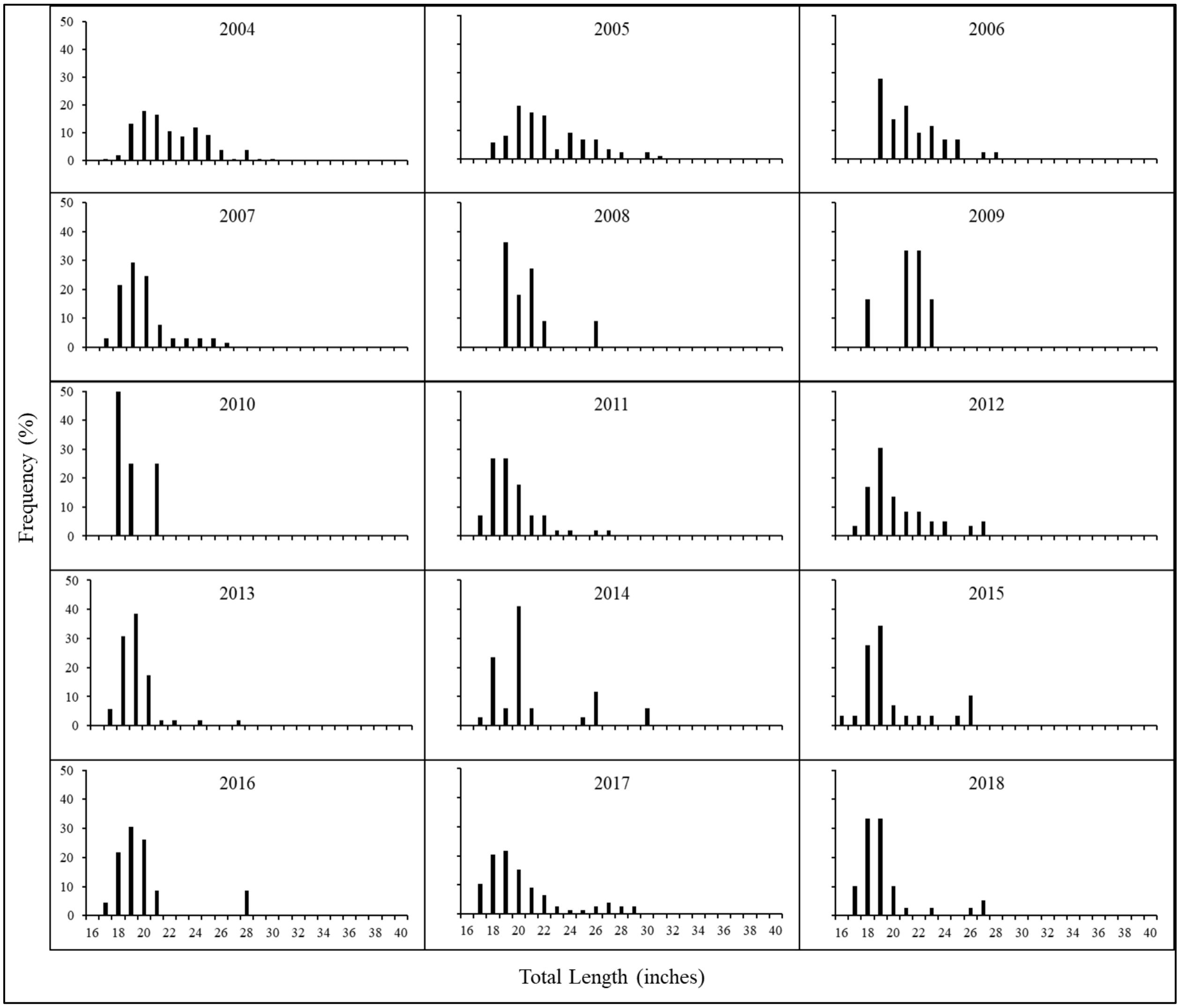


Figure 2.11. Length frequency of CSMA striped bass recreationally harvested in the Neuse River, 2004–2018.

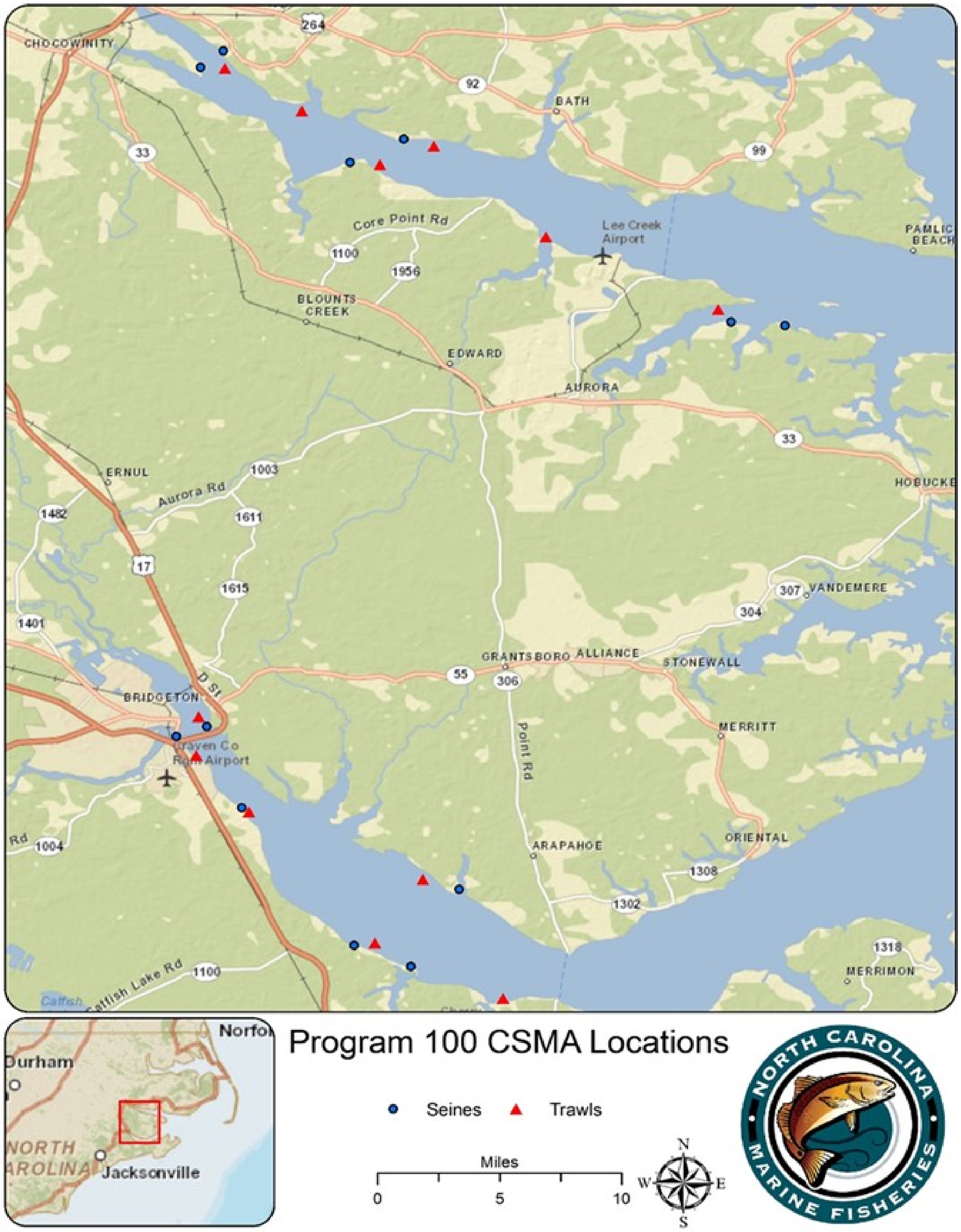
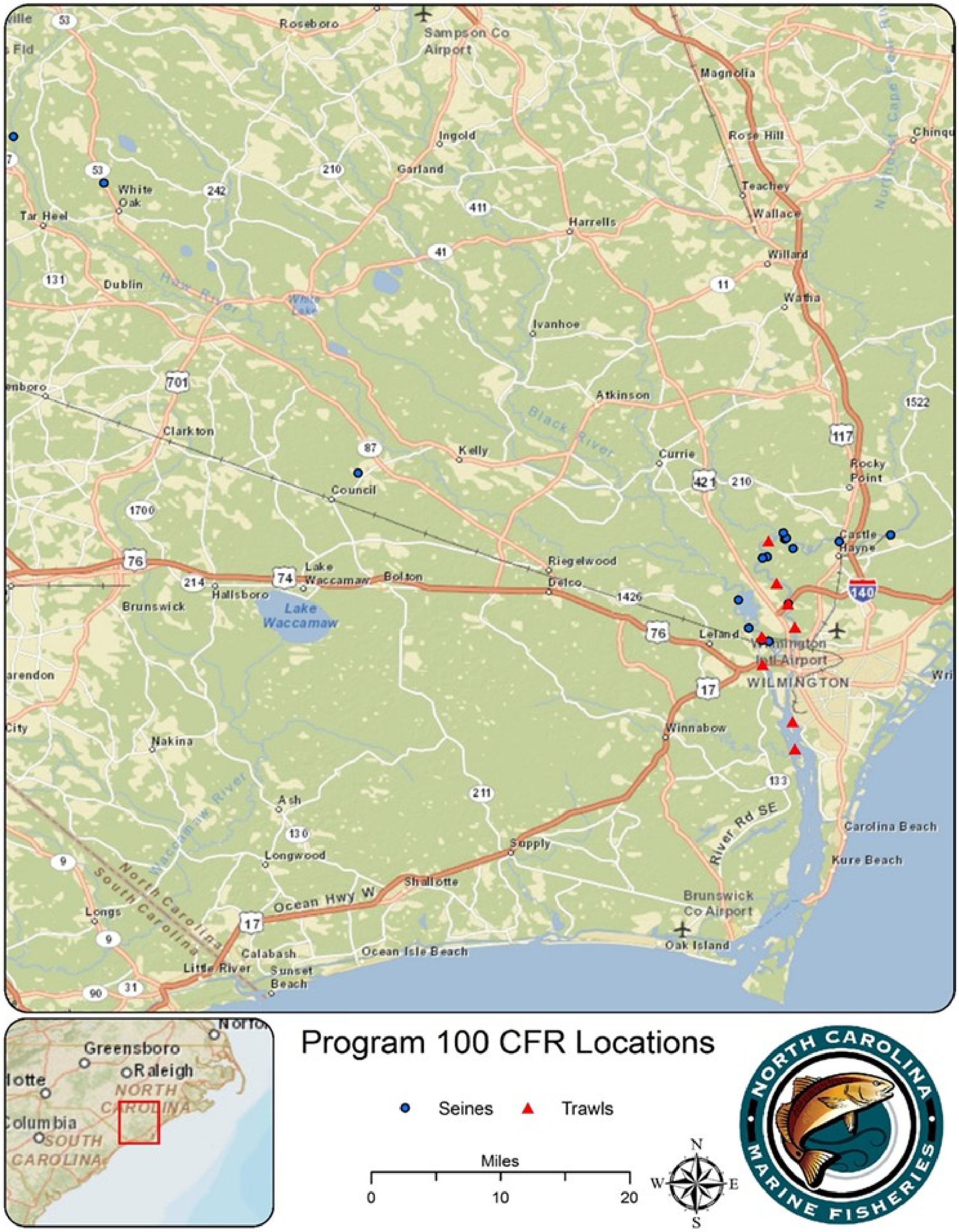


Figure 2.12. Location of Central Southern Management Area (CSMA) juvenile striped bass beach seine and trawl sites, Tar-Pamlico and Neuse rivers, NC.



Program 100 CFR Locations

Figure 2.13. Location of Cape Fear River juvenile striped bass beach seine and trawl sites, CapeFear River, NC.

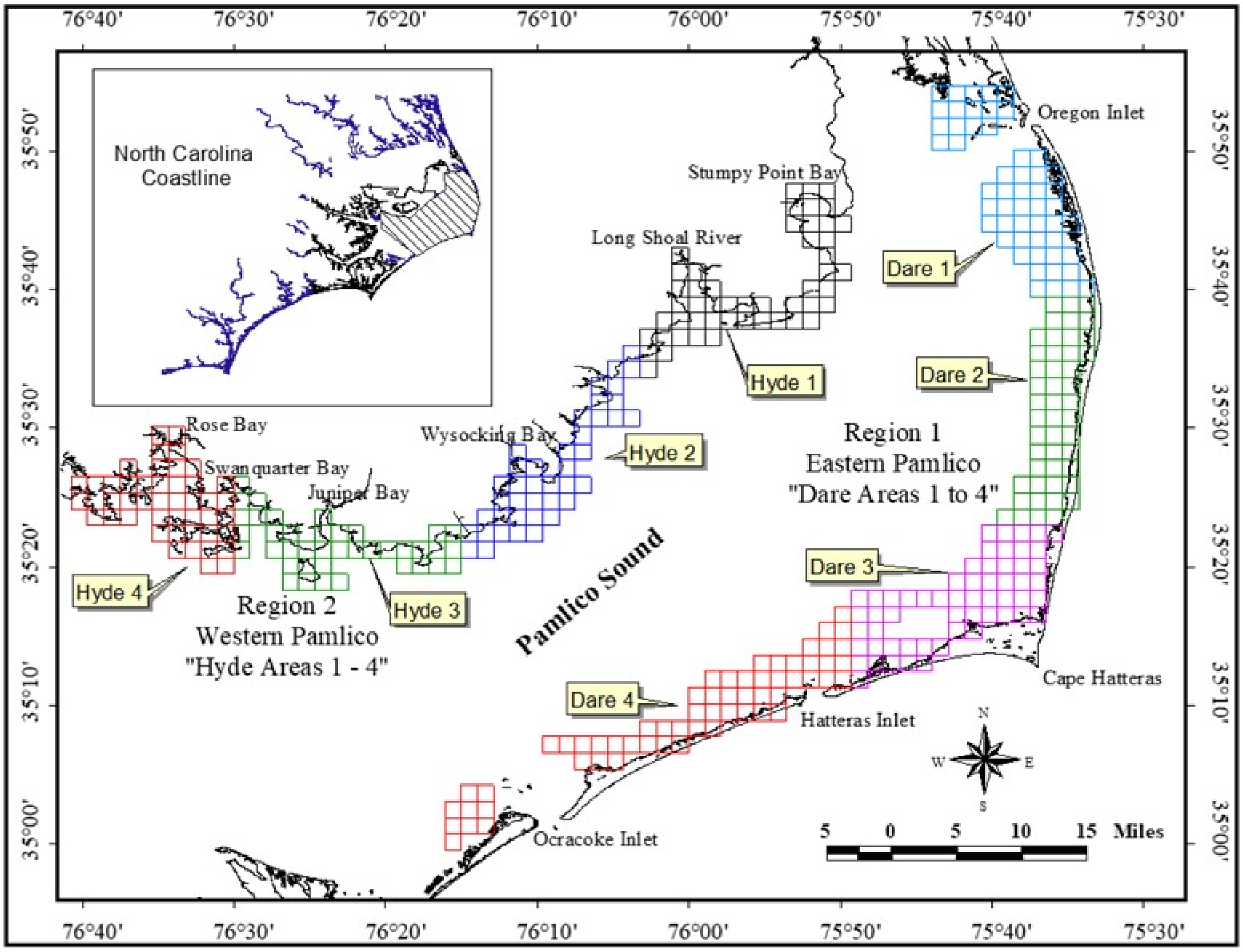


Figure 2.14. The sample regions and grid system for P915 in Dare (Region 1) and Hyde (Region 2) counties.

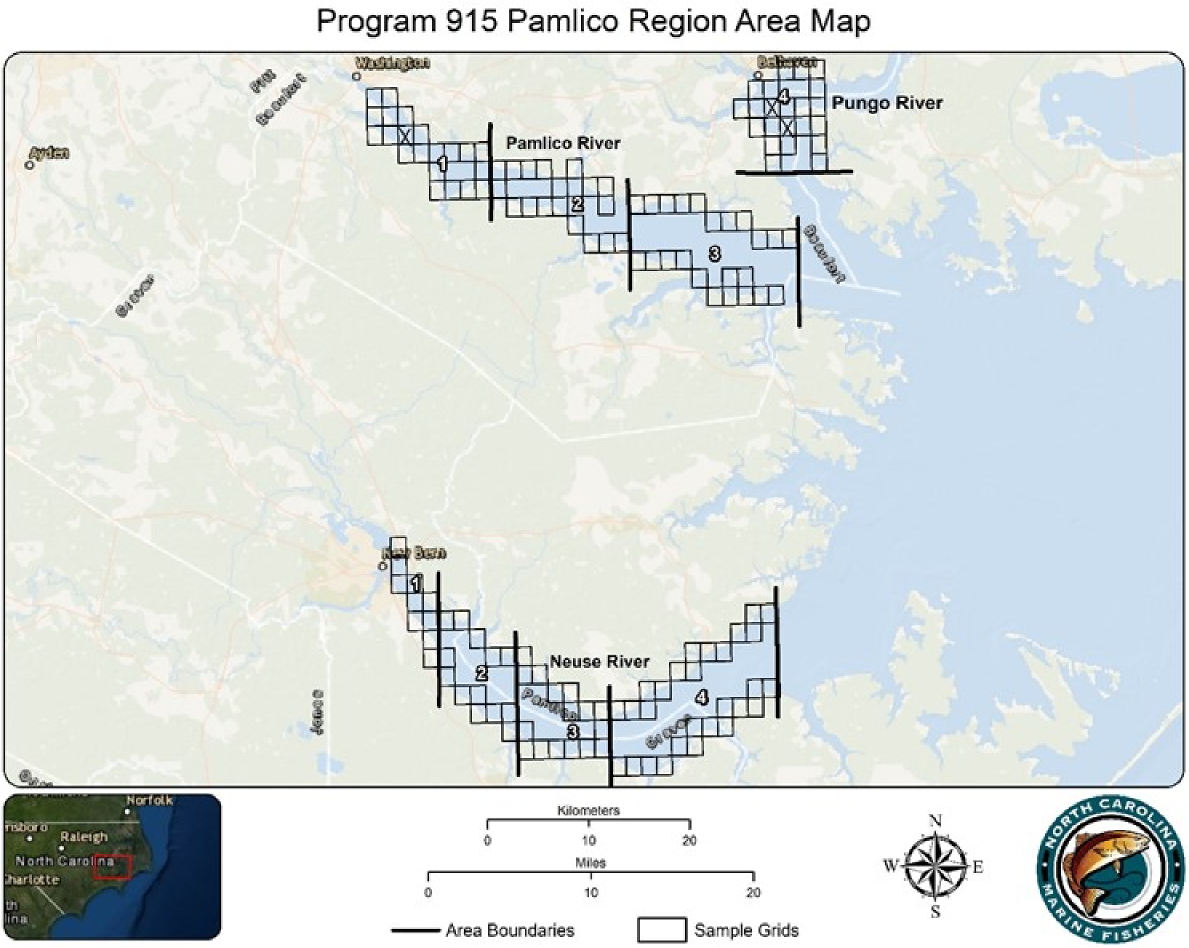


Figure 2.15. The sample areas and grid system for P915 in the Pamlico Region (Pamlico, Pungo and Neuse rivers) with areas numbered Pamlico/Pungo: 1—Upper, 2—Middle, 3—Lower, 4—Pungo; Neuse: 1—Upper, 2—Upper-middle, 3—Lower-middle, and 4—Lower).

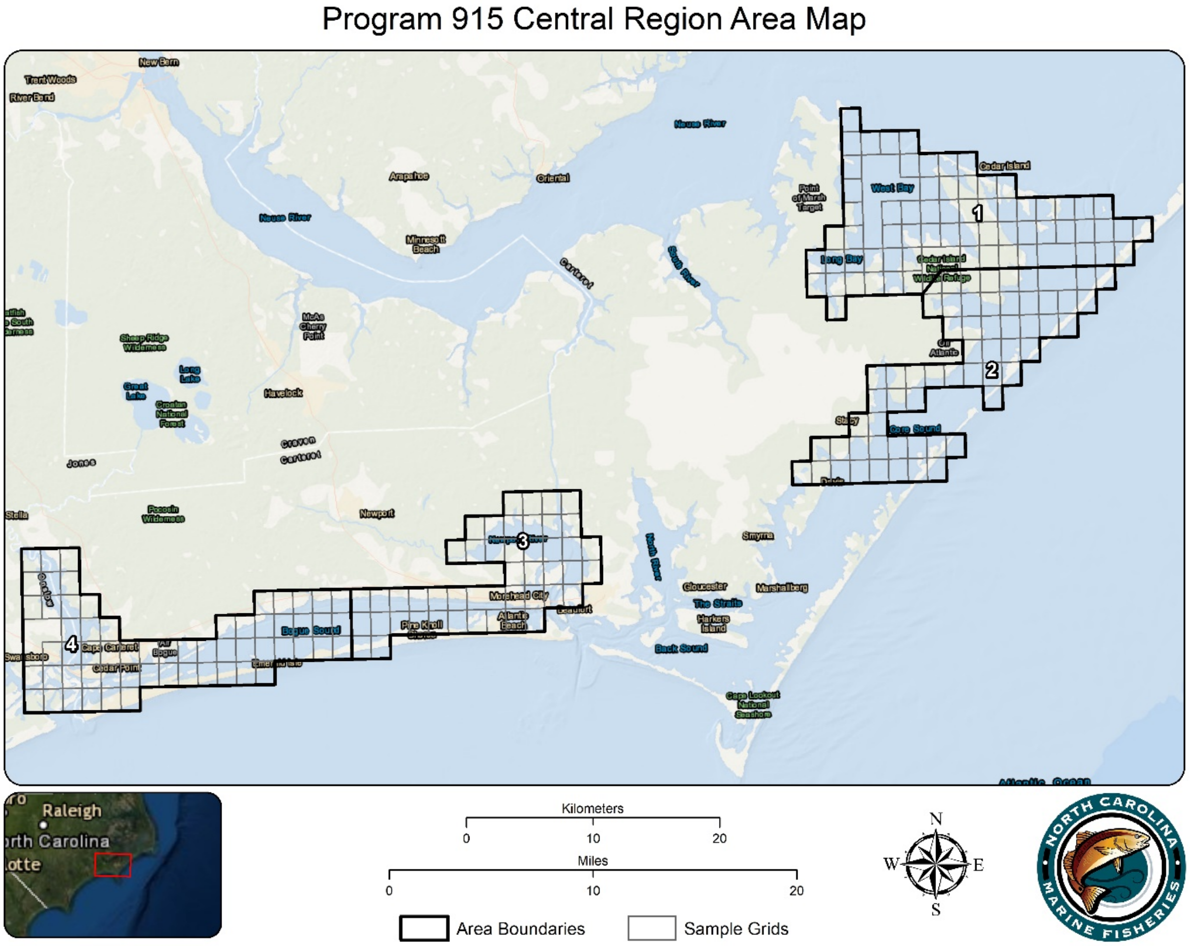


Figure 2.16. The sample areas and grid system for P915 in the Central Region with areas numbered (1—West Bay/Upper Core Sound, 2—Lower Core Sound, 3—Newport River/Bogue Sound, and 4—Bogue Sound/White Oak River). Sampling began May 2018.

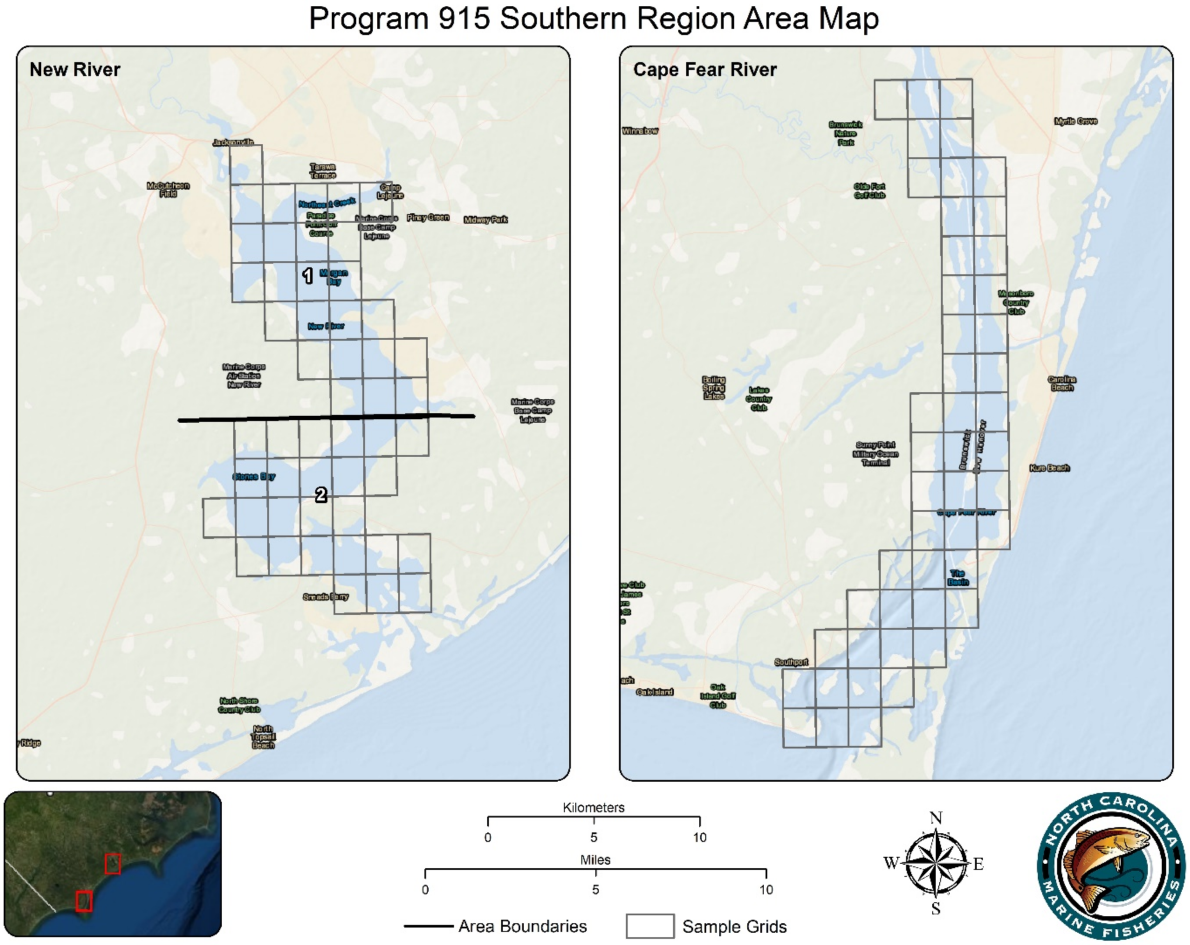


Figure 2.17. The sample areas and grid system for P915 in the Southern Region (New and Cape Fear rivers) with areas numbered (New: 1—Upper, 2—Lower, Cape Fear).

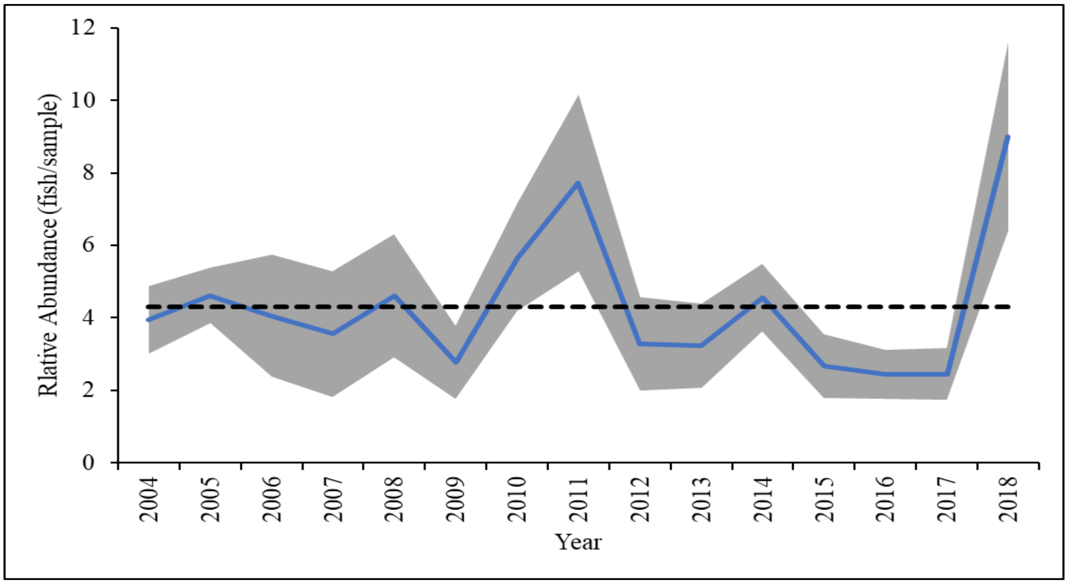


Figure 2.18. Striped bass annual weighted relative abundance index (# fish per sample; sample=240 yards of gill net) in P915, 2004–2018 (Tar-Pamlico River, shallow sets, April and October–November). Dashed black line represents time-series average. Shaded area represents standard error. Soak times were not used in calculating the index.

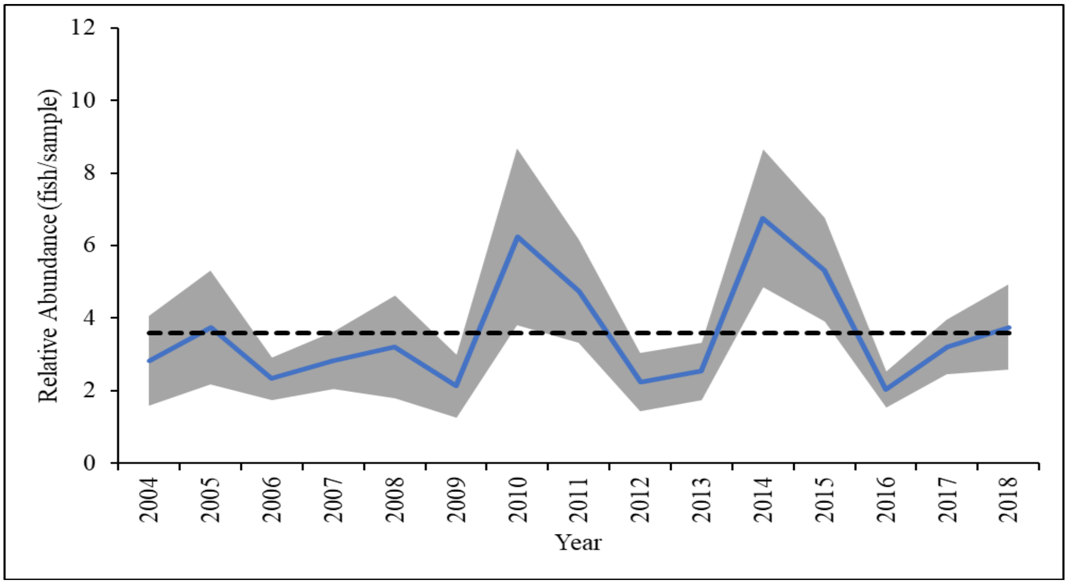


Figure 2.19. Striped bass annual weighted relative abundance index (# fish per sample; sample=240 yards of gill net) in P915, 2004–2018 (Neuse River, shallow sets, April and October–November). Dashed black line represents time-series average. Shaded area represents standard error. Soak times were not used in calculating the index.

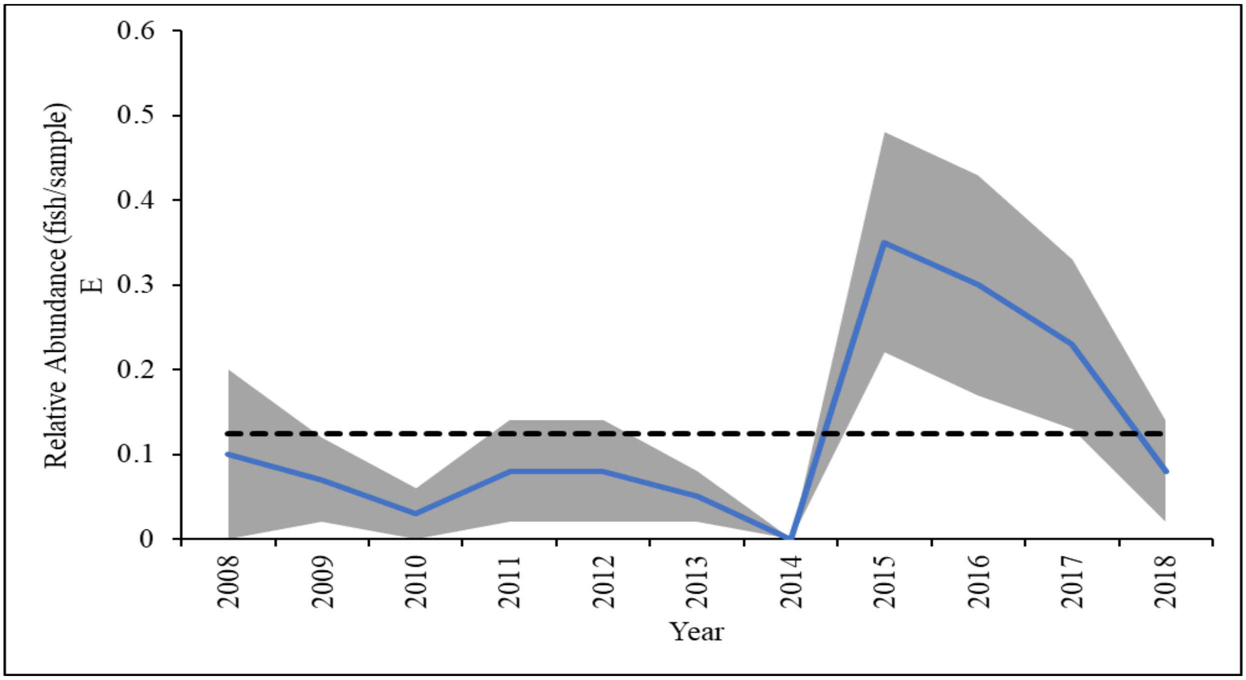


Figure 2.20. Striped bass annual weighted relative abundance index (# fish per sample; sample=240 yards of gill net) in P915, 2008–2018 (Cape Fear River, shallow sets). Dashed black line represents time-series average. Shaded area represents standard error. Soak times were not used in calculating the index.

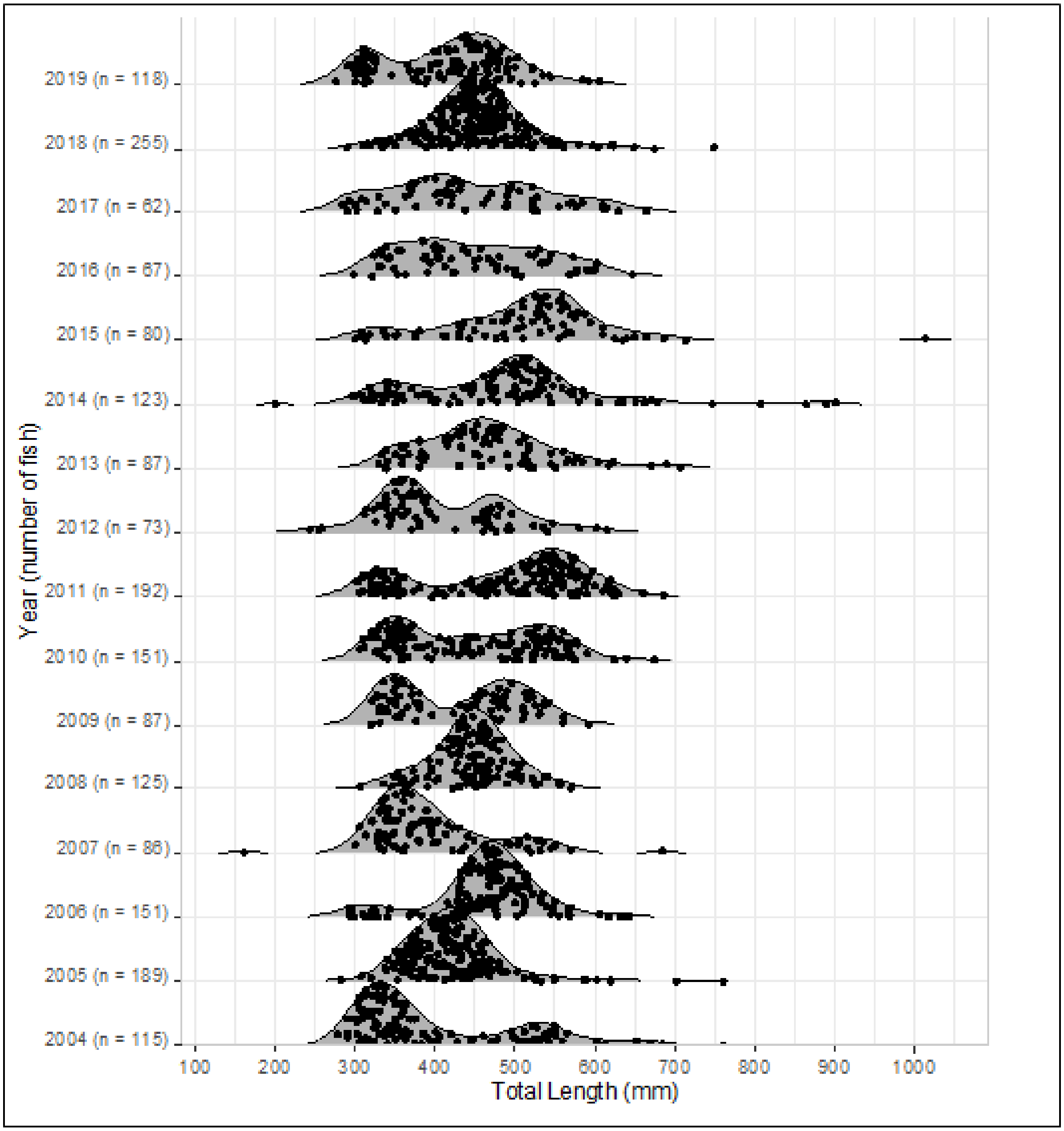


Figure 2.21. Length frequency distribution of CSMA striped bass captured in P915 in the Tar-Pamlico River, 2004–2019 (deep and shallow sets, April and October–November).

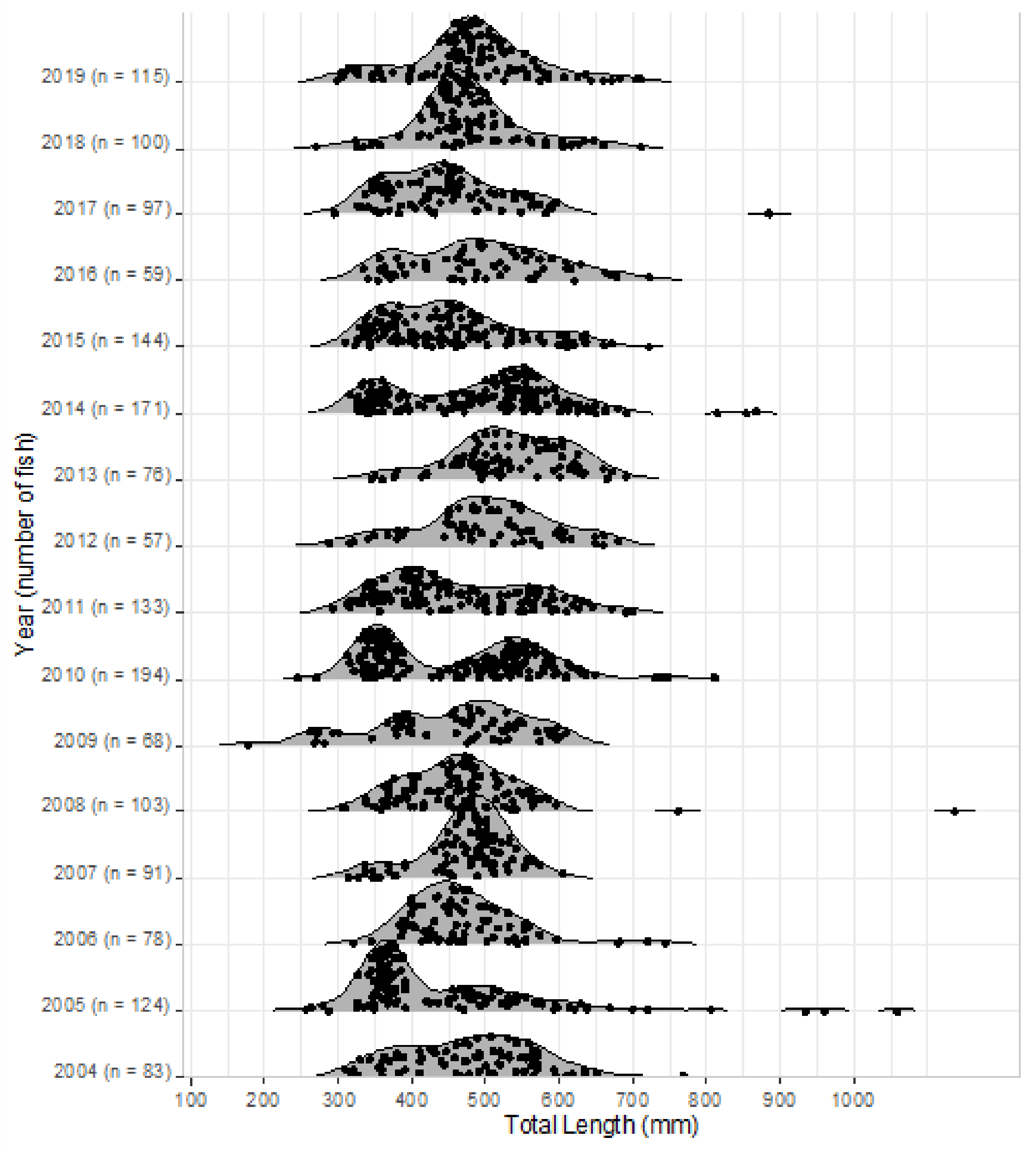


Figure 2.22. Length frequency distribution of CSMA striped bass captured in P915 the Neuse River, 2004–2019 (deep and shallow sets, April and October–November).

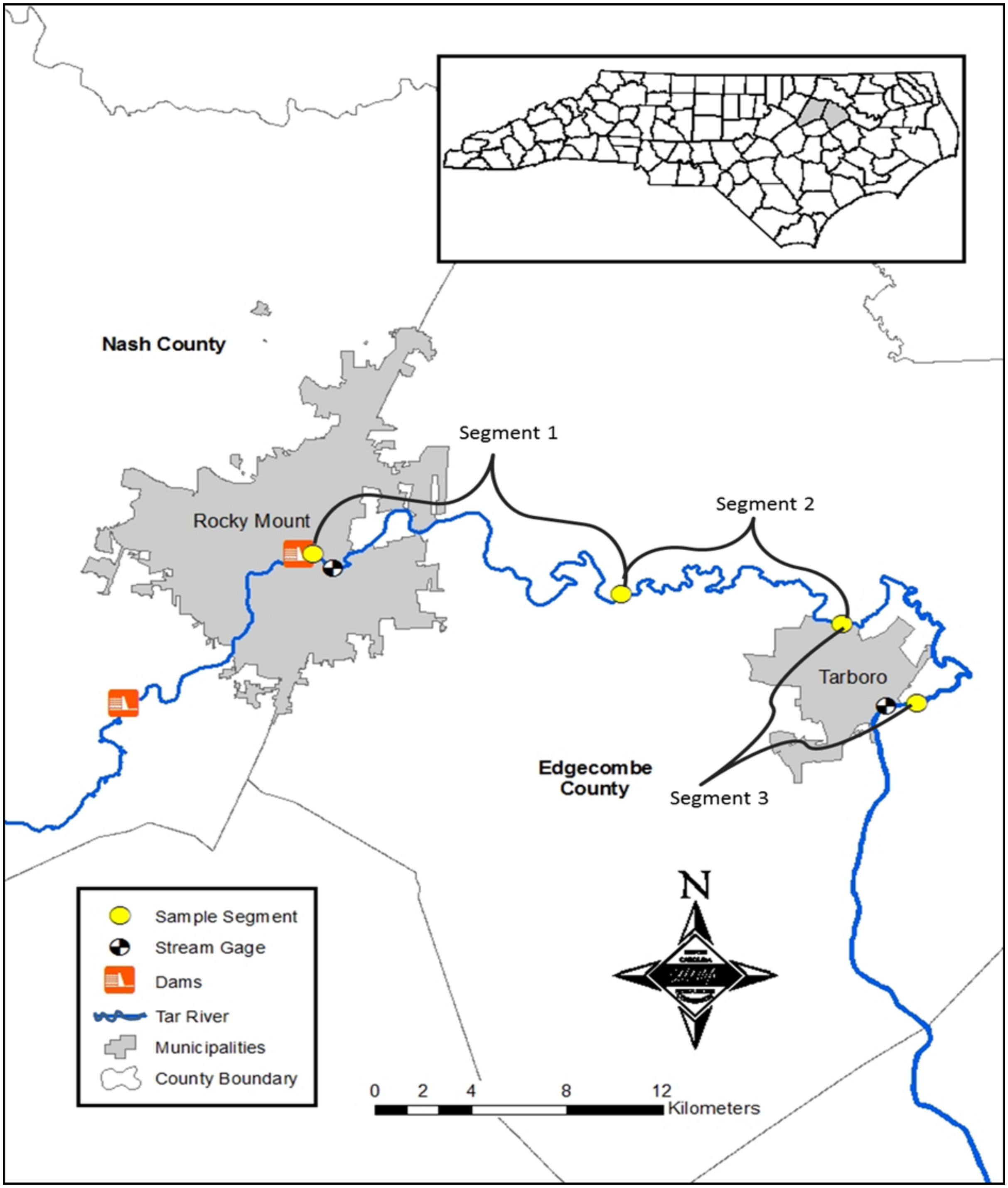


Figure 2.23. NCWRC electrofishing survey segments on the Tar-Pamlico River.

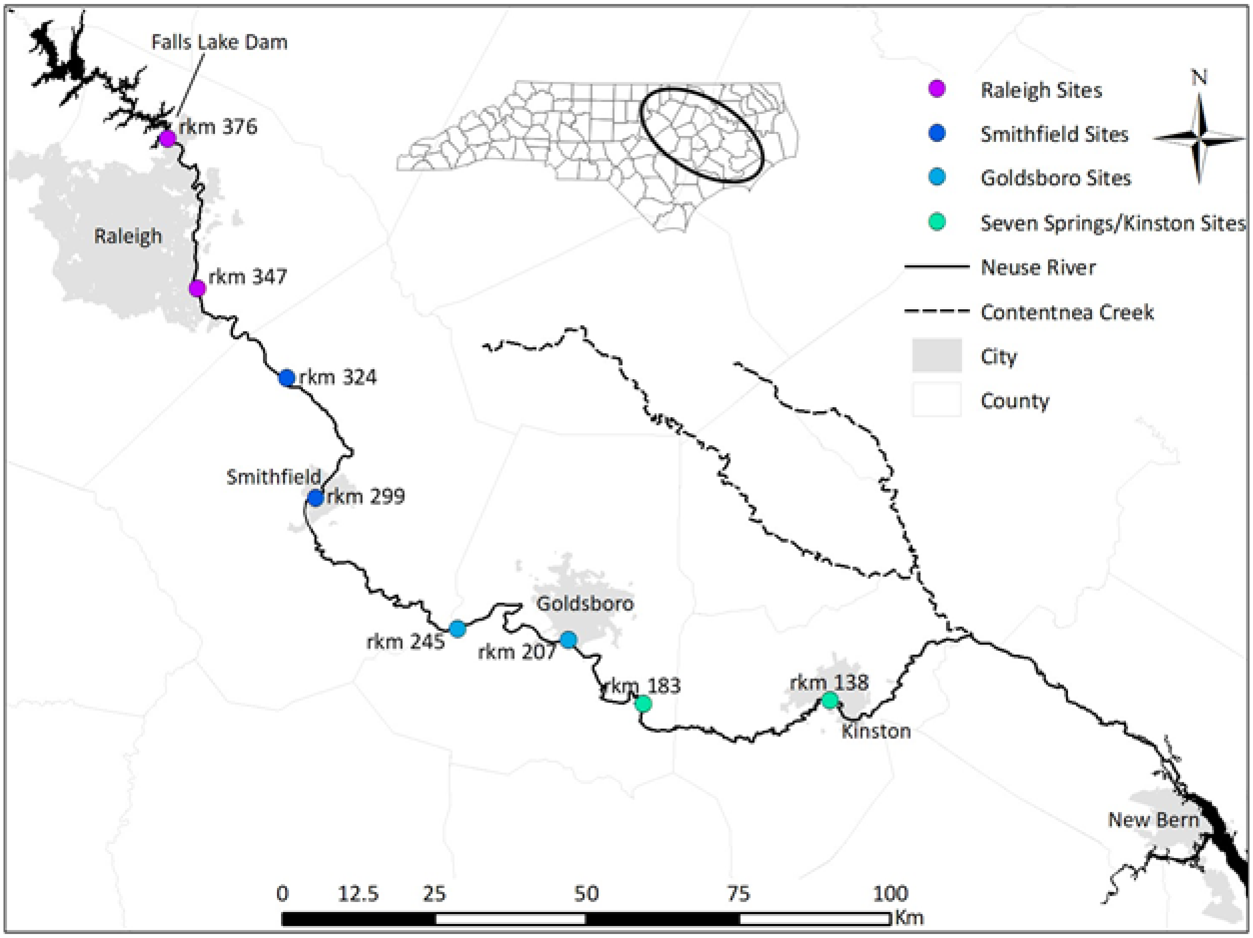


Figure 2.24. NCWRC electrofishing survey area on the Neuse River. The upstream and downstream extent of four sampling strata are by colored markers.

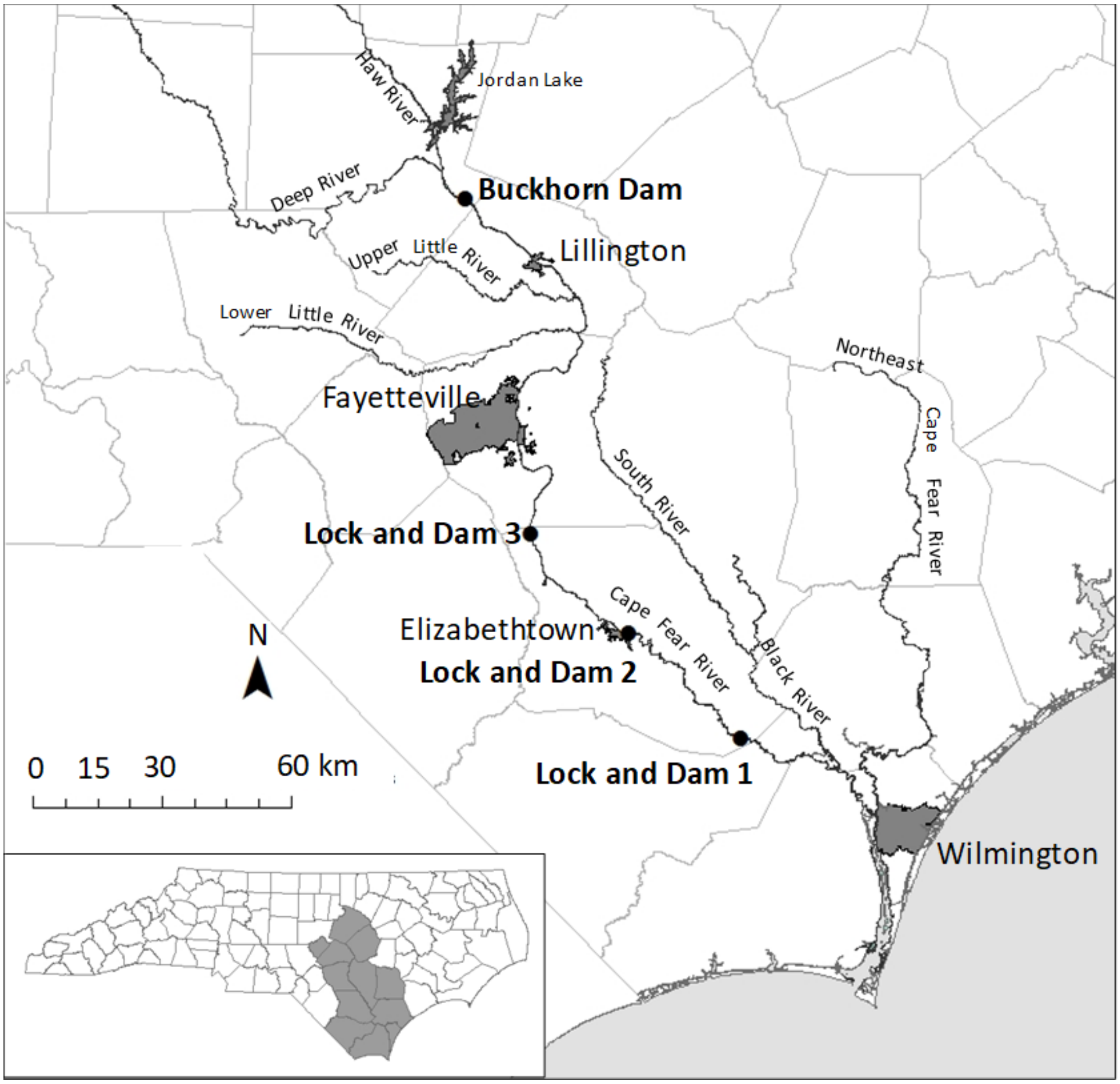


Figure 2.25. NCWRC electrofishing sampling sites (indicated by black circles in bold) at Lock and Dams 1, 2, 3, and Buckhorn Dam on the Cape Fear River.

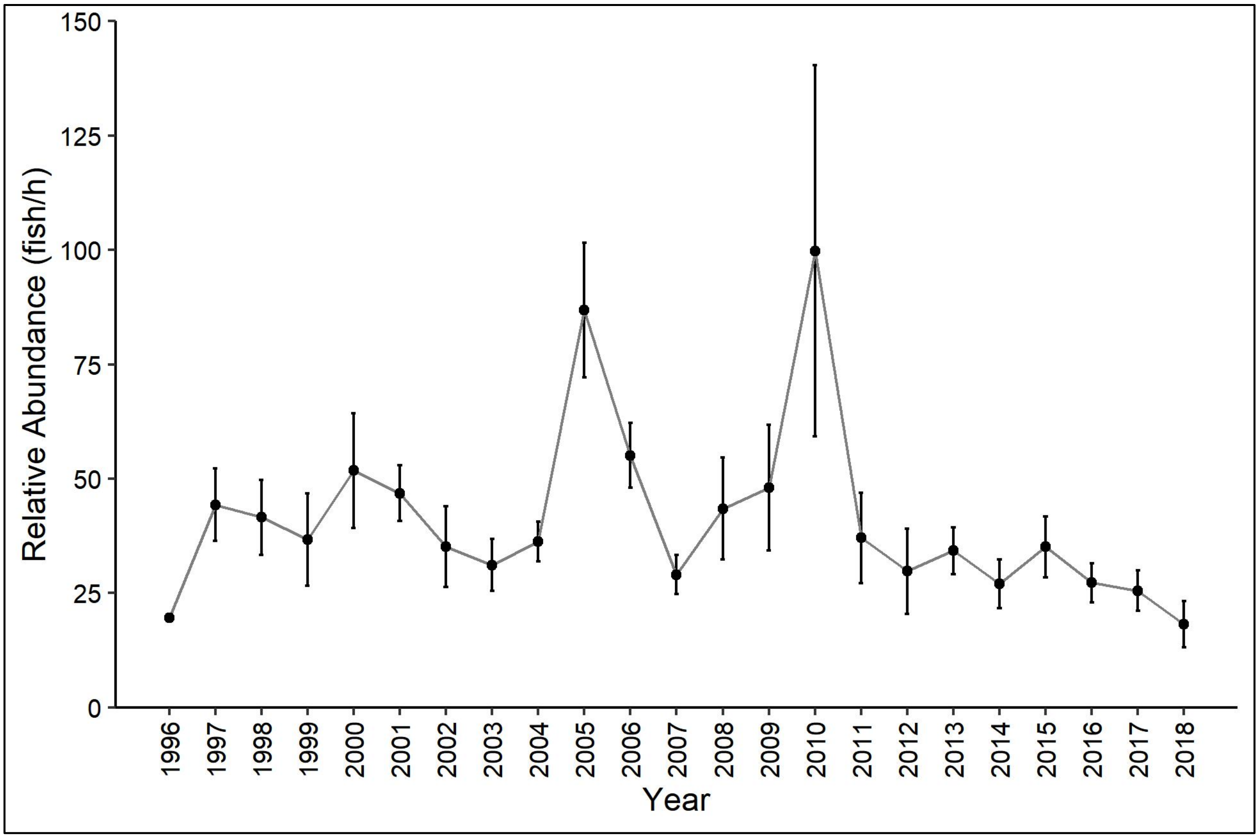


Figure 2.26. Relative abundance (with associated standard error) of striped bass collected during the NCWRC Tar River electrofishing surveys, 1996–2018.

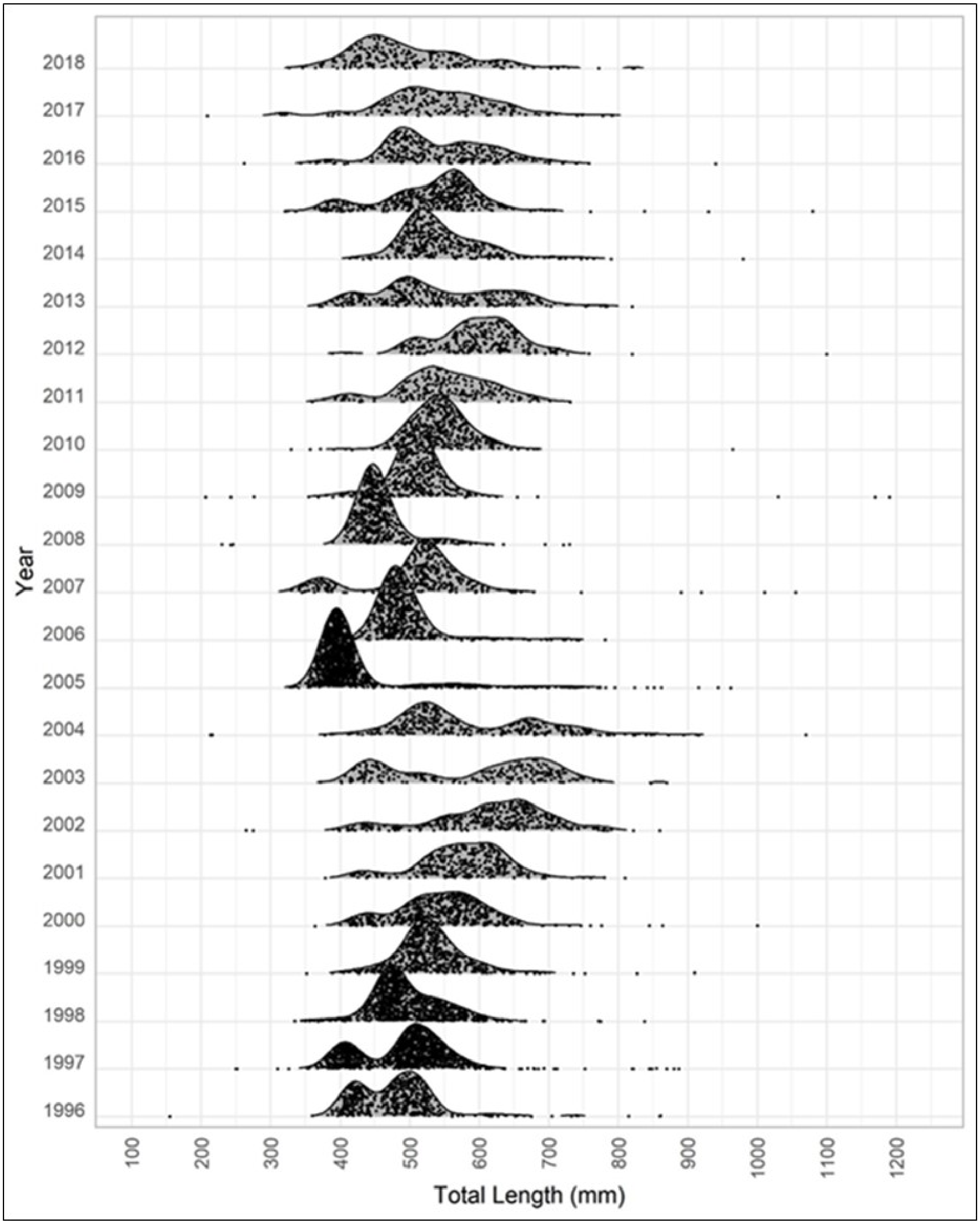


Figure 2.27. Length distributions for striped bass collected during the NCWRC Tar River electrofishing surveys, 1996–2018. Dots indicate individual length measurements.

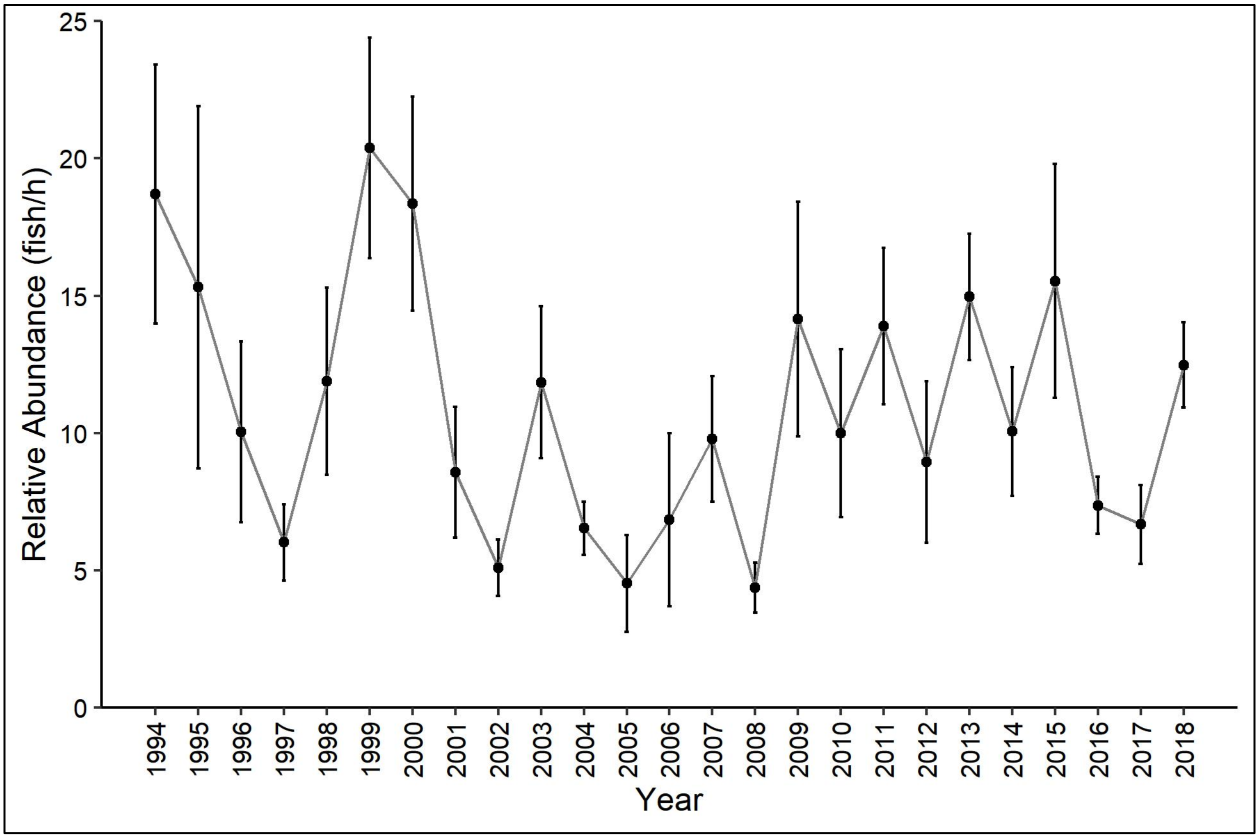


Figure 2.28. Relative abundance (with associated standard error) of striped bass collected during the NCWRC Neuse River electrofishing surveys, 1994–2018.

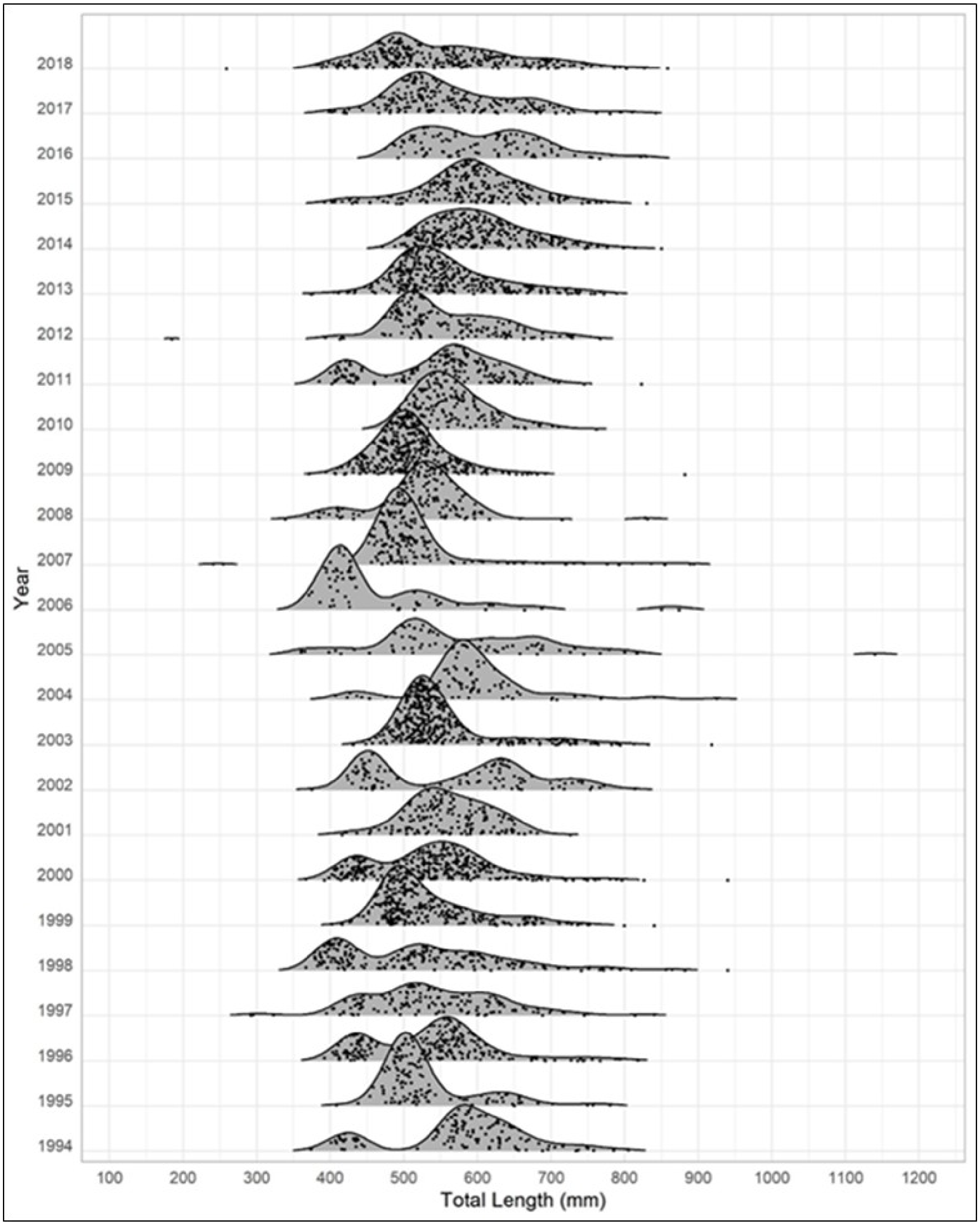


Figure 2.29. Striped bass length distributions for the NCWRC Neuse River electrofishing surveys, 1994–2018. Dots indicate individual length measurements.

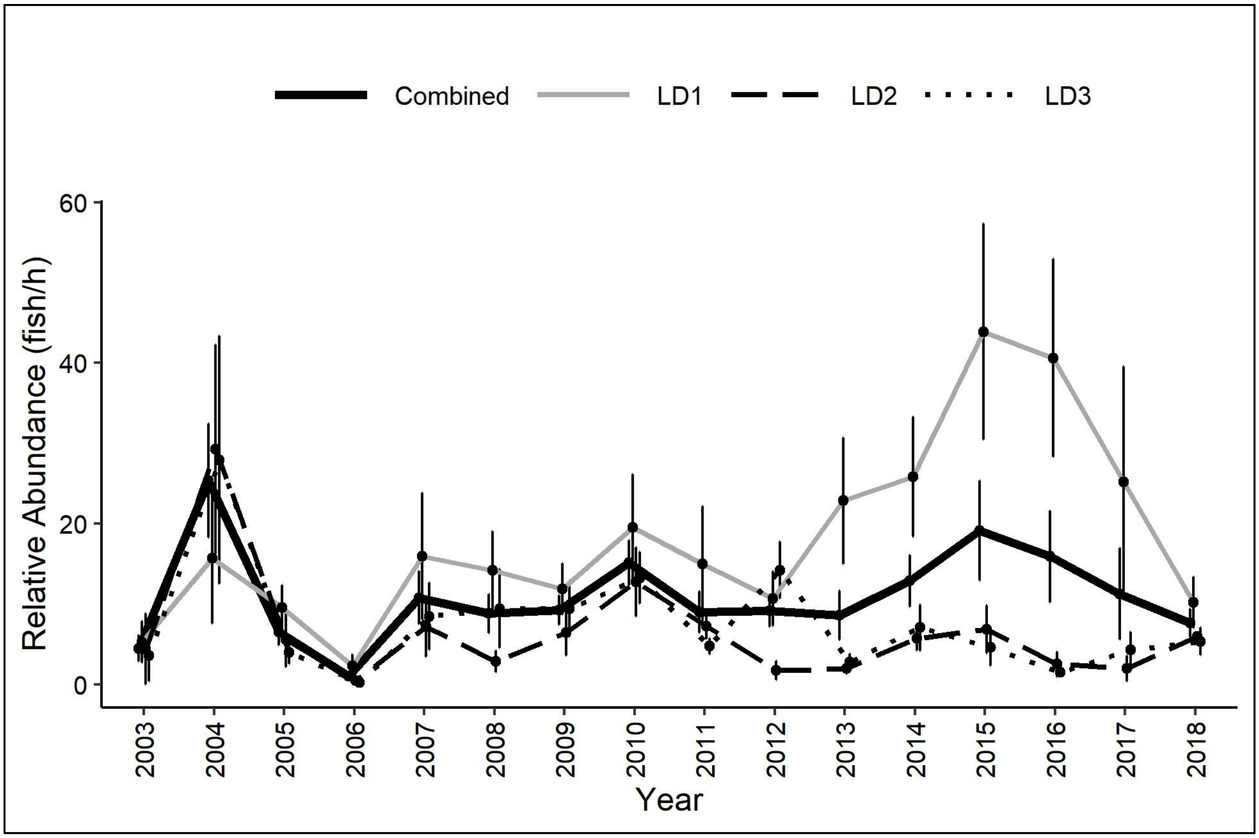


Figure 2.30. Relative abundance (with associated standard error) of striped bass collected at three sample sites in the Cape Fear River, NC, 2003–2018.

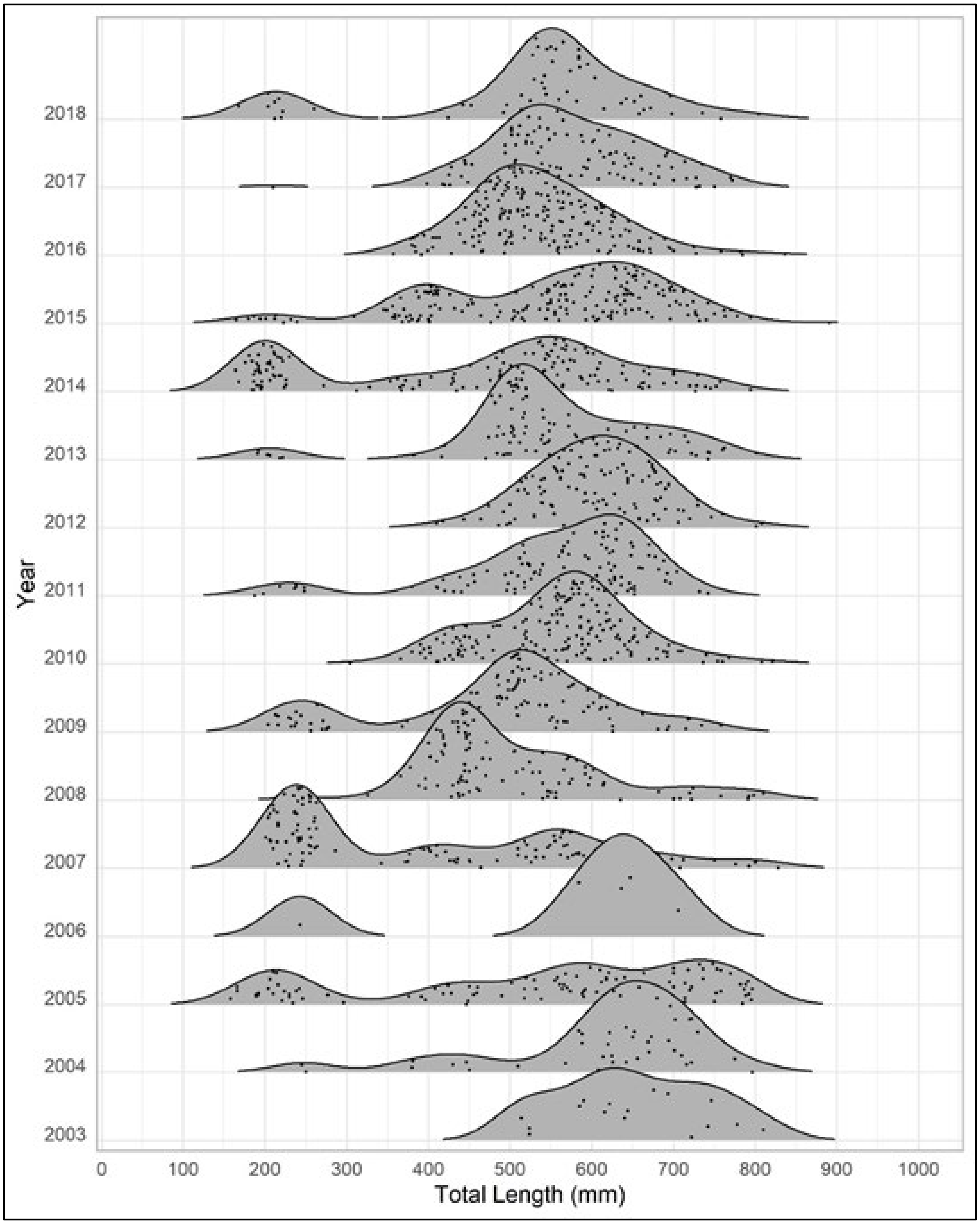


Figure 2.31. Length distributions for striped bass collected during the NCWRC Cape Fear River electrofishing surveys, 2003–2018. Dots indicate individual length measurements.

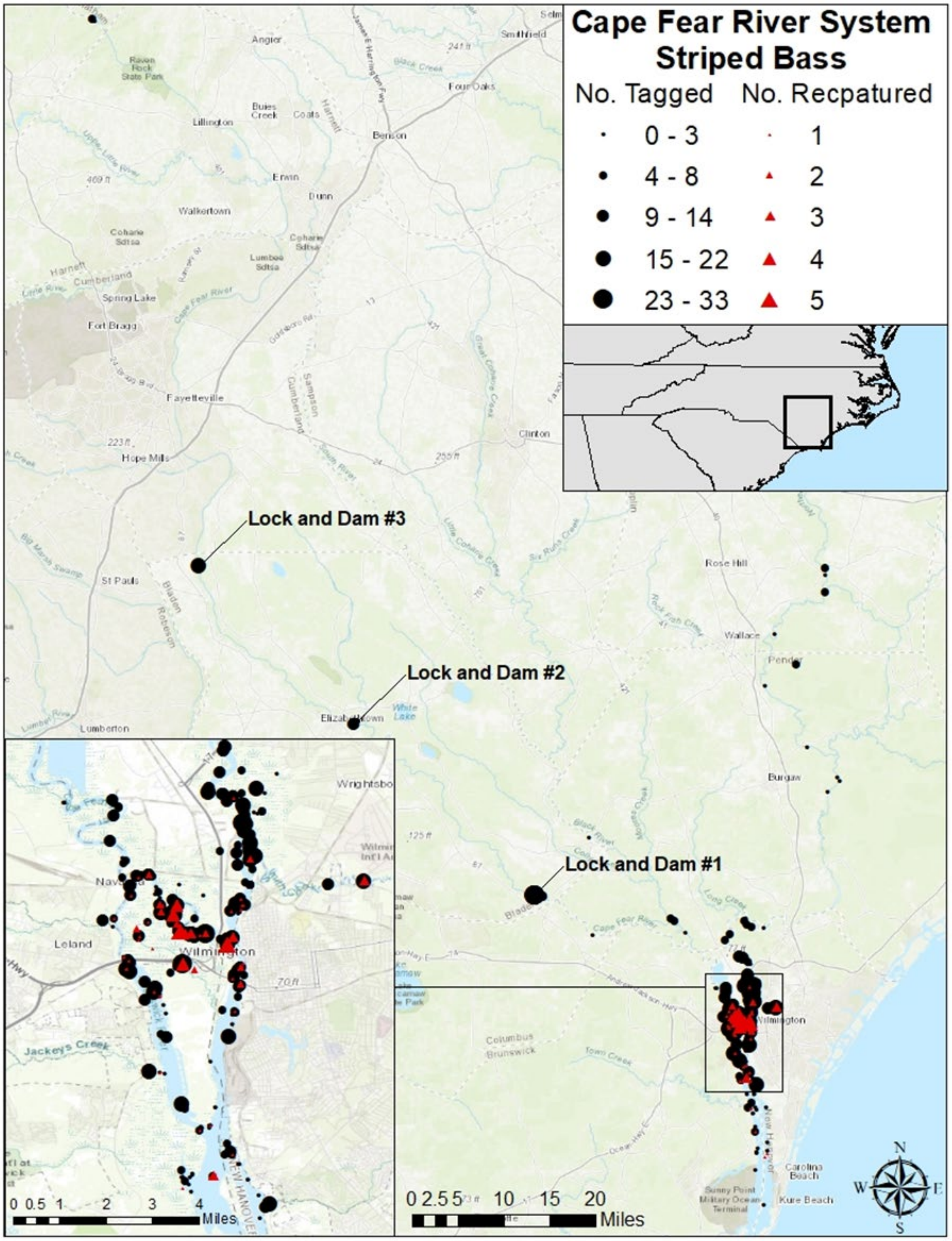


Figure 2.32. Cape Fear River striped bass tagging and recapture locations, 2012–2018.

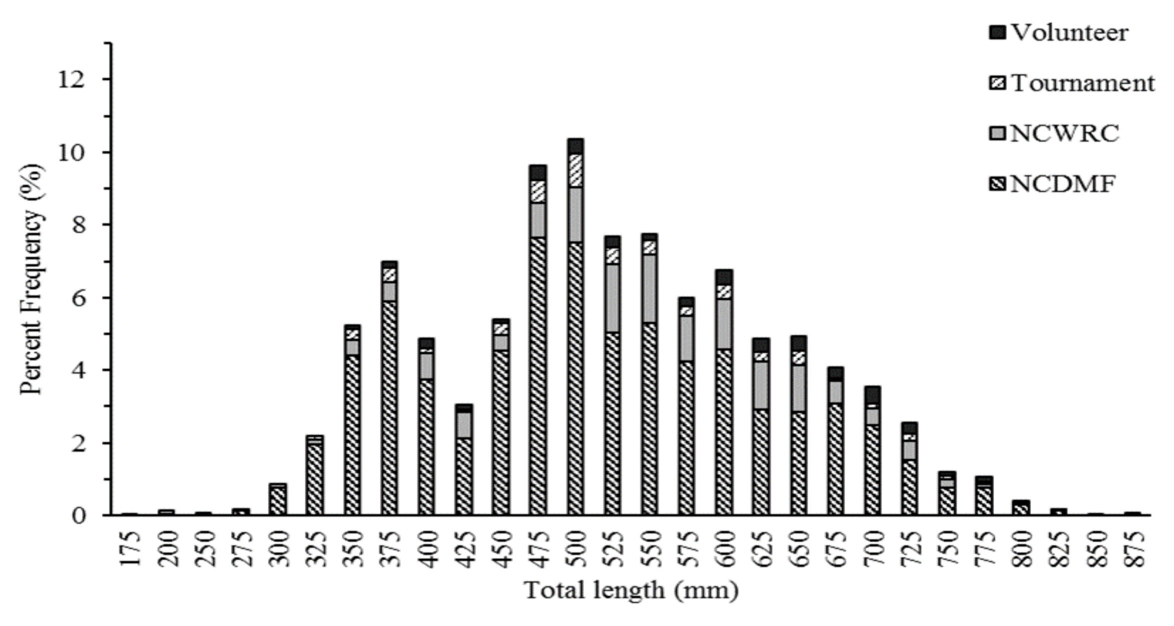


Figure 2.33. Length-frequency distribution of tagged striped bass included in the tagging model by tagger affiliation in the Cape Fear River, 2012–2018.

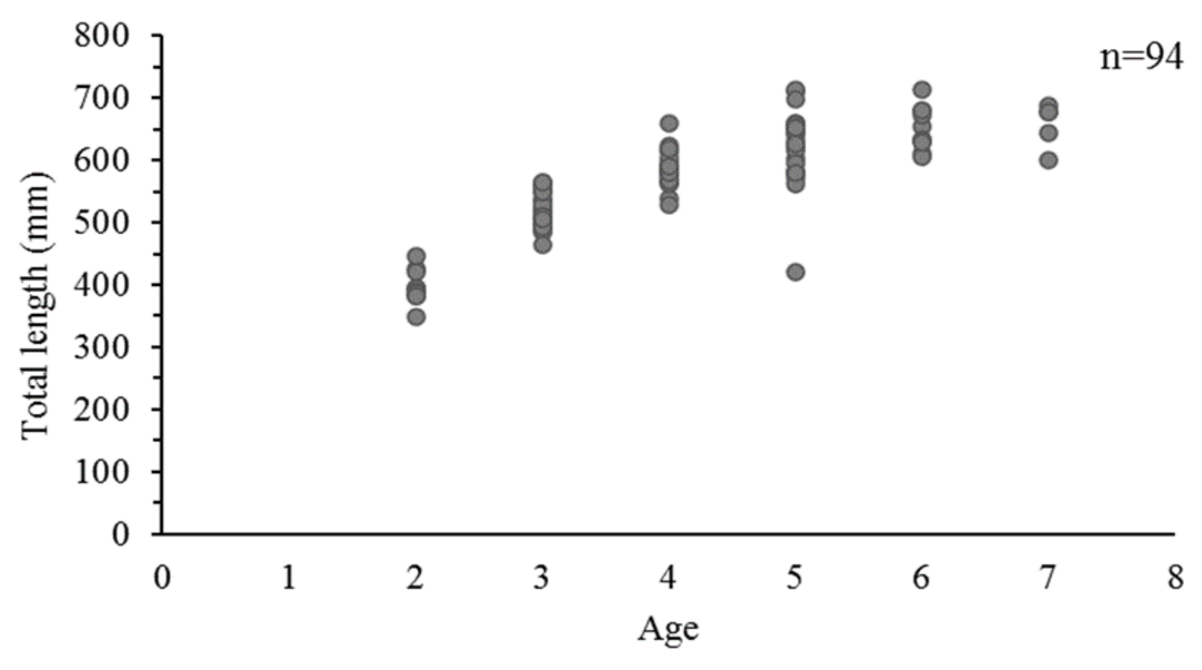


Figure 2.34. Genetically derived age at length of Cape Fear River striped bass, 2016–2017.

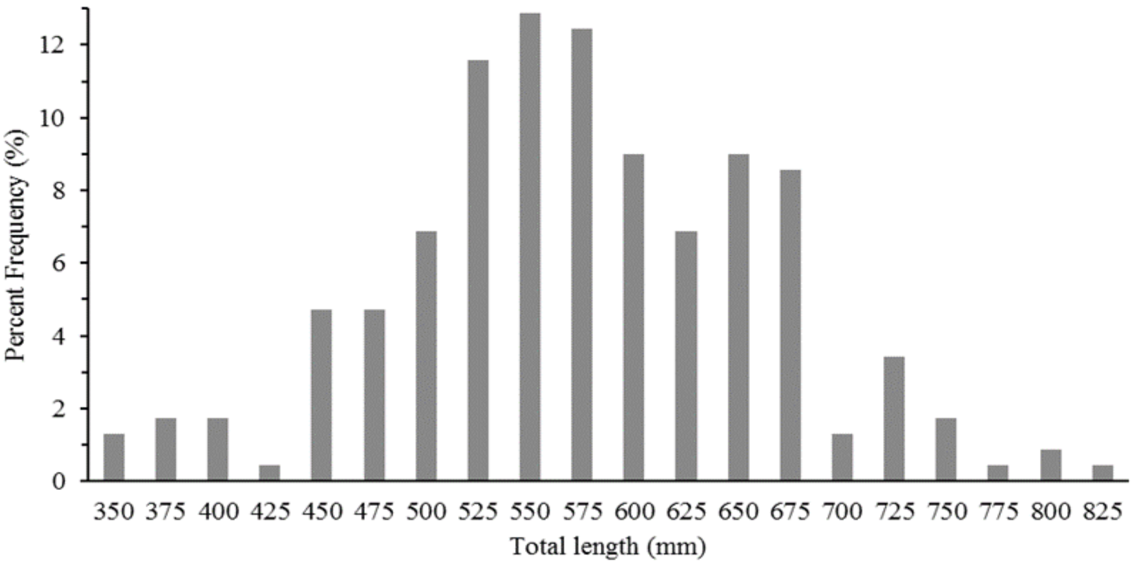


Figure 2.35. Length-frequency distribution of recaptured striped bass included in the tagging model by tagger affiliation in the Cape Fear River, 2012–2018.

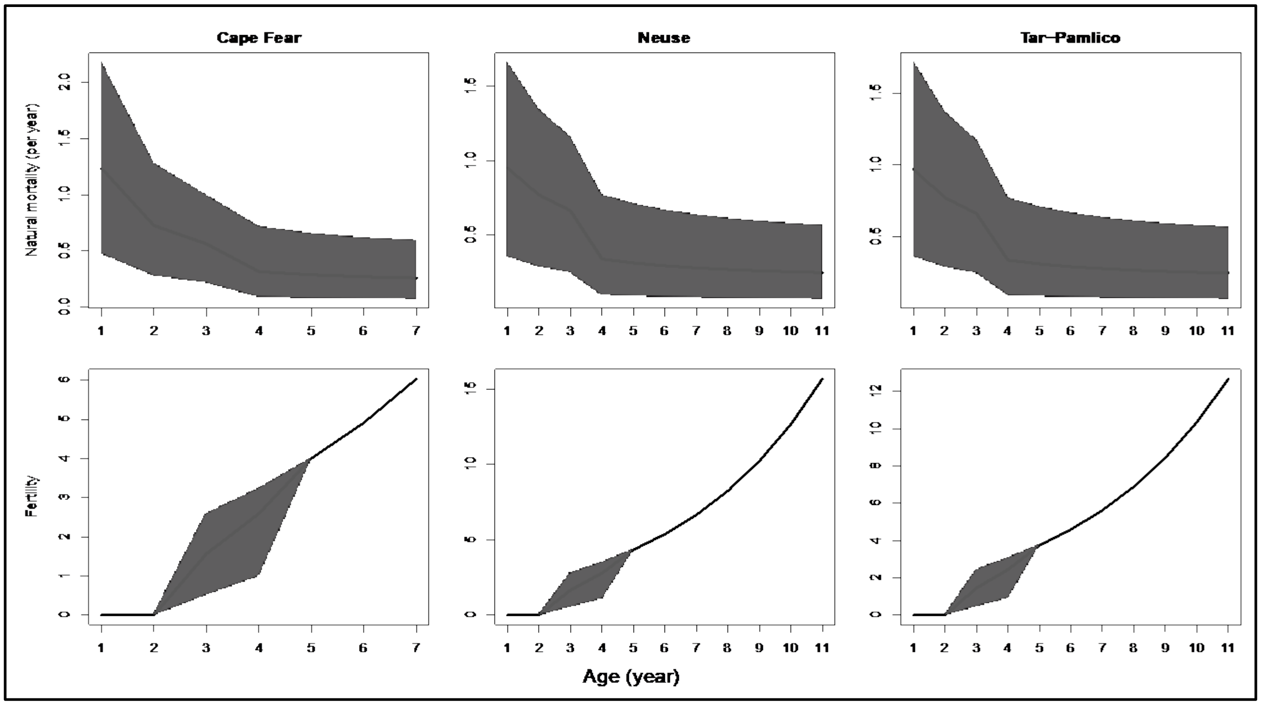


Figure 3.1. Age-specific natural mortality and fertility used in the matrix model. Black line is median and grey area is 95% confidence interval.

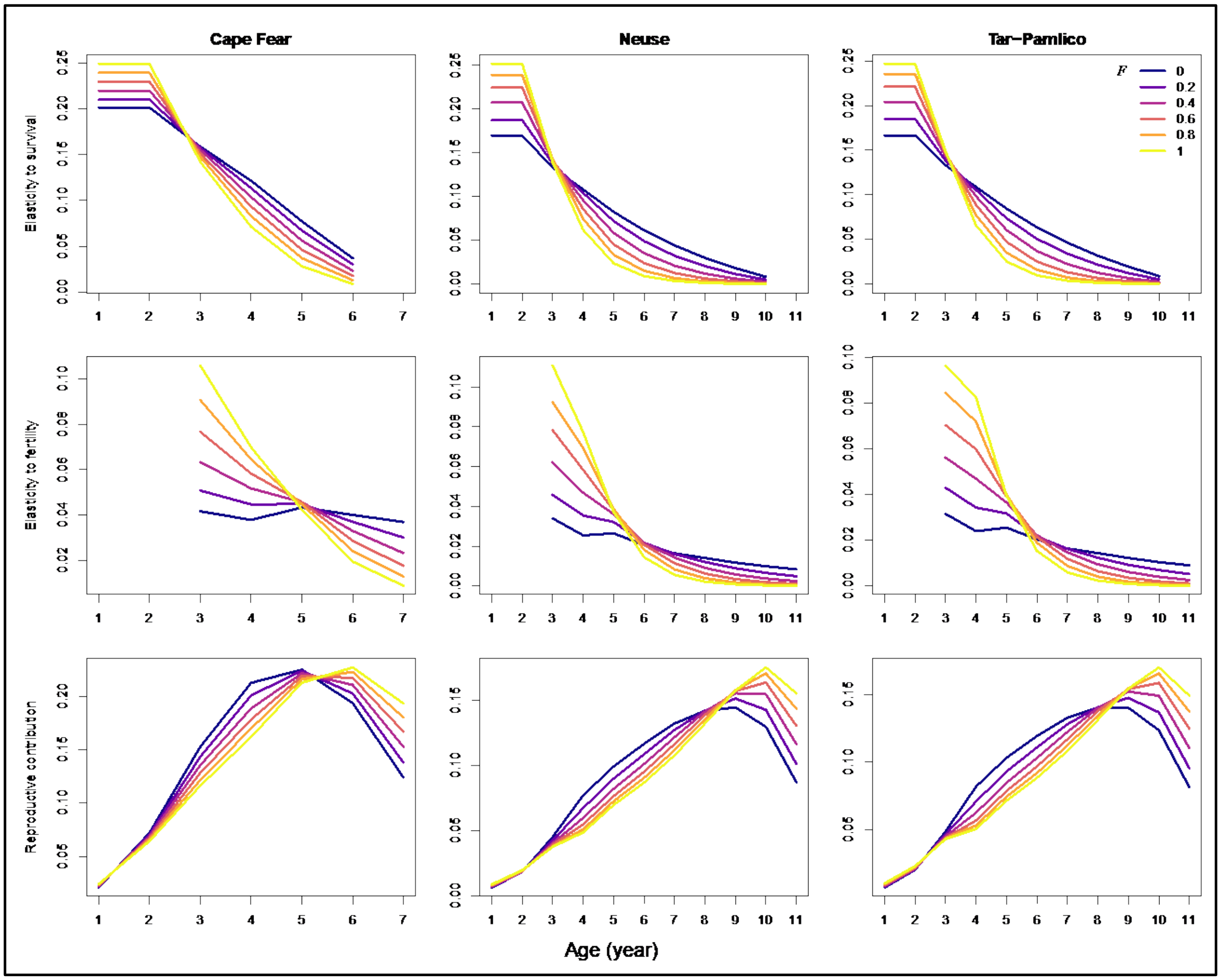


Figure 3.2. Elasticity of population growth rate to survival and fertility and age-specific reproduction contribution. Lines represent various fishing mortality (*F*) values. Lines show the median from 10,000 iterations.

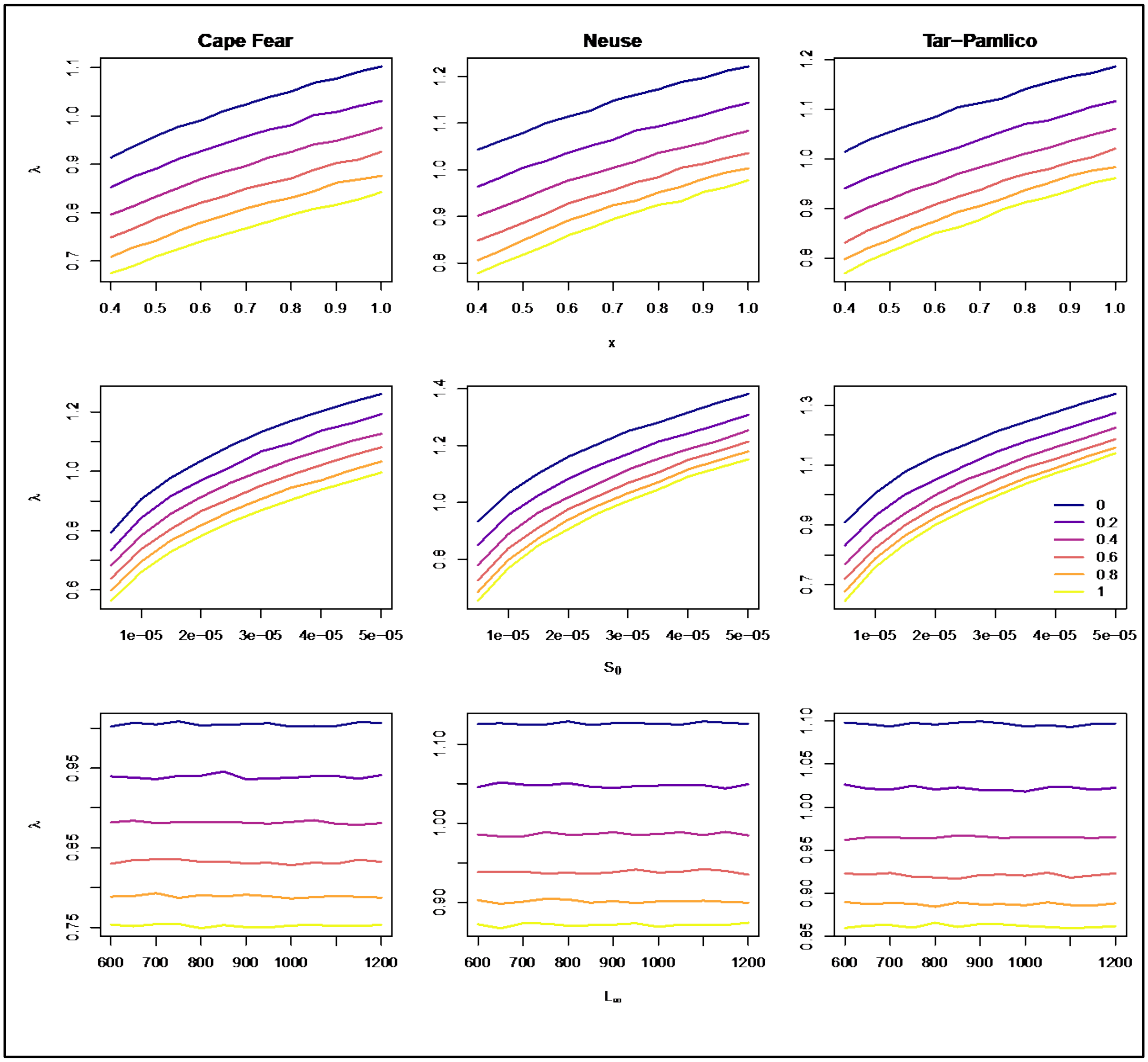


Figure 3.3. Sensitivity of population growth rate to viable egg proportion (x), age-0 survival (S_0) and the asymptotic length (L_∞). Lines represent various fishing mortality (F) values. Lines show the median from 10,000 iterations.

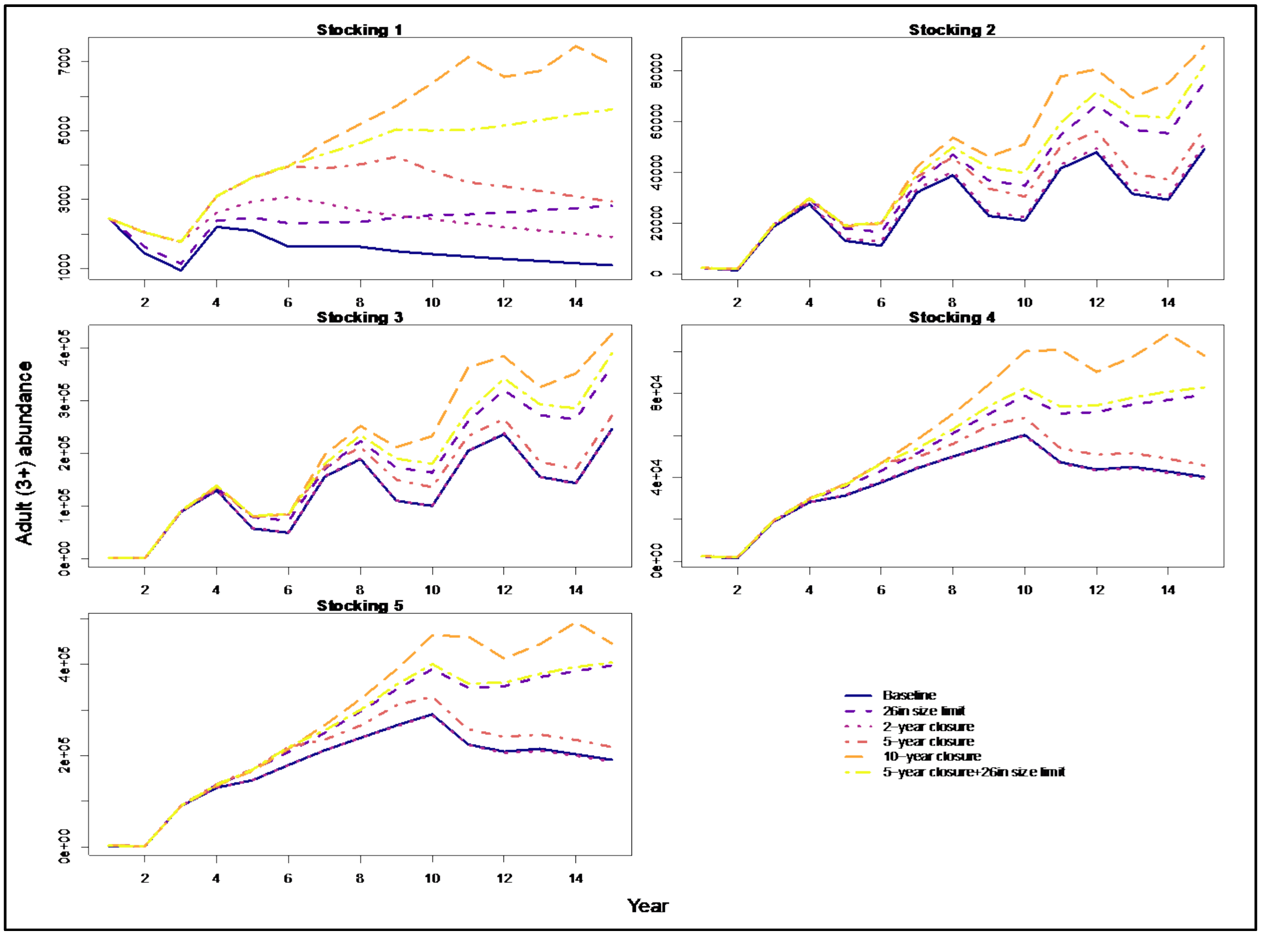


Figure 3.4. Abundance of adults (age 3+) projected under five stocking strategies and six fishing strategies. Stocking 1—no stocking; Stocking 2—stocking 100,000 fish per year with 2-year stocking and 2-year no stocking alternating for 15 years (8 years of stocking in total); Stocking 3—stocking 500,000 fish per year with 2-year stocking and 2-year no stocking alternating for 15 years (8 years of stocking in total); Stocking 4—stocking 100,000 fish per year with 8-year continuous stocking; Stocking 5—stocking 500,000 fish per year with 8-year continuous stocking. Lines show the median from 10,000 iterations.

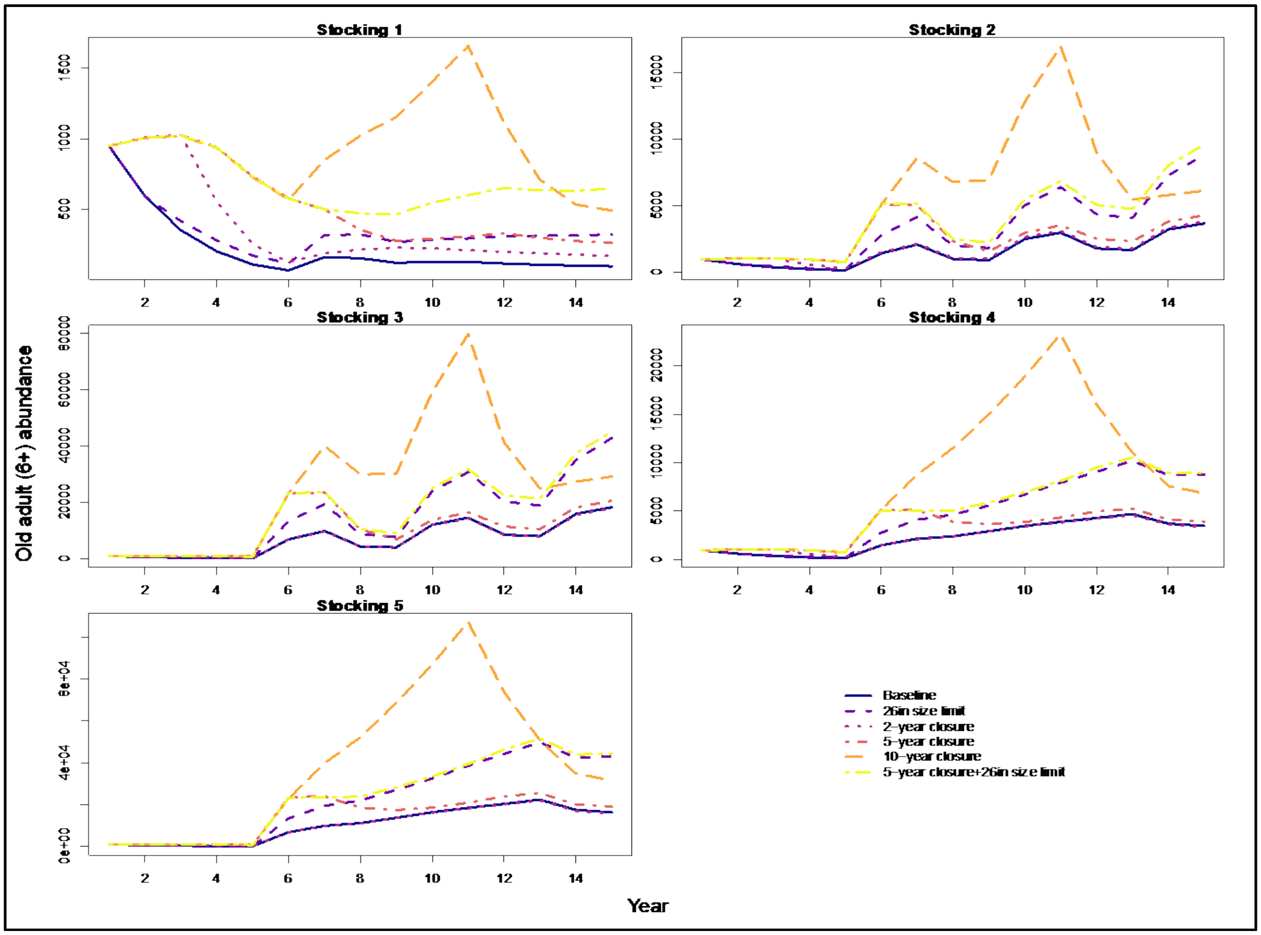


Figure 3.5. Abundance of old adults (age 6+) projected under five stocking strategies and six fishing strategies. Lines show the median from 10,000 iterations. See Figure 3.4 caption for explanation of the five stocking strategies.

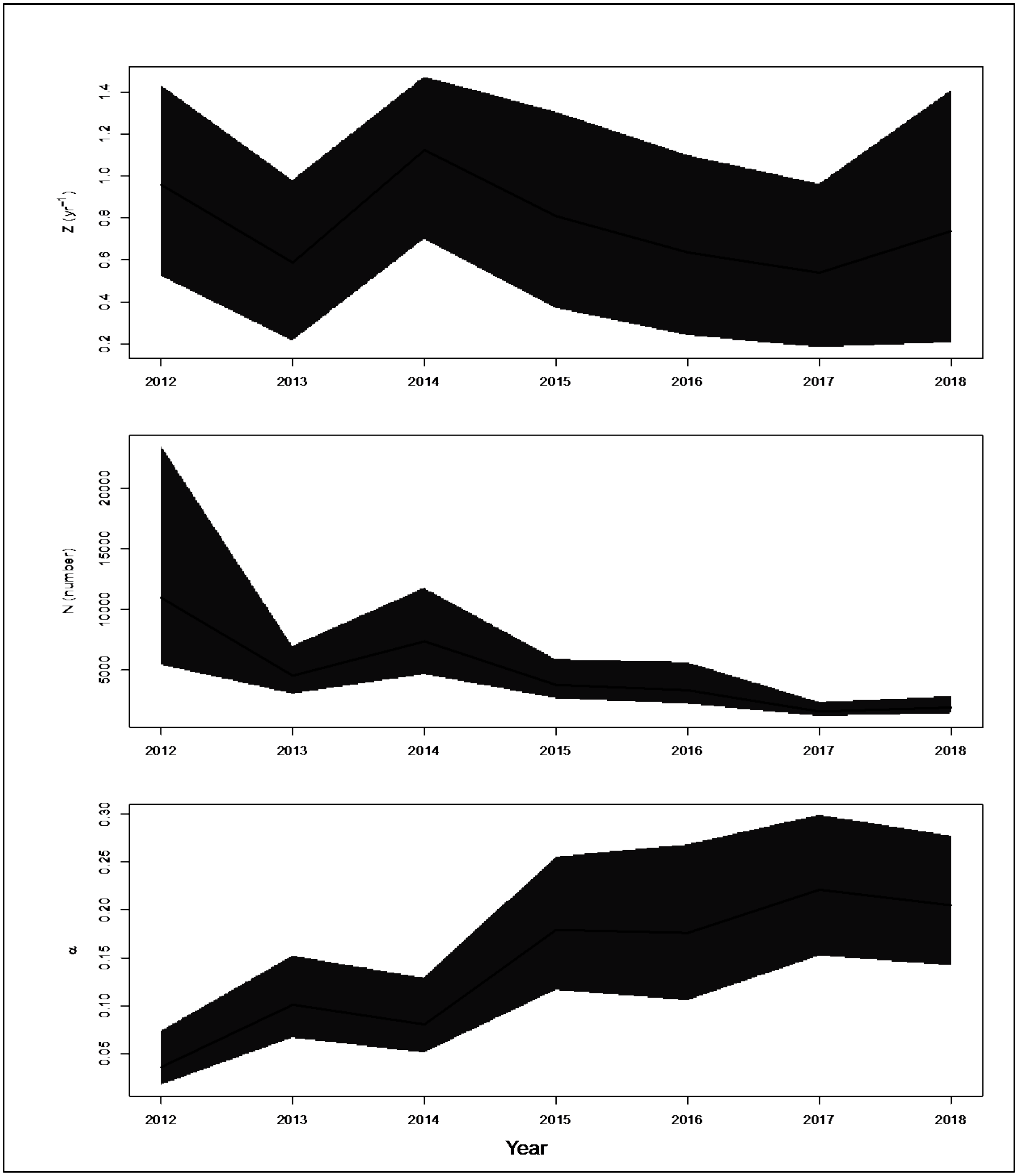


Figure 4.1. Estimated instantaneous total mortality (Z, yr^{-1}) due to natural causes and fishing, estimated abundance (N, number) and estimated capture probability (α) from the tagging model. Line is posterior median and shaded area is 95% credible interval.

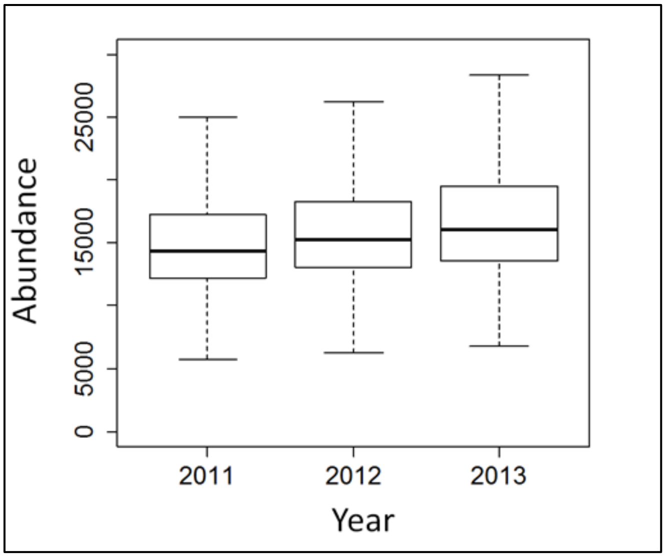


Figure 4.2. Posterior distributions of annual abundance estimated using a Jolly-Seber model and capture probabilities estimated by the multistate model in the Cape Fear River. The whiskers of the boxplots indicate 95% credible intervals of the estimates; boxes of the boxplots represent 50% credible intervals and the bolded lines of each boxplot represent abundance estimates. (Source: Collier et al. 2013)

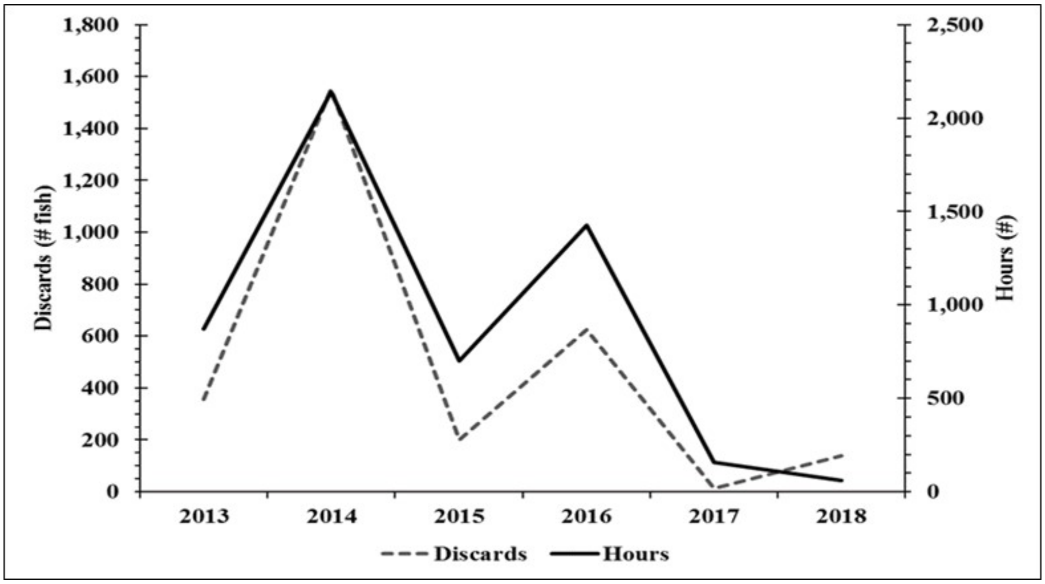
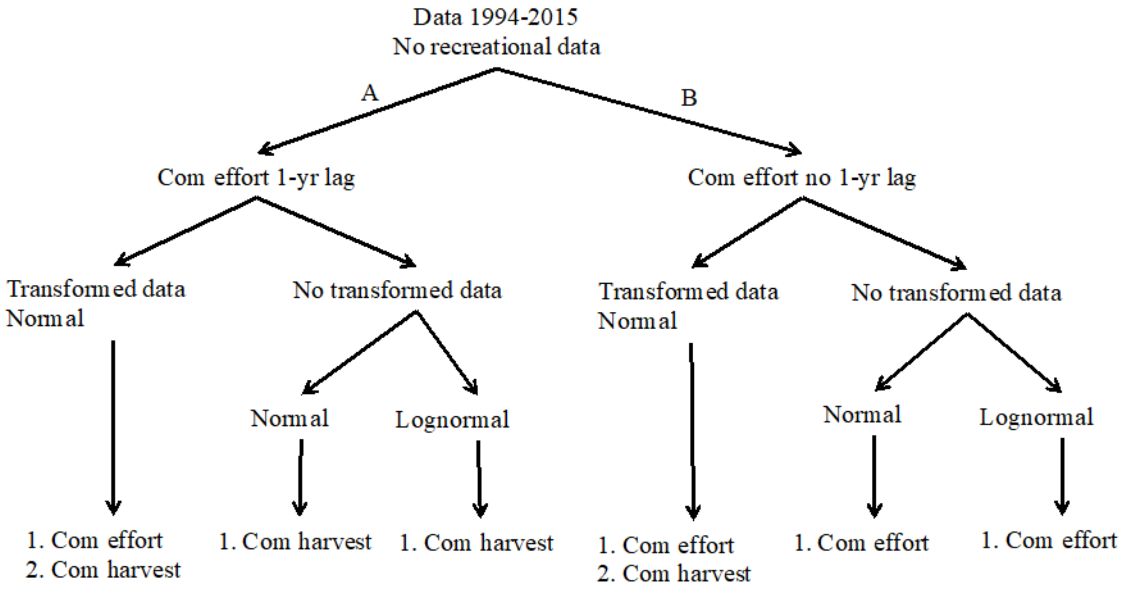


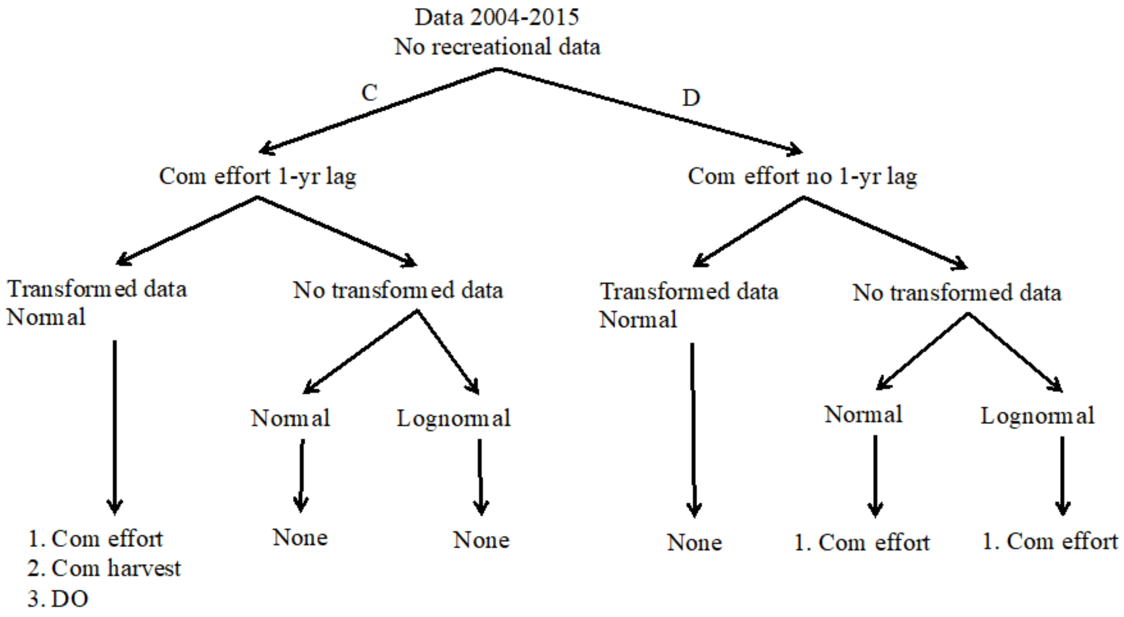
Figure 4.3. NCDMF recreational creel survey estimated striped bass discards (number; dotted line) and recreational fishing effort (hours; solid line) in the Cape Fear River, 2013–2018. In 2013, due to comparatively low recreational striped bass catch, American and hickory shad became the target species.

Figure 4.4. Dead striped bass at Battleship Park, Wilmington, NC following extensive flooding from Hurricane Florence in September 2018.

(A)


Data 1994-2015
No recreational data
A
B
Com effort 1-yr lag
Com effort no 1-yr lag
Transformed data
Normal
No transformed data
Normal
Lognormal
1. Com effort
2. Com harvest
1. Com harvest
1. Com harvest
Transformed data
Normal
No transformed data
Normal
Lognormal
1. Com effort
2. Com harvest
1. Com effort
1. Com effort

(B)


Data 2004-2015
No recreational data
C
D
Com effort 1-yr lag
Com effort no 1-yr lag
Transformed data
Normal
No transformed data
Normal
Lognormal
1. Com effort
2. Com harvest
3. DO
None
None
Transformed data
Normal
No transformed data
Normal
Lognormal
None
1. Com effort
1. Com effort

(C)

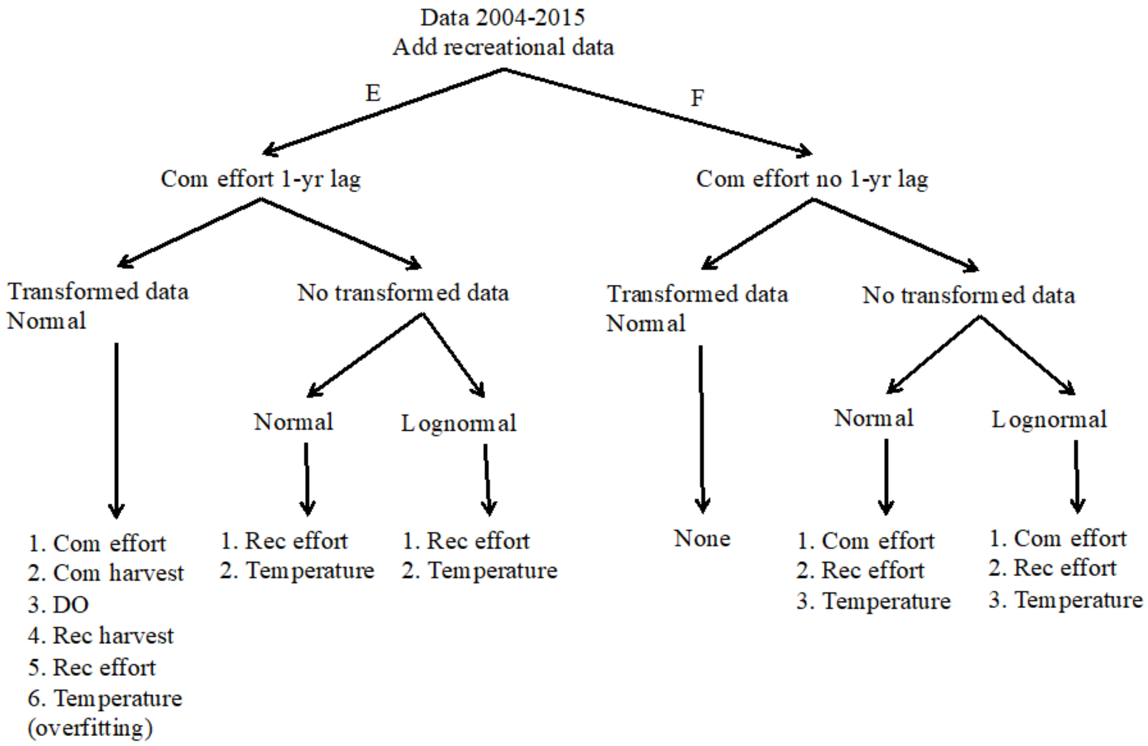


Figure 5.1. Important factors selected in the model when using data from (A) 1994–2015, and (B) data from 2004–2015 without considering recreational information, and (C) when using data from 2004–2015 with recreational information included. These factors are listed in the order of importance from the most important to the least important ones. See the caption of Table 1 for abbreviations of the predictor variables.

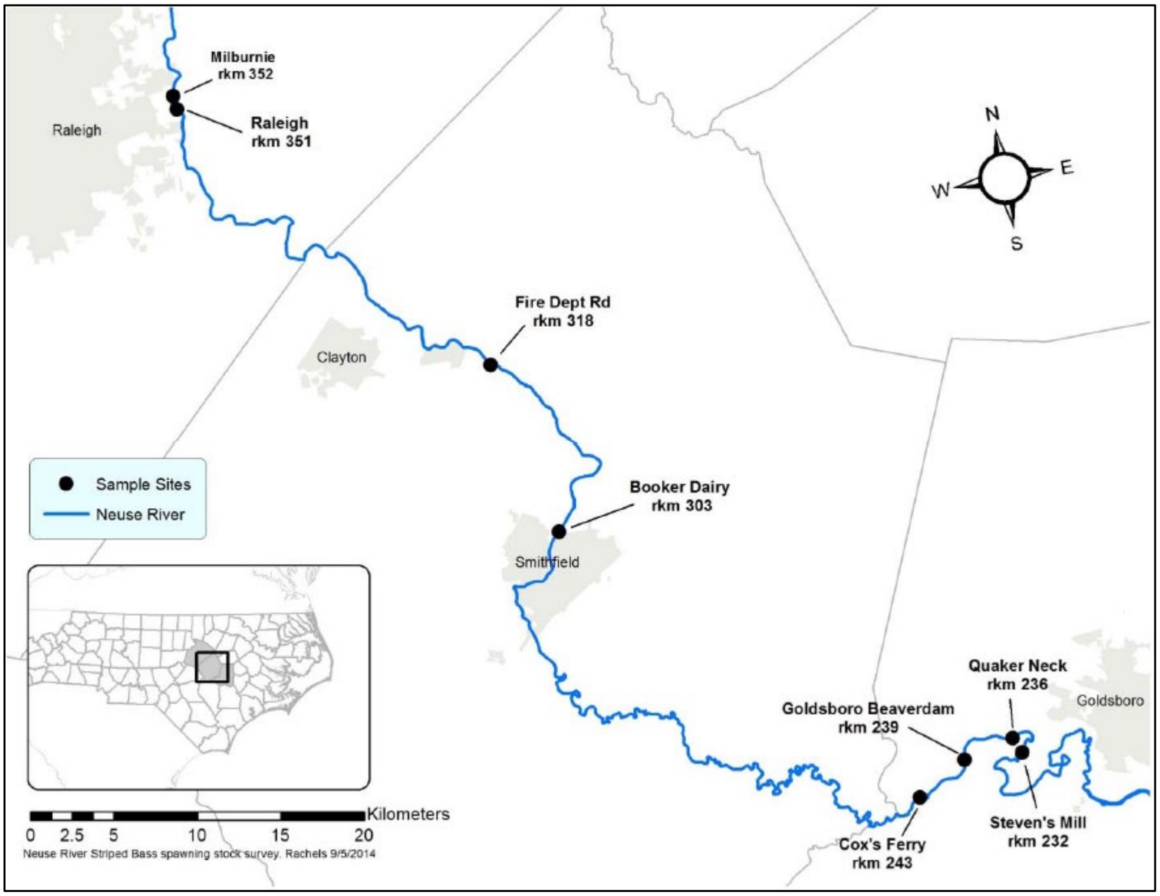


Figure 6.1. Sampling sites in the Neuse River for the NCWRC's Spawning Stock Survey.

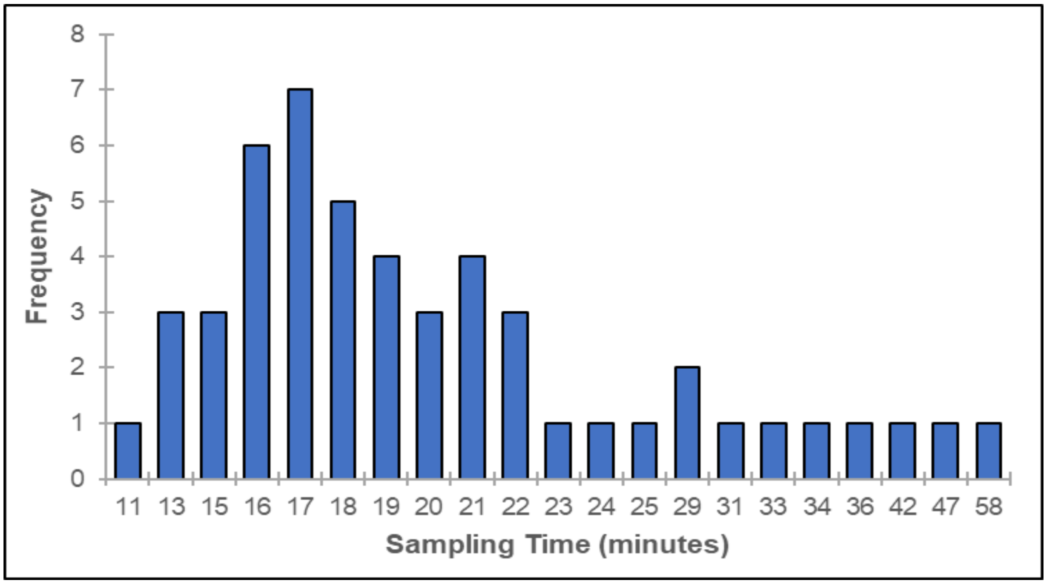


Figure 6.2. Range of sampling times for individual sampling trips from the NCWRC's Spawning Stock Survey in 2017.

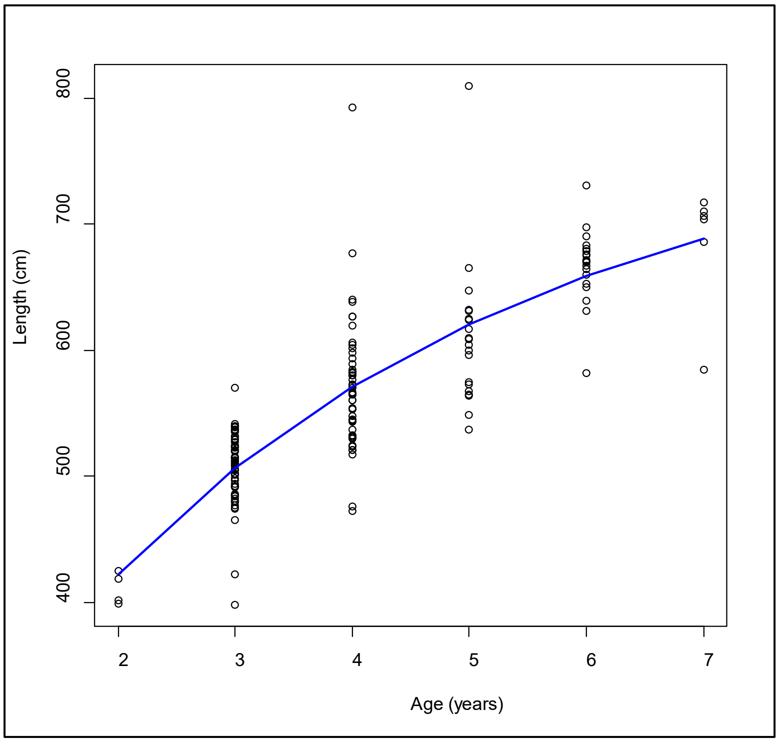


Figure 6.3. Observed (black circles) and predicted (blue line) values of the von Bertalanffy age-length relationship.

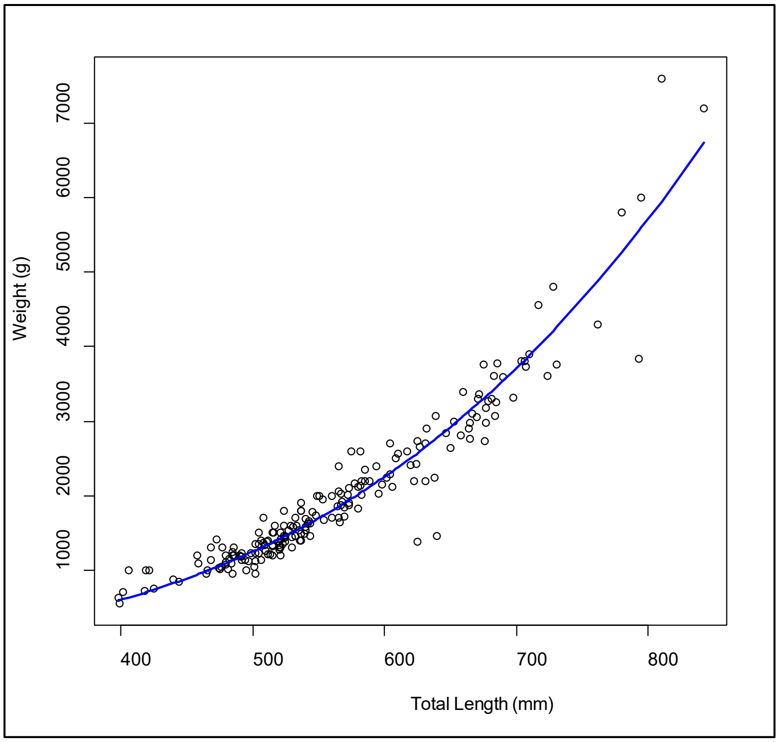


Figure 6.4. Observed (open black circles) and predicted (blue line) values of the length-weight relationship.

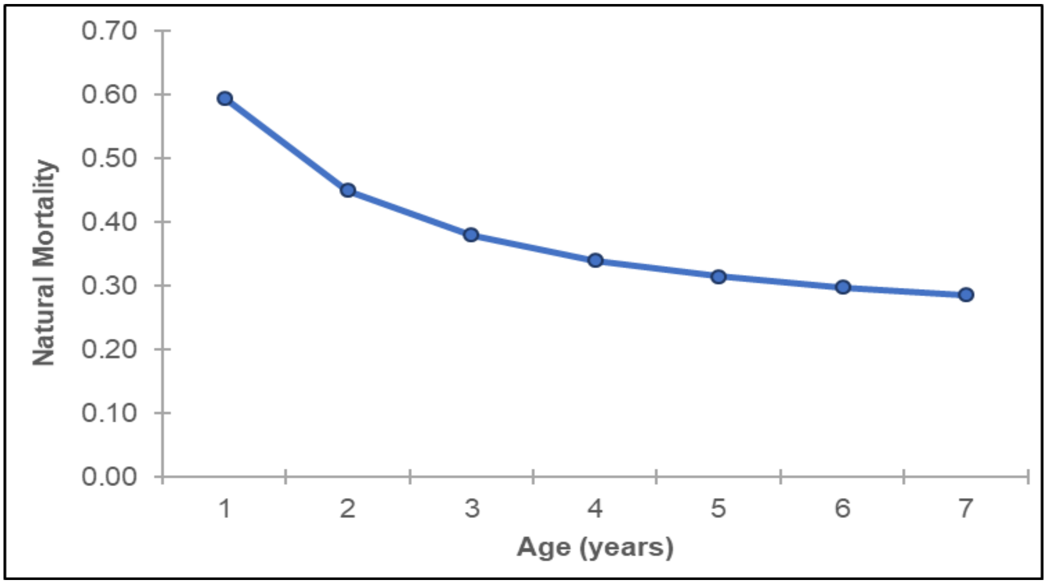


Figure 6.5. Estimated natural mortality at age based on Lorenzen's (1996) approach. The values shown represent instantaneous rates.

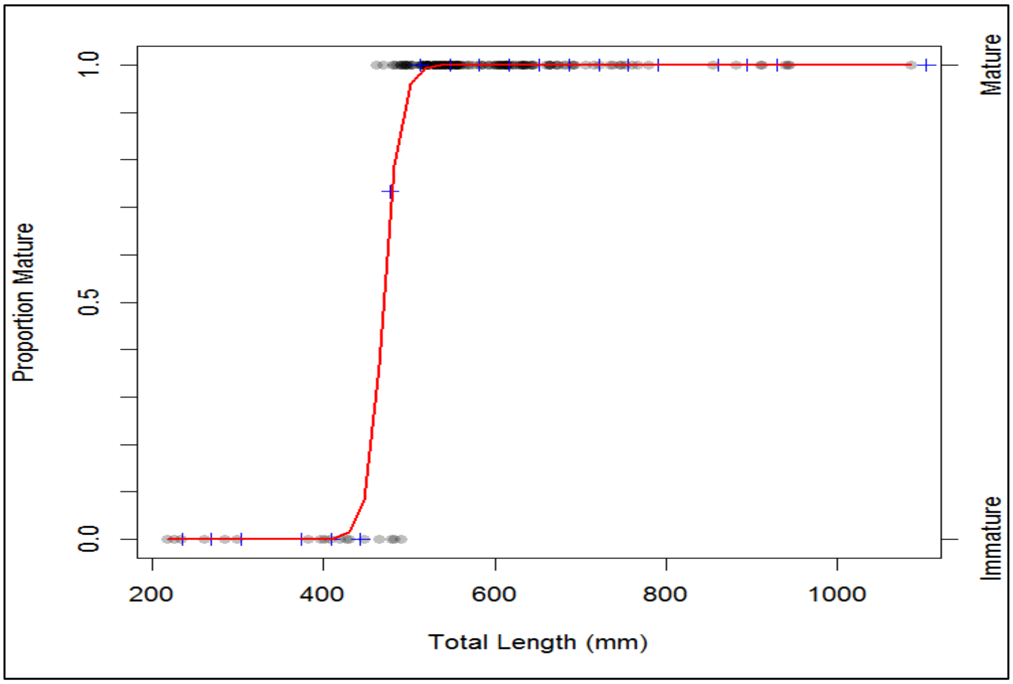


Figure 6.6. Observed (grey circles) and predicted (red line) values of the length-maturity relationship. The blue plus signs represent the proportion mature for selected length categories.

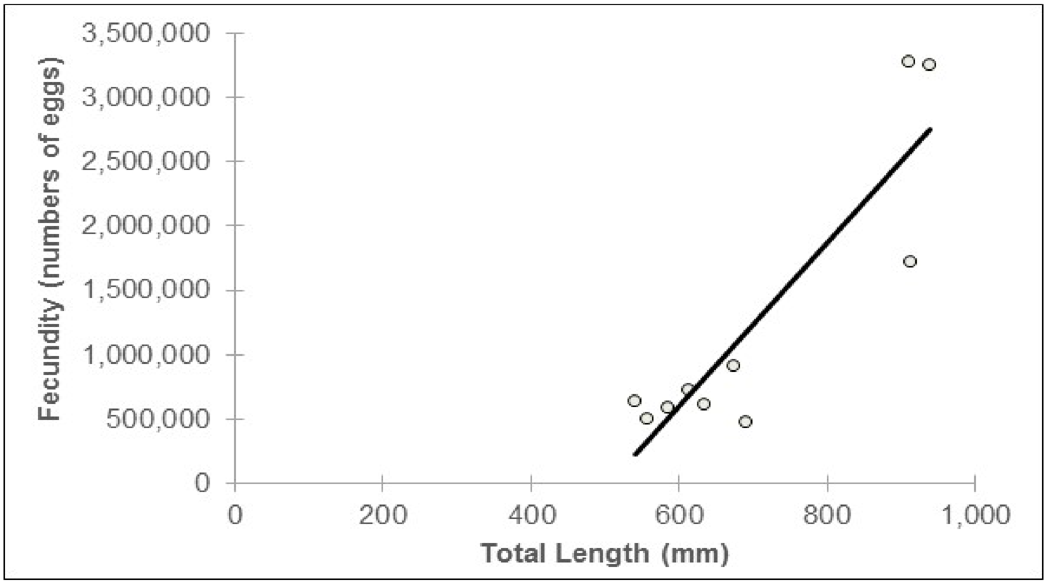


Figure 6.7. Observed (grey circles) and predicted (black line) values of the length-fecundity relationship for non-hatchery origin fish.

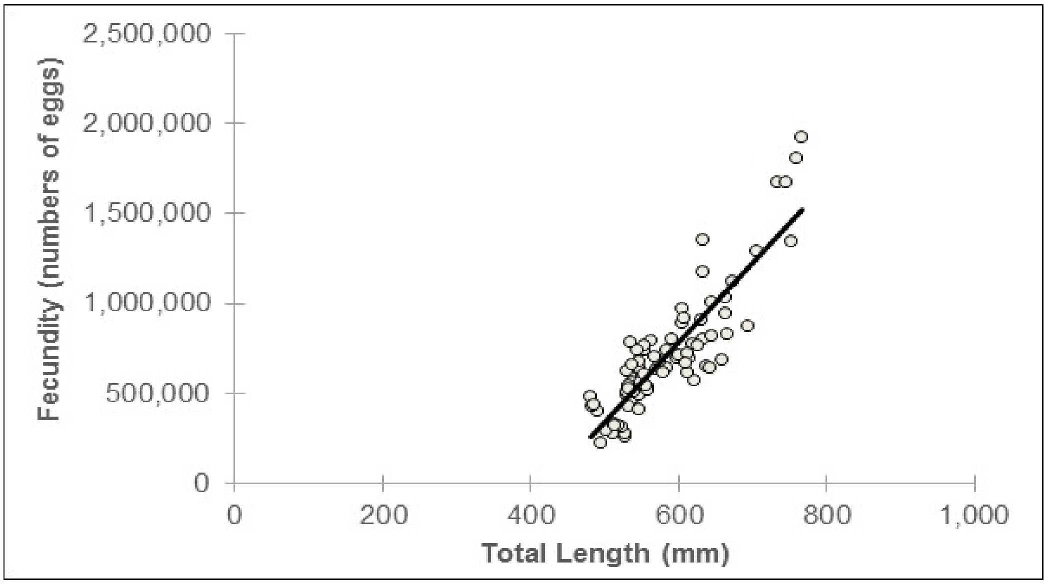


Figure 6.8. Observed (grey circles) and predicted (black line) values of the length-fecundity relationship for hatchery-origin fish.

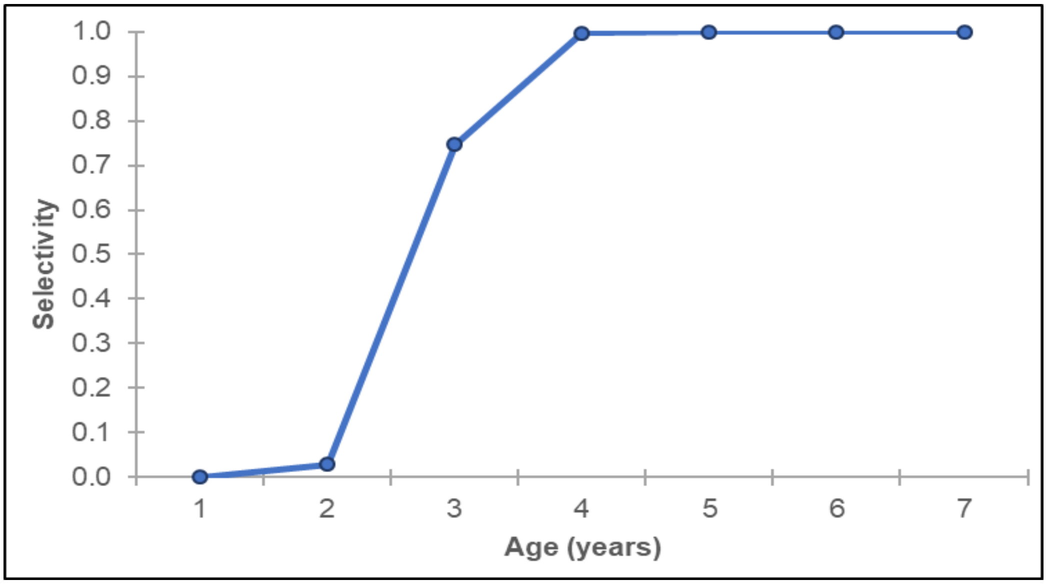


Figure 6.9. Selectivity at age assumed in the per-recruit analyses.

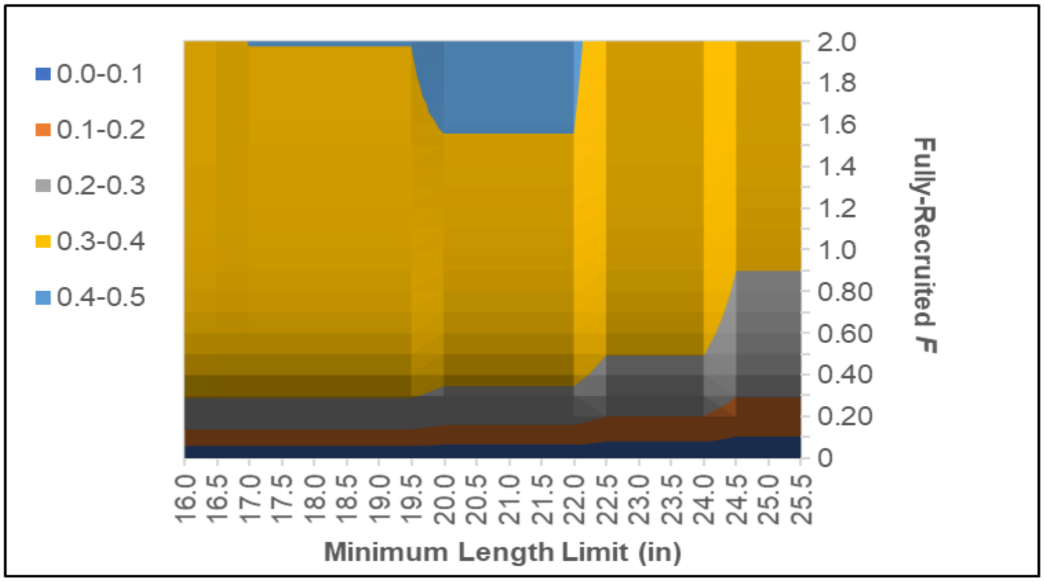


Figure 6.10. Yield per recruit in terms of weight (kilograms) at various combinations of fully-recruited fishing mortality (*F*) and minimum length limits.

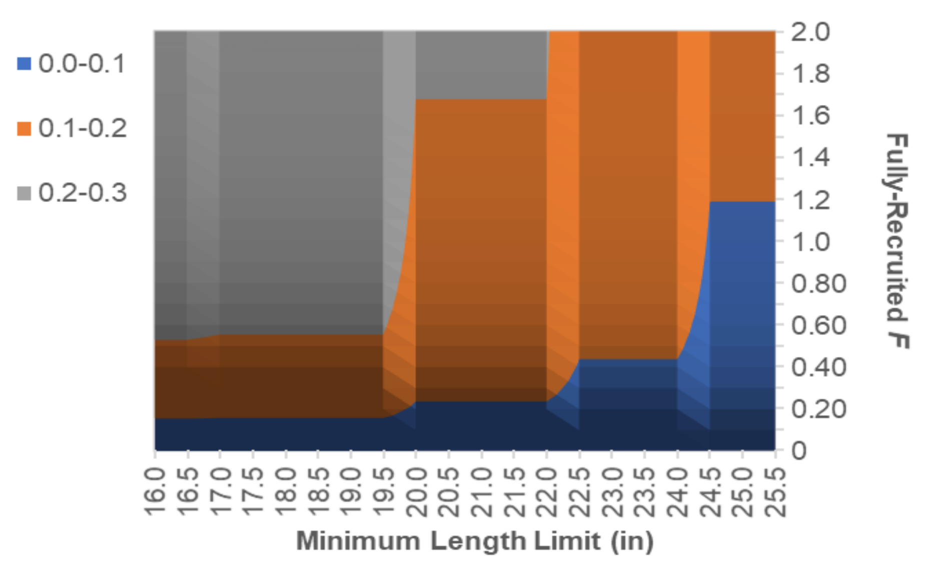


Figure 6.11. Yield per recruit in terms of numbers at various combinations of fully-recruited fishing mortality (*F*) and minimum length limits.

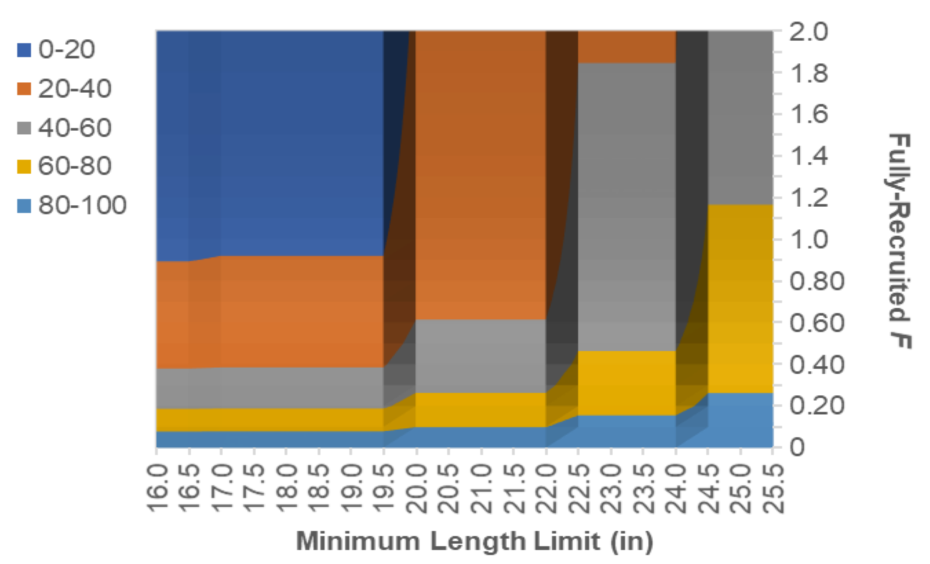


Figure 6.12. Spawning potential ratio (%SPR) at various combinations of fully-recruited fishing mortality (*F*) and minimum length limits.

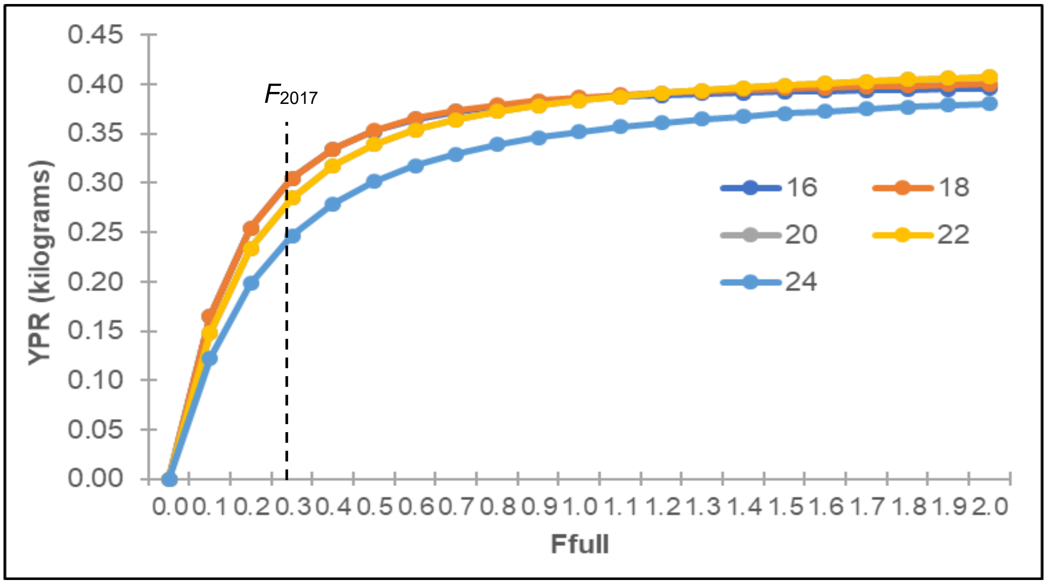


Figure 6.13. Yield per recruit in terms of weight (kilograms) over a range of fully-recruited fishing mortality rates (F_{full}) for select minimum length limits.

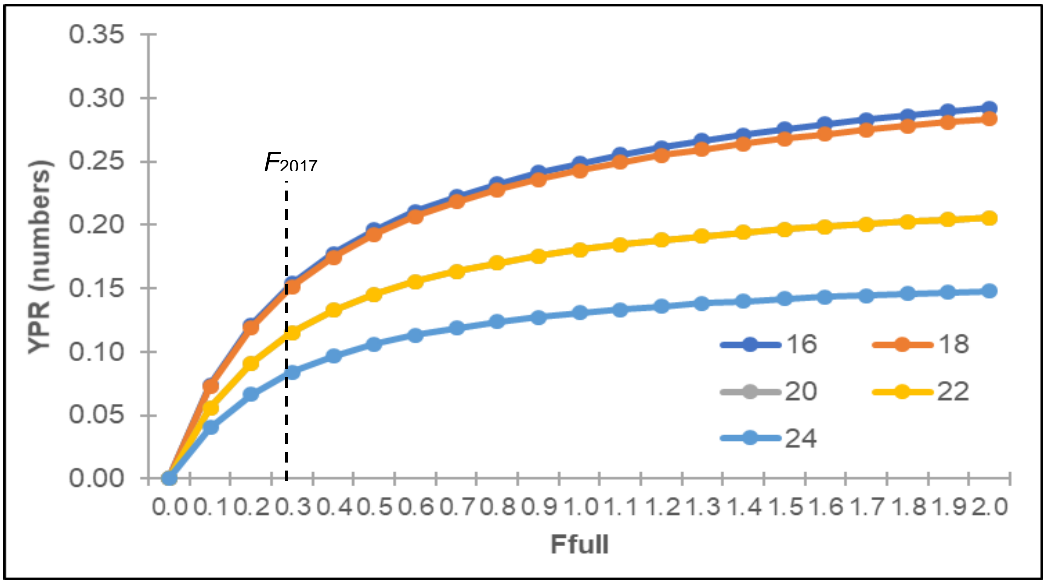


Figure 6.14. Yield per recruit in terms of numbers over a range of fully-recruited fishing mortality rates (F_{full}) for select minimum length limits.

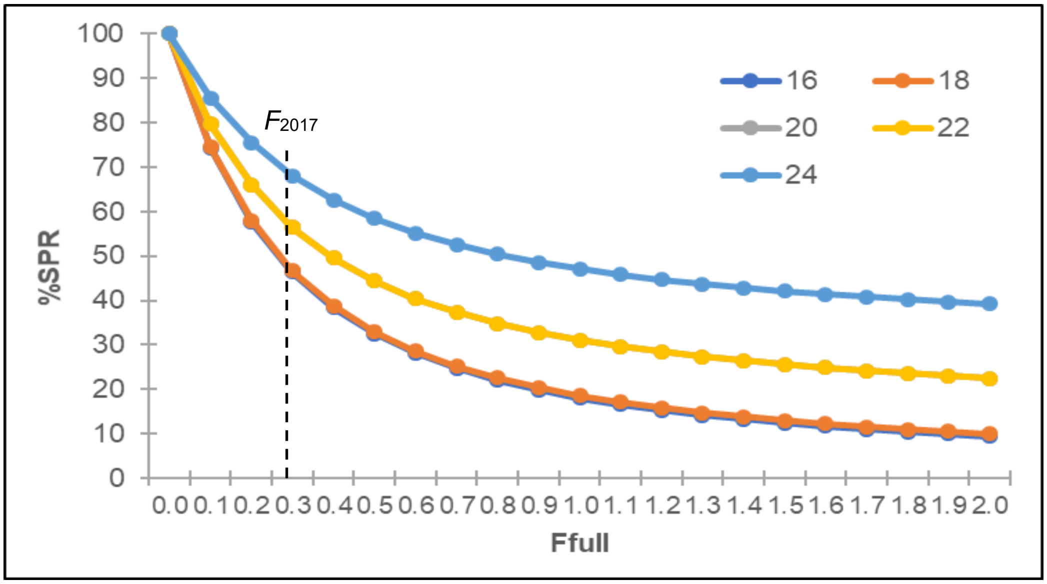


Figure 6.15. Spawning potential ratio (%SPR) over a range of fully-recruited fishing mortality rates (F_{full}) for select minimum length limits.

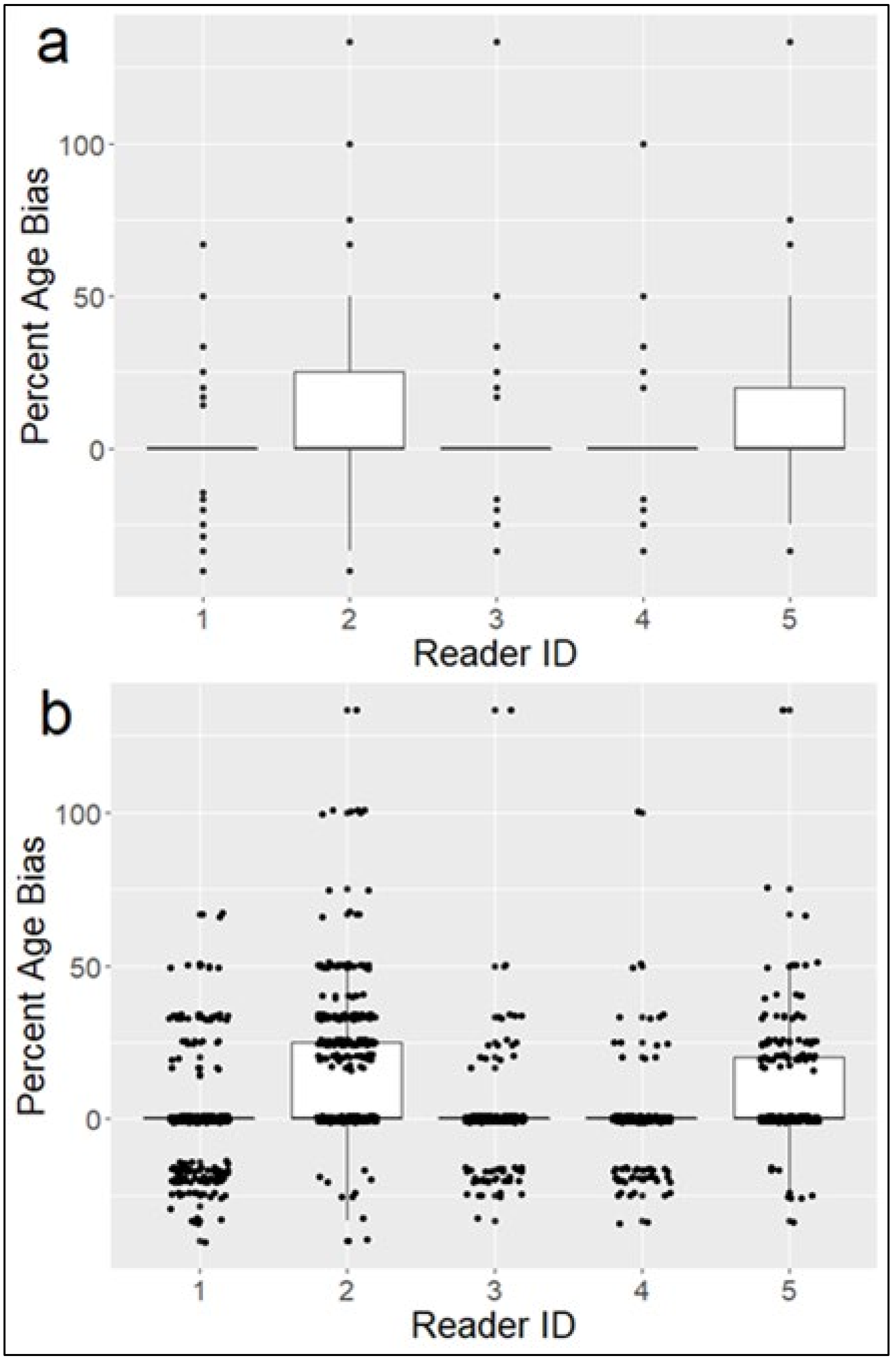


Figure 7.1. Boxplot of percentage age bias by reader ID. The majority of the data points overlapped each other as shown in graph a so the points were jittered (given slightly increased or decreased values) in graph b in order to provide contrasts in data points. The jittered values were not used in the analysis, only to aid in visual inspection of the data.

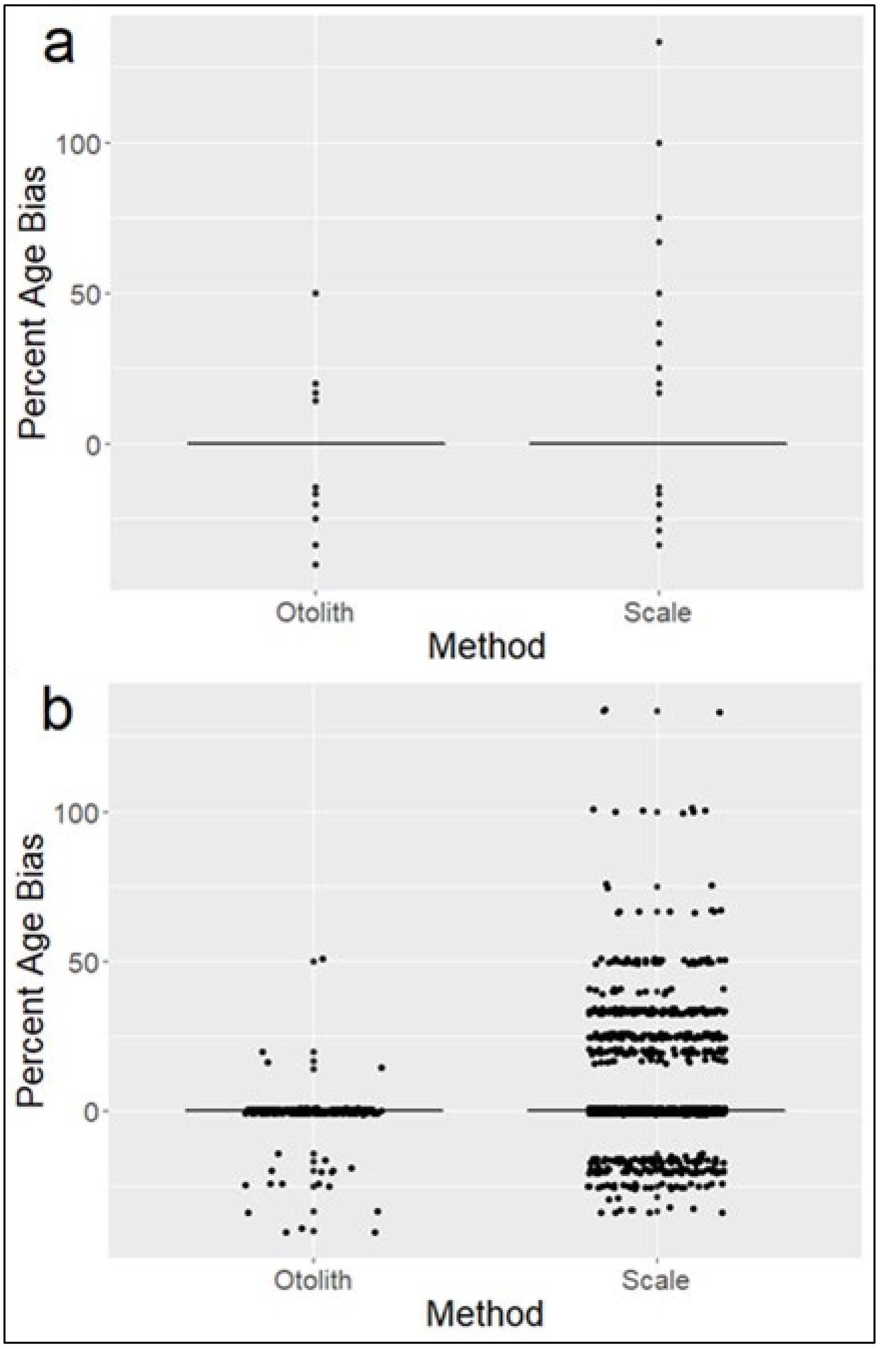


Figure 7.2. Boxplot of percentage age bias by ageing method. The majority of the data points overlapped each other as shown in graph a so the points were jittered (given slightly increased or decreased values) in graph b in order to provide contrasts in data points. The jittered values were not used in the analysis, only to aid in visual inspection of the data.

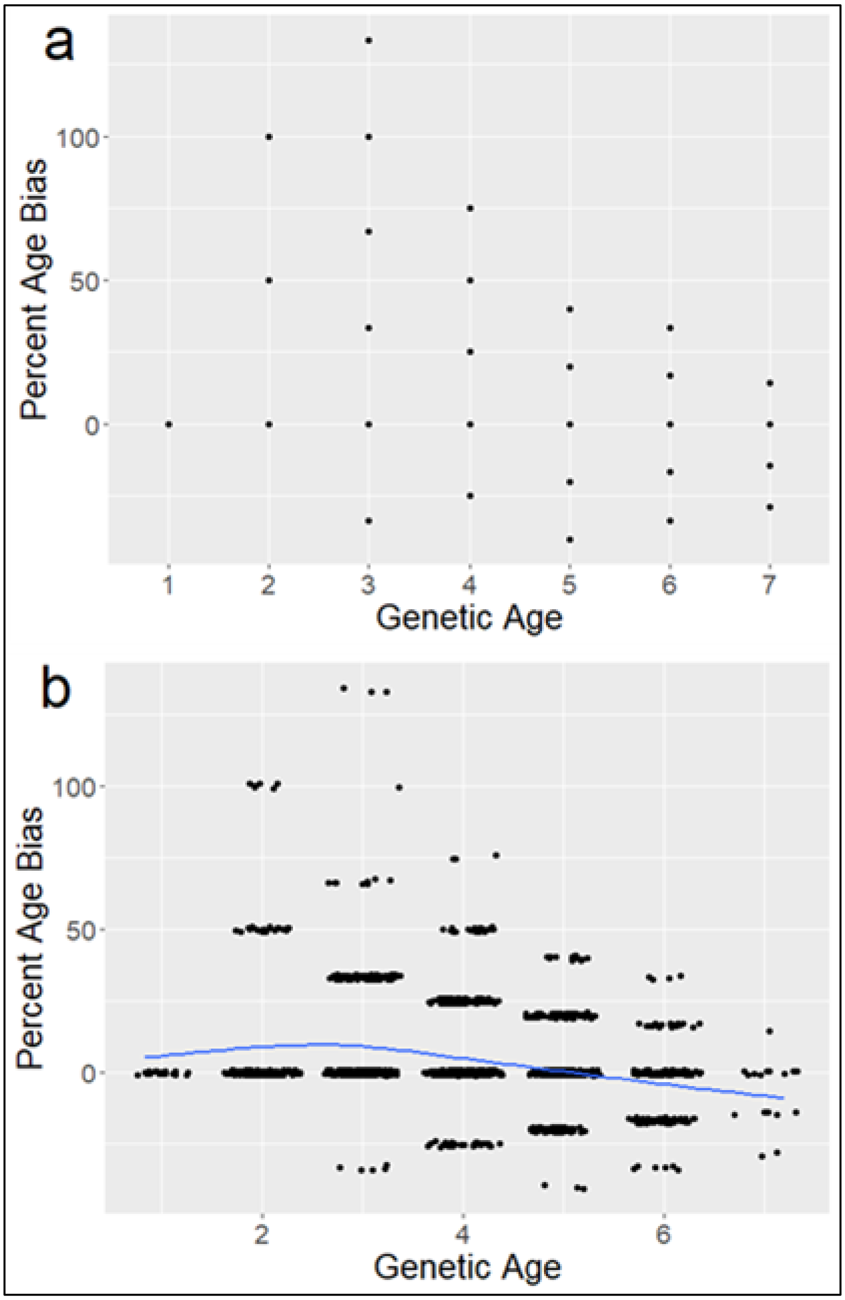


Figure 7.3. Percentage age bias by genetic age (from parental base tagging) with trend line (solid line). The majority of the data points overlapped each other as shown in graph a so the points were jittered (given slightly increased or decreased values) in graph b in order to provide contrasts in data points. The jittered values were not used in the analysis, only to aid in visual inspection of the data.

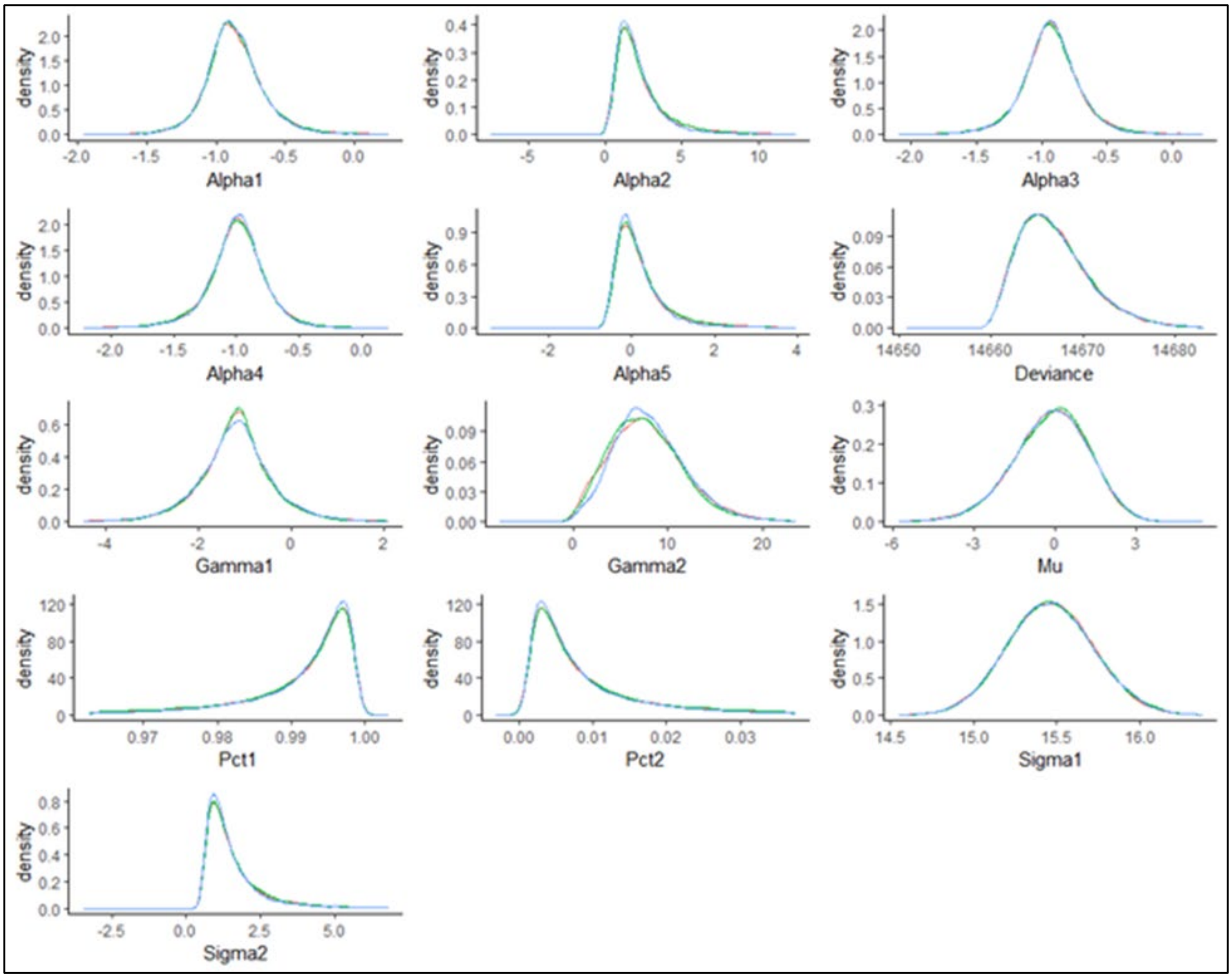


Figure 7.4. Posterior distributions for three chains of parameter estimates from Bayesian generalized linear mixed effects model. Alpha's represent reader effects, gamma's represent method effects, mu represents the overall average bias, pct1 represents percentage of error explained by random error, pct2 represents percentage of error explained by reader effects, sigma1 represents standard deviation associated with random error, sigma2 represents standard deviation associated with reader effects, and deviance is a goodness-of-fit estimate.

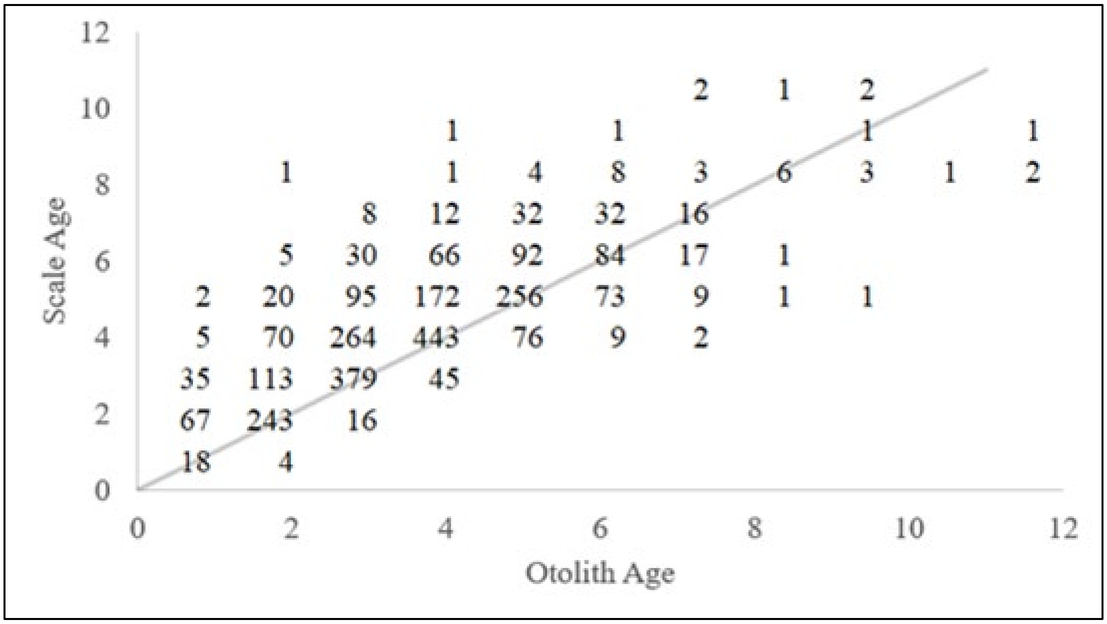


Figure 7.5. Contingency table for number of fish in each scale age for each otolith age. Numbers represent number of fish assigned scale age for a given otolith age.

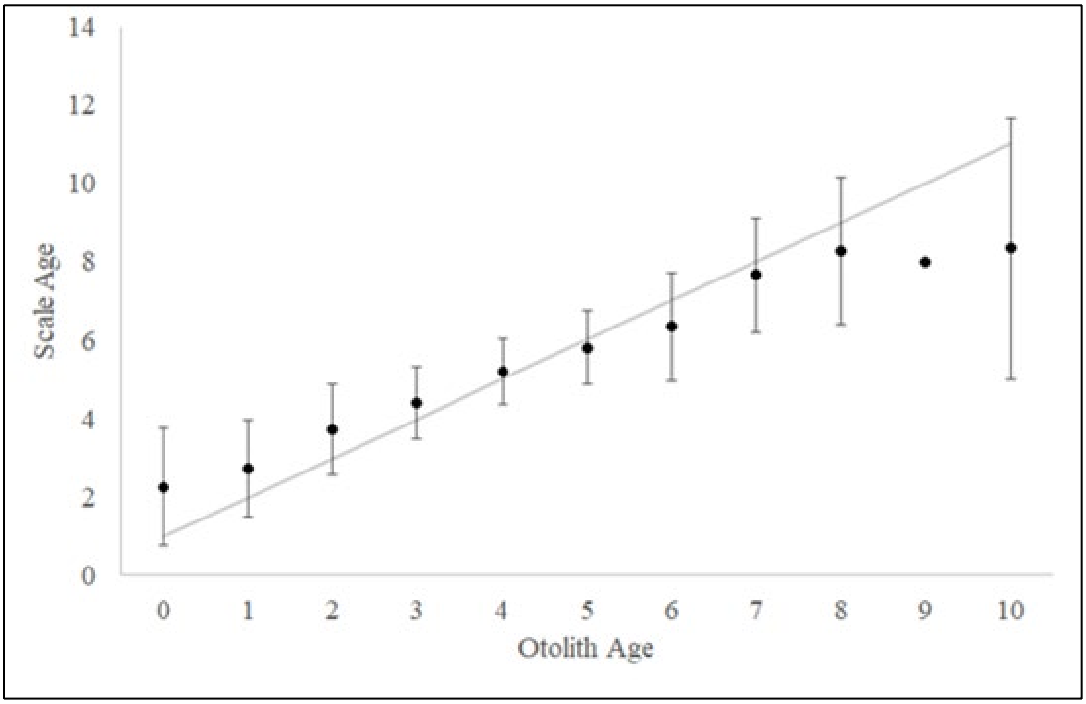


Figure 7.6. Age-bias plot for average scale age for each otolith age with standard deviation.

12 APPENDIX A

FORK LENGTH/ TOTAL LENGTH CONVERSION WORKING PAPER

ESTUARINE STRIPED BASS DATA WORKSHOP
Planning Workshop
March 20, 2017

NC DIVISION OF MARINE FISHERIES
PROGRAM 135 STRIPED BASS INDEPENDENT GILLNET SURVEY (ASMA)
PROGRAM 311 CAPE FEAR RIVER STRIPED BASS MARK RECAPTURE STUDY (CSMA – CAPE FEAR)
PROGRAM 366 MULTI-SPECIES TAGGING PROGRAM (CSMA – CAPE FEAR)
PROGRAM 930 COMPREHENSIVE LIFE HISTORY (CSMA – TAR-PAMLICO, NEUSE, AND CAPE FEAR)

Prepared by: Todd Mathes, Marine Fisheries Biologist I, Washington, NC

Analysis Overview

Differences in striped bass length measurement types collected between and within North Carolina State agencies necessitates standardization to compare samples among systems. The 2017 estuarine striped bass stock assessment planning workshop terms of reference established total length as the standard unit of measurement for the striped bass stock assessment. To this end, simple linear regression was used to compare total length as a function of fork length to establish a conversion for instances where only fork length was recorded.

Data were provided from the divisions' biological database from various fishery independent and dependent data collection programs (Table 1). Geographic areas analyzed included: Albemarle Sound Management Area (ASMA), Central Southern Management Area (CSMA; Pamlico Sound and Tar/Pamlico, Pungo, and Neuse rivers), and CSMA (Cape Fear River).

Program Objectives

The Striped Bass Independent Gillnet Survey (P135) is used to monitor the Albemarle/Roanoke striped bass population. The principle objectives are to describe the striped bass population as to length, age, sex, and relative abundance.

The Cape Fear River Striped Bass Mark Recapture Study (P311) is a tagging study used to: 1) estimate the population size of striped bass in the Cape Fear River, 2) estimate tag loss of internal anchor tags, and 3) compare recapture rates of striped bass caught with hook and line, electrofishing, and gill net gears. Secondary objectives of the study are obtaining age samples from striped bass in the Cape Fear River and determine residency patterns of striped bass in the Cape Fear River.

The Multi-Species Tagging Program (P366) was developed to standardize protocols for coding tag data amongst various existing programs conducted by the division and designed to accommodate future tagging projects as needed regardless of species being tagged. The overall objective is to provide a multi-species tagging program with a standardized coding procedure for conventional tags. The specific objectives are to: 1) estimate tag-retention rates, tag-reporting rates, fishing mortality by fishing sector, and migration rates for red drum, striped bass, spotted seatrout, southern flounder, and cobia 2) estimate fishing mortality by fate (harvest or release), age, and fishing sector and to provide selectivity estimates by fate, age and fishing sector for red drum, striped bass, spotted seatrout, southern flounder, and cobia, and 3) assess annual variation in fishing and natural mortalities using a tag-return model, conventional catch-at-age stock assessment model, or an integrated tag-return catch-at-age model for red drum, striped bass, spotted seatrout, southern flounder, and cobia.

The Comprehensive Life History Program (P930), created in 1985, was developed to increase the understanding of the population dynamics and life history of North Carolina fishes and to collect fish ageing structures and other biological data to develop and validate life history information.

Survey Design & Methods

Data Source

The Striped Bass Independent Gillnet Survey (P135), ongoing since October 1990, is a random stratified multi-mesh monofilament gillnet survey. Mesh sizes used in the survey consist of 2.5 through 7.0 inch stretched mesh (ISM) at ½ inch increments, and 8.0 and 10.0 ISM. The fishing year is divided into three segments: (1) a fall/winter survey period, which begins approximately 1 November and continues through 28 February, (2) a spring survey period which begins 1 March and continues through approximately 30 June, and (3) a summer survey period which starts 1 July and continues through 30 October.

The Cape Fear River Striped Bass Mark Recapture Study (P311), 2010-2014, sampled thirty-two fixed stations in addition to randomly selected stations that were sampled in January to April each year. In 2015 striped bass tagging from this program transitioned to P366 and its sampling protocols.

The Multi-Species Tagging Program (P366), implemented 1 October, 2014, is the primary program for documenting the divisions' conventional fish tagging. Red drum, striped bass, spotted seatrout, sturgeon, southern flounder, and cobia are tagged by division staff using a variety of methods. Fish are captured through division fishery independent and dependent sampling programs. A limited number of recreational hook-and-line fishermen recruited by division staff will also tag these fish species. Sampling for this program is diverse both geographically and by gear type to achieve the studies objectives.

The Comprehensive Life History Program (P930) began collecting and ageing of fish otoliths and scales in the late 1970's. Currently, regular data collection occurs for approximately 20 recreationally and commercially important North Carolina finfish species. In the past, P930 has had no specific sampling design; ageing samples have been collected opportunistically or as needed from division fishery independent sampling, commercial catches, and recreational catches, depending on the species. Otoliths and/or scales are collected monthly from American shad, Atlantic croaker, Atlantic menhaden, black drum, black sea bass, bluefish, cobia, kingfishes, mackerels, flounders, red drum, sheepshead, spotted seatrout, spot, striped bass, striped mullet, and weakfish.

Analysis Methods

Due to the large number of observations within the ASMA data set, spanning 1990 to present, only years 2000-2016 were used for the analysis. Initial data provided were screened to remove outliers. Two methodologies were used to establish a threshold to identify outliers: (1) ***(TL-FL)/TL>15%***, and (2) ***FL>TL***. Once the outliers were identified/removed, data were further cleaned to ensure accuracy of coding. Simple linear regression was then used to compare total length as a function of fork length. Simple linear regression is a parametric statistical test predicated on assumptions of normality, and homoscedasticity (equality of variances). Linear regression tests the null hypothesis that there would be no significant prediction of total length by fork length. All data were analyzed using SAS 9.3.

Our hypotheses are as follows:

H_0: $\rho=0$ there is no correlation between fork length and total length within our population

H_0: $\rho\neq0$ there is a significant correlation between fork length and total length

Where ρ is our correlation coefficient (measures the strength and direction of a linear relationship between two variables)

A student's t-test is used to determine if the relationship between our independent (fork length) and dependent variables (total length) are different from zero.

$t = r\sqrt{}(n\text{-}2)/(1\text{-}r^2)$

where, $r = 1/n\text{-}1\sum(x_i\text{-}\ x)(y_i\text{-}y)/s_x s_y$

Results

Results of the analyses validates that the assumptions of normality had been met (Figure 1, Figure 3, and Figure 5), and that the amount of variability within datasets were very low (Figure 2, Figure 4, and Figure 6) demonstrating equality of variances.

Conclusion

Regressions from all three areas exhibited essentially the same slopes and Y intercepts differed by less than 5 millimeters. Based on these results, it is appropriate to pool data from all the regions. In conclusion, when converting fork length to total length, pooled data can be used to accurately predict total length. Listed below are the formulas for converting fork length to total length, as well as a reciprocal equation in case there is an instance where total length needs to be converted to fork length.

FL to TL Conversion Formula:
Total Length = 6.206909513 + (1.055954699 * Fork Length)

Example:
FL = 640 mm, what's the TL?
TL = 6.206909513 + (1.055954699 * 640) =
TL = 6.206909513 + 675.811 =
TL = 682.0179 mm
TL = 682 mm

Reciprocal TL to FL Conversion Formula:
Fork Length = (Total Length * 0.945673822) – 5.277089838

Example:
TL = 682 mm, what's the FL?
TL = (682 * 0.945673822) – 5.277089838 =
TL = 644.949546604 – 5.277089838 =
TL = 639.6724 mm
TL = 640 mm

Dataset Information

Charlton Godwin, Charlton.Godwin@ncdenr.gov,
File Location:
U:\striped bass\Stock Assessment Benchmark FMP 2017\2_Data Workshop\Data\Life History\FL-TL Conversion
P135 dataset:
AR STB FL TL conversion.xlsx

Chris Stewart, Chris.Stewart@ncdenr.gov
File Location:
U:\striped bass\Stock Assessment Benchmark FMP 2017\2_Data Workshop\Data\Life History\FL-TL Conversion
P311, P366, and P930 dataset:
p311&366_cfr_stb.sas7bdat
cfr_stb.sas7bdat

Chris Wilson, Chris.Wilson@ncdenr.gov
File Location:
U:\striped bass\Stock Assessment Benchmark FMP 2017\2_Data Workshop\Data\Life History\FL-TL Conversion
SAS Program:
length regression.sas
Analysis dataset:
sbass.sas7bdat
eg_clean.sas7bdat

Todd Mathes, Todd.Mathes@ncdenr.gov
File Location:
U:\striped bass\Stock Assessment Benchmark FMP 2017\2_Data Workshop\Data\Life History\FL-TL Conversion
P930 dataset:
CSMA STB FL to TL conversion (4-20-17).xls

Tables

Table 1. FL to TL conversion data description.

Area	Program	n	Years	Data Source
ASMA	P135	40,073	2000–2016	Charlton Godwin
CSMA—Tar-Pamlico	P930	3,764	2000–2016	Todd Mathes
CSMA—Neuse	P930	2,482	2000–2016	Todd Mathes
CSMA—Cape Fear	P311, P366, P930	2,372	2011–2016	Chris Stewart

Figures

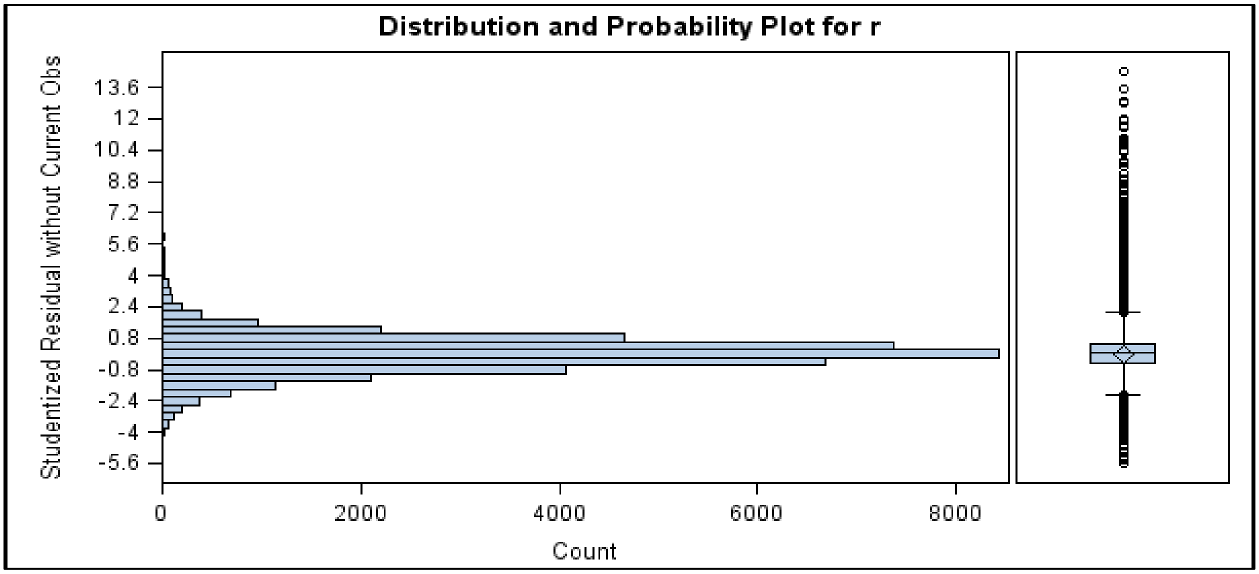


Figure 1. ASMA residual plot validating assumptions of normality.

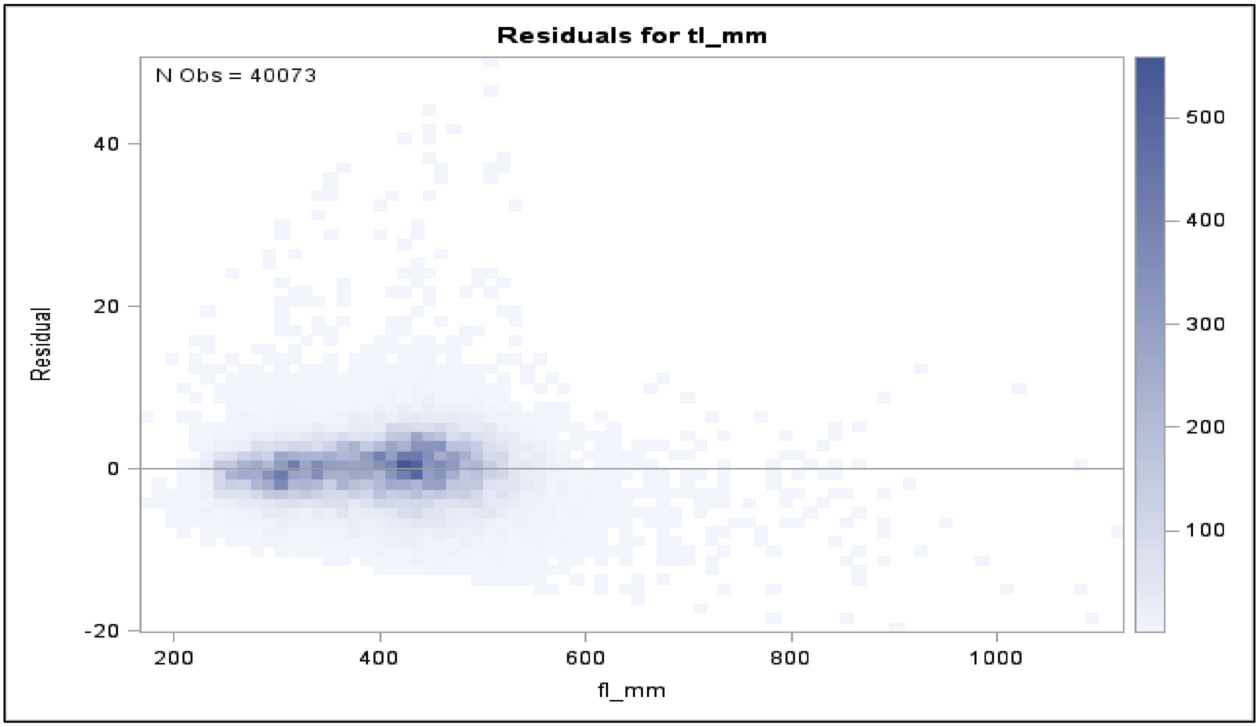


Figure 2. ASMA residuals demonstrate low variability associated with the best fit line.

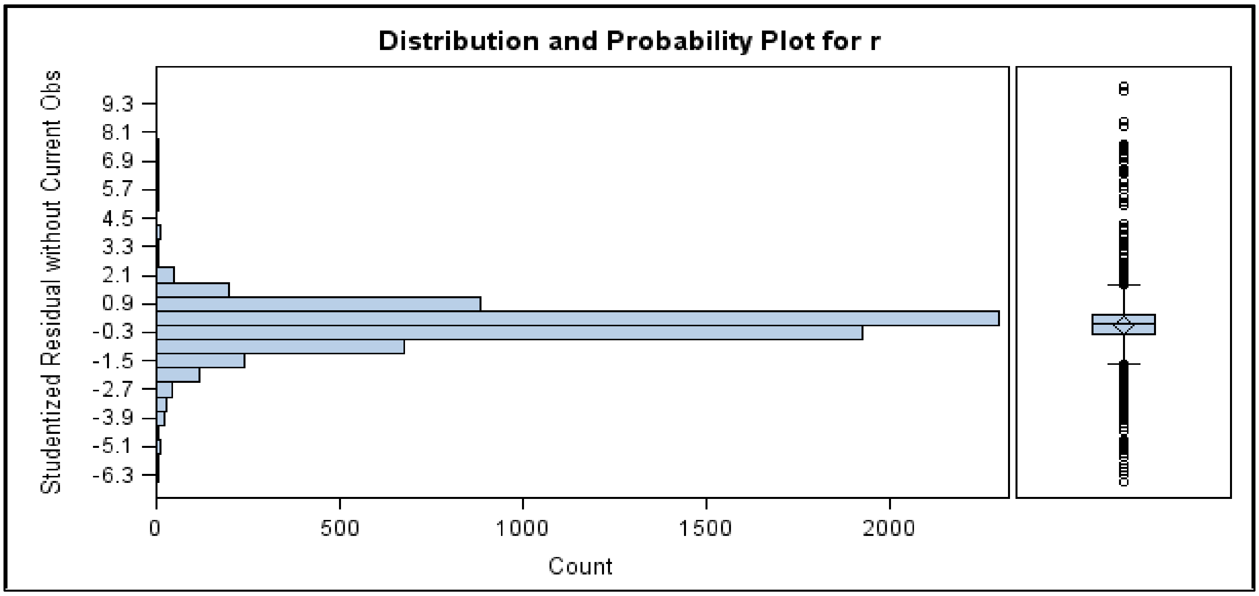


Figure 3. CSMA residual plot validating assumptions of normality.

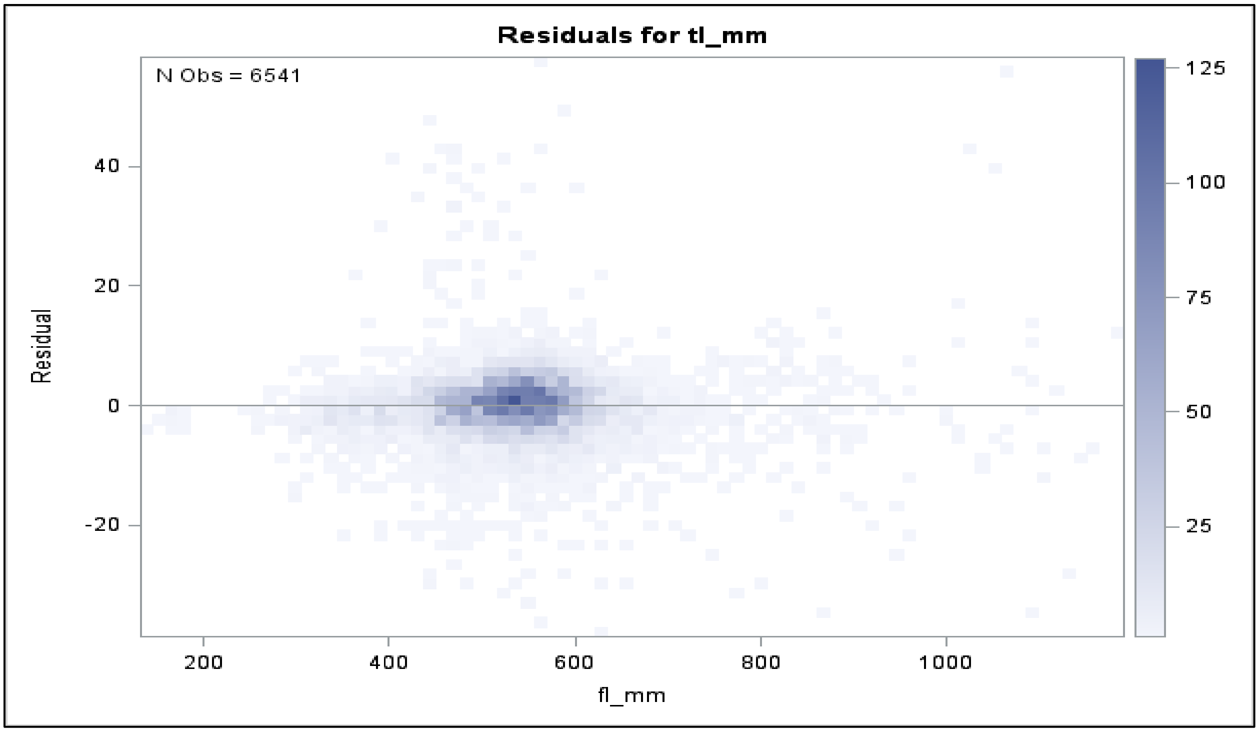


Figure 4. CSMA residuals demonstrate low variability associated with the best fit line.

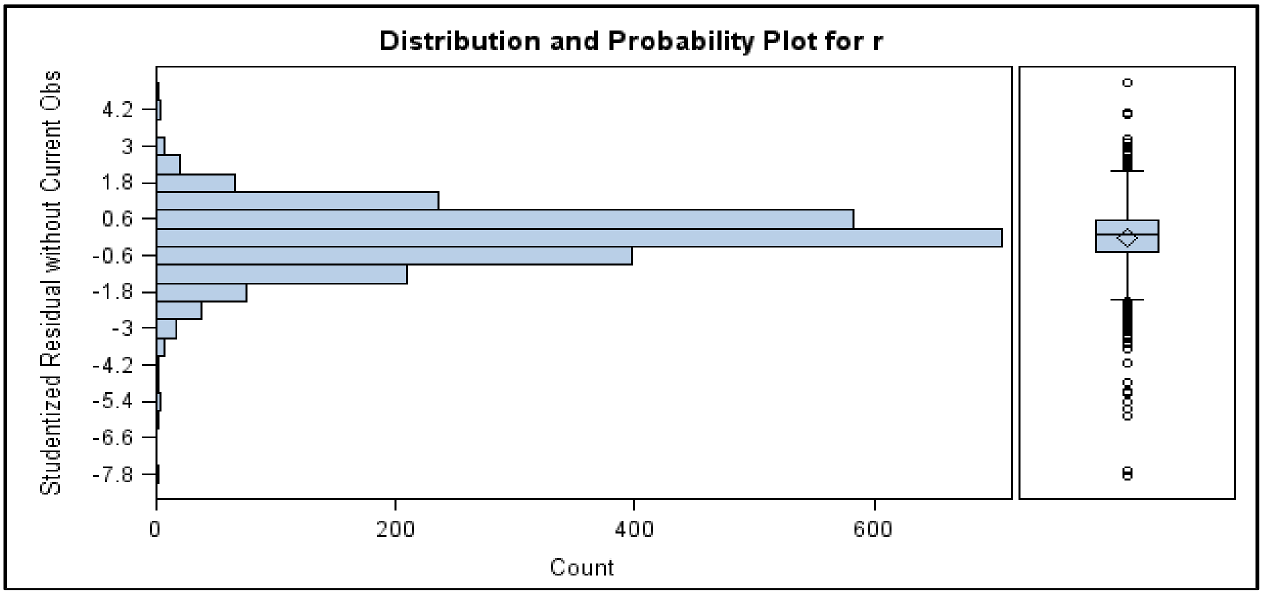


Figure 5. Cape Fear residual plot validating assumptions of normality.

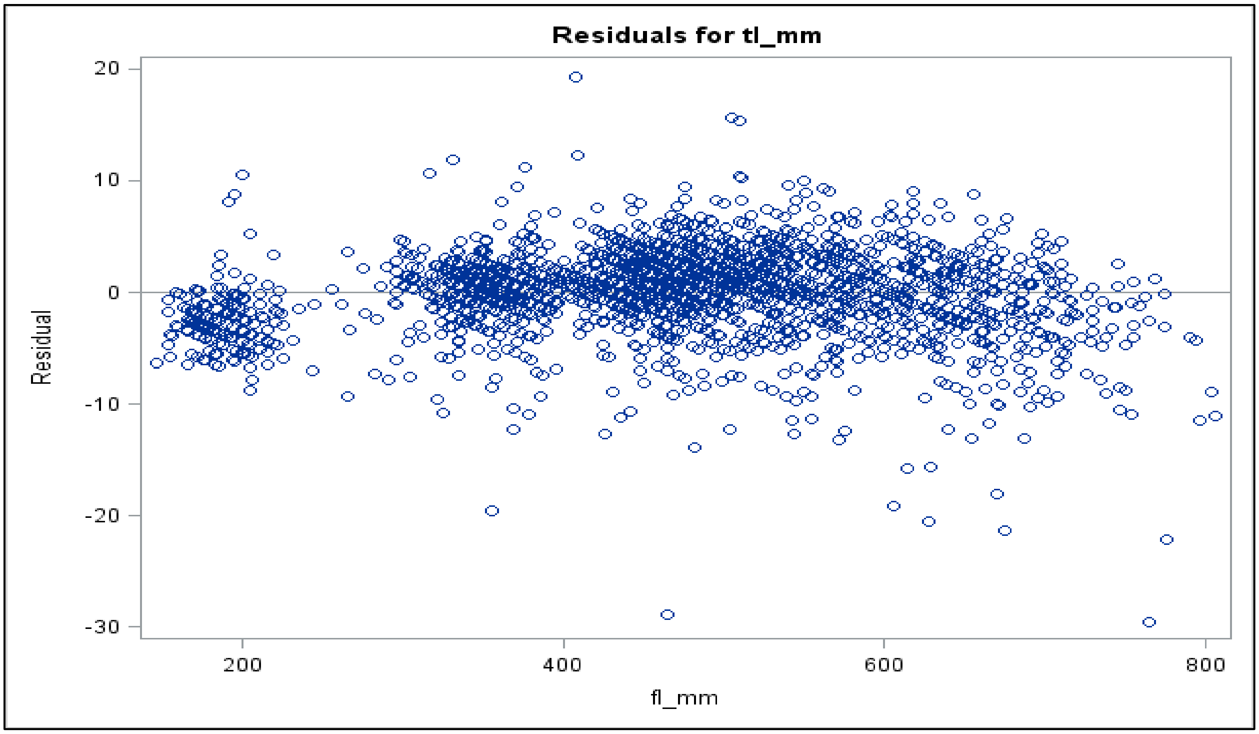


Figure 6. Cape Fear residuals demonstrate low variability associated with the best fit line (number of observations=2,372).

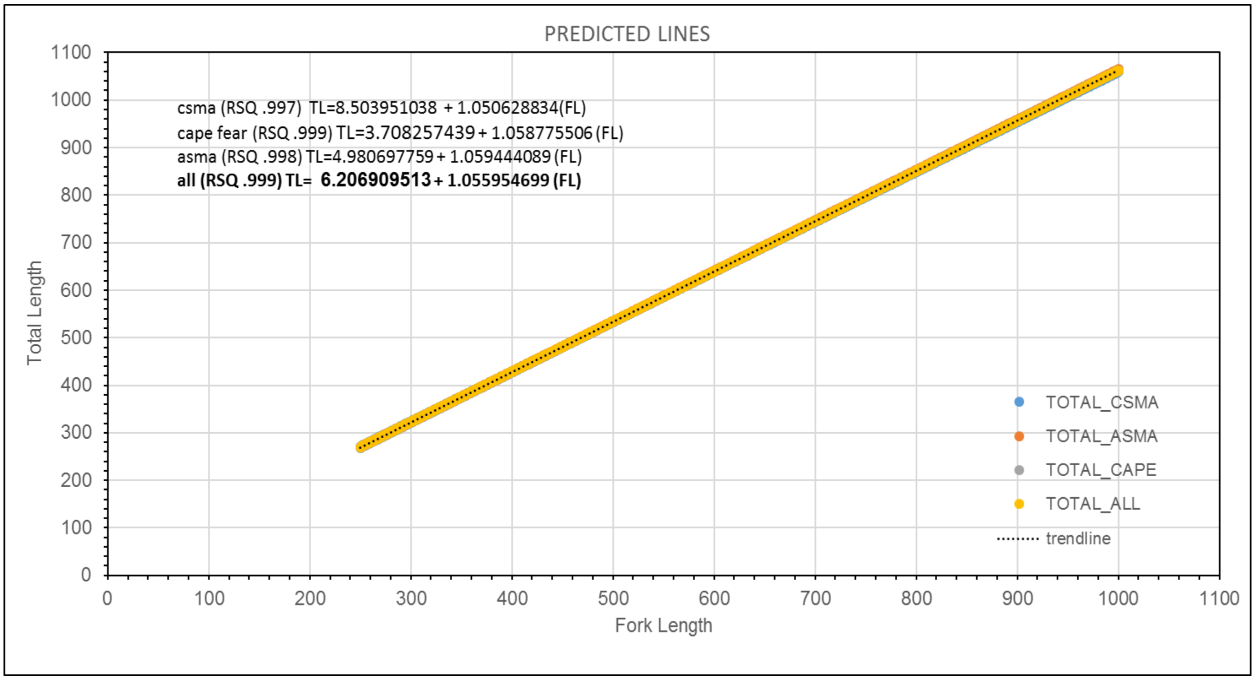


Figure 7. Regression analyses show strong relationships for CSMA, Cape Fear, ASMA, and all areas combined. The high RSQ value indicates a strong fit.

13 APPENDIX B

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ARTICLE

Exploring Causal Factors of Spawning Stock Mortality in a Riverine Striped Bass Population

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Abstract
The recovery of the Atlantic Striped Bass *Morone saxatilis* stock in the 1990s is an important example of effective natural resources management. Implementation of Atlantic States Marine Fisheries Commission (ASMFC) harvest regulations reduced mortality, protected older and more fecund females, and contributed to the formation of dominant year-classes in the 1980s and 1990s. However, Striped Bass stocks south of Albemarle Sound, North Carolina, are not subject to ASMFC management plans, and many populations have failed to attain recovery goals. Catch-curve analyses indicate that the Neuse River Striped Bass population continues to experience spawning stock exploitation rates similar to those implicated in the decline of the Atlantic Migratory and Albemarle Sound/Roanoke River stocks in the 1970s. From 1994 to 2015, Striped Bass instantaneous fishing mortality (F) in the Neuse River ranged from 0.12 to 0.84 and exceeded the overfishing threshold ($F_{Threshold} = 0.41$) in 12 of 22 years. A global linear model using environmental and exploitation factors accounted for 55% of the variability in spawning stock discrete annual mortality. An information-theoretic approach was used to elucidate the best linear model for predicting discrete annual mortality. The best model included previous-year gill-net effort and same-year commercial harvest (Akaike weight = 0.64, $R^2 = 0.50$). Model-averaged coefficients for gill-net effort and commercial harvest suggested total exploitation impacts that were congruent with other studies of Neuse River Striped Bass. Results indicate that reducing exploitation to target levels will require substantial reductions in gill-net effort in areas of the Neuse River where Striped Bass occur. Reducing exploitation may increase spawning stock biomass and advance the age structure of spawning females, conferring an increased likelihood of successful recruitment and production of dominant year-classes during periods of favorable environmental conditions.

Striped Bass *Morone saxatilis* populations sustained severe declines in abundance throughout the U.S. Atlantic coast in the 1970s after several years of record commercial harvest combined with poor recruitment (Boreman and Austin 1985; Richards and Deuel 1987). In North Carolina, Striped Bass commercial landings declined by 80% between 1973 and 1983 (Boreman and Austin 1985). Recovery efforts began with the development of the Atlantic States Marine Fisheries Commission's (ASMFC) Interstate Fisheries Management Plan for Striped Bass (IFMP) in 1981 (Richards and Rago 1999). A centerpiece of the IFMP and its amendments was the use of harvest restrictions to curtail overexploitation. The harvest provisions of the IFMP were implemented in North Carolina beginning in 1984, along with an expansion of Striped Bass stocking programs and continued development of optimized streamflow releases from Roanoke Rapids Dam to improve spawning conditions in the Roanoke River, North Carolina (Figure 1; NCDENR 2004, 2013). Albemarle Sound/Roanoke River

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Striped Bass were declared recovered in 1997 (NCDENR 2004).

In North Carolina, Striped Bass populations south of Albemarle Sound (Figure 1) are not subject to compliance with ASMFC management plans due to their minimal contribution to the Atlantic Migratory stock (Merriman 1941; Greene et al. 2009). These populations are collectively managed as the Central Southern Management Area (CSMA) stock under a collaborative agreement by the North Carolina Division of Marine Fisheries (NCDMF; coastal waters) and the North Carolina Wildlife Resources Commission (NCWRC; inland waters). Of the populations comprising the CSMA, Neuse River Striped Bass were among the first to receive targeted monitoring and management actions (Hammers et al. 1995).

Although Striped Bass are documented as historically utilizing all major coastal North Carolina rivers (Smith 1907), the Neuse River population was among the most studied by early ichthyologists. In the 19th century, the population was subject to the second-largest Striped Bass fishery in North Carolina after the fisheries operating on the Albemarle Sound/Roanoke River stock. Yarrow (1877) described Striped Bass in the Neuse River as "exceedingly plenty" and reported that 3,000 were sold to New Bern (Figure 1) fish houses from January to April 1873 (Yarrow 1874). By 1880, almost 16,000 Striped Bass were harvested and shipped from New Bern to northern cities, with an additional unknown quantity consumed locally during the fishing season (McDonald 1884). Despite their former abundance, declines were evident before the end of the 19th century, leading McDonald (1884) to note that "…the supply has materially decreased…owing to overfishing and the erection of obstructions." By 1939, only 318 kg of Striped Bass were commercially harvested in Craven County (Figure 1; Chestnut and Davis 1975).

Although fishing records during World War II are sparse, acquisition of fishing vessels and labor for the war effort likely reduced Striped Bass harvest and allowed for stock rebuilding. Fishing restrictions and labor shortages were eased toward the end of the war, leading to the harvest of 18,000 kg of Striped Bass in Craven County during 1945 (Anderson and Power 1949). However, construction of Quaker Neck Dam in 1952 prohibited access to essentially all spawning habitat (Burdick and Hightower 2006). By the mid-1960s, recreational and commercial anglers reported population declines, and a subsequent 3-year NCWRC survey collected only 12 adult fish (Miller 1975). Despite minimal harvest restrictions, commercial landings remained low throughout the latter half of the 20th century and did not exceed 4,500 kg again until 2010 (NCDMF, unpublished data). It is possible that the intensity of post-war fishing in the lower Neuse River

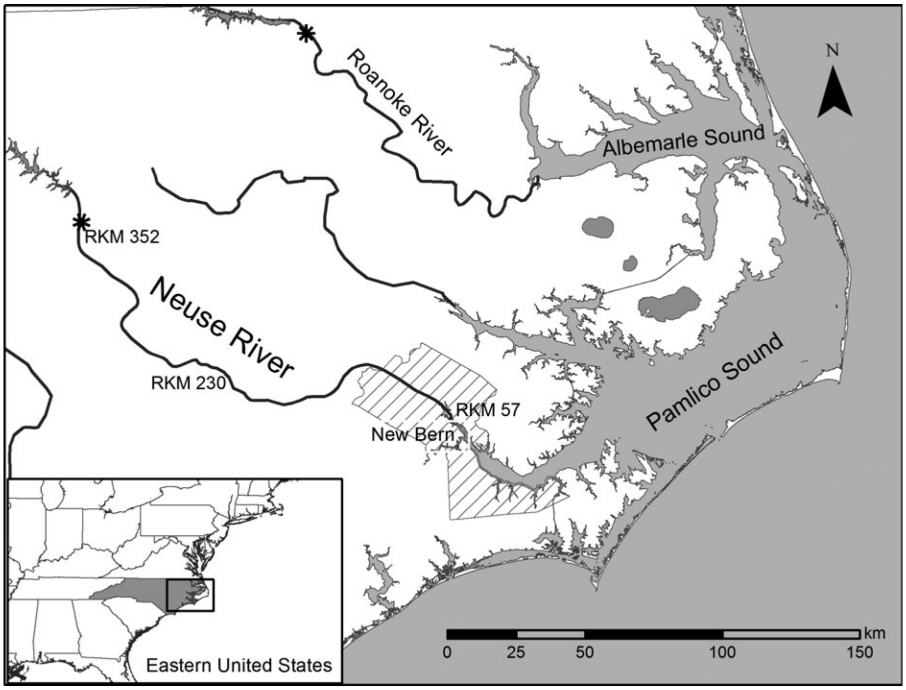

FIGURE 1. Coastal North Carolina, showing the Neuse River in relation to Pamlico Sound; RKM denotes river kilometers from the confluence of the Neuse River and Pamlico Sound. The first impediments to upstream migration (Milburnie Dam on the Neuse River; Roanoke Rapids Dam on the Roanoke River) are indicated by black asterisks. Gray diagonal lines denote Craven County.

combined with an inability to access suitable spawning habitat led to the near extirpation of the population.

Active management efforts in the Neuse River began with the implementation of an annual stocking regime in 1992 (although intermittent stocking began as early as 1931). In 1994, annual spawning ground surveys commenced, and a 11,340-kg commercial harvest quota was established for the entire CSMA stock (NCDENR 2004). The removal of Quaker Neck Dam in 1998 allowed unobstructed access to approximately 120 km of historical spawning habitat (Burdick and Hightower 2006). Finally, gill-net use was prohibited in NCWRC-managed inland waters in 2001 (NCDENR 2013).

Recovery efforts were first formalized in 2004 as part of the North Carolina Estuarine Striped Bass Management Plan (NCDENR 2004) that was jointly developed by NCDMF and NCWRC. Unweighted linearized catch-curve analyses of age structures collected on the Neuse River spawning grounds indicated that overfishing was occurring (NCDENR 2004), leading to the implementation of gill-net restrictions in 2008 (established minimum distance from shore and use of tie-downs during the closed harvest season; NCDENR 2013). A stock assessment conducted in 2010 using unweighted linearized catch curves again documented high mortality, but the assessment was deemed unsuitable for management use due to large confidence intervals around the mortality estimate. However, the need for continued conservation management measures was supported by truncated size and age distributions, low CPUE, and an absence of older fish in spawning ground samples. Albemarle Sound/Roanoke River spawning potential ratios of 45% and 40% were used to develop biological reference points for the Neuse River, resulting in an instantaneous fishing mortality rate (F) target (F_{Target}) of 0.33 and an overfishing threshold ($F_{Threshold}$) of 0.41 (NCDENR 2013, 2014).

Electrofishing assessments on the spawning grounds indicate that size and age distributions have not expanded since the 2010 stock assessment (Rachels and Ricks 2015). Additionally, recent results utilizing parentage-based tagging (PBT) indicate that hatchery fish (Table 1) comprise at least two-thirds of the spawning stock (O'Donnell et al. 2016) and may approach 100% stocking contribution (Rachels and Ricks 2015; O'Donnell et al. 2016). The development of recommendations for catch-curve best practices (Smith et al. 2012) render former Neuse River Striped Bass stock assessments obsolete and present an opportunity to re-evaluate spawning ground age-structure data. Our objectives were two-fold: (1) to improve the precision of catch-curve mortality estimates by using current methodology and an expanded time series; and (2) to use linear modeling in an information-theoretic approach (Burnham and Anderson 2002) to elucidate factors responsible for driving the observed mortality rates.

METHODS

Study area.— The Neuse River flows approximately 400 km from its origin at the confluence of the Eno and Flat rivers before discharging into Pamlico Sound, North Carolina (Figure 1). The lower 60 km constitute a wind-mixed mesohaline estuary, although salinity can range from 0‰ to 27‰ depending on precipitation and streamflow (Burkholder et al. 2006). The Neuse River estuary has been classified as "Nutrient Sensitive Waters" since 1988 (NCDENR 2006) and experienced numerous algae blooms and fish kills during the 1990s resulting from nitrogen and phosphorus inputs (Burkholder et al. 1995, 2006; Rothenberger et al. 2009).

Mortality estimation.— From 1994 to 2015, boat-mounted electrofishing (Smith-Root 7.5 GPP; 120 Hz; 5,000–7,000 W) was used to collect Striped Bass from the spawning grounds during annual spawning migrations (March–May). Collections primarily occurred between river kilometer (RKM) 230 of the Neuse River (measuring from its confluence with Pamlico Sound) and RKM 352. Few Striped Bass were collected above Quaker Neck Dam (RKM 230; Figure 1) before its removal in 1998.

Striped Bass were measured for TL (mm) and weighed (g), and sex was determined by applying pressure to the abdomen and observing the vent for discharge of milt or eggs. Scales for age estimation were removed from the left side of each fish between the dorsal fin and lateral line. From 1994 to 2014, 15 fish of each sex per 25-mm size-class were aged by either directly reading scales (1994–2010) or reading scale impressions on acetate slides (2011–2014). Since sampling occurred during the time of year when annuli are formed, scale age was based on (1) the actual number of annuli if an annulus was present on the scale margin; or (2) the number of annuli plus 1 if there was a considerable gap between the last annulus and the scale margin (NCWRC and NCDMF 2011). A 20% subsample of each size-class was aged by a second reader. Discrepancies between primary and secondary readers' estimates were resolved by jointly reading and reaching consensus (NCWRC and NCDMF 2011). In 2015, a partial pelvic fin clip from each fish was preserved in a 95% solution of ethyl alcohol to determine hatchery or wild origin using PBT. Hatchery-origin fish were aged using PBT, while fish of unknown origin were assigned ages with sex-specific age–length keys developed using scale-aged fish from 2010 to 2014.

The Chapman–Robson estimator was used to estimate instantaneous total mortality (Z) for each year in the time series via the recommendations of Smith et al. (2012). As with other catch-curve methods, assumptions included the following: (1) the proportion of ages in the population is estimated without error, (2) recruitment varies without trend for all age-classes, (3) mortality is stationary through time and across age-classes, and (4) all age-classes are equally vulnerable to the sampling gear (Robson and Chapman 1961; Smith et al. 2012). Of the various catch-curve methods, the Chapman–Robson estimator is the most

TABLE 1. Number of hatchery-origin Striped Bass stocked into the Neuse River, North Carolina, and exploitation and environmental factors.

Year	Number stocked	Commercial effort (trips)	Commercial harvest (kg)	Summer dissolved oxygen (mg/L)	Summer water temperature (°C)
1994	182,990	2,531	3,760	7.1	27.5
1995	99,176	2,601	1,792	6.7	26.9
1996	200,760	3,018	3,159	6.5	28.0
1997	100,000	3,084	2,424	8.6	27.8
1998	290,925	3,209	2,511	6.3	27.9
1999	100,000	2,527	2,764	9.0	28.9
2000	229,993	3,030	2,181	6.6	27.3
2001	103,000	2,619	3,149	6.8	27.7
2002	147,654	3,317	1,869	9.5	29.1
2003	100,000	3,196	2,621	6.4	28.1
2004	268,011	2,159	3,547	7.3	28.5
2005	114,000	2,305	2,346	9.1	29.9
2006	245,935	2,777	3,216	7.7	28.1
2007	242,835	2,893	3,053	8.8	28.8
2008	313,798	1,980	2,190	9.7	29.6
2009	204,289	2,464	3,758	7.9	28.2
2010	107,142	1,583	5,092	8.0	30.1
2011	102,089	1,485	7,081	7.8	29.1
2012	140,358	1,577	1,946	6.2	27.8
2013	295,161	2,206	5,328	5.9	27.0
2014	158,730	1,603	2,801	6.7	28.2
2015	109,144	1,091	3,793	6.1	27.8

robust to violations of these assumptions (Murphy 1997; Smith et al. 2012). In accordance with Smith et al. (2012), age at full recruitment to the catch curve was the age of peak catch plus 1 year (peak-plus criterion). In addition, an overdispersion parameter c (Burnham and Anderson 2002; Smith et al. 2012) was calculated for each year to correct the SE of the mortality estimate and to assess structural fit of the Chapman–Robson estimator to the age-structure data ($c > 4$ indicates poor model fit; Burnham and Anderson 2002). Instantaneous fishing mortality was calculated for each year by subtracting instantaneous natural mortality ($M = 0.24$; Bradley 2016) from Z. Uncertainty in the mortality estimates was characterized by calculating the relative standard error (RSE; Z/SE) and bootstrapping from the distributions of Z and M (Gamma distributed; Bolker 2008) to estimate 90% confidence intervals for F.

Mortality modeling.— Linear models were developed to evaluate environmental and exploitation factors that potentially influence discrete annual mortality ($A = 1 - e^{-Z}$) over the time series 1994–2015, including summer dissolved oxygen, summer water temperature, gill-net effort, and commercial harvest. We hypothesized that low dissolved oxygen and warm summer temperatures may lead to increased natural mortality. Hypoxic conditions can be prevalent in the Neuse River estuary during the summer months as a result of nutrient loading and water column stratification (Luettich et al. 2000; NCDENR 2001). These hypoxic conditions have been implicated in many of the 236 fish kills occurring between 1996 and 2015, which primarily affected Atlantic Menhaden *Brevoortia tyrannus* in the Neuse River basin (NCDENR 2001; NCDEQ 2015). Hypoxic events and resulting fish kills have also been implied as negatively affecting Striped Bass (NCDENR 2013). Water quality data were obtained from the Neuse River Estuary Modeling and Monitoring Project (ModMon; UNC 2016), which is one of the few programs that has continuously monitored water quality in the lower Neuse River since 1994. The summer (June–August) mean surface dissolved oxygen (mg/L) and summer mean surface water temperature (°C) at ModMon station 30 (RKM 57; Figure 1) were used as environmental factors. Results of an acoustic telemetry study (Bradley et al. 2018) determined that the highest densities of adult and juvenile Striped Bass occur in the vicinity of the selected ModMon station.

In addition to the suite of environmental factors, several long-term data sets were available from NCDMF to allow investigation of the effects of exploitation. Beginning in 1994, a mandatory trip ticket program was implemented to monitor commercial landings at the first point of sale. Information collected by this program includes harvest (kg) landed by species, gear type, and location (NCDENR 2013). Neuse River Striped Bass commercial harvest was used as a direct exploitation factor (NCDMF, unpublished data). However, gill-net fisheries continue to pursue other marketable species after the Striped Bass harvest season is closed. Therefore, the annual number of gill-net trips in the Neuse River was used as a measure of gill-net effort that potentially accounts for harvest, discard, and unreported or misreported mortality (NCDMF, unpublished data). Unfortunately, measures of recreational fishing effort for Striped Bass were not available for the entire time series. A recreational creel survey has been conducted annually in the lower Neuse River since 2004, yet there is limited information for prior years (for exceptions, see Borawa 1983 and Rundle et al. 2004). Several recreational fishing surveys administered by National Oceanic and Atmospheric Administration Fisheries, including the Marine Recreational Information Program, the Marine Recreational Fisheries Statistics Survey, and the Coastal Household Telephone Survey, were investigated for potential use as a surrogate recreational fishing effort metric. However, these surveys lacked the data resolution necessary to specifically assess Neuse River recreational fisheries.

Since age-structure collections occurred in the spring (March–May), it was likely that factors occurring throughout the previous year (gill-net effort) or during the previous summer (dissolved oxygen and surface water temperature) had a greater influence on the estimated mortality rate than same-year measures. Therefore, these predictor variables were modeled using a 1-year time lag. Commercial harvest was not modeled with a time lag since the commercial Striped Bass harvest season occurs in the early spring before electrofishing collections on the spawning grounds; any effects of commercial harvest should be detected using same-year measures. Striped Bass discrete annual mortality was nonstationary; the global model was of the form

$$A'_t = \beta_0 + \sum(\theta_i x'_{i,t-1}) + \theta_C X'_{C,t} + \varepsilon_t,$$

where A = discrete annual mortality; β_0 = intercept; X = variable i; θ_i = effect of variable X_i; t = year; C = commercial harvest; and ε = an independently and identically distributed white noise vector. Note that A'_t and $X'_{i,t}$ were first-differenced to ensure stationarity and remove serial correlation as given by

$$A'_t = A_t - A_{t-1}, \text{and } X'_{i,t} = X_{i,t} - X_{i,t-1}.$$

In the case of four predictor variables, there are 15 main-effects models and 26 total models if we consider first-order interactions. Given our small sample size (22 observations) and the potential for "too many models" (Anderson and Burnham 2002; Burnham et al. 2011; Dochtermann and Jenkins 2011), we did not consider all-subsets regression. Instead, we constrained our analyses to 12 main-effects models (example R code provided in the Supplement available separately online) incorporating dissolved oxygen, surface water temperature, gill-net effort, and commercial harvest using the information-theoretic framework described by Burnham and Anderson (2002). The second-order Akaike's information criterion (AIC_c) was computed for each model, and the difference in AIC_c value (Δ_i) from the model with the smallest AIC_c was used to assess the relative strength of the models. After ensuring that A' and X' differencing removed time trends ($\beta_0 = 0$; $\alpha = 0.05$), the intercept was removed from final models, and AIC_c and Δ_i were recalculated. The reduced parameterization improved AIC_c for all models. Akaike weights (ω_i) were calculated to evaluate the relative likelihood of each model (Burnham and Anderson 2002). The relative importance of each predictor variable was assessed by decomposing global model variance using the Lindeman–Merenda–Gold (LMG) method (Grömping 2007). Model-averaged estimates of the effect of each predictor variable were calculated by multiplying the coefficients of each factor in the models in which they appeared by the ω_i of that model (Burnham and Anderson 2002). The model-averaged effect for gill-net effort and commercial harvest was multiplied by the 1994–2015 mean number of gill-net trips and mean harvest, respectively, to estimate each factor's long-term average effect on discrete annual mortality ($\Delta A \equiv u$; discrete annual fishing mortality). Linear models were fitted using ordinary least-squares (OLS) regression with package "dynlm" in R version 3.2.5.

Model assumptions.— Assumptions for OLS time series regression depart in some respects from those considered in classical linear modeling. Assumptions of time series regression include a mean of zero, constant variance, and constant covariance structure through time (stationarity; Hyndman and Athanasopoulos 2014). The augmented Dickey–Fuller (ADF) test ($\alpha = 0.05$; Hyndman and Athanasopoulos 2014) assumes H_0 = nonstationary and was employed in the R package "stats" to assess stationarity in the mortality time series. The partial autocorrelation function (PACF; Derryberry 2014) in the "stats" package was utilized to examine the potential for autocorrelation in the spawning stock discrete annual mortality time series. Multicollinearity among the predictor variables was assessed by calculating variance inflation factors (VIFs; Fox and Weisberg 2011) in the R package "car." Variance inflation factors are generally considered to indicate the presence of multicollinearity if any VIF exceeds 10 (see O'Brien 2007).

RESULTS

Mortality Estimation

The number of Striped Bass collected on the spawning grounds varied throughout the time series, ranging from

TABLE 2. Chapman–Robson mortality estimator metrics and mortality rates (Z = instantaneous total mortality rate; A = discrete annual mortality; F = instantaneous fishing mortality rate; u = discrete annual exploitation rate) for Neuse River Striped Bass, 1994–2015 (N = total catch; N_c = number in catch curve; T_c = age at recruitment to catch curve [peak-plus]; c = overdispersion parameter; LCL = lower 90% confidence limit; UCL = upper 90% confidence limit; RSE = relative standard error).

	Year of sample																					
Metric	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
N	120	221	226	143	219	292	357	155	102	403	90	125	58	172	141	373	141	176	144	341	311	239
N_c	36	107	71	81	148	151	111	69	67	98	48	97	21	96	24	231	71	55	67	106	129	95
T_c	7	5	6	5	4	5	5	5	4	6	6	4	4	4	6	4	4	5	4	5	5	5
c	0.57	1.60	1.10	2.23	1.64	1.97	4.17	3.90	5.53	2.20	0.12	1.81	1.57	2.52	3.19	4.96	0.13	2.41	0.85	0.42	1.51	0.90
Z	1.08	0.73	0.85	0.61	0.45	0.75	0.45	0.52	0.36	0.65	0.78	0.44	0.53	0.63	0.98	0.84	0.94	0.84	0.62	0.74	0.86	0.94
SE_c	0.19	0.09	0.11	0.10	0.05	0.09	0.09	0.13	0.10	0.10	0.12	0.06	0.15	0.10	0.37	0.13	0.12	0.18	0.08	0.07	0.10	0.10
Z LCL	0.77	0.58	0.67	0.44	0.37	0.61	0.31	0.32	0.19	0.49	0.59	0.34	0.29	0.46	0.37	0.63	0.75	0.54	0.49	0.62	0.70	0.78
Z UCL	1.39	0.88	1.03	0.77	0.53	0.90	0.60	0.73	0.53	0.82	0.97	0.54	0.77	0.80	1.59	1.05	1.13	1.14	0.75	0.87	1.02	1.11
RSE (%)	17	12	13	17	11	12	20	24	29	15	15	14	28	16	38	15	12	22	12	10	11	11
A	0.66	0.52	0.57	0.45	0.36	0.53	0.36	0.41	0.30	0.48	0.54	0.36	0.41	0.47	0.62	0.57	0.61	0.57	0.46	0.53	0.58	0.61
A LCL	0.54	0.44	0.49	0.35	0.31	0.45	0.26	0.27	0.17	0.39	0.44	0.29	0.25	0.37	0.31	0.47	0.53	0.42	0.39	0.46	0.50	0.54
A UCL	0.75	0.58	0.64	0.54	0.41	0.59	0.45	0.52	0.41	0.56	0.62	0.42	0.53	0.55	0.80	0.65	0.68	0.68	0.53	0.58	0.64	0.67
F	0.84	0.48	0.61	0.36	0.21	0.51	0.21	0.28	0.11	0.41	0.53	0.20	0.28	0.38	0.73	0.59	0.69	0.59	0.37	0.50	0.61	0.70
F LCL	0.49	0.23	0.34	0.10	−0.02	0.25	−0.04	−0.01	−0.15	0.15	0.26	−0.03	0.02	0.11	0.17	0.31	0.43	0.25	0.12	0.26	0.36	0.44
F UCL	1.20	0.71	0.86	0.60	0.38	0.73	0.43	0.55	0.36	0.64	0.79	0.39	0.59	0.61	1.44	0.86	0.95	0.96	0.58	0.70	0.84	0.93
u	0.51	0.34	0.41	0.27	0.17	0.36	0.17	0.22	0.10	0.30	0.37	0.16	0.22	0.28	0.47	0.40	0.45	0.40	0.28	0.35	0.41	0.45

58 fish in 2006 to 403 fish in 2003 (Table 2). Scale ages were reasonably precise, as scale readers had a high rate of agreement within 1 year of age (87–100%; NCWRC, unpublished data). Recruitment to the catch curve typically occurred at age 4 or age 5. Although the oldest Striped Bass encountered on the spawning grounds was an age-13 female collected in 2005, only 73 (1.6%) of the 4,549 fish collected during the time series were age 9 or older.

The Chapman–Robson mortality estimator generally performed well, as c was greater than 4 in only 3 of 22 years (Table 2). Mortality estimates were reasonably precise (RSE < 30%) and only exhibited a high degree of uncertainty in 2008. Instantaneous total mortality Z varied considerably throughout the time series, ranging from 0.36 to 1.08. Mortality was generally lowest during 1997–2007 and highest during 2008–2011. Values of F ranged from 0.12 to 0.84 (Table 2; Figure 2), assuming that the M given by Bradley (2016) remained constant throughout the time series. Fishing mortality was greater than $F_{Threshold}$ in 12 of the 22 years.

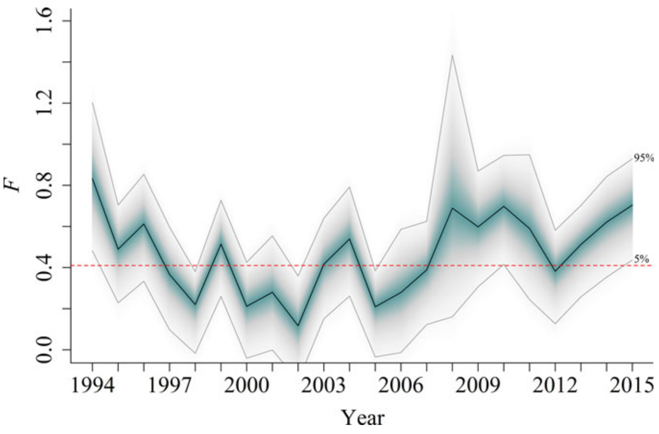

FIGURE 2. Striped Bass spawning stock fishing mortality (F) in the Neuse River, North Carolina, during 1994–2015. The 90% confidence interval is denoted by gray lines, while the interquartile range is within a green color gradient. The dashed red line represents the overfishing threshold ($F_{Threshold}$ = 0.41).

Mortality Modeling

Model assumptions.— The ADF test indicated that spawning stock discrete annual mortality was nonstationary (P = 0.181). Therefore, all modeled variables were first-differenced (Hyndman and Athanasopoulos 2014). The PACF indicated a correlation of 0.34 between A_t and A_{t-1}, suggesting weak autocorrelation. We did not consider this level of autocorrelation sufficient to warrant modeling as a first-order autoregressive process given the small sample size and the potential for model overspecification. The VIFs ranged from 1.1 to 2.5, indicating a low likelihood of multicollinearity among predictor variables.

Model results.— The best linear model supported by the data contained gill-net effort and commercial harvest as predictors of discrete annual mortality (Table 3). The global model containing all predictor variables accounted for 55% of the variability in spawning stock mortality, while the best model accounted for 50%. Every model receiving at least modest support as the best model ($\Delta_i < 7$) incorporated gill-net effort as a predictor variable.

Gill-net effort was the most important predictor of spawning stock mortality relative to the four predictor variables examined (Table 4; Figure 3). Commercial harvest was the second most important predictor of spawning stock mortality, while summer dissolved oxygen and

TABLE 3. Linear models exploring the effect of environmental and exploitation factors on Striped Bass spawning stock discrete annual mortality, 1994–2015 (EFFORT = gill-net effort; DO = dissolved oxygen; HARV = commercial harvest; TEMP = surface water temperature). The number of estimated model parameters (K) includes the predicting factors and an error term; final model runs did not include an intercept parameter. Akaike's information criterion (AIC$_c$), Akaike difference (Δ_i), Akaike weight (ω_i), and R^2 are presented.

Model	K	AIC$_c$	Δ_i	ω_i	R^2
EFFORT, HARV	3	−39.95	0.00	0.64	0.50
EFFORT	2	−36.98	2.97	0.15	0.34
EFFORT, HARV, DO, TEMP	5	−34.88	5.07	0.05	0.55
EFFORT, DO	3	−34.81	5.14	0.05	0.36
EFFORT, TEMP	3	−34.60	5.36	0.04	0.35
EFFORT, DO, TEMP	4	−34.40	5.56	0.04	0.44
HARV	2	−31.68	8.27	0.01	0.14
DO	2	−30.67	9.29	0.01	0.09
HARV, DO	3	−30.38	9.57	0.01	0.20
HARV, TEMP	3	−29.83	10.12	0.00	0.10
DO, TEMP	3	−27.98	11.97	0.00	0.10
HARV, DO, TEMP	4	−27.23	12.72	0.00	0.20

surface water temperature did not substantially influence spawning stock mortality (Tables 3, 4). Multiplying the model-averaged gill-net coefficient by the mean number of gill-net trips for 1994–2015 (2,421 trips) suggests the gill-net fishery mean discrete annual exploitation rate (*u*) was 0.29. Using the same procedure for commercial harvest (3,199 kg) suggests commercial harvest *u* is 0.08.

DISCUSSION

Catch-curve methodologies recommended by Smith et al. (2012) considerably reduced uncertainty in the *Z*-estimates compared to previous Neuse River stock assessments. The SEs of *Z* in our study ranged from 0.05 to 0.37, compared to 0.06–0.61 in the most recent stock assessment (Table 11 in NCDENR 2013). Similarly, RSE exceeded 30% in only 1 of the 22 years in our study, compared to 13 of the 16 years in the previous stock assessment (NCDENR 2013).

The catch-curve analysis indicates that the Neuse River Striped Bass spawning stock has been subjected to overfishing throughout much of the last two decades. The 22-year mean *F* in this study ($F = 0.46$) is similar to the 18-year mean rate ($F = 0.47$) that preceded the depletion of Albemarle Sound/Roanoke River Striped Bass in the 1970s (Hassler et al. 1981; NCDENR 2013). These high *F*-values also approach the level of exploitation that was deemed a major factor in the Atlantic Striped Bass stock

TABLE 4. Relative importance of predictor variables affecting Striped Bass spawning stock mortality (Lindeman–Merenda–Gold [LMG] method).

Predictor variable	Model-averaged coefficient θ	Model-averaged coefficient SE	Relative importance (LMG)
Gill-net effort	1.21×10^{-4}	3.54×10^{-5}	0.62
Commercial harvest	2.37×10^{-5}	1.00×10^{-5}	0.23
Dissolved oxygen	-1.73×10^{-2}	1.63×10^{-2}	0.10
Surface water temperature	2.50×10^{-2}	2.71×10^{-2}	0.05

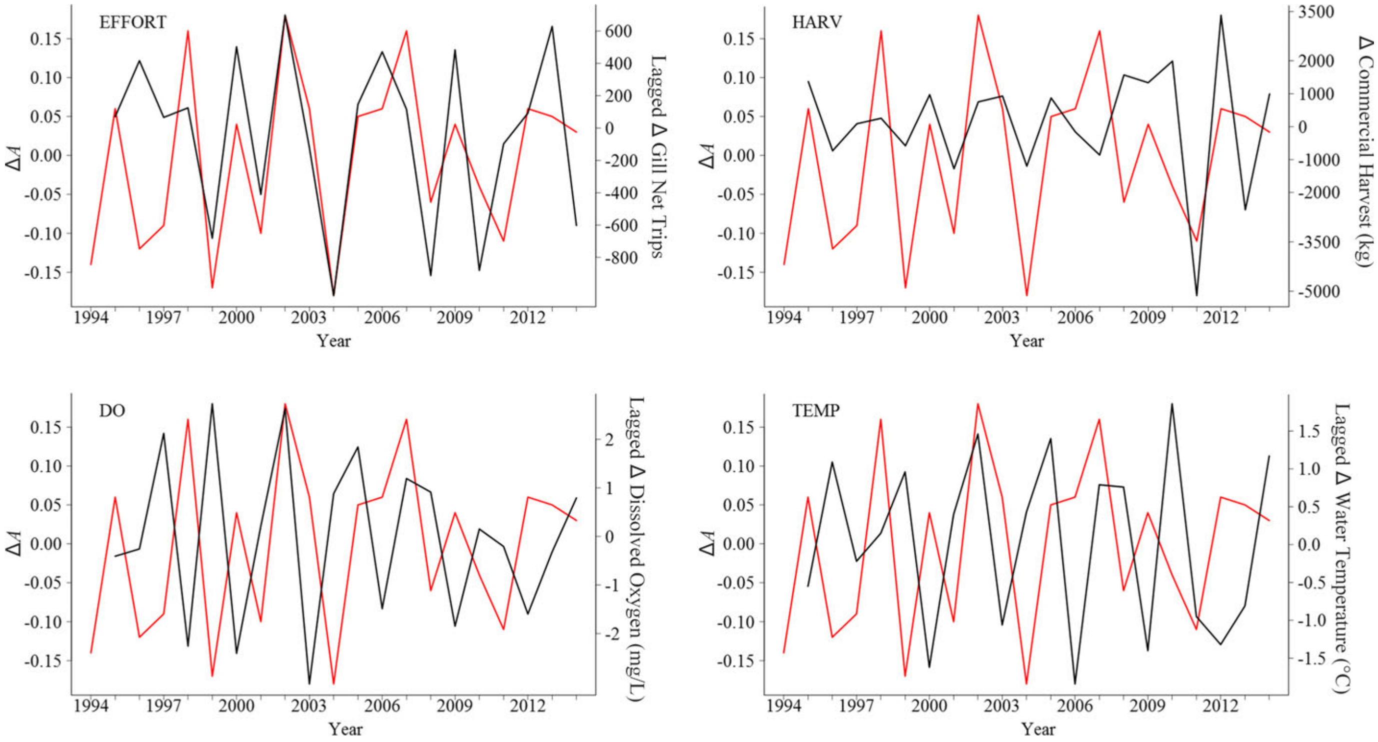

FIGURE 3. Differenced (Δ) Striped Bass spawning stock discrete annual mortality (*A*; red) and differenced exploitation and environmental predictor variables (black) in the Neuse River, North Carolina (EFFORT = gill-net effort; DO = summer mean surface dissolved oxygen; HARV = commercial harvest; TEMP = summer mean surface water temperature). Gill-net effort, DO, and TEMP were modeled with 1-year time lags.

collapse (ASMFC 1989; Richards and Rago 1999). Mortality has not trended toward F_{Target} despite the development of two comprehensive management plans and increasingly restrictive recreational and commercial harvest regulations (see Appendix 14.5 in NCDENR 2013).

Linear modeling indicates that gill-net effort is the most important factor influencing spawning stock mortality among the exploitation and environmental factors examined. Gill-net effort accounted for substantially greater variability in spawning stock mortality than commercial harvest, and the model-averaged coefficient identified a discrete annual exploitation rate of 0.29 for gill net effort. This suggests that the commercial multispecies gill-net fishery imparts substantial mortality even when the Striped Bass harvest season is closed. The reason for this mortality is obscure, but it may be attributable to dead discard mortality; over-quota and high-grading mortality; avoidance, predation, and drop-out mortality; or unreported, misreported, and illegal harvest (ICES 1995; Gilman et al. 2013; Batsleer et al. 2015; Uhlmann and Broadhurst 2015). In particular, discard mortality should be carefully considered, as Clark and Kahn (2009) found that Striped Bass are acutely susceptible to discard mortality in multispecies gill-net fisheries. Furthermore, Striped Bass discards in the large-mesh gill-net fishery were identified as the primary source of mortality within the CSMA (NCDENR 2013). The effect of gill-net effort on discrete annual mortality as estimated by linear modeling was within 3% of the estimated effect of cryptic mortality in a cohort-based model ($u = 0.26$; Table B.3 in Rachels and Ricks 2015), while the effect of commercial harvest was identical to the estimated discrete annual fishing mortality rate from commercial harvest in that study.

Contrary to exploitation factors, the environmental factors examined did not account for much variability in spawning stock mortality. Bradley et al. (2018) also failed to detect a relationship between dissolved oxygen, water temperature, and Striped Bass mortality between summer 2014 and summer 2015. Although numerous Atlantic Menhaden fish kills have occurred due to hypoxic conditions throughout the time period encompassing our research, it appears that these events have relatively little impact on Striped Bass spawning stock mortality. Campbell and Rice (2014) observed that estuarine fish can rapidly detect and avoid hypoxic areas in the Neuse River. However, they also found that habitat compression due to hypoxic conditions likely reduced growth rates in juvenile Spot *Leiostomus xanthurus* and Atlantic Croaker *Micropogonias undulatus*. Neuse River Striped Bass exhibit the fastest growth rates among coastal North Carolina Striped Bass populations (Rachels and Ricks 2015). It is likely that negative impacts of hypoxic conditions or water temperatures exceeding Striped Bass thermal optima would manifest through reduced growth rates before mortality effects are observed. Nonetheless, the parameter coefficients for summer mean dissolved oxygen and summer mean surface water temperature indicate the potential for increased spawning stock mortality as dissolved oxygen decreases and water temperature increases. These effects were minimal—approximately 2% change in discrete annual mortality per unit change in temperature or dissolved oxygen—compared to the cumulative effects of gill-net effort and commercial harvest.

The inability to include recreational angling as an exploitation factor reduces the amount of variability in spawning stock mortality that can be accounted for in this study. The median annual recreational harvest during 2004–2015 was 2,337 kg and is similar to the median commercial harvest of 3,355 kg for the same time period (NCDMF, unpublished data). Thus, the actual commercial harvest and recreational harvest exploitation rates are similar, an observation supported by simulation studies (Rachels and Ricks 2015; Bradley 2016). It is likely that inclusion of factors that represent recreational harvest and discard would perform comparably to the results of the commercial harvest factor used in linear modeling. However, time-dynamic trends in the level of recreational fishing effort or harvest could influence its importance relative to commercial harvest in a regression analysis. In fact, recreational effort declined dramatically during 2005–2010, concurrent with increases in discrete annual mortality. The continued collection of recreational creel survey data is warranted to elucidate long-term effects of angling on Neuse River Striped Bass mortality.

Since the population is supported almost entirely by hatchery-origin fish, changes to stocking practices may affect recruitment and mortality estimation. Although the annual stocking goal is 100,000 phase-II (160–200 mm TL) Striped Bass, the actual stocking rate (Table 1) has varied (coefficient of variation = 46%) and has included phase-I fish (50 mm TL) in some years. Survival rates of phase-I and phase-II Striped Bass may be similar. Stocking practices in the nearby Cape Fear River are the same as those in the Neuse River, and phase-I and phase-II Striped Bass that were stocked at similar rates contributed almost equally to the Cape Fear River population (NCWRC, unpublished data). Additionally, the effect of variable recruitment on catch-curve mortality estimation has been extensively explored by others. Ricker (1975) determined that recruitment variation up to a factor of 5 did not prohibit catch-curve use so long as the variability was random. Similarly, Allen (1997) found that catch curves were useful for estimating mortality in populations that exhibited higher recruitment variation (55–84%) than the stocking variability observed in our study. Finally, although it does not yield insight into much of the entire time series of our data, our mortality estimates were very similar to those reported by Bradley et al. (2018) for 2014–2015. The methodologies used in these studies (telemetry versus age structure) have different underlying assumptions, increasing confidence that mortality during the overlapping time periods was considerable.

Periodic strategists such as Striped Bass are resilient to periods of extended recruitment failure through the storage effect (Warner and Chesson 1985; Winemiller and Rose 1992). Recovery is contingent upon building spawning stock biomass by advancing the female age structure to older, more fecund fish (Secor 2000). Although regulating fishing mortality is one of the principal tools available to fisheries managers, "historical precedence is often invoked as a reason to continue unwise fishery management practices" (Richards and Rago 1999). However, the effectiveness of coordinated multi-jurisdictional management efforts in significantly reducing exploitation has been demonstrated by the restoration of the Atlantic Striped Bass stock (Field 1997; Richards and Rago 1999).

Current high exploitation rates combined with low stock abundance and a high contribution of hatchery fish to the spawning stock (Rachels and Ricks 2015; Bradley et al. 2018) suggest that the expected recovery time of Neuse River Striped Bass continues to be "both uncertain and long" (Hilborn et al. 2014). Our research indicates that fisheries managers should reduce exploitation by focusing on reductions in gill-net effort in areas of the Neuse River that are utilized by Striped Bass. Reducing spawning stock exploitation may confer an increased likelihood of recruitment during periods of favorable environmental conditions, thereby leading to improvements in population abundance and increased numbers of wild fish in the spawning stock.

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SUPPORTING INFORMATION

Additional supplemental material may be found online in the Supporting Information section at the end of the article.