Stock Assessment of the North Carolina Blue Crab (*Callinectes sapidus*), 1995–2016

Prepared by

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EXECUTIVE SUMMARY

The North Carolina Fisheries Reform Act requires that fishery management plans be developed for all commercially and recreationally significant species or fisheries that comprise State marine or estuarine resources. The goal of these plans shall be to ensure the long-term viability of the State's commercially and recreationally significant species or fisheries. Stock assessments are the primary tools used by managers to assist in determining the status of stocks and developing appropriate management measures to ensure the long-term viability of stocks.

In December 1998, the North Carolina Division of Marine Fisheries (NCDMF) adopted a Fishery Management Plan for the blue crab resource. The 2004 amendment (Amendment 1) adopted a spawning stock trigger and associated measures to protect the blue crab spawning stock. Amendment 2 (2013) repealed the spawning stock trigger and associated measures and adopted the traffic light approach in conjunction with an adaptive management plan to manage the blue crab stock. The 2016 revision to Amendment 2 implemented additional management measures (no harvest of immature females, no harvest of dark sponge crabs from April 1 to April 30, no targeted crab dredging, and adding a third cull ring to crab pots) because a management threshold identified in Amendment 2 was reached. Amendment 3 to the Fishery Management Plan is currently in development and this stock assessment was performed in support of the amendment.

A comprehensive stock assessment approach, the sex-specific two-stage model, was applied to available data to assess the status of North Carolina's blue crab stock during 1995–2016. Data were available from commercial fishery monitoring programs and several fishery-independent surveys. The two-stage model was developed based on the catch-survey analysis designed for species lacking information on the age structure of the population. The model synthesized information from multiple sources, tracked population dynamics of male and female recruits and fully recruited animals, estimated critical demographic and fishery parameters such as natural and fishing mortality, and thus, provided a comprehensive assessment of blue crab status in North Carolina. The hierarchical Bayesian approach was used to estimate model parameters, which can incorporate uncertainty associated with the data and model assumptions.

The model estimated an overall declining trend in catch, relative abundance indices, population size of both male and female recruits and fully recruited crabs, with a rebound starting in 2007. Females had higher natural mortality estimates than males. The estimated fishing mortality remained high before 2007, and decreased by approximately 50% afterwards.

The stock status of North Carolina blue crab in the current assessment (2016) was determined based maximum sustainable yield (MSY). Based on the results of this assessment, the North Carolina blue crab resource in 2016 is overfished with a probability of 0.98, given the average spawner abundance in 2016 being estimated at 50 million (below the threshold estimate of 64 million). And, overfishing is occurring in 2016 with a probability of 0.52, given the average fishing mortality in 2016 being estimated at 1.48 (above the fishing mortality threshold estimate of 1.46).

A number of recommendations for research and monitoring are offered to identify how deficiencies in the understanding of blue crab stock dynamics can be addressed.

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1 INTRODUCTION

1.1 The Resource

Blue crabs (*Callinectes sapidus*) are present from Nova Scotia to the northern coast of Brazil (Hay 1905; Guillory et al. 2001), supporting commercial and recreational fisheries along the Atlantic and Gulf coasts of the United States. The blue crab resource supports North Carolina's most valuable commercial fishery. Blue crabs are also commonly harvested by recreational fishermen in North Carolina.

Before 1995, the North Carolina Division of Marine Fisheries (NCDMF) did not have a sampling program dedicated to blue crabs, although limited information (landings statistics, juvenile abundance) was collected through other programs. Realizing the increasing importance of the blue crab fishery to the coastal economy, crabbers petitioned the North Carolina General Assembly in 1994 to allocate funding specifically for a blue crab assessment project. The resulting program focused on the establishment of fishery-dependent and -independent databases state-wide. Section 5.5 of the Fishery Reform Act of 1997 specifically required that the North Carolina Marine Fisheries Commission adopt a Fishery Management Plan (FMP) for the blue crab fishery by January 1, 1999. The plan was adopted by the Marine Fisheries Commission on December 11, 1998 (NCDMF 1998). All of North Carolina's state Fishery Management Plans are reviewed and updated every five years. If the FMP includes a stock assessment, the assessment is reviewed and updated at the same time as the FMP. The Blue Crab FMP was first amended December 3, 2004 (NCDMF 2004), followed by a second amendment in November 2013 (NCDMF 2013) and a revision to Amendment 2 was adopted in May 2016 (NCDMF 2016). Amendment 3 to the Blue Crab FMP is currently in development.

The last benchmark assessment (a comprehensive assessment conducted every five years by re-evaluating data and modeling methods) for North Carolina blue crab stock was conducted for management purposes in 2011 using a Traffic Light approach, as part of the review and amendment of the Blue Crab FMP (NCDMF 2011). An overfishing definition and status relative to overfishing could not be determined because available data were considered insufficient for estimating reliable fishing mortality rates. Therefore, the previous assessment considered the status of the North Carolina blue crab stock relative to overfishing as unknown. The previous assessment recommended defining the overfished condition based on the blue crab production characteristic of the Traffic Light such that when the proportion of red for the production characteristic is greater than or equal to the third quartile (>=0.75) for three consecutive years, the blue crab stock is considered overfished. Based on this definition, the results of the previous assessment suggested the North Carolina blue crab stock was not overfished.

However, the NCDMF currently lists the stock as one of "concern" in its annual stock status report (NCDMF 2017). The blue crab stock was listed as one of concern due to reduced commercial landings of hard blue crabs during 2000 through 2002, 2005 through 2007, 2012 through 2014 and 2016 following record-high commercial landings observed during 1996 through 1999. Commercial blue crab landings in 2016 were the third lowest on record during the 10-year period of 2007 through 2016.

The current stock assessment was developed as part of Amendment 3 to the Blue Crab FMP.

1.2 Life History

1.2.1 Stock Definitions

The blue crab, *Callinectes sapidus*, inhabits estuarine and nearshore coastal habitats throughout the western Atlantic and Caribbean from Maine to northern Argentina (Hay 1905; Williams 1984; Steele and Bert 1994; Guillroy et al. 2001), as well as the Gulf of Mexico (Darden 2004; McMillen-Jackson et el. 1994). The blue crab is common to all North Carolina coastal waters, but the largest aggregations tend to live in the Albemarle and Pamlico sounds and the tributaries associated with these regions.

Although blue crab larvae mix when in the larval stages on the continental shelf, the interchange of larvae from North Carolina and other states is assumed to be negligible. The unit stock includes blue crabs occurring in all coastal fishing waters of North Carolina. Tagging data from NCDMF indicate that while blue crabs do exhibit seasonal migrations, they remain in North Carolina estuarine or coastal waters (NCDMF 2008).

While there is little genetic information on blue crabs in North Carolina waters, genetic studies in the Chesapeake Bay (Zohar et al 2008), Florida (Darden 2004)., and their range in the eastern United States (McMillen-Jackson et al. 1994) indicate that populations of blue crab geographically close together are more genetically similar than populations geographically far apart.

1.2.2 Movements & Migration

The first larval stage (zoea) occurs offshore for several weeks where it undergoes several developmental stages before metamorphosing into megalopae (Van Engel 1958; Epifanio 1995). Because of the lack of inlets in Albemarle Sound, megalopae are transported through the inlets (primarily into Pamlico Sound, North Carolina) via onshore wind events and nighttime incoming spring tides (Forward et al. 2004), which may be overshadowed by tropical storm forcing, depending on frequency and wind direction (Eggleston et al. 2010). Megalopae then settle in seagrass beds in the seaward portion of the sounds before exhibiting density-dependent secondary dispersal resulting in juveniles being widely distributed throughout the estuaries of North Carolina (Etherington and Eggleston 2000).

After growth and maturation, females migrate to spawn in the high-salinity waters near the inlets (Whitaker 2006). Mature female blue crabs are more commonly found in higher salinity waters (>10 ppt) and males prefer lower salinities (3 to 15 ppt). Other studies have also shown the migratory behavior of mature female blue crabs continues between clutches, and spawning females are continually moving seaward through the spawning season (Hench et al. 2004; Forward et al. 2005; Darnell et al. 2009). Males do not migrate regularly as adults and are found predominantly in the rivers and on the western side of the sounds.

A tagging study conducted in North Carolina during 2002 through 2005 demonstrated that most mature female blue crabs were recaptured shortly after release near the release site (NCDMF 2008). However, dispersal was greater and long-distance returns were more prevalent in 2003 from the north to the south. Additionally, releases in the upper and mid-estuaries of the Albemarle-Pamlico systems and Cape Fear River show a general pattern of summer to fall movement towards the lower estuary areas and coastal inlets. This results in a general characterization of mature female movement seaward throughout the growing season.

Mature female blue crabs tagged in the southern coastal area (i.e., south of the Pamlico region) have a southward pattern of movement (NCDMF 2008). A similar trend was noted in mature female crabs released in the Atlantic Ocean south of the Cape Fear River during February to April 2005 and 2006 and suggested the warming of the estuarine waters was a cue to female blue crab movement (Logothetis et al. 2007). A significant portion of mature females in the southern area overwinter in the ocean near the coastal inlets and move back into the estuaries the following spring to forage and potentially spawn multiple times (NCDMF 2008).

1.2.3 Age & Size

Fischler (1965) reported an average life span of three years for blue crabs in North Carolina and a maximum size of around 217 mm. Estimates of maximum age have ranged between five and eight years for blue crabs in the Chesapeake Bay (Rugolo et al. 1997). Age determination of crustaceans is difficult because, unlike finfish, they lack permanent hard structures because crabs shed their hard parts through molting.

Biochemical measures for ageing blue crabs have been attempted on those in the Chesapeake Bay (Ju et al. 1999; Ju et al. 2001; Puckett et al. 2008) and Florida (Crowley 2012). Cellular oxidation products termed “lipofuscins” (LF) are used, which accumulate as stable fluorescent by-products in specific tissues of the blue crab. The amount of LF held in the tissues increases with age (Puckett et al. 2008). The level of LF was found to be positively correlated with chronological age of crabs raised in both the laboratory and in artificial ponds (Ju et al. 1999). However, a study in Florida, using two known age cohorts, found that lipofuscin indices were negatively correlated to age (Crowley 2012). These results suggest that more research is needed before this method can be used to age blue crabs.

Another method that has been used to determine age in crustaceans uses growth bands found around the calcified region of the eyestalk or gastric mill in shrimp, crabs, and lobsters (Kilada et al. 2012). While this method has been successful to estimate age in longer-lived, cold water crustaceans like the American lobster (*Homarus americanus*), this method has not been tested in blue crabs.

1.2.4 Growth

Traditional growth models used for finfish are impractical to apply to crustaceans in general because the models assume growth is continuous (von Bertalanffy 1938; Schnute 1981). For blue crabs and other crustaceans, the shell grows in discrete stages via shedding of the exoskeleton (molt). However, the von Bertalanffy growth function returned similar results to crustacean-specific growth models that accounted for the unique growth characteristics of the blue crab (Eggleston et al. 2004; Johnson 2004). The similarity of the two growth models is likely due to the increasing time between molts that occurs as the crabs grow larger, mirroring the decreasing rate of growth with size evident in the von Bertalanffy growth function.

Carapace-width-to-length relationships have been estimated for blue crabs sampled from many estuaries throughout their range in the eastern United States. Murphy et al. (2007) used carapace width and body weight of blue crabs collected commercially from six locations in Florida. The carapace-width (mm)-to-weight (g) relationships for crabs collected in Florida (females: n = 2,254, males: n = 3,050) were:

Female: $W = 0.0000551 * CW^{1.8660}$; $r^2 = 0.620$

Male: $W = 0.0000397 * CW^{2.1430}$; $r^2 = 0.602$

Rothschild and Ault (1992) estimated a carapace-width-to-length relationship for blue crabs using 5,000 crabs collected in Chesapeake Bay. Their sex-specific carapace-width (mm)-to-weight (g) relations were:

Female: $W = 0.0034865 * CW^{2.1165}$

Male: $W = 0.00022105 * CW^{2.7208}$

Growth in blue crabs is rapid the first summer and is dependent on temperature, molt frequency, food quality and availability, and life stage. Optimum growth of blue crabs occurs at temperatures between 15^{o}C to 30^{o}C, and growth stops when the temperature goes below 10^{o}C (Cadman and Weinstein 1988). In temperate regions, where winter temperatures regularly fall below this threshold, blue crabs bury into the sediment. During this dormant period, no growth occurs, thereby extending the time to reach maturity (Bauer and Miller 2010). Laboratory observations indicate blue crabs grow 12% to 35% per molt (Cadman and Weinstein 1988). Most blue crabs go through 18 to 20 post-larval molts before becoming sexually mature (Van Engel 1958).

1.2.5 Reproduction

Blue crabs mature between one and two years of age in North Carolina (Johnson 2004). Mating occurs during the spring or summer in brackish estuarine waters as female blue crabs molt into maturity (Forward et al. 2003; Whitaker 2006). Males may mate after their third or fourth intermolt, females mate only once in their lives (Hill et al. 1989). The sperm from this mating is stored in seminal receptacles of the female and used as often as the female spawns during a one or two year period (Hill et al. 1989). All young produced by a female must be fertilized by stored sperm (Darnell et al. 2009). Spawning typically occurs within two months after mating if mating occurs early in the growing season; however, females can retain sperm through the winter for spawning the following spring (Hill et al. 1989; Forward et al. 2003).

Spawning is initiated after migration to high-salinity areas near oceanic inlets. In the Chesapeake Bay, Prager et al. (1990) found that fecundity was significantly related to carapace width and estimated the average fecundity was 3,200,000 eggs per clutch. Females may spawn once or several times a season. Spawning has two peak pulses, April–June and August–September, in North Carolina (Darnell et al. 2009).

For the current assessment, length at maturity (50% mature, L_{50}) for female blue crabs was determined by fitting a logistic model to the available maturity data. It was necessary to pool maturity data across multiple programs and areas to ensure sufficient sample sizes. Additionally, Otto et al. (1990, cited by Hjelset et al. 2009) recommended pooling data from different sampling methods to reduce bias in estimates of size at maturity. Maturity data collected by the NCDMF's Estuarine Trawl Survey (Program 120), Juvenile Anadromous Trawl Survey (Program 100), Pamlico Sound Survey (Program 195), and commercial fish house sampling (Program 436) were included in the model. Programs 100, 120, and 195 are described in more detail in section 2.2 of this report. Program 436 is described in more detail in section 2.1.1.3 of this report. Length at maturity was estimated by year for 1987 through 2015 to derive annual estimates of length at 50% maturity (L_{50}). Estimates of L_{50} ranges from 98.8 mm in 1999 to 125.7 mm in 2015 (Figure 1.1). Estimates were used to determine maturity of female recruits and fully recruited females in the assessment method (see section 3.2 of this report).

1.2.6 Mortality

The natural mortality rate (*M*) is a key parameter in stock assessments but often is one of the most uncertain. Johnson (2004) estimated natural mortality of blue crabs in North Carolina using Hoenig's method (1983), which relates *M* to the maximum age in the population. Assuming a maximum age of 5 years, Johnson (2004) estimated *M* to equal 0.87. This value of *M* was assumed in the 2004 stock assessment of North Carolina blue crabs (Eggleston et al. 2004).

Hewitt et al. (2007) estimated *M* for blue crabs in the Chesapeake Bay using a variety of methods and concluded that *M* values ranging between 0.7 and 1.1 per year were reasonable for that stock. Wong (2010) assumed $M = 0.80$ in the 2010 assessment of the Delaware Bay blue crab stock.

Total mortality (*Z*) is the sum of natural, fishing, and any other sources of mortality. Johnson (2004) and Eggleston et al. (2004) estimated *Z* using length-based methods based on data collected during June by NCDMF Program 195. The length-based *Z* estimates ranged from 0.91 to 1.22 between 1987 and 2003 and averaged 1.03 per year during that time period. Estimates of *Z* for blue crabs in the Chesapeake Bay in the 1990s ranged from 1.0 to 1.5 (Rugolo et al. 1997). Estimates of Z derived from the results of a catch-survey analysis applied to the Delaware Bay blue crab stock ranged from 0.50 to 2.69 and averaged 1.51 per year during 1978 to 2009 (Wong 2010).

Fishing mortality rates (F) can be estimated directly (e.g., tagging studies) or indirectly. The results of a catch-survey analysis applied to the North Carolina blue crab stock were used to derive estimates of F, which ranged from 0.13 to 2.03 between 1987 and 2003 when M was assumed equal to 0.87 (Eggleston et al. 2004; Johnson 2004). Wong (2010) applied a catch-survey analysis to the Delaware Bay blue crab stock and the results were used to estimate the upper bound of F (see reference for details). Estimates of the upper bound for F ranged between 0.22 and 1.74 during 1978 to 2009 and averaged 0.75 per year.

Fishing mortality rates are difficult to estimate, especially when losses to the fishery are unknown. For example, reporting of discards and bycatch is not always required; if these quantities are significant and associated mortality is high, estimating F is made increasingly difficult. For blue crabs, the mortality associated with shedding operations may be substantial, with estimated losses of 10 to 30% daily after the crabs are taken from the water but before they are sold as soft crabs (Chaves and Eggleston 2003).

1.2.7 Food & Feeding Habits

Blue crabs consume a wide variety of food, fulfilling roles as predators and detritivores. They are large consumers of annelids, polychaetes, crustaceans, live or dead fish, vegetation, detritus, and feed heavily on oyster spat and juvenile clams (Williams 1984). Bivalve mollusks are a major portion of blue crab diets (Hines et al. 1990; Laughlin 1982; Cordero and Seitz 2014). They are also cannibalistic, and larger crabs are capable of exhibiting a check on population growth by consuming large amounts of small crabs and juveniles.

1.3 Habitat

1.3.1 Overview

The blue crab life cycle consists of an offshore phase and an estuarine phase. The offshore phase primarily consists of mature females that spawn in ocean waters, and planktonic larvae prior to migrating into the estuary. Blue crabs use a wide range of habitats based on life stage, sex, maturity, and associated salinity preferences, and occur across a broad spectrum of water quality parameters (Table 1.1). Wetlands, submerged aquatic vegetation (SAV), shell bottom, and unvegetated estuarine and ocean soft bottom are used by this species at various stages of their life cycle. The blue crab is common to all North Carolina coastal waters.

1.3.2 Spawning Habitat

Blue crabs spawn weeks after mating in late spring to early fall (Whitaker 2006). After mating, inseminated female blue crabs migrate from their usual brackish areas to high-salinity waters near ocean inlets. Females rely on high-salinity cues to ensure eggs are released for their development on the continental shelf. Ogburn and Habegger (2015) used SEAMAP data from 1990-2011 to assess spawning habitat in the South Atlantic Bight. Using reproductive condition of mature females as an indicator of spawning, they found that blue crabs spawned throughout the South Atlantic Bight and as far as 13 km offshore. In North Carolina, mature females were most abundant in the ocean in the summer, where approximately 84% had spawned and had only remnant eggs. The analysis indicated a South Atlantic regional decline in the number of offshore spawners, high inter-annual fluctuations in female crab density in Raleigh Bay, moderate but consistent densities in Onslow Bay, and low and declining densities in Long Bay. Results of this study and Ramach et al. (2009) suggest that inlets are serving more as migration corridors to the ocean where eggs are released and dispersed.

The first larval stage (zoeae) is carried offshore by ocean currents (Costlow and Bookhout 1959; Costlow et al. 1959; Epifanio 1995). Zoeae larvae are restricted to high salinity areas because of their intolerance of low salinity water (Costlow and Bookhout 1959). Their intolerance of low salinity water continues into the megalopal stages, when they return to the estuary.

1.3.3 Nursery & Juvenile Habitat

Once within the estuary, postlarvae (megalopae) settle in beds of submerged aquatic vegetation and other available complex habitats (i.e., salt marsh, detritus, and oyster shell) where they undergo further metamorphosis to become juveniles (Heck and Thoman 1981; Orth and van

Montfrans 1987; Hill et al. 1989; Ruiz et al. 1993; Pardieck et al. 1999; Posey et al. 1999; Etherington and Eggleston 2000).

Submerged aquatic vegetation is an important nursery habitat, particularly for early juveniles (<12 mm carapace width) that provide refuge from predators. In the Albemarle-Pamlico system, most initial recruitment of juvenile crabs occurs in SAV beds around inlets behind the Outer Banks, excepting major storm events. In years with large storm events, crabs disperse into lower salinity habitats (Etherington and Eggleston 2000). Studies have indicated that juvenile blue crabs occur in greater abundance in large or continuous SAV than in shallow unvegetated bottom or small patchy grass beds (Williams et al. 1990; Murphey and Fonseca 1995; Eggleston et al. 1998; Hovel 2003). Subtidal oyster reefs are also used as nursery habitat for early juveniles (Eggleston et al. 1998). After metamorphosis, juveniles undergo a secondary migration to shallow, less-saline waters in the upper estuaries and rivers or western Pamlico Sound (Etherington and Eggleston 2000). Ralph (2014), using a habitat-specific demographic model to quantify the effects of habitat on population fitness, found increased survival of age-0 crabs when vegetated habitats were present, which resulted in increased population growth rates. They concluded that since the vegetated habitats provided protection from fishing and predator mortality, the population could be subjected to higher fishing mortality rates and still maintain or increase population size.

Where SAV and subtidal oyster reefs are absent from estuaries in North Carolina and in the South Atlantic, lower salinity regions in the river-dominated estuaries provide important nursery areas for the blue crab population (Posey et al. 2005). Research in the Cape Fear and New rivers confirmed that marsh and shallow soft bottom in oligohaline and mesohaline portions of these rivers were important nursery areas with increased growth and reduced predation relative to the lower more saline portions of the rivers (Posey et al. 2005). The NCDMF estuarine trawl survey data show that blue crab is one of the dominant juvenile species in marshes and shallow tidal creeks (NCDMF unpub. data; Epperly and Ross 1986).

Wetlands, SAV, oyster reefs, and shallow soft bottom provide refuge and foraging area for juvenile crabs. Blue crabs forage heavily on oyster reefs, particularly oyster spat (Coen et al. 1999; Posey et al. 2004). Connectivity between these habitats provides a corridor for blue crabs to move through the estuary and enhances the ability to forage (Micheli and Peterson 1999; Grabowski et al. 2000).

1.3.4 Adult Habitat

Adult blue crabs use many of the same habitats as juveniles and are an important predator on submerged soft flats, marsh edge, and oyster reefs (NCDEQ 2016). Habitat partitioning by sex, maturity state, egg stage and salinity has been documented (Millikin and Williams 1984; Hines et al. 1987; Wolcott and Hines 1990; Ramach et al. 2009). General patterns include adult males and juvenile females being located further upstream and away from the waterbody mouth than females; juvenile females in shallower water than males and mature females in deeper water than juveniles and males; and females with late-stage eggs closer to the waterbody’s mouth than females with early stage eggs. Egg bearing crabs migrate out of the estuary using ebb tide transport (Forward et al. 2003; Carr et al. 2004). Since females undergo a spawning migration and are observed migrating even when not gravid (Darnell et al. 2009), they are more likely to be found in higher-salinity waters near the oceanic inlets than in oligohaline areas.

1.3.5 Habitat Issues & Concerns

Portions of estuarine habitats used by various life stages of blue crab have been degraded or lost over time by a variety of anthropogenic sources (NCDEQ 2016). Dredge and fill activities, navigational dredging, shoreline stabilization, and erosion from boat wakes and natural sources have contributed to wetland loss. When assessing the effect of bulkheads and living shorelines on fish and invertebrates, Scyphers et al. (2011) found living shorelines to support a greater abundance and diversity of aquatic life, with blue crabs being the most clearly enhanced (300% more abundant). Land use changes, ditching and draining, and land disturbance lead to increased stormwater runoff, which can carry nutrients, sediment, toxins, and pathogens into surface waters. This, along with point source wastewater discharges and impacts from water based activities like marinas, can degrade water quality, resulting in loss of SAV, and water quality conditions that are stressful to blue crabs (e.g., low dissolved oxygen, increased susceptibility to disease, excessive nutrients, high organic loading, and chemical pollution). Sea level rise, subsidence, invasive species, and storms are also stressors that impact critical habitat. The effect of anthropogenic threats on SAV, wetlands, shell bottom, soft bottom, and water quality are summarized in the NC Coastal Habitat Protection Plan (NCDEQ 2016).

Although indirect, blue crabs are affected by natural disturbances of their environment. In particular, tropical cyclones can affect blue crab harvest in the short term by concentrating blue crabs in areas where they are vulnerable to fishing gear (Eggleston et al. 2004). These effects can have long-term effects as well. Since the relocation of individuals induces a change in localized abundance, harvest could be affected. Not all the effects of tropical cyclones are detrimental. For example, peaks in post-larval blue crab settlement coincided with tropical cyclone tracks that came from a southwesterly direction (Eggleston et al. 2010). The massive ingress of post-larval blue crabs could make a significant contribution to the blue crab population. The caveat is that storm forces must be moderate. Excessive freshwater input can alter the salinity of large bodies of water, increasing megalopae and juvenile blue crab mortality, and thereby negating the benefits of increased settlement.

Prevalence and lethality of diseases and parasites can increase under stressful conditions and potentially impact blue crab populations. For example, infection rates by the parasitic dinoflagellate *Hematodinium perezi* along the Atlantic and Gulf coasts can exceed 50% and is usually lethal (Butler et al. 2014). A Gulf coast study found shell disease present in blue crabs at a rate of 55%, and *Vibrio* spp. present in the hemolymph of 22% of blue crabs (Rogers et al. 2015).

Endocrine disrupting chemicals that enter surface waters through point or nonpoint sources can cause mortality or sub-lethal stress on shellfish and crustaceans, depending on the concentration and extent of exposure. Flame retardants (polybrominated diphenyl ethers), which have widespread occurrence in surface waters, have been linked to inhibiting molting in blue crabs (Booth and Zou 2016).

1.4 Description of Fisheries

1.4.1 Commercial Fishery

The blue crab resource supports North Carolina’s most valuable commercial fishery. During 1950 through 2016, commercial landings of blue crabs have ranged from a low of 6.29 million pounds per year to a high of 67.1 million pounds per year (Figures 1.2 and 1.3). During the last decade (2007-2016), an average of 26.9 million pounds per year has been landed by the commercial fishery. The ex-vessel value of commercial blue crab landings was highest during 1994 through 2003, averaging 54.6 million dollars (2016 USD)[1] per year. Before 1994, the average ex-vessel value of North Carolina's commercial blue crab landings was 9.9 million dollars (2016 USD) per year (1950–1993 average). During 2004 through 2016, the ex-vessel value of commercial blue crab landings averaged 28.0 million dollars (2016 USD) per year.

Commercial fishermen have harvested blue crabs with a variety of different gears over time, including dredges, trotlines, pots, and trawls (Figure 1.2). The majority of blue crabs (83.5%) landed from 1950 to 2016 was harvested by pots. Pots have accounted for 98.5% of North Carolina's commercial blue crab landings during the last decade (2007-2016).

Peeler and soft crabs have been a relatively small portion of the commercial fishery for blue crabs, comprising 2.1% of the total blue crab landings reported from 1950 to 2016 (Figure 1.3). Peeler crabs are a value-added harvest that is captured via peeler pots and trawling for hard crabs and shrimp, mainly during the spring, as well as peeler trawls that target peeler crabs. The peelers are then held in shedding systems until they molt and are sold as soft crabs, either shipped live or cleaned and frozen. The peeler crab portion of the overall blue crab commercial fishery is small; however, the impact of the peeler crab fishery may be underestimated due to unreported mortality in shedding operations. Blue crabs placed in shedding operations are not reported until they are sold and thus any mortalities are not currently represented in the landings.

The commercial fishery for blue crab primarily occurs during late spring through the fall (Figure 1.4). Reported landings are highest in July and August, and this pattern has persisted for at least the last four decades.

The number of commercial fishermen that have reported landings of blue crabs and the associated number of trips have generally decreased from 1994 to 2016 (Table 1.2). The number of commercial fishermen that have reported landings of blue crabs has ranged between 884 and 2,287 during that time period. The number of trips in which blue crabs were landed in North Carolina ranged from a low of 51,707 to a high of 143,055 over the same period.

1.4.2 Recreational Fishery

Recreational fishermen in North Carolina harvest blue crabs with a variety of gears, including pots (collapsible and rigid), gill nets, trawls, hand lines, and dip nets. A separate license category, the Recreational Commercial Gear License (RCGL), allows recreational fishermen to use limited amounts of certain commercial gear to harvest seafood for personal consumption (see section 1.5.4.2, this report). Estimates of the RCGL blue crab harvest are available from NCDMF surveys conducted from 2002 to 2008. During 2002 through 2008, an estimated average of 26,402 RCGL recreational fishing trips per year was directed at blue crabs (Table 1.3). In that same time period, RCGL-licensed recreational fishermen harvested from 94.6 thousand pounds to 117 thousand pounds of blue crabs per year. In terms of number of blue crabs, recreational harvest by RCGL licensees has averaged 321 thousand blue crabs per year between 2002 and 2008. The amount of blue crabs discarded by recreational fishermen has been approximately half the recreational harvest during this time period. Total catch (including

[1] All values converted to 2016 U.S. dollars (USD) based on the annual average producer price index (PPI) values (U.S. Bureau of Labor Statistics, pers. comm.). The PPI is used to deflate revenue streams to measure real growth in output. The PPI tracks changes in manufacturer selling prices for consumer goods. For 1981-2016 the PPI for unprocessed shellfish was used, prior to 1981 the meat, poultry, and fish PPI was used to adjust values for inflation.

harvest and discards) during 2011-2016 is based on the Coastal Angling Program (CAP) recreational crabbing mail survey (see section 2.1.2, this report) was estimated ranging between 131,690-200,051 crabs annually (Table 1.4). The mortality of blue crabs discarded from the recreational fishery is unknown.

Individuals are allowed to fish one pot per person from privately owned land or a privately owned pier with no license. It is not known whether this unlicensed recreational fishery constitutes a significant proportion of total recreational fishery for blue crabs.

1.5 Fisheries Management

1.5.1 Management Authority

The NCDMF is responsible for the management of estuarine and marine resources occurring in all state coastal fishing waters extending to three miles offshore (Figure 1.5). There are no federal or interstate FMPs that apply specifically to the blue crab fishery in North Carolina.

1.5.2 Management Unit Definition

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

1.5.3 Regulatory History

In December 1998, the first FMP for blue crabs was approved for North Carolina (NCDMF 1998). The 1998 FMP maintained the previously established minimum size limit of 5 inches and a 10% tolerance per container for undersize blue crabs on commercial fishing vessels. Mature females, soft crabs, and peeler crabs were exempt from the minimum size limit. The original FMP also modified existing rules to clarify language on fishing in or near blue crab spawning sanctuaries and recommended use of a 4 or 4.5-inch mesh trawl in inland waters. These changes included limits on allowable blue crab landings as bycatch from the shrimp fishery (50 crabs per person and a 100 crab vessel limit for RCGL holders and the larger of 50% of combined catch or 300 pounds for commercial operations), prohibited the baiting of peeler pots with anything but live male crabs, and made it unlawful to possess white-line peeler crabs between June 1 and September 1.

The Blue Crab FMP was amended in 2004 (NCDMF 2004). The 2004 amendment adopted a spawning stock trigger and associated measures to protect the blue crab spawning stock (see section 1.5.4.3, this report). Management measures included implementing by proclamation a seasonal maximum size limit of 6.75 inches (5% tolerance) for mature female hard crabs and 5.25 inches for mature female peeler crabs from September 1 through April 30 when the spawning stock index is abnormally low. This maximum size limit was enacted in January of 2006 and remained in effect through April 2014. Compliance with the female seasonal maximum size limit was marginal and largely ineffective at protecting large mature females. Even when crabbers complied with the management measure by releasing large females, these females may have been captured multiple times and injured, or ultimately harvested by another crabber during their migration to the lower estuaries and into the sounds.

The Blue Crab FMP was amended again in 2013 (NCDMF 2013). The 2013 amendment removed the spawning stock trigger and its associated measures. The amendment incorporated the use of a traffic light stock assessment and an adaptive management plan for management of the blue crab stock. The traffic light is divided into three characteristics: 1) adult abundance, 2) recruit abundance, and 3) production. Each characteristic uses data from several division biological surveys and sampling programs to determine the relative abundance of adult and recruit blue crabs in the population and various production indictors for the stock each year. Under the adaptive management framework, the traffic light is updated annually and evaluated for management need. Moderate management measures (Table 1.5) will be implemented in the blue crab fishery if either the adult abundance or production characteristic of the traffic light are at or above the 50% red threshold for three consecutive years. Elevated management measures will be implemented if either the adult abundance or production characteristic of the traffic light are at or above the 75% red threshold for two of three consecutive years. The recruit abundance indicator, while not used to trigger management action, may be used to augment any management action taken if a trigger is activated. The three-year time period was chosen to prevent taking management action as a result of annual variability in the blue crab stock and instead base any management response on the observation of a short but continued declining trend in the population. The 2013 amendment also established the blue crab stock is considered overfished when the proportion of red in the production characteristic of the traffic light is greater than or equal to 75% red for three consecutive years.

In May 2016, a revision to the 2013 amendment was adopted in response to the moderate management trigger being met for the adult abundance characteristic of the traffic light (NCDMF 2016). This revision required one additional escape ring in crab pots and one of the three escape rings must be located within one full mesh of the corner of the pot and within one full mesh of the bottom of the apron/stairs (divider) of the upper chamber of the pot; eliminated the harvest of v-apron immature female hard crabs (excluding peeler crabs) and included v-apron immature female hard crabs in the culling tolerance; prohibited the harvest of dark sponge crabs (brown and black) from April 1 to April 30 each year and included dark sponge crabs in the culling tolerance; lowered the culling tolerance from 10 percent to 5 percent for all crabs, except mature females; and prohibited the harvest of crabs with dredges except incidental to lawful oyster dredging as outlined in North Carolina Marine Fisheries Commission (NCMFC) Rule 15A NCAC 03L .0203(a)(2).

1.5.4 Current Regulations

1.5.4.1 Commercial Fishery

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

There is no regulatory season for commercial harvesting of blue crabs with the exception of a restriction on crab dredge usage from January 1 to March 1 and a cleanup period for lost and abandoned pots between January 15 and February 7. For trawls, a 4-inch stretch mesh tailbag is required west of a line dividing Pamlico Sound down the middle and a 3-inch stretch mesh tailbag is required to the east of this line.

From March 1 to August 31, it is unlawful to use trawls, pots, and mechanical methods for oysters or clams or take blue crabs with the use of commercial fishing equipment from crab spawning sanctuaries (Figure 1.6). During the remainder of the year the director of the NCDMF may, by proclamation, close these areas and may impose any or all of the following restrictions:

number of days, areas, means and methods which may be employed in the taking, time period, and limit the quantity.

Prior to June 6, 2016

Commercial fishery regulations include a year-round carapace width minimum size limit of 5 inches for male and immature female hard blue crabs and a 10% tolerance for undersize blue crabs based on the number of blue crabs in any storage container on a vessel. Mature females, soft and peeler crabs, and male crabs for use as peeler bait are exempt from this size limit. If pots are used, they must contain two unobstructed escape rings no less than 2 5/16 inches in inside diameter and must be fished at least every five days. Peeler pots with a mesh size less than 1 ½ inches are exempt from the escape ring requirement. Targeted crab dredging is allowed from January 1 to March 1 in a northern area of Pamlico Sound adjacent to Oregon Inlet. Oyster dredges may also be used to harvest blue crabs but blue crabs cannot exceed 50% of the total weight of the oyster and crab catch or 500 pounds, whichever is less.

June 6, 2016–Present

Commercial fishery regulations include a year-round carapace width minimum size limit of 5 inches for male hard blue crabs, no size limit for mature female blue crabs, no possession of immature female blue crabs (excluding peeler crabs), and no possession of dark sponge crabs (brown and black) from April 1 through April 30. Soft and peeler crabs, and male crabs for use as peeler bait are exempt from this size limit. A 5% tolerance for immature female, dark sponge crabs, and undersize male blue crabs based on number in any storage container on a vessel. Peeler pots with a mesh size less than 1 ½ inches are exempt from the escape ring requirement. The harvest of blue crabs with dredges is prohibited except incidental to lawful oyster dredging.

January 15, 2017–Present

Pots used to harvest blue crabs must contain three unobstructed escape rings no less than 2 5/16 inches in inside diameter and one escape ring must be located within one full mesh of the corner of the pot and within one full mesh of the bottom of the apron/stairs (divider) of the upper chamber of the pot.

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

1.5.4.2 Recreational Fishery

Prior to 1999, no recreational fishing license was required unless a vessel was used. After July 1, 1999, the RCGL was required when using certain allowable commercial gear. No license is required for the following non-commercial equipment: collapsible crab traps, cast nets, dip nets, and seines less than 30 feet. A RCGL is required to use commercial gear to harvest finfish and crustaceans for personal consumption. Recreational crabbers are prohibited by law from selling their catch, even if in possession of a RCGL. With a RCGL, a maximum of five pots of any type (peeler pots are disallowed) is allowed and must be fished at least every five days; pots cannot be fished at night. Pots must be removed from the water during January 15 through February 7. One pot per person may be used without a RCGL to fish from privately owned land or a privately owned pier with no license. The recreational fishery is not subject to reporting requirements. The current possession limit for the recreational fishery is 50 blue crabs per person per day not to exceed 100 blue crabs per vessel per day.

Prior to June 6, 2016

Recreational fishery regulations include a year-round carapace width minimum size limit of 5 inches for male and immature female hard blue crabs and a 10% tolerance for undersize blue crabs based on the number of blue crabs in any storage container on a vessel. Mature females, soft and peeler crabs are exempt from this size limit. If pots are used, they must contain two unobstructed escape rings no less than 2 5/16-inches in inside diameter.

June 6, 2016–Present

Recreational fishery regulations include a year-round carapace width minimum size limit of 5 inches for male hard blue crabs, no size limit for mature female blue crabs, no possession of immature female blue crabs (excluding peeler crabs), and no possession of dark sponge crabs (brown and black) from April 1 through April 30. A 5% tolerance for immature female, dark sponge crabs, and undersize male blue crabs based on number in any storage container on a vessel.

January 15, 2017–Present

Pots used to harvest blue crabs must contain three unobstructed escape rings no less than 2 5/16-inches in inside diameter and one escape ring must be located within one full mesh of the corner of the pot and within one full mesh of the bottom of the apron/stairs (divider) of the upper chamber of the pot.

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

1.5.4.3 Spawning Stock Trigger

In addition to the regulations described above, the 2004 amendment to the Blue Crab FMP adopted a spawning stock trigger to protect the blue crab spawning stock (NCDMF 2004). A spawning stock index derived from September data collected by the NCDMF Pamlico Sound Survey (Program 195; see section 2.2.3, this report) is evaluated annually to determine whether the trigger has been activated (Figure 1.7). The spawning stock index is calculated as the sum of the carapace widths of mature female blue crabs divided by the total number of tows. The trigger is activated when the spawning stock index falls below the lower 90% confidence limit of the reference baseline average for two consecutive years. In the 2004 amendment, the reference baseline was 1987 through 2003. The amendment states that the reference baseline will be updated every five years as part of the FMP review. However, if the trigger is active at the time of the review, the reference baseline update will be delayed until the trigger is no longer active.

When the trigger is activated, the NCDMF has the proclamation authority to implement spawning stock protection measures. These measures include a 6 ¾-inch maximum size limit on mature female blue crabs and a 5 ¼-inch maximum size limit on female peeler crabs from September through April for all fisheries in order to protect mature female crabs during their spawning migration. In addition, the culling tolerance of blue crabs in any container on a vessel in the commercial fishery will be lowered from 10% by number to 5% by number.

The spawning stock trigger was activated every year from 2006 through 2013 (repealed effective in 2014; NCDMF 2013), and the associated measures were implemented.

1.5.5 Management Performance

The decline of commercial blue crab landings continued after the adoption of the Blue Crab FMP in 1998 (Figures 1.2 and 1.3). Based on data collected from the NCDMF Trip Ticket Program (see section 2.2.1, this report), commercial landings of blue crabs during 1994 through 1997 averaged 55.8 million pounds per year. During 1998 through 2016, commercial fishermen landed an average of 33.4 million pounds of blue crabs per year. The decrease in commercial landings is due, at least partly, to the shutting down of crab processing plants, which reduced the amount of crabs that seafood dealers could move, thereby reducing demand and ultimately reducing harvest. It is not certain how much of the decline in landings is attributable to the FMP. Changes in stock size may also be a factor in the decline. Other potential contributing factors could include changes in effort and environmental variability.

1.6 Assessment History

1.6.1 Review of Previous Methods & Results

The last benchmark assessment of blue crab in North Carolina waters for management purposes was performed by NCDMF in 2011. The assessment applied the Traffic Light approach to evaluate stock status. The previous assessment recommended defining the overfished condition based on the blue crab production Traffic Light such that when the proportion of red for the production Traffic Light is greater than or equal to the third quartile (>=0.75) for three consecutive years, the blue crab stock is considered overfished. Based on this definition, the results of the previous assessment suggested the North Carolina blue crab stock was not overfished. An overfishing definition and status relative to overfishing could not be determined because available data were considered insufficient for estimating reliable fishing mortality rates. Therefore, the previous assessment considered the status of the North Carolina blue crab stock relative to overfishing as unknown. Details of the Traffic Light approach are provided in Appendix A.

1.6.2 Previous Research Recommendations

Research recommendations identified from the 2011 stock assessment (NCDMF 2011) focused on the lack of sufficient data to apply a traditional method to assess the status of the blue crab stock as identified in Amendment 1 (NCDMF 2004). To address this deficiency, the following recommendations for research and monitoring were offered (no particular order):

- Continue existing programs that have been used to monitor North Carolina's blue crab stock to maintain baseline data
- Identify key environmental factors that significantly impact North Carolina's blue crab stock and investigate assessment methods that can account for these environmental factors
- Conduct a study of the selectivity of the gear used in the Juvenile Anadromous Trawl Survey (Program 100) to evaluate the size at which blue crabs are fully-selected to the survey gear; the results of such a study could help determine whether the survey data could be used to develop a reliable index of blue crab recruitment for the Albemarle region; no such index is currently available
- Expand spatial coverage of the Estuarine Trawl Survey (Program 120) to include shallow-water habitat in Albemarle Sound; sampling in shallow-water habitat is intended to target juvenile blue crabs so that a recruitment index for the Albemarle Sound could be developed

- Expand temporal coverage of the Estuarine Trawl Survey (Program 120) beyond May and June sampling; additional sampling later in the blue crab's growing season would provide more information on within-year changes in growth, mortality, and abundance; at a minimum, recommend addition of September sampling in order to capture the fall settlement peak
- Expand spatial coverage of Pamlico Sound Survey (Program 195) to include deepwater habitat in Albemarle Sound and the Southern Region; expanding the sampling region of adult blue crab habitat would allow for a more spatially-comprehensive adult index; additionally, there would be increased confidence in comparison of adult abundance trends among regions since all would derive from the same sampling methodology
- Implement a statewide survey with the primary goal of monitoring the abundance of blue crabs in the entire state; such a survey would need to be stratified by water depth to ensure capture of all stages of the blue crabs' life cycle and standardized among North Carolina waters
- Implementing monitoring of megalopal settlement near the ocean inlets could potentially add a predictive function to the blue crab stock assessments in the future; Forward et al. (2004) detected a positive, linear relationship between megalopal abundance and commercial landings of hard blue crabs for both the local estuarine area and the entire state of North Carolina when a two-year time lag was implemented (Forward et al. 2004); such monitoring is critical to track larval ingress peaks and the effect of natural forces, such as tropical storms and prevailing winds, on ingress.
- Continue surveys of recreational harvest and effort to improve characterization of the recreational fishery for blue crabs
- Identify programs outside the NCDMF that collect data of potential use to the stock assessment of North Carolina's blue crabs
- Perform in-depth analysis of available data; consider standardization techniques to account for year and other effects in development of indices; explore utility of spatial analysis in assessing the blue crab stock.

2 DATA

2.1 Fisheries-Dependent

2.1.1 Commercial Fishery Monitoring

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

2.1.1.1 Survey Design & Methods

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

The majority of trips reported to the NCDMF TTP only record one gear per trip; however, as many as three gears can be reported on a trip ticket and are entered by the program's data clerks in no particular order. When multiple gears are listed on a trip ticket, the first gear may not be the gear used to catch a specific species if multiple species were listed on the same ticket but caught with different gears. In 2004, electronic reporting of trip tickets became available to commercial dealers and made it possible to associate a specific gear for each species reported. This increased the accuracy of reporting by documenting the correct relationship between gear and species. In 2004, electronic reporting of trip tickets became available to all dealers who chose to use it. In 2013, a NCMFC rule was implemented making it mandatory to report electronically if a seafood dealer averaged 50,000 pounds of finfish over the most recent three-year period. Many federal dealers were already required to report electronically to NMFS and used the NC Trip Ticket Software Program to meet their reporting requirements for NMFS and NC.

2.1.1.2 Sampling Intensity

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

2.1.1.3 Biological Sampling

Program 436 (P436) was initiated in April 1995 to collect fisheries-dependent data at fish houses from North Carolina's commercial blue crab fishery. The program aimed to determine size, sex, and maturity (female) for blue crabs and length/weight of non-blue crab species harvested in the commercial crab fisheries and obtain information from the commercial harvester on harvest location, soak time, weight of catch (Trip Ticket information), and specifications on gear type and amount. Initially, sampling was limited to the northeast and Pamlico Sound regions of North Carolina. Statewide sampling was initiated in 1998. Subsamples of sorted (by market category) and unsorted catches are taken and biological information is recorded. All blue crabs in a subsample are measured and sexed, and maturity of females is recorded. Program 436 only samples voluntarily cooperative fish houses, and sampling distribution may not reflect landing patterns.

2.1.1.4 Biases

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

Another potential bias relates to the reporting of multiple gears on a single trip ticket. This bias is considered minimal for blue crab landings because the commercial blue crab fishery uses gears specific to crabbing (e.g., crab pots, crab trawls, trotlines). Therefore, it is often possible to identify the gear used to catch blue crabs on a trip ticket that lists multiple gears and species.

2.1.1.5 Development of Estimates

All trips landing blue crab from 1994 to 2016 were subset from the trip ticket database. This subset contains 51,305,547 observations and 48 variables including species other than blue crab caught on each trip. Blue crab landings are divided into hard blue crabs, peeler blue crabs, and soft blue crabs. Each type of blue crab is recorded with its own unique species code. Therefore, landings can be split between hard, peeler, and soft blue crabs as opposed to years prior to 1994.

The length-frequency distribution of blue crabs in North Carolina's commercial landings was calculated using biological sampling data from P436. The length-frequency distributions were computed by year for 1995 to 2016.

2.1.1.6 Estimates

The landings of blue crab have generally declined overall since 1994. However, in recent years, the landings have started to show an increasing trend (Figures 1.2 and 1.3). Also, the majority of landings occur from two areas, the Pamlico Area (51%) and Albemarle Area (44%). Historically, the majority of the blue crab landings came from the Pamlico Area, but in more recent years, the Albemarle Area has been the top producer (Figures 2.1). The majority of hard blue crabs occurred during the summer months while peeler and soft crabs were primarily landed during spring months (Figure 2.2).

The modal peak of hard crabs is 140 mm CW bin with the majority of crabs in the 130 through 150 mm CW bins (Figure 2.3). Peeler crabs have a modal peak in the 110 mm CW bin with the majority of crabs in the 90 through 120 mm CW bins.

The commercial catch data during 1995-2016 were further partitioned by sex and stage (<127 mm CW as recruits and ≥127 mm CW as fully recruited crabs; Figure 2.4) for assessment model input based on the biological sampling from P436. See Section 3 of this report for assessment model input.

2.1.2 Recreational Fishery Monitoring

2.1.2.1 Survey Design & Methods

During 2001 through 2002, a telephone survey of RCGL holders was conducted to determine the 2001 recreational harvest of blue crabs (Nobles et al. 2002). Phone surveys of 388 RCGL holders were conducted between September 2001 and March 2002 to determine use of the RCGL, type of equipment, location of harvest, number of days harvesting, and daily and seasonal harvest estimates.

A mail survey of coastal and estuarine landowners was conducted in North Carolina between May 1, 2002 and April 30, 2003 (Vogelsong et al. 2003). The survey requested information on property characteristics, crabbing effort, and harvest. A total of 382 surveys were returned.

The NCDMF conducted monthly surveys of RCGL holders from 2002 to 2008 to collect information on recreational fishing. Participants were randomly selected and were asked about the number of trips taken and the type and number of gears used during the survey month. Participants were also asked to provide estimates for the numbers and pounds of each species caught and retained as well as the numbers of each species discarded.

From 2007 to 2010, the NCDMF surveyed approximately 20% of Coastal Recreational Fishing License (CRFL) holders regarding their participation in saltwater fishing activities including gigging, use of a cast net, shellfish collection, and crabbing.

Since 2010 through present, the NCDMF the Costal Angling Program (CAP) evaluates recreational crabbing with a mail survey. The CAP survey aims to collect data for estimating the participation in recreational crabbing among CRFL and grandfathered license holders, the number of trips taken and the amount of catch including harvest and discards. Descriptive characteristics of crabbing trips including: duration, party size, methods of harvest, county, waterbody, and access locations are also collected during this survey. Individuals are randomly selected and stratified by a combination of region of residence and license duration. The survey was conducted every two months.

2.1.2.2 Biological Sampling

There are currently no programs that collect biological samples of blue crabs from North Carolina's recreational fishery.

2.1.2.3 Biases

The Nobles et al. (2002) survey and NCDMF survey of RCGL holders were limited to fishermen in possession of a RCGL, thereby omitting non-licensed recreational fishermen that harvested blue crabs. The NCDMF survey of CRFL holders also omitted non-licensed recreational fishermen that harvested blue crabs. Estimates of recreational harvest by non-licensed fishermen are unknown. While initiating an estuarine landowner survey filled some of this gap, including many recreational crabbers who are exempt from RCGL and CRFL licensing, it does not take into account harvest from renters or that of fishermen legally harvesting blue crabs without a license.

2.1.2.4 Development of Estimates

In the CAP program, the number of potential participants is a product of the number of valid recreational licenses for the survey period and the percent of those who answered affirmatively to a crabbing participation question at the time of license purchase (or while updating contact information). The ineligibility rate is the number of anglers reporting they do not participate in crabbing divided by the total number of responses received. The estimated participation is a product of the number of potential participants and one minus the ineligibility rate. The mean number of trips per license holder is calculated by dividing the sum of all trips reported by all respondents by the number of respondents. Estimated effort is the product of the estimated number of potential crabbers participating and the mean trip per license holder. Catch is the number of a species harvested by each angler expanded to represent the population of license holders. The mean number of crabs caught per license holder is calculated by dividing the sum of crabs reported by all respondents by the number of respondents. Estimated catch is the product of the estimated number of potential crabbers participating and the mean number of crabs harvested per crabber.

2.1.2.5 Estimates

Fifty percent of all blue crabs were harvested along the Intracoastal Waterway, between Pamlico Sound and the Cape Fear River (Nobles et al. 2002). The total estimated blue crab harvest from RCGL holders in 2001 was 118,051 pounds. In this survey, 23.5% of the surveyed RCGL holders indicated that they targeted blue crabs.

The NCDMF survey of RCGL holders estimated that RCGL licensees took an average of 26,402 blue crab directed trips per year between 2002 and 2008 (Table 1.3). During this time period, RCGL holders harvested an average of 116,797 pounds per year, which amounted to 20% of the total estimated RCGL harvest.

Estimated blue crab harvest by RCGL holders was less than 0.40% of total blue crab commercial landings for 2001 through 2008. While the harvest of exempted shore- and pier-based pots and other non-commercial gear are unknown, it is unlikely that recreational harvest of blue crabs is significant in North Carolina.

The CAP survey estimated 44% of trips from central coastal area (Figure 2.5). Majority of the trips were contributed by Carteret (19%), Dare (21%), and Brunswick (17%) counties. Total catch (harvest + discards) ranged between 131,690 and 200,051 crabs annually (Table 1.4). Total effort and catch were concentrated during the summer and fall with a marked increase in trips being observed between May and October.

Recreational catch was not included in this assessment because the recreational catch of blue crab in North Carolina accounts for less than 0.4% of its commercial catch and no detailed information regarding recreational catch is available throughout the assessment time period.

2.2 Fisheries-Independent

2.2.1 Estuarine Trawl Survey (Program 120)

2.2.1.1 Survey Design & Methods

In 1971, the NCDMF initiated a statewide Estuarine Trawl Survey, also known as Program 120 (P120). The objectives of the program are to: 1) identify primary nursery areas and other critical habitats, 2) provide a long-term data base of annual juvenile recruitment for economically important species, and 3) provide a database for evaluation/permit comment on projects with potential environmental impact.

The survey samples shallow-water areas south of the Albemarle Sound system (Figure 2.6). Major gear changes and standardization in sampling occurred in 1978 and 1989. In 1978 tow times were set at one minute during the daylight hours. In 1989 an analysis was conducted to determine a more efficient sampling time frame to produce juvenile abundance indices with acceptable precision levels for the target species. A set of 104 core stations was identified, sampling would be conducted in May and June only, except for July sampling for weakfish (dropped in 1998, program 195 deemed adequate), and only the 10.5 ft. head rope trawl would be used. July sampling for a subset of the cores was reinstituted in 2004 in order to produce a better index for spotted seatrout.

The current gear is a 3.2-m otter trawl with 6.4-mm bar mesh body netting of 210/6 size twine and a tailbag mesh of 3.2-mm Delta-style knotless nylon with a 150-mesh circumference and 450-mesh length. The gear is towed for one minute during daylight hours during similar tidal stages and covers 75 yards.

All species taken are sorted, identified, and a total number is recorded for each species. For target species, a subset of at least 30-60 individuals is measured. Environmental data are recorded, including temperature, salinity, dissolved oxygen, wind speed, and direction. Additional habitat fields were added in 2008.

2.2.1.2 Sampling Intensity

Prior to 1989, sampling was year-round. From 1989 to 2003, a set of 104 fixed core stations was identified and sampling was conducted in May and June only. Since 2004, additional July sampling of a subset of the core stations has been conducted.

2.2.1.3 Biological Sampling

All blue crabs caught are counted. The catch of blue crabs is subsampled if there are more than 30 individuals that are less than 20 mm carapace width (CW). These crabs (<20 mm CW) are measured but not sexed. Larger blue crabs (>=20 mm CW) are sexed and measured.

2.2.1.4 Biases

Mature female blue crabs are present throughout the coastal waterways of North Carolina. When it is time to spawn, mature females migrate to the oceanic inlets near the barrier islands. Depending on the timing of sampling, the migration could artificially inflate the perceived abundance of mature females in Pamlico Sound by including transient, not resident, mature female crabs. Adult blue crabs more commonly occupy deeper water (<2 m) and are therefore less likely to be encountered by the gear in the locations sampled by Program 120.

2.2.1.5 Development of Estimates

Overall, a total of 7,779 samples captured 55,894 blue crabs from 1971 to 2016 (Table 2.1). The number of samples per year from core stations ranged from a low of zero (1972) to a high of 209 (1988). The number of blue crabs caught annually ranged from 18 to 2,794. The modal peak for blue crabs captured was 10 mm CW, with approximately 65% of blue crabs being less than 50 mm CW (Figure 2.7). The CW for blue crab ranged from 3 to 266 mm. The mean annual CW varied little throughout the time series, hovering around 50 mm.

Examination of the available data lead to the decision to develop sex-specific indices of relative abundance for blue crab recruits (crabs less than 127 mm CW). To generate these sex-specific indices, when individual sex information was unavailable the overall male:female sex ratio (60:40) was applied to the unsexed portions of the catch.

The nominal annual CPUE for both male and female recruits shows inter-annual variability with an overall declining trend through the time series (Figure 2.8). Male recruit CPUE ranged from a high of 7.9 in 1996 to a low of 1.6 in 2016. Female recruit CPUE ranged from a high 5.2 in 1996 to a low of 1.1 in 2016.

The standardized indices were input to the assessment models. A generalized linear model (GLM) framework was used to develop the standardized indices. Both Poisson and negative binomial error distributions were considered and the selected distribution was based on the estimate of dispersion (ratio of variance to the mean; Zuur et al. 2009). The Poisson distribution assumes equi-dispersion—that is, the variance is equal to the mean. Count data are more often characterized by a variance larger than the mean, known as overdispersion. Some causes of overdispersion include missing covariates, missing interactions, outliers, modeling non-linear effects as linear, ignoring hierarchical data structure, ignoring temporal or spatial correlation, excessive number of zeros, and noisy data (Zuur et al. 2009, 2012). A less common situation is underdispersion in which the variance is less than the mean. Underdispersion may be due to the model fitting several outliers too well or inclusion of too many covariates or interactions (Zuur et al. 2009). Data were first fit with a standard Poisson GLM and the degree of dispersion was then evaluated. If over- or underdispersion was detected, an attempt was made to identify and eliminate the cause of the over- or underdispersion (to the extent allowed by the data) before considering alternative models, as suggested by Zuur et al. (2012). In the case of overdispersion, a negative binomial distribution can be used as it allows for overdispersion relative to the Poisson distribution. Alternatively, one can use a quasi-GLM model to correct the standard errors for overdispersion. If the overdispersion results from an excessive number of zeros (more than expected for a Poisson or negative binomial), then a model designed to account for these excess zeros (e.g., zero-inflated model) can be applied.

Potential covariates were evaluated for collinearity by calculating variance inflation factors, applying a correlation analysis, or both. Collinearity exists when there is correlation between covariates and its presence causes inflated *P*-values.

Covariate selection started with a null model including only the intercept. The significant covariates were identified and added to the null model through a forward selection procedure based on Akaike Information Criterion (AIC, Akaike, 1974; Burnham and Anderson, 2002). At each step, the covariate that most greatly reduced the AIC value was added to the null model, and this process was repeated until inclusion of an additional covariate would not substantially improve model performance (i.e. the decrease in AIC was less than five).

2.2.1.6 Estimates

The GLM frequently selected depth, salinity, sediment size (i.e., hard rock, hard sand, soft mud, hard mud, clay, silt, muddy sand, sandy mud, sand and mud) and bottom composition (i.e., shell, grass, algae and detritus) as significant covariates for both male and female recruit abundance indices. The standardized CPUE for both male and female recruits varied annually with relatively low recruits in last three years, especially in 2016 (Figure 2.9).

2.2.2 Juvenile Anadromous Trawl Survey (Program 100)

2.2.2.1 Survey Design & Methods

The NCDMF Juvenile Anadromous Trawl Survey, also known as Program 100 (P100), was initiated in 1982 to determine relative abundance, growth, and distribution of juvenile alosine fishes and striped bass in Albemarle Sound (Figure 2.10). Since its inception, the survey has sampled seven stations (Hassler stations) in western Albemarle Sound. In July 1984, twelve sampling stations were added in the central Albemarle Sound area (Central Sound stations) to monitor juvenile striped bass abundance and to determine if a shift in the striped bass nursery area had occurred.

The program surveys a total of 62 fixed trawl sites, of which 19 are considered core sites. Continuous time series are available for Hassler and Central Sound trawls. Historic trawls were introduced to the program in 2004.

The survey uses an 18-foot semi-balloon trawl with a body mesh size of 0.75 inch and a 0.25-mesh tailbag. A 10 or 15-minute tow pulled at 2.4 knots with the balloon trawl constitutes one unit of effort. Hassler trawls are pulled for 15 minutes while all others are 10 minute tows. Water quality and habitat information such as temperature, salinity, and dissolved oxygen are recorded. In 2004, forty-three stations were reactivated. Not all sampling was conducted in 2005 due to a gas shortage. In 2010 blue crab sex became a mandatory field and maturity and sponge stage fields were added.

2.2.2.2 Sampling Intensity

Program 100 trawls are conducted June through October, except Hassler and Central Sound trawls are conducted bimonthly from July through October. Due to difference in sampling and lack of blue crab catch in June, only July through October were used in this analysis.

2.2.2.3 Biological Sampling

The catch of each tow is sorted by species, counted, and measured. The carapace width, sex, and maturity (if female) are recorded for blue crabs. Subsampling methods are used if the catch of blue crabs is excessive.

2.2.2.4 Biases

The Program 100 survey samples only a couple of deep-water areas in Albemarle Sound, and the sampling does not include many of the tributaries or parts of the sound east of the Alligator River. This gap in sampling potentially omits mature females on their spawning migration to the oceanic inlets. Also, the survey trawl cannot sample in shallow waters in Albemarle Sound because of the complex structure, primarily stumps, associated with the shoreline. This potentially omits capture of juvenile blue crabs using the complex, shallow-water habitat as refuge from predators.

2.2.2.5 Development of Estimates

Data was analyzed for July through October. Core stations (Hassler and Central Sound trawls) were used for the analysis as they represent stations that were sampled continuously throughout the assessment period. CPUE was evaluated with effort being equal to one tow.

Overall, a total of 5,163 samples captured 27,453 blue crabs from 1972 to 2016 (Table 2.2). The number of samples per year from core stations ranged from a low of 12 (1972) to a high of 162 (1987). The number of blue crabs caught annually ranged from 3 to 3,593. There are modal peaks for blue crabs captured at 110 and 150 mm CW (Figure 2.11). The CW for blue crab ranged from 2 to 210 mm. The mean annual CW varied throughout the time series, averaging around 115 mm.

Examination of the available data lead to the decision to develop seasonal sex-specific indices of relative abundance for fully recruited blue crabs (crabs greater or equal to 127 mm CW). The summer season is July-August and the fall season is September-October. To generate these seasonal sex-specific indices, when individual sex information was unavailable the overall male:female sex ratio (63.5:36.5) was applied to the unsexed portions of the catch.

The annual summer CPUE for both male and female fully recruited blue crabs shows inter-annual variability with an increasing trend in recent years (Figure 2.12). Male fully recruited summer CPUE ranged from a high of 6.0 in 2008 to a low of 0.01 in 1997. Female fully recruited summer CPUE ranged from a high 2.3 in 2009 to a low of zero in 1997. The annual fall CPUE for both male and female fully recruited blue crabs were lower in the earlier years of the time series and have been more variable since 2008. Male fully recruited fall CPUE ranged from a high of 15.0 in 2008 to a low of 0.03 in 1997. Female fully recruited fall CPUE ranged from a high of 10.5 in 2008 to a low of 0.04 in 1997.

The abundance indices were standardized for assessment model input. See Section 2.2.1.5 for CPUE standardization procedure.

2.2.2.6 Estimates

The GLM model frequently selected salinity and dissolved oxygen as significant covariates for explaining annual variation in fully recruited crab abundance indices. The standardized indices from P100 increased since 2007 for both male and female fully recruited crabs (Figure 2.13).

2.2.3 Pamlico Sound Survey (Program 195)

2.2.3.1 Survey Design & Methods

The Pamlico Sound Survey, also known as Program 195 (P195), was instituted in March 1987 to provide a long-term, fishery-independent database for important recreational and commercial fish species in the Pamlico Sound, and the lower Neuse, and Pamlico rivers (Figure 2.14). Data collected from the survey have been used to calculate juvenile abundance indices and estimate population parameters for interstate and statewide stock assessments of recreationally and commercially important fish stocks.

This is a stratified-random survey. Fifty-two to fifty-four randomly selected stations are trawled each sampling event for a minimum of 104 stations trawled each year. Initially stations were allocated in proportion to the size of the strata (Table 2.3). The number of stations per strata was determined by the following formula:

$$N_S = N_T*(F_S / F_T)$$

Where N_S = number of hauls per stratum
N_T = total number of hauls
F_S = area of stratums
F_T = total survey area

Currently randomly drawn stations are optimally allocated among the strata based upon all the previous sampling in order to provide the most accurate abundance estimates (PSE <20) for selected species (BDB program NCEFF42S). A minimum of three stations (replicates) are maintained in each stratum, and 5 stations each are set for the Neuse and Pamlico rivers and 3 stations for the Pungo River.

Sampling is conducted aboard the RV *Carolina Coast*, equipped with double-rigged demersal mongoose trawls. The RV *Carolina Coast* is a 44-ft fiberglass hulled double-rigged trawler. The trawl consists of a body made of #9 twine with 1.875-in (47.6-mm) stretch mesh. The codend of the net is constructed of #30 twine with 1.5-in (38.1-mm) stretch mesh. The tailbag is 80 meshes around and 80 meshes long (approximately 10-ft). A 120-ft (36.58-m) three-lead bridle is attached to each of a pair of wooden doors that measure 4 ft by 2 ft (1.22-m X .061-m) and to a tongue centered on the headrope. A 60-cm "poly-ball" is attached between the end of the tongue and the tongue bridle cable. A 0.1875-in (4.76-mm) tickler chain that is 3.0-ft (0.9.-m) shorter than the 34-ft (10.36-m) footrope is connected to the door next to the footrope. A bib or tongue of webbing is built into the center of the top body panel. This tongue extends forward from the point that would be the headrope location on a flat, balloon, or semi-balloon trawl. Use of a large float at the point of the tongue where it is attached to a center bridle allows the tongue to fish higher in the water column. The tongue helps to reduce escapement over the top of the trawl. Tow duration is 20 minutes at 2.5 knots.

Environmental and habitat data are recorded during the haul back of each trawl. Parameters measured include: weather description, light phase, surface and bottom temperature (°C), surface and bottom salinity (ppt), surface and bottom dissolved oxygen (DO)(mg/L), start time, secchi depth (cm; added 2008), sediment size, wind speed (knots), wind direction, precipitation, start and end latitude, and start and end longitude.

The entire catch is sorted by species; each species is enumerated and a total weight is taken for each species. Individuals of each target species are measured. If present in large numbers, a sub-sample of 30-60 individuals of each target species is measured and a total weight of the measured individuals for each species is taken. If not on the target species list, the species is enumerated and a total weight taken. Blue crab are on the target species list and measured to the nearest millimeter carapace width and an aggregate weight of all individuals is taken to the nearest 0.1 kg.

2.2.3.2 Sampling Intensity

Currently, sampling occurs annually during the months of June and September, typically during the middle two weeks of each month. Sampling has undergone some changes. From 1987 to 1989 sampling occurred in eastern Albemarle Sound. From 1987 to March 1989, sampling occurred in March and December (in addition to June and September). The Pungo River was added to the survey area in 1990.

There were six years where the survey did not occur over the same time series; 1988, 1999, 2003, 2009, 2012, and 2013. In 1988, the December leg of the cruise was partially extended into January 1989 because of scheduling conflicts and adverse weather conditions. In 1999, samples were collected during the month of July and the end of September and beginning of October because vessel repairs and hurricanes prevented following the normal schedule. In September 2003, hurricane Isabel caused a delay and sampling was completed two days into October. In September 2009, vessel repairs caused a delay and sampling was completed during the first week of October. In June 2012, vessel repairs caused a delay in sampling causing the cruise to extend into a third week. In 2013, weather delays caused sampling to extend to a third week in June and September.

2.2.3.3 Biological Sampling

All blue crabs are counted and the sum weight of the catch is recorded. Carapace width, sex, maturity stage, and sponge color are recorded for all mature female blue crabs and from all subsampled blue crabs.

Beginning in September 2002, catches of blue crabs that were too large to process efficiently in the field were set aside for processing later. Subsamples were taken if the amount of crabs in the catch consisted of about ¼ of a 50-lb orange basket or more. The subsampling process involved dumping the basket on the culling table and immediately dividing the sample into quarters. The carapace width and sex were recorded and the sum of the crab weights in the subsample was taken. The remaining crabs (the other three quarters) were counted and mature females segregated. The sum weight of mature females was recorded and the carapace width of mature females was taken.

In 2005, the subsampling protocol was modified for situations where the number of blue crabs caught exceeds 100 individuals. In this situation, all mature females are separated, counted, weighed, and measured. The sum weight of all remaining crabs (males and immature females) is recorded before being subdivided into quarters. One quarter of the sample is then processed, recording the same data that are recorded for samples with fewer than 100 crabs. This process is repeated if necessary until a minimum of 100 crabs are measured.

2.2.3.4 Biases

One shortfall is that this survey, due to the vessel's size, cannot sample shallow water. The survey also cannot sample areas with complex benthic structure, like stumps or other submerged aquatic vegetation. These two limitations could omit important blue crab habitat.

Mature female blue crabs are present throughout the waterways of North Carolina. When it is time to spawn, mature females migrate to the oceanic inlets. Depending on the timing of sampling, the migration could artificially inflate the perceived abundance of mature females in Pamlico Sound by including transient, not resident, mature female crabs.

2.2.3.5 Development of Estimates

Effort is defined at the sample level with a sample consisting of double rigged trawls towed for 20 minutes. Precision of CPUE estimates was evaluated using the proportional standard error (PSE). Index values are design-based but data is available to develop model-based estimators (e.g. GLM). Indices represent the relative abundance of recruit, fully recruited, and mature female blue crabs in the survey.

A total of 3,153 samples captured 150,878 blue crabs from 1987 to 2016 (Table 2.4). The number of samples per year ranged from 90 to 108. The number of blue crabs caught annually ranged from 106 to 15,524. The modal peak for blue crabs captured in June was 50 mm CW, with approximately 50% of blue crabs occurring in the 40 mm to 70mm CW bins (Figure 2.15). In September there were modal peaks at both the 60 mm and 130 mm CW bins. The CW for blue crab ranged from 5 to 235 mm in June and from 14 to 200 mm in September (Figures 2.16). The mean CW in June appears to show a declining trend through the time series, averaging 83 mm from 1987-2003 and falling to an average of 71 mm from 2004 to 2016. The mean CW in September varied little throughout the time series, hovering around 100 mm.

Examination of the available data lead to the development of sex-specific indices of relative abundance for blue crab recruits (crabs less than 127 mm CW) and fully recruited blue crabs separately by month, and a September index of mature female blue crabs. To generate the sex-specific indices, when individual sex information was unavailable the overall male:female sex ratio by stage (recruit 49.3:50.7 and fully recruited 37.3:62.7) was applied to the unsexed portions of the catch. To account for the different sizes of the strata sampled, a weighted CPUE was used for the indices based on the number of grids in each stratum (Table 2.3).

The annual June weighted CPUE (wCPUE) for both male and female recruits shows inter-annual variability with an overall declining trend through the time series (Figure 2.17). Male recruit wCPUE ranged from a high of 55.3 in 1997 to a low of 3.9 in 2009. Female recruit wCPUE ranged from a high 62.6 in 1997 to a low of 4.7 in 2009. The annual September wCPUE for both male and female recruits was much higher in the earlier years of the time series and have been at stable low levels since 2000 (Figure 2.18). Male recruit wCPUE ranged from a high of 12.2 in 1996 to a low of 0.7 in 2011 and 2015. Female recruit wCPUE ranged from a high of 14.9 in 1996 to a low of 0.4 in 2008.

The annual June weighted CPUE (wCPUE) for both male and female fully recruited blue crabs shows inter-annual variability with an overall declining trend through the time series (Figure 2.18). Male fully recruited wCPUE ranged from a high of 10.0 in 1999 to a low of 0.1 in 2007 and 2009. Female fully recruited wCPUE ranged from a high 9.6 in 2004 to a low of 0.5 in 2007. The annual September wCPUE for both male and female fully recruited blue crabs were higher in the earlier years of the time series and have been at stable low levels since 2000. Male fully recruited wCPUE ranged from a high of 7.2 in 1996 to a low of <0.1 in 2006. Female recruit wCPUE ranged from a high of 26.6 in 1996 to a low of 0.3 in 2014.

The September mature female wCPUE has been variably but generally low since 2000 (Figure 2.19). Mature female wCPUE ranged from a high of 29.2 in 1996 to a low of 0.3 in 2014.

The abundance indices were standardized for assessment model input. See Section 2.2.1.5 for CPUE standardization procedure.

2.2.3.6 Estimates

The GLM model frequently selected strata, salinity, water temperature and water depth as significant covariates for male and female recruits and fully recruited crabs. All standardized indices showed an overall declining trend over years with a rebound since 2007 (Figures 2.20).

2.2.4 SEAMAP Trawl Survey

2.2.4.1 Survey Design and Methods

This program is a shallow water trawl survey to monitor the status and trends of coastal species in the South Atlantic Bight, including fish, shrimp, crabs, horseshoe crabs, sea turtles, mantis shrimp, and squid, to amass a long-term data base for research and fisheries management use. Samples are taken by trawl from the coastal zone of the South Atlantic Bight between Cape Hatteras, North Carolina, and Cape Canaveral, Florida (Figure 2.21).

Strata are delineated by the 4-m depth contour inshore and the 10-m depth contour offshore. Stations are randomly selected from a pool of stations within each stratum. The number of stations sampled in each stratum is determined by optimal allocation. A total of 102 stations are sampled each season within twenty-four shallow water strata.

The R/V Lady Lisa, a 75 ft. (23 m) wooden-hulled, double-rigged, St. Augustine shrimp trawler owned and operated by SCDNR, is used to tow paired 75 ft. (22.9 m) mongoose-type Falcon trawl nets without turtle excluder devices. The body of the trawl is constructed of #15 twine with 1.875 in (47.6 mm) stretch mesh. The cod end of the net is constructed of #30 twine with 1.625 in (41.3 mm) stretch mesh and is protected by chafing gear of #84 twine with 4 inch (10 cm) stretch "scallop" mesh. A 300 ft. (91.4-m) three-lead bridle is attached to each of a pair of wooden chain doors which measured 10 ft. x 40 in (3.0 m x 1.0 m), and to a tongue centered on the head-rope. The 86-ft (26.3 m) head-rope, excluding the tongue, had one large (60 cm) Norwegian "polyball" float attached top center of the net between the end of the tongue and the tongue bridle cable and two 9-in (22.3 cm) PVC foam floats located one-quarter of the distance from each end of the net webbing. A 1ft chain drop-back is used to attach the 89-ft. foot-rope to the trawl door. A 0.25-in (0.6 cm) tickler chain, which is 3.0 ft. (0.9 m) shorter than the combined length of the foot-rope and drop-back, is connected to the door alongside the foot-rope.

Trawls are towed for twenty minutes, excluding wire-out and haul-back time, exclusively during daylight hours (1 hour after sunrise to 1 hour before sunset). Contents of each net are sorted separately to species, and total biomass and number of individuals are recorded for all species of finfish, elasmobranchs, decapod and stomatopod, crustaceans, cephalopods, sea turtles, xiphosurans, and cannonball jellies. Only total biomass is recorded for all other miscellaneous invertebrates (excluding cannonball jellies) and algae, which are treated as two separate taxonomic groups.

Where large numbers of individuals of a species occur in a collection, the entire catch is sorted and all individuals of that species are weighed, but only a randomly selected subsample are processed and total number is calculated. For large trawl catches, the contents of each net are weighed prior to sorting and a randomly chosen subsample of the total catch is then sorted and processed. In every collection, each of the priority species is weighed collectively and individuals are measured. For large collections of the priority species, a random subsample consisting of thirty to fifty individuals is weighed and measured. Depending on the species, measurements of finfish are recorded as total length or fork length, measured to the nearest centimeter.

Additional data are collected on individual specimens of penaeid shrimp, blue crabs, sharks, horseshoe crabs, and sea turtles. Gonad and otolith specimens are also collected during seasonal cruises. A representative sample of specimens from each centimeter size range within each stratum are measured to the nearest mm (TL and SL), weighed to the nearest gram, and assigned a sex and maturity code. Sagittal otoliths and a representative series of gonadal tissue are removed, preserved, and transported to the laboratory at MRRI, where samples are processed. Hydrographic data collected with a Seabird SBE-19 CTD profiler at each station.

Fewer (78) stations were sampled in the same strata by the trawl survey in 1990-2000. In 1990-2000, stations were sampled in deeper strata with station depths ranging from 10 to 19 meters to gather data on the reproductive condition of commercial penaeid shrimp. Those strata were abandoned in 2001 to intensify sampling in the shallower depth-zone. From 2001 to 2008, a total of 102 stations were sampled each season (306 stations/year) within twenty-four shallow water strata, representing an increase from 78 stations previously sampled in those strata by the trawl survey (1990-2000). In 2009, the number of stations sampled each season increased to 112 (336 total). In the spring of 2013, the Raleigh Bay region of the North Carolina coast was not sampled due to weather and boat issues

2.2.4.2 Sampling Intensity

Multi-legged cruises are conducted in spring (early April - mid-May), summer (mid-July - early August), and fall (October - mid-November).

2.2.4.3 Biological Sampling

The contents of each net are sorted separately to species, and total biomass and number of individuals are recorded for all species of finfish, elasmobranchs, decapod and stomatopod crustaceans, and cephalopods. Only total biomass is recorded for all other miscellaneous invertebrates and algae, which are treated as two separate taxonomic groups. Marine turtles captured incidentally are measured, weighed, tagged, and released according to NMFS permitting guidelines. When large numbers of specimens of a species occur in a collection, the entire catch is sorted and all individuals of that species are weighed, but only a randomly selected subsample is processed and total number is calculated. For trawl catches where visual estimation of weight of total catch per trawl exceeds 500 kg, the contents of each net are weighed prior to sorting and a randomly chosen subsample of the total catch is then sorted and processed. In every collection, each of the twenty-seven target species is weighed collectively and individuals are measured to the nearest centimeter. For large collections of the target species, a random subsample consisting of thirty to fifty individuals is weighed and measured.

2.2.4.4 Biases

While sampling covers many different bottom types, tows cannot be conducted over hard bottom structures such as artificial reefs where blue crabs have been observed.

2.2.4.5 Development of Estimates

A total of 2,107 samples captured 4,086 blue crabs from 1989 to 2016 (Table 2.5). The number of samples per year ranged from 39 to 102. The number of blue crabs caught annually ranged from 22 to 715. Most blue crabs were captured in the summer portion of the survey (approximately 81%). The modal peak for blue crabs captured in the spring was 140 mm CW and 130 mm CW in both the summer and fall (Figure 2.22). The CW for blue crab ranged from 65 to 184 mm in the spring, 42 to 200 mm in the summer and from 36 to 175 mm in the fall (Figures 2.23). The mean CW in spring is difficult to interpret because in many years no blue crabs were caught or measured. The mean CW in the summer was variable but averaged approximate 130 mm through the time series. The mean CW in the fall was variable but is difficult to interpret due to low catch numbers.

Examination of the available data lead to the development of a summer index of relative abundance for mature female blue crabs. Most blue crabs captured in the summer are female (Figure 2.24) and although maturity stage is not recorded, immature females are rare in the survey (SCDNR personal communication). In developing the estimate all female blue crabs were assumed to be mature.

The September mature female wCPUE has been variably but generally low since 2007 (Figure 2.25). Mature female wCPUE ranged from a high of 22.8 in 1990 to a low of 0.3 in 2008.

The abundance indices were standardized for assessment model input. See Section 2.2.1.5 for CPUE standardization procedure.

2.2.4.6 Estimates

The GLM model selected salinity and water temperature as significant covariates for explaining annual variation in spawner abundance index from SEAMAP. The standardized spawner index declined to a low level since 2008 (Figures 2.26).

3 ASSESSMENT

3.1 Overview

3.1.1 Scope

In this assessment, the unit stock contains all blue crabs occurring within North Carolina coastal fishing waters, and the assessment is conducted for the time period of 1995-2016.

3.1.2 Previous Method

Establishing a comprehensive stock assessment (e.g., statistical catch-at-age or catch-at-length analysis; Quinn and Deriso 1999) for blue crab has been challenging. Determination of age for blue crabs is still an unresolved issue or is at best uncertain because they do not retain any hard parts throughout their life cycle, such as otoliths and scales. This difficulty in ageing has limited the application of age-based and length-based analysis for blue crabs (Hilborn and Walters 1992).

The surplus production model and the traffic light method have been used in the 2004 (Eggleston et al. 2004) and 2011 (NCDMF 2011) blue crab stock assessment in North Carolina, respectively. The surplus production model, as one of the age-aggregated methods, does not require any age-structure, but may fail to produce reliable estimates for management purposes when data lack contrast or when fluctuations in recruitment rather than harvest intensity drive population dynamics, and it cannot incorporate a recruitment or spawner abundance index even if available (Hilborn and Walters 1992). The traffic light method is a qualitative approach that heavily relies on abundance indices as indicators (e.g., Halliday et al. 2001; Ceriola et al. 2007). Selection of indicators and determination of thresholds are arbitrary and conclusions are limited to theoretical applications.

Catch-survey analysis (Collie and Sissenwine 1983) has been widely applied to crustaceans that are difficult to age (e.g., Zheng et al. 1997; Cadrin 2000), and has been adapted to blue crab stock assessments along the east coast of the USA with various modifications (e.g., Eggleston et al. 2004; Murphy et al. 2007; Wong 2010; Miller et al. 2011; VanderKooy 2013). For example, the 2011 Chesapeake Bay blue crab stock assessment used a sex-specific catch-survey analysis (Miller et al. 2011), and 2007 Florida blue crab stock assessment applied a catch-survey analysis with a 6-month time step (Murphy et al. 2007). Instead of requiring a full age structure, as in an age-based model, the catch-survey analysis splits the population into two stages in which the recruit stage can be easily distinguished from the fully recruited stage containing older animals. The animals in the recruit stage grow to the fully recruited stage at the next time step, which is the same assumption in age-based models if the time step is one year.

For North Carolina blue crabs, catch-survey analysis was attempted in the 2004 stock assessment but was not included in development of the management plan (Eggleston et al. 2004). Major reasons that catch-survey analysis was not adopted in recent stock assessments include: (1) lack of information to determine the partial fishing mortality on recruits and natural mortality, (2) environmental factors play an important role in population variability, (3) recruitment is very dynamic, and (4) abundance indices show spatial variation and the lack of a state-wide index.

3.1.3 Summary of Current Method

In this assessment, the working group developed a sex-specific two-stage model that is adapted from catch-survey analysis for assessing North Carolina blue crabs. In this model, a sex-specific recruits fishery selectivity and a sex- and stage-specific natural mortality are assumed free parameters to estimate based on data; standardized abundance indices were used to avoid influences of environmental factors on annual trend, including spatial locations and geographic features such as sediment size and bottom habitat structure; recruitment was modeled as free parameters to estimate instead of assuming any spawner-recruitment relationship; both process error and observation error were included to account for natural variation in population additional to the variation in response to harvesting; the Bayesian approach was applied to sufficiently incorporate data uncertainty and expert opinion in parameter estimation.

3.2 Two-Stage Model

3.2.1 Model Structure and Assumptions

In the two-stage model (also known as catch-survey analysis, Figure 3.1), the blue crab population consists of two stages, the recruit and the fully recruited crabs (Collie and Sissenwine 1983). The recruit stage contained crabs smaller than 127 mm CW, that is the legal harvestable size for male and immature female blue crabs in North Carolina, and the fully recruited stage included crabs larger than or equal to 127 mm CW. In the model, all fully recruited blue crabs were subject to fishing mortality, and the recruits were subject to a partial fishing mortality because mature females at this stage are harvestable, and those male and immature female blue crabs at this stage may also be retained if so long as they do not account for more than 10% of the catch. The population was modeled at annual time step. All recruits became fully recruited at the beginning of the next year. The population dynamics of blue crab in the sex-specific two-stage model was described in terms of the number of male and female crabs at each stage over time (Miller et al. 2011):

Population size of fully recruited animals

$$N_{y+1,\,s} = \left(N_{y,\,s}\exp\left(-M_{N,\,s} - F_{N,\,y,\,s}\right) + R_{y,\,s}\exp\left(-M_{R,\,s} - F_{R,\,y,\,s}\right)\right)\exp\left(\varepsilon_{N,\,y+1,\,s}\right),$$

Population size of recruits

$$R_y = \bar{R}\exp\left(\varepsilon_{R,\,y}\right),$$

$$R_{y,\,s} = R_y v_s,$$

Catch of fully recruited animals

$$C_{N,\,y,\,s} = \left(\frac{F_{N,\,y,\,s}}{F_{N,\,y,\,s} + M_{N,\,s}}\left(1 - \exp\left(-M_{N,\,s} - F_{N,\,y,\,s}\right)\right)N_{y,\,s}\right)\exp\left(\varepsilon_{CN,\,y,\,s}\right),$$

Catch of recruits

$$C_{R,\,y,\,s} = \left(\frac{F_{R,\,y,\,s}}{F_{R,\,y,\,s} + M_{R,\,s}}\left(1 - \exp\left(-M_{R,\,s} - F_{R,\,y,\,s}\right)\right)R_{y,\,s}\right)\exp\left(\varepsilon_{CR,\,y,\,s}\right),$$

Fishing mortality of fully recruited animals

$$F_{N,\,y,\,s} = F_y g_{N,\,s},$$

Fishing mortality of recruits

$$F_{R,\,y,\,s} = F_y g_{R,\,s},$$

Population size of spawners

$$N_{sp,\,y} = N_{y,\,s=female} w_N + R_{y,\,s=female} w_R,$$

Abundance indices of spawners

$$I_{sp,\,y,\,j} = \left(q_{sp,\,j} N_{sp,\,y}\right)\exp\left(\varepsilon_{sp,\,y,\,j}\right),$$

Abundance indices of fully recruited animals

$$I_{N,\,y,\,s,\,j} = \left(q_{N,\,s,\,j} N_{y,\,s}\right)\exp\left(\varepsilon_{IN,\,y,\,s,\,j}\right),$$

Abundance indices of recruits

$$I_{R,\,y,\,s,\,j} = \left(q_{R,\,s,\,j} R_{y,\,s}\right)\exp\left(\varepsilon_{IR,\,y,\,s,\,j}\right),$$

where R and N are the population size of recruits and fully recruited animals at the beginning of the year respectively, M and F are natural mortality and fishing mortality, v is the proportion of male or female in recruits, C is catch in number, g is selectivity, w is proportion of matured female in female recruits or female fully recruited animals, I is fishery-independent abundance index, q is the catchability; $\varepsilon_{N,\, y+1,\, s} \sim Normal\left(0, \sigma_N^2\right)$ and $\varepsilon_{R,\, y} \sim Normal\left(0, \sigma_R^2\right)$ are process errors, and $\varepsilon_{CN,\, y,\, s} \sim Normal\left(0, \sigma_{CN,\, s}^2\right)$, $\varepsilon_{CR,\, y,\, s} \sim Normal\left(0, \sigma_{CR,\, s}^2\right)$, $\varepsilon_{sp,\, y,\, j} \sim Normal\left(0, \sigma_{sp,\, j}^2\right)$, $\varepsilon_{IN,\, y,\, s,\, j} \sim Normal\left(0, \sigma_{IN,\, s,\, j}^2\right)$, and $\varepsilon_{IR,\, y,\, s,\, j} \sim Normal\left(0, \sigma_{IR,\, s,\, j}^2\right)$ are observation errors, which follow a normal distribution with a mean of zero and a standard deviation of σ; the subscript y indexes the yth year, s represents either male or female, j indexes the jth fishery-independent abundance index, R and N in subscripts denote the recruits and the fully recruited respectively, sp in subscripts denotes spawner.

In the model, a 1:1 sex ratio and sex-specific natural mortalities ($M_{N,\, s}$ and $M_{R,\, s}$) were assumed. The natural mortality was assumed constant over time. The mature female proportion for female recruits (w_R) and female fully recruited (w_N) was set to be 0.044 and 0.9 (Eggleston et al. 2004). The selectivity for fully recruited animals ($g_{N,\, s}$) was set to be one (Rudershausen and Hightower 2016), and selectivity for recruits ($g_{R,\, s}$) was assumed sex-specific and free parameters to estimate in the model. The annual recruitment $R_{y,s}$ was directly estimated to avoid assuming a fixed spawner-recruitment relationship because the spawner size can often only explain a small amount of the high variation in recruitment (Jiao et al. 2012). The annual recruitment $R_{y,s}$ was assumed to follow a lognormal distribution that centers around an average of $\bar{R}$. In North Carolina, fall is the primary spawning season for blue crab, and most harvest occurs during May-October. Thus, in the model, indices sampled since September in the current year (i.e., the P100 fall and P195 September indices) were related to the abundance in the following year, except for the spawner indices (i.e., P195 spawner and SEAMAP spawner indices).

3.2.2 Model Calibration

In this assessment, the Bayesian approach was applied to estimate parameters. 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 500,000 iterations for each chain. The first 470,000 iterations were discarded as burn-in and every 10th iteration from the remaining sample from each chain was used for analysis. The working group used JAGS (Version 4.0.1) to run the Bayesian analysis.

Noninformative priors were used, i.e., uniform priors, for initial population size ($N_{y=1997,\, s}$), averange annual recruitment ($\bar{R}$), fishing mortaltiy (F_y), recruts selectivity ($g_{R,\, s}$), catchability ($q_{sp,\, j}$, $q_{N,\, s,\, j}$ and $q_{R,\, s,\, j}$), and standard deviation (σ_N, σ_R, σ_{CN}, σ_{CR}, $\sigma_{sp,\, j}$, $\sigma_{IN,\, s,\, j}$ and $\sigma_{IR,\, s,\, j}$) of process and obseration errors. The working group constructed a hierarchical prior for natrual mortality parameters where $M_{N,\, s}$ and $M_{R,\, s}$ follow an unknown lognormal distribution centering around $\bar{M}$ that is further governed by a uniform distribution bounded by m_1 and m_2:

$$M_{N,\, s} \;\; or \;\; M_{R,\, s} = \bar{M} \exp\left(\varepsilon_M\right),$$

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

where $\varepsilon_M \sim Normal\left(0, \sigma_M\right)$ is a random error. Priors and parameters are listed in Tables 3.1 and 3.2.

3.2.3 Sensitivity Analysis

In addition to the baseline model above (Model 1), the working group considered three more candidate models (Models 2-4, Table 3.3). These candidate models were similar to Model 1 except that the Model 2 assumed a constant unknown natural mortality over sex and stage; Model 3 used a constant known natural mortality (M = 0.55; Eggleston et al. 2004) for both sexes and stages; Model 4 assumed a Ricker stock-recruitment model for recruits (Ricker 1954):

$$R_{y+1} = \left(\alpha N_{sp,\,y} \exp\left(-\beta N_{sp,\,y}\right)\right) \exp\left(\varepsilon_{R,\,y+1}\right),$$

$$\varepsilon_{R,\,y} \sim N\left(0,\, \sigma_R^2\right),$$

where α is the productivity parameter that represents the number of recuits per spawner at low density of spawners and is proportional to fecundity, β ($\beta > 0$) is the density-dependent parameter that controls the level of density dependence. Other major sensitivity runs that the working group have tested but are not presented here include time-block catchability, random-walk catchability, recruits June index only, recruits September index only, initial year of 1997 (when abundance indices start), sex-constant recruits selectivity to estimate, sex-constant recruits selectivity to input (0.03; Rudershausen and Hightower 2016), sex-constant recruits natural mortality, wider natural mortality constraint, and fixed catch and index standard deviation input.

The working group also conducted a retrospective analysis on spawner abundance and F for the baseline model (Model 1), which estimates the systematic changes in these two parameters as additional years of data were added (Mohn 1999). The working group started with the data from 1995 to 2011, and added one additional year of data at a time up to 2016. The retrospective error is calculated as follows (Mohn 1999; Hurtado-Ferro et al. 2015):

$$\frac{1}{n_{peel}} \sum_{t=2016-n_{peel}}^{2016} \frac{X_t \middle| data\ to\ year\ t - X_t \middle| data\ to\ year\ 2016}{X_t \middle| data\ to\ year\ 2016},$$

where X = spawner abundance or F, and n_{peel} = 5 is the total number of years that are "peeled off". Hurtado-Ferro et al. (2015) suggested a range between -0.22 and 0.3 for short-lived species that any values falling outside this range should indicate a problem of retrospective error and should be cause for concern. Retrospective error may either result from inconsistent or insufficient data, or result from natural variation in population dynamics.

3.2.4 Results

In the baseline model, catch data were fitted well but the fits of abundance index data were not as well as the catch data (Figures 3.2-3.3). Estimated catch for both sexes and both stages declined overall from 1995 to 2016 with a rebound occurring near 2007, especially for fully recruited crabs, but the estimated catch remained low since then (Figure 3.2). The models yielded a declining trend in all abundance indices before 2007 and a rebound afterwards (Figure 3.3). High uncertainty was associated with early years' index estimates either due to lack of data (e.g., 1995 and 1996 in some indices) or due to large across-year variation in index data (e.g., 2007-2014 of P100 indices).

Estimated population size of male recruits, female recruits and overall recruitment showed an overall declining trend with some intermittent periods of population increase, especially the period of 2007-2013 (Figure 3.4). Estimated population size of fully recruited male, female and spawners remained high until a sharp decrease starting in 1998, then followed by a rebound starting in 2007. This rebound sustained the population size of fully recruited females and spawners approximately 50%-75% of those in mid 1990s, and sustained the population size of fully recruited males almost equivalent to the level in mid 1990s. Females had higher natural mortality estimates than males (Figure 3.5). Natural mortality estimates for fully recruited females were associated with higher uncertainty than other stages.

The estimated fishing mortality was high from 1995 to 2006, with a mean ranging from 1.78 to 2.64 (Fig. 3.6). Starting in 2007, fishing mortality estimates decreased to at least 50% of those before 2007, with a mean ranging from 0.72 to 1.49 and the lowest value of 0.72 occurring in 2013. Estimates of fishing mortality in the early years before 2007 were associated with large uncertainty.

Retrospective analysis showed consistent estimates of spawner abundance and *F* with additional years of data added (Figure 3.7). The retrospective errors for spawner abundance and *F* were 0.012 and 0.018, respectively, which fell within the recommended range of -0.22–0.3 and suggested that the retrospective error is less of a concern in this analysis.

The four candidate models produced consistent outcomes (Figures 3.8-3.12). In the two candidate models with sex- and stage-constant natural mortality, the estimated natural mortality from Model 2 (mean = 0.48 and 95% credible interval, 95%CI = 0.4-0.68) was close to the one input in Model 3 (0.55; Figure 3.11). Recruitment estimates from Models 1-3 showed density-dependence (Figure 3.13). At low spawner population size, estimated recruitment tended to be high with more spawners, but tended to decline with more spawners at high spawner population size.

3.2.5 Discussion

The previously established minimum size limit of five inches (127 mm) for North Carolina blue crabs was maintained in the 1998 Fishery Management Plan (FMP), with mature females, soft, and peeler crabs exempted from this size limit. The Blue Crab FMP was amended in 2004 by adopting a spawning stock trigger meant to protect the spawning stock. The 2004 Amendment implemented a seasonal maximum size limit for mature females (6.75 inch for hard crabs and 5.25 inch for peeler crabs) from September 1 through April 30 when the spawning trigger was met. The seasonal maximum size limit was enacted in 2006 and remained in effect through April 2014. This may have contributed to the large reduction in fishing mortality estimates and the rebound in population size estimates, especially for fully recruited female crabs and the boost in SPR estimates since 2007, although industry compliance with this measure is uncertain.

Blue crab is sensitive to flow and salinity, larval and juvenile crabs depends on flow to distribute spatially before settling down (Etherington and Eggleston 2000). North Carolina experienced three sequential destructive hurricanes in 1999, namely Dennis (end of August), Floyd (mid-September) and Irene (mid-October). Heavy rainfall during the first two hurricanes caused massive flooding, reduced salinity, and anoxic conditions in the Pamlico and Neuse River systems, which forced blue crabs out of the rivers and aggregate in Pamlico Sound where the harvest of crabs was high in 1999 (Paerl et al. 2001; Burgess et al. 2007). Statewide catch of fully recruited crabs and female recruits in 1999 was among the highest of the study time period. Low recruitment estimates during 2000-2001 in this assessment may represent a recruitment failure due to the low spawning stock size caused by intense harvest of spawners after the 1999 hurricane season and the potential disruption in larval dispersal and initial settlement caused by the hurricanes (Etherington and Eggleston 2000; Eggleston et al. 2004).

The models fit to index data not as well as to catch data, which reflects the quality of these different types of index datasets. For example, in the SEAMAP spawner data, all samples in certain years (e.g., 1992, 2015) were collected in July, samples in certain years (e.g., 2014, 2016) were collected in both July and August, and samples in certain years such as 2014 were not well balanced among month or location, e.g., in 2014, 27 samples were collected in July versus only four samples were collected in August; all these July samples were from Raleigh Bay and Onslow Bay, and these August samples were from Long Bay. Thus, a sampling scheme that is consistent and well-balanced across year and region would provide better-quality data to improve the model fit to index data.

This assessment did not include discards due to a lack of data. However, discards of blue crabs in North Carolina waters could be a significant source of mortality, especially in the commercial gill net fishery. This assessment, without discards considered, could be overestimating population size. Thus, it is important to establish data collection programs for fishery discards to help improve future stock assessments.

4 STATUS DETERMINATION

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

The 2004 FMP for blue crab defined the overfished condition for the blue crab stock based on commercial landings trends (NCDMF 2004). The blue crab resource was considered overfished when annual commercial landings declined for five consecutive years. No overfishing definition was developed.

The 2011 FMP for blue crab defined the overfished condition based on the blue crab production characteristic of the Traffic Light such that when the proportion of red for the production characteristic is greater than or equal to the third quartile (>=0.75) for three consecutive years, the blue crab stock is considered overfished. No overfishing definition was developed.

In this assessment, the working group evaluated blue crab stock status based on maximum sustainable yield (MSY). The MSY-based biological reference points (BRPs) have been widely used in fishery stock assessments including blue crabs, e.g., Chesapeake Bay 2001 (Miller et al. 2011), Florida 2007 (Murphy et al. 2007) and Gulf of Mexico 2013 assessments (VanderKooy 2013). In this assessment, the MSY-based BRPs were developed by estimating a Ricker spawner-recruit relationship outside the two-stage model (Shepherd 1982). Specifically,

Spawner-per-recruit (SPR) (Quinn and Deriso 1999)

$$SPR = v_{s=female}\left(w_R + w_N \frac{\exp\left(-Fg_{R,\ s=female} - M_{R,\ s=female}\right)}{1-\exp\left(-Fg_{N,\ s=female} - M_{N,\ s=female}\right)} \right),$$

Yield-per-recruit (YPR)

$$YPR = \sum_s \left(\frac{v_s Fg_{R,s}}{Fg_{R,s} + M_{R,s}} \left(1 - \exp\left(-Fg_{R,s} - M_{R,s}\right)\right) \right) + \sum_s \left(\frac{v_s Fg_{N,s}}{Fg_{N,s} + M_{N,s}} \exp\left(-Fg_{R,s} - M_{R,s}\right) \right),$$

Equilibrium spawner abundance

$$N_{sp}^* = \frac{\ln(\alpha) + \ln(SPR)}{\beta},$$

Equilibrium recruitment

$$R^* = \frac{N_{sp}^*}{SPR},$$

Total yield

$$Total\ \ yield = R^* \times YPR.$$

The fishing mortality that maximizes the total yield (F_{MSY}) was set to be the threshold for overfishing, and 0.75F_{MSY} was set to be the target fishing mortality. The spawner abundance at F_{MSY} (SP_{MSY}) and 0.75 F_{MSY} was set to be the threshold and target for overfished population, respectively. In the current stock assessment, the populaion is determined being overfished if the average spawner abundance in 2016 falls below SP_{MSY}, and is determined to be undergoing overfishing if the average F in 2016 remains above F_{MSY}.

For the current assessment (2016), determination of the current population status is based on the baseline model (Figure 3.6). In the baseline model, the threshold SP_{MSY} was estimated to be 64 million on average, and the target spawner abundance was estimated to be 73 million on average. The average spawner abundance of the year 2016 was estimated to be 50 million (< the threshold) with a 95%CI of 37-68 million, which determines the population in 2016 is overfished with a probability of 0.98. In the baseline model, the F threshold F_{MSY} and F target 0.75F_{MSY} was estimated to be 1.46 and 1.22 on average respectively, and the fishing mortality of 2016 was averaged 1.48 (> F threshold) with a 95%CI of 0.86-2.42, which determines overfishing is occurring in 2016 with a probability of 0.52.

In this assessment, the working group did not use spawning potential ratio (SPR/SPR at virgin level) based BRPs that compare with the virgin level, e.g., North Carolina 2004 assessment (Eggleston et al. 2004) and Louisiana 2016 assessment (West et al. 2016). This assessment spans from 1995 to 2016 due to data limitation, and the fishery began in the 1950s. The model may not sufficiently capture the population dynamics back to the virgin level due to such a short time series of data relative to history of the fishery, which makes it difficult to obtain reliable BRP estimates that compare with the virgin level.

5 SUITABILITY FOR MANAGEMENT

Stocks assessments performed by the NCDMF in support of fishery management plans are subject to an extensive review process. Internal reviews are conducted by various groups within the NCDMF including the species plan development team and the Management Review Team. External reviews are designed to provide an independent peer review and are conducted by experts in stock assessment science and experts in the biology and ecology of the species. The goal of the external review is to ensure the results are based on sound science and provide a valid basis for management. The external peer reviewer panel accepted the baseline two-stage model as appropriate for management use for the next five years, and agree the determination of North Carolina blue crab stock status concurs with professional opinion and observations. The reviewers also agree that: (1) the justification of inclusion and exclusion of data sources are appropriate; (2) the data sources used in this assessment are appropriate; (3) the baseline two-stage model is a significant improvement over the traffic light approach used previously, and is robust to assumptions that have been explored in sensitivity analysis, such as assumptions regarding natural mortality and growth; (4) determination of stock status is robust to model assumptions; (5) although reviewers expressed concerns regarding spatial coverage of abundance indices and model complexity, sensitivity analysis indicates model results and stock status determination are robust to the reviewers' primary areas of concerns. Detailed comments from the external peer reviewers are provided in Appendix B, and results of additional sensitivity analyses requested by the reviewers are provided in Appendix C.

6 RESEARCH RECOMMENDATIONS

This assessment successfully applied a comprehensive stock assessment method, however, the performance of the assessment model could be improved with additional data. To address this, the following research recommendations are offered. Those research recommendations denoted with an asterisk (*) were suggested (and ranked) by the external peer reviewers.

<u>High</u>

- Develop statewide fishery-independent survey(s) to monitor the abundance of all blue crab life stages
- Expand time and area coverage of existing fishery-independent surveys
- Better characterize the magnitude of recreational harvest *
- Develop better estimates of life-history parameters, especially growth and natural mortality *
- Explore alternative biological reference points *

<u>Medium</u>

- Identify key environmental factors that significantly impact North Carolina's blue crab stock and investigate assessment methods that can account for these environmental factors
- Implement monitoring of hazardous events (e.g., hurricane, extreme heat or cold weather) affecting blue crab population dynamics and harvest
- Explore alternative model types *

<u>Low</u>

- Investigate and support research on promising methods to age blue crabs
- Evaluate the genetic stock structure of blue crabs within North Carolina and the magnitude of mixing between populations
- Identify programs outside the NCDMF that collect data of potential use to the stock assessment of North Carolina's blue crabs

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8 TABLES

Table 1.1. Water quality parameters required by and habitats associated with different life stages of blue crab. No documented data where blank (Funderburk et al.1991; Pattilo et al. 1997; Wannamaker and Rice (2000); NOAA 2001).

Life Stage	Salinity (ppt)	Temperature (C)	DO (mg/l)	Associated Habitats
Adult	0-30	5-39	>3	Entire estuary
Spawning Female	23-28	19-29		Inlet and Ocean
Larvae	>20	16-30		Inlet and Ocean
Juveniles	2-21	16-30		Wetlands, SAV, Shell Bottom, Soft Bottom

Table 1.2. Number of fishermen (excluding crew) that reported landings of blue crabs in North Carolina, associated number of trips, average crew size, and estimated total number of participants (fishermen + crew), 1994–2016.

Year	Number of Fishermen	Number of Trips	Average Crew Size	Total Participants
1994	2,059	121,833		
1995	2,211	125,974		
1996	2,287	123,900		
1997	2,284	132,493		
1998	2,004	143,055		
1999	1,916	124,378	1.40	2,690
2000	1,756	111,213	1.39	2,442
2001	1,787	113,571	1.41	2,526
2002	1,681	93,620	1.47	2,473
2003	1,578	91,730	1.45	2,292
2004	1,489	80,828	1.46	2,169
2005	1,216	64,029	1.43	1,735
2006	1,010	52,886	1.42	1,437
2007	952	53,833	1.46	1,387
2008	914	52,654	1.54	1,409
2009	990	59,313	1.60	1,587
2010	984	54,977	1.52	1,498
2011	925	52,406	1.59	1,472
2012	895	52,696	1.57	1,403
2013	863	52,630	1.55	1,340
2014	923	56,217	1.54	1,425
2015	923	57,603	1.58	1,454
2016	884	51,707	1.61	1,424

Table 1.3. Estimated number of blue crab directed recreational fishing trips compared to estimated total number of recreational fishing trips, and estimated number of blue crabs harvested and discarded by RCGL license holders in North Carolina, 2002–2008.

	Number of Trips		Percent of total trips	Harvest	Discards
Year	Total	Directed			
2002	80,159	28,324	35%	346,550	185,939
2003	55,787	27,907	50%	354,425	124,196
2004	53,488	28,021	52%	329,478	138,316
2005	47,120	26,278	56%	323,531	152,905
2006	43,384	24,401	56%	297,875	123,787
2007	41,617	25,153	60%	286,856	102,695
2008	40,556	24,732	61%	311,690	132,519

Table 1.4. Total effort and catch (in numbers of crabs) estimates based on CAP shellfish mail survey, 2011-2016.

Year	Wave	Total Effort	Total Harvest	Total Release	Total Catch
2011	Jan/Feb	658	2,253	1,287	3,540
	Mar/Apr	1,570	5,472	4,725	10,197
	May/Jun	8,253	36,477	19,310	55,786
	Jul/Aug	7,416	33,159	32,266	65,426
	Sep/Oct	5,333	29,034	20,718	49,752
	Nov/Dec	1,588	8,031	3,457	11,488
	Total	24,818	114,426	81,763	196,189
2012	Jan/Feb	781	1,215	330	1,545
	Mar/Apr	2,196	8,230	5,504	13,734
	May/Jun	7,311	23,564	14,762	38,326
	Jul/Aug	11,262	61,648	40,210	101,858
	Sep/Oct	3,625	19,563	13,405	32,968
	Nov/Dec	1,688	6,759	4,861	11,620
	Total	26,863	120,979	79,072	200,051
2013	Jan/Feb	161	0	0	0
	Mar/Apr	1,784	1,528	1,162	2,690
	May/Jun	6,225	23,150	11,528	34,678
	Jul/Aug	9,555	40,004	20,143	60,147
	Sep/Oct	10,599	25,976	25,872	51,848
	Nov/Dec	2,408	3,516	2,747	6,263
	Total	30,732	94,174	61,452	155,626
2014	Jan/Feb	335	0	0	0
	Mar/Apr	1,222	2,872	2,322	5,195
	May/Jun	8,477	25,749	18,019	43,768
	Jul/Aug	5,584	35,911	23,067	58,978
	Sep/Oct	7,282	35,882	23,975	59,856
	Nov/Dec	481	183	30	213
	Total	23,381	100,597	67,413	168,010
2015	Jan/Feb	760	0	0	0
	Mar/Apr	2,993	4,648	5,897	10,546
	May/Jun	5,182	22,461	14,429	36,890
	Jul/Aug	10,880	31,483	28,123	59,605
	Sep/Oct	5,743	12,309	8,925	21,234
	Nov/Dec	2,405	686	2,761	3,415
	Total	27,963	71,587	60,135	131,690
2016	Jan/Feb	1,218	0	0	0
	Mar/Apr	1,111	4,696	3,351	8,047
	May/Jun	5,192	16,720	18,446	35,166
	Jul/Aug	7,435	21,722	41,521	63,243
	Sep/Oct	7,537	40,047	19,157	59,204
	Nov/Dec	832	1,694	305	1,999
	Total	23,325	84,879	82,780	167,659

Table 1.5. Management measures in N.C. Blue Crab Fishery Management Plan Amendment 2 that may be implemented by proclamation as described in the blue crab adaptive management framework when a stock characteristic exceeds a designated management threshold.

Characteristic	Moderate management level	Elevated management level
Adult abundance	A1. Increase in minimum size limit for male and immature female crabs	A4. Closure of the fishery (season and/or gear)
	A2. Reduction in tolerance of sub-legal size blue crabs (to a minimum of 5%) and/or implement gear modifications to reduce sublegal catch	A5. Reduction in tolerance of sub-legal size blue crabs (to a minimum of 1%) and/or implement gear modifications to reduce sublegal catch
	A3. Eliminate harvest of v-apron immature hard crab females	A6. Time restrictions
Recruit abundance	R1. Establish a seasonal size limit on peeler crabs	R4. Prohibit harvest of sponge crabs (all) and/or require sponge crab excluders in pots in specific areas
	R2. Restrict trip level harvest of sponge crabs (tolerance, quantity, sponge color)	R5. Expand existing and/or designate new crab spawning sanctuaries
	R3. Close the crab spawning sanctuaries from September 1 to February 28 and may impose further restrictions	R6. Closure of the fishery (season and/or gear)
		R7. Gear modifications in the crab trawl fishery
Production	P1. Restrict trip level harvest of sponge crabs (tolerance, quantity, sponge color)	P4. Prohibit harvest of sponge crabs (all) and/or require sponge crab excluders in pots for specific areas
	P2. Minimum and/or maximum size limit for mature female crabs	P5. Reduce peeler harvest (no white line peelers and/or peeler size limit)
	P3. Close the crab spawning sanctuaries from September 1 to February 28 and may impose further restrictions	P6. Expand existing and/or designate new crab spawning sanctuaries
		P7. Closure of the fishery (season and/or gear)

Table 2.1. Frequency of occurrence, number of samples, CPUE, standard error, minimum number caught in a sample, maximum number caught in a sample, and total number caught by year for all blue crab from Program 120 core stations, 1971-2016.

Year	Percent Frequency of Occurrence	Total Number of Samples	CPUE	Standard Error	Minimum Number per Sample	Maximum Number per Sample	Total Number of Blue Crab
1971	100	3	6.00	1.53	3	8	18
1972*	.	.	.	.	.	.	.
1973	61.5	26	2.46	0.92	0	23	64
1974	79.2	24	20.42	6.55	0	120	490
1975	64.1	39	4.69	1.31	0	30	183
1976	66.7	14	15.21	5.37	0	52	213
1977	76.9	13	14.54	8.52	0	113	189
1978	64.4	87	3.09	0.60	0	39	269
1979	71.3	136	3.79	0.41	0	29	516
1980	77.2	145	4.42	0.49	0	34	641
1981	87.0	146	8.92	1.15	0	106	1,302
1982	85.7	154	8.44	1.03	0	102	1,299
1983	83.6	183	7.33	0.91	0	83	1,342
1984	86.6	186	8.64	0.92	0	114	1,607
1985	87.7	195	8.97	0.73	0	70	1,750
1986	74.5	204	5.33	0.67	0	92	1,087
1987	83.0	206	9.38	2.03	0	396	1,933
1988	80.4	209	10.23	1.30	0	124	2,139
1989	70.0	207	4.49	0.64	0	73	930
1990	78.2	206	7.57	0.80	0	64	1,559
1991	70.5	207	5.25	0.56	0	53	1,086
1992	66.3	208	4.36	0.53	0	71	907
1993	71.7	204	7.70	1.25	0	163	1,570
1994	77.6	205	8.12	1.39	0	237	1,665
1995	75.5	208	8.05	0.89	0	92	1,674
1996	83.6	207	13.50	1.37	0	107	2,794
1997	74.9	207	9.29	0.97	0	66	1,922
1998	69.2	208	6.51	0.86	0	115	1,354
1999	79.1	206	10.68	1.16	0	120	2,200
2000	77.9	208	4.40	0.45	0	47	915

Year	Percent Frequency of Occurrence	Total Number of Samples	CPUE	Standard Error	Minimum Number per Sample	Maximum Number per Sample	Total Number of Blue Crab
2001	67.3	208	7.55	1.54	0	285	1,571
2002	80.8	208	9.44	1.05	0	107	1,963
2003	70.2	208	5.75	0.74	0	90	1,197
2004	83.7	208	9.98	1.09	0	105	2,076
2005	75.0	208	6.49	0.84	0	122	1,350
2006	69.2	208	6.30	0.80	0	61	1,310
2007	68.8	208	5.52	0.75	0	95	1,149
2008	76.0	208	8.12	0.84	0	79	1,688
2009	65.9	208	7.80	1.52	0	202	1,622
2010	74.0	208	7.80	0.88	0	124	1,622
2011	74.0	208	7.43	0.76	0	78	1,546
2012	73.6	208	8.81	0.97	0	106	1,832
2013	65.4	208	3.58	0.46	0	51	744
2014	59.1	208	3.64	0.61	0	89	758
2015	69.7	208	5.85	0.83	0	126	1,216
2016	61.5	208	3.04	0.37	0	49	632

* No samples from core stations in 1972

Table 2.2. Frequency of occurrence, number of samples, CPUE, standard error, minimum number caught in a sample, maximum number caught in a sample, and total number caught by year for all blue crab from Program 100 core stations, 1972-2016.

Year	Percent Frequency of Occurrence	Total Number of Samples	CPUE	Standard Error	Minimum Number per Sample	Maximum Number per Sample	Total Number of Blue Crabs
1972	25.0	12	0.67	0.40	0	4	8
1973	25.0	28	0.39	0.15	0	3	11
1974	46.9	49	4.49	1.92	0	86	220
1975	62.5	24	2.67	0.90	0	16	64
1976	60.0	20	2.05	0.63	0	9	41
1977	66.7	18	1.72	0.46	0	7	31
1978	15.0	60	0.23	0.09	0	4	14
1979	10.8	37	0.16	0.09	0	3	6
1980	2.7	37	0.08	0.08	0	3	3
1981	34.2	38	0.74	0.22	0	6	28
1982	6.9	101	0.07	0.03	0	1	7
1983	11.7	137	0.15	0.04	0	3	21
1984	7.1	126	0.08	0.03	0	2	10
1985	47.6	147	1.04	0.13	0	7	153
1986	70.6	119	6.43	0.99	0	61	765
1987	48.8	162	1.57	0.27	0	22	254
1988	59.3	140	4.44	0.59	0	34	621
1989	43.6	140	2.90	0.70	0	49	406
1990	24.3	140	0.53	0.13	0	13	74
1991	36.4	140	0.73	0.13	0	12	102
1992	47.9	140	1.57	0.28	0	22	220
1993	32.9	140	0.63	0.10	0	6	88
1994	60.7	140	3.37	0.52	0	46	472
1995	81.4	140	5.78	0.79	0	62	809
1996	45.0	140	1.24	0.28	0	34	174
1997	7.9	140	0.11	0.04	0	4	15
1998	40.0	140	3.46	2.19	0	305	484
1999	58.6	140	4.89	1.37	0	180	684
2000	40.7	140	1.71	0.30	0	21	240
2001	25.0	140	0.46	0.09	0	9	65
2002	72.9	140	4.47	0.74	0	85	626
2003	68.6	140	6.71	0.89	0	51	940
2004	31.4	140	0.76	0.15	0	13	107
2005	62.5	128	2.23	0.32	0	25	286
2006	77.1	140	4.76	0.57	0	45	667
2007	74.3	140	4.34	0.59	0	51	607
2008	92.9	140	25.66	3.75	0	346	3593

Year	Percent Frequency of Occurrence	Total Number of Samples	CPUE	Standard Error	Minimum Number per Sample	Maximum Number per Sample	Total Number of Blue Crabs
2009	96.4	140	20.04	1.99	0	173	2806
2010	97.1	140	24.29	2.35	0	157	3401
2011	79.3	140	10.09	1.23	0	64	1413
2012	84.3	140	10.56	2.64	0	352	1479
2013	76.4	140	4.21	0.70	0	65	589
2014	55.0	140	3.67	0.64	0	40	514
2015	93.6	140	19.29	3.10	0	294	2700
2016	85.7	140	11.68	1.27	0	96	1635

Table 2.3. Number of sample grids per strata used as weighting factors for catch-per-unit-effort calculations for Program 195.

Strata	Strata Abbreviation	Number of Grids
Neuse River	NR	93
Pamlico River	PR	64
Pungo River	PUR	18
Pamlico Sound Deep East	PDE	554
Pamlico Sound Shallow East	PSE	206
Pamlico Sound Deep West	PDW	312
Pamlico Sound Shallow West	PSW	135

Table 2.4. Frequency of occurrence, number of samples, weighted CPUE, standard error, minimum number caught in a sample, maximum number caught in a sample, and total number caught by year for all blue crabs from Program 195, 1987 – 2016.

Year	Percent Frequency of Occurrence	Total Number of Samples	Weighted CPUE	Standard Error	Minimum Number per Sample	Maximum Number per Sample	Total Number of Blue Crabs
1987	92.7	96	68.83	12.33	0	769	6,806
1988	92.6	95	33.42	5.39	0	323	3,316
1989	90.0	90	45.13	8.52	0	551	3,890
1990	100	105	155.64	26.86	1	1,706	15,475
1991	86.8	106	138.04	21.07	0	1,521	14,967
1992	94.3	105	63.39	9.79	0	557	6,448
1993	97.2	107	62.27	9.72	0	508	6,416
1994	93.1	102	53.54	6.34	0	394	5,359
1995	100	105	31.70	4.16	1	193	3,607
1996	97.1	105	63.41	8.58	0	401	6,589
1997	96.2	106	71.39	10.21	0	430	7,467
1998	93.4	106	55.82	11.96	0	1,052	6,027
1999	93.4	106	76.24	8.28	0	374	8,207
2000	93.4	106	28.93	3.69	0	451	3,598
2001	69.8	106	31.25	5.95	0	277	3,111
2002	81.0	105	49.73	8.08	0	387	5,528
2003	85.8	106	56.51	12.25	0	800	5,817
2004	84.1	107	52.22	10.62	0	682	7,208
2005	88.5	104	27.05	3.78	0	217	3,213
2006	73.1	108	18.03	3.14	0	575	3,007
2007	77.1	105	12.54	2.73	0	156	1,590
2008	72.2	108	20.13	4.12	0	229	2,508
2009	66.7	108	6.53	1.45	0	152	952
2010	82.4	108	58.69	11.62	0	732	6,831
2011	76.9	108	15.72	4.15	0	337	2,557
2012	73.1	108	17.09	3.02	0	269	2,128
2013	72.2	108	25.04	5.17	0	334	2,578
2014	68.5	108	11.09	1.82	0	106	1,215
2015	66.7	108	9.16	2.64	0	515	1,656
2016	82.4	108	17.19	2.75	0	526	2,807

Table 2.5. Frequency of occurrence, number of samples, CPUE, standard error, minimum number caught in a sample, maximum number caught in a sample, and total number caught by year for all blue crabs from the SEAMAP Coastal Survey by season, 1989 – 2016.

	Spring							Summer							Fall						
Year	Percent Frequency of Occurrence	Total Number of Samples	CPUE	Standard Error	Minimum Number per Sample	Maximum Number per Sample	Total Number of Blue Crab	Percent Frequency of Occurrence	Total Number of Samples	CPUE	Standard Error	Minimum Number per Sample	Maximum Number per Sample	Total Number of Blue Crab	Percent Frequency of Occurrence	Total Number of Samples	CPUE	Standard Error	Minimum Number per Sample	Maximum Number per Sample	Total Number of Blue Crab
1989	0.0	13	0	.	.	.	0	46.2	13	2.38	0.78	0	7	31	61.5	13	2.23	0.66	0	7	29
1990	11.1	18	0.11	0.07	0	1	2	94.4	18	22.78	7.11	0	99	410	82.4	17	6.00	3.90	0	70	102
1991	22.2	18	0.22	0.10	0	1	4	61.1	18	4.00	2.45	0	46	72	29.4	17	0.82	0.57	0	10	14
1992	5.6	18	0.44	0.43	0	8	8	50.0	18	3.06	1.38	0	22	55	44.4	18	1.17	0.43	0	7	21
1993	11.1	18	0.17	0.12	0	2	3	61.1	18	16.72	6.14	0	83	301	33.3	18	1.89	1.02	0	18	34
1994	11.1	18	0.28	0.22	0	4	5	66.7	18	5.17	2.23	0	39	93	38.9	18	1.06	0.43	0	7	19
1995	0.0	18	0	.	.	.	0	50.0	18	4.50	1.87	0	32	81	11.1	18	0.11	0.07	0	1	2
1996	5.6	18	0.11	0.11	0	2	2	77.8	18	17.94	6.76	0	118	323	33.3	18	0.50	0.23	0	4	9
1997	22.2	18	0.33	0.16	0	2	6	50.0	18	2.06	0.71	0	10	37	5.6	18	0.22	0.22	0	4	4
1998	11.1	18	0.11	0.07	0	1	2	66.7	18	7.83	2.92	0	46	141	16.7	18	0.67	0.54	0	10	12
1999	5.6	18	0.06	0.05	0	1	1	38.9	18	1.00	0.36	0	5	18	38.9	18	2.39	1.27	0	23	43
2000	0.0	18	0	.	.	.	0	66.7	18	2.83	0.95	0	17	51	5.6	18	0.06	0.05	0	1	1
2001	6.5	31	0.10	0.07	0	2	3	54.8	31	8.52	4.73	0	145	264	29.0	31	0.58	0.24	0	6	18
2002	6.7	30	0.20	0.14	0	3	6	56.7	30	1.73	0.59	0	17	52	13.3	30	0.23	0.12	0	3	7
2003	6.7	30	0.23	0.20	0	6	7	43.3	30	1.97	0.57	0	11	59	46.7	30	0.77	0.19	0	4	23
2004	6.1	33	0.67	0.47	0	14	22	66.7	33	18.45	6.42	0	197	609	24.2	33	2.55	1.25	0	38	84
2005	12.1	33	0.21	0.13	0	4	7	39.4	33	3.97	1.28	0	31	131	9.1	33	0.12	0.07	0	2	4
2006	0.0	30	0	.	.	.	0	48.3	29	4.66	1.20	0	21	135	20.0	30	1.67	0.77	0	16	50
2007	0.0	28	0	.	.	.	0	25.0	28	1.54	0.87	0	21	43	0.0	28	0	.	.	.	0
2008	0.0	27	0	.	.	.	0	14.8	27	0.26	0.15	0	4	7	11.1	27	0.56	0.31	0	6	15
2009	0.0	30	0	.	.	.	0	36.7	30	2.23	1.36	0	41	67	3.3	30	0.03	0.03	0	1	1
2010	9.7	31	0.13	0.08	0	2	4	32.3	31	0.97	0.36	0	10	30	9.7	31	0.10	0.05	0	1	3
2011	36.4	33	1.06	0.57	0	19	35	30.3	33	1.82	0.66	0	17	60	33.3	33	0.76	0.24	0	5	25
2012	45.5	33	1.76	0.68	0	21	58	36.4	33	1.00	0.34	0	9	33	12.1	33	0.15	0.08	0	2	5
2013	21.1	19	0.21	0.09	0	1	4	40.0	30	1.13	0.34	0	7	34	23.3	30	0.50	0.20	0	4	15
2014	12.9	31	0.13	0.06	0	1	4	29.0	31	2.23	0.79	0	20	69	12.9	31	0.13	0.06	0	1	4
2015	3.2	31	0.03	0.03	0	1	1	23.5	34	1.74	0.74	0	16	59	9.7	31	0.52	0.34	0	9	16
2016	5.9	34	0.06	0.04	0	1	2	29.4	34	1.06	0.39	0	9	36	17.6	34	1.15	0.51	0	13	39

Table 3.1. Parameters and priors. U denotes uniform distribution.

Parameters	Values	Reference
Input parameters		
Sex ratio	1:1	
Selectivity for fully recruited	$g_{N,\,s}=1$	Rudershausen and Hightower 2016
Proportion of mature females	$w_N=0.9$; $w_R=0.044$	Eggleston et al. 2004
Natural mortality (Model 3)	M=0.55	Eggleston et al. 2004
Priors		
Initial population size (10^6)	$N_{y=1997,\,s=male}\sim$ U(58, 5800) $N_{y=1997,\,s=female}\sim$ U(58, 5800)	Derived from catch data in initial year (1995)[a]
Average recruitment (10^6)	$\bar{R}\sim$ U(10, 1000)	Derived from catch data[b]
Initial recruitment (10^6; Model 4)	$R_{y=1997}\sim$ U(10, 1000)	
Natural mortality (yr^{-1})	$\bar{M}\sim$ U(0.5, 2)	Miller et al. 2011; Murphy et al. 2007
Fishing mortality (yr^{-1})	$F_y\sim$ U(0.001, 3)	Eggleston et al. 2004
Selectivity for recruits	$g_{R,\,s}\sim$ U(0, 0.6)	Rudershausen and Hightower 2016
Ricker productivity parameter (#offspring per spawner; Model 4)	$\alpha\sim$ U(1, 15)	Eggleston et al. 2004; VanderKooy 2013
Ricker density-dependence parameter (Model 4)	$\beta=0.005$	Eggleston et al. 2004; VanderKooy 2013
Standard deviation of process errors	σ_N, $\sigma_R\sim$ U(0.001, 10)	
Standard deviation of observation errors	$\sigma_{CN,\,s}$, $\sigma_{CR,s}\sim$ U(0.001, 10) $\sigma_{sp,\,j}$, $\sigma_{IN,\,s,\,j}$, $\sigma_{IR,\,s,\,j}\sim$ U(0.001, 10)	
Standard deviation of natural mortality error	σ_{MM}, $\sigma_M\sim$ U(0.001, 1)	

Table 3.2. Priors for catchability (q; 10^{-6}). U denotes uniform distribution. Derived from catch and abundance index data by assuming catch is the lower bound for population size and 100 x catch is the upper bound. Set minimum index /(100 x maximum catch) as lower bound, and maximum index /minimum catch as upper bound.

Abundance index	Priors
P120 male recruits	U(0.0001, 4)
P195 male recruits June	U(0.0001, 58)
P195 male recruits September	U(0.0001, 13)
P120 female recruits	U(0.0001, 8)
P195 female recruits June	U(0.0001, 202)
P195 female recruits September	U(0.0001, 32)
P100 male fully recruited summer	U(0.0001, 0.5)
P100 male fully recruited fall	U(0.0001, 0.5)
P195 male fully recruited June	U(0.0001, 0.5)
P195 male fully recruited September	U(0.0001, 0.5)
P100 female fully recruited summer	U(0.0001, 0.1)
P100 female fully recruited fall	U(0.0001, 1)
P195 female fully recruited June	U(0.0001, 1)
P195 female fully recruited September	U(0.0001, 0.5)
P195 spawner	U(0.0001, 1)
SEAMAP spawner	U(0.0001, 1.5)

Table 3.3. Candidate models.

Model	Features
Model 1 (baseline)	Sex- and stage-specific natural mortality
	Recruitment free parameter to estimate (lognormal distribution)
	Time-constant catchability
	All abundance indices
	Initial year when catch data start (1995)
	Sex-specific recruits selectivity to estimate
Model 2	Same as Model 1 except a constant natural mortality to estimate
Model 3	Same as Model 1 except a constant natural mortality to input
Model 4	Same as Model 1 except recruitment follows a Ricker model

9 FIGURES

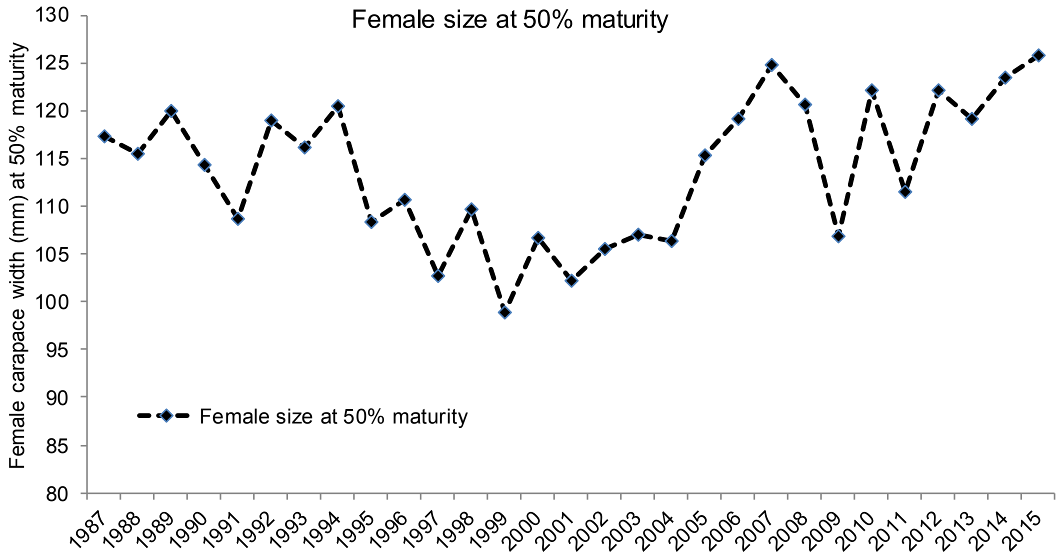


Figure 1.1. Annual carapace width at 50% maturity for female blue crabs collected in several NCDMF sampling programs and North Carolina water bodies, 1987-2015.

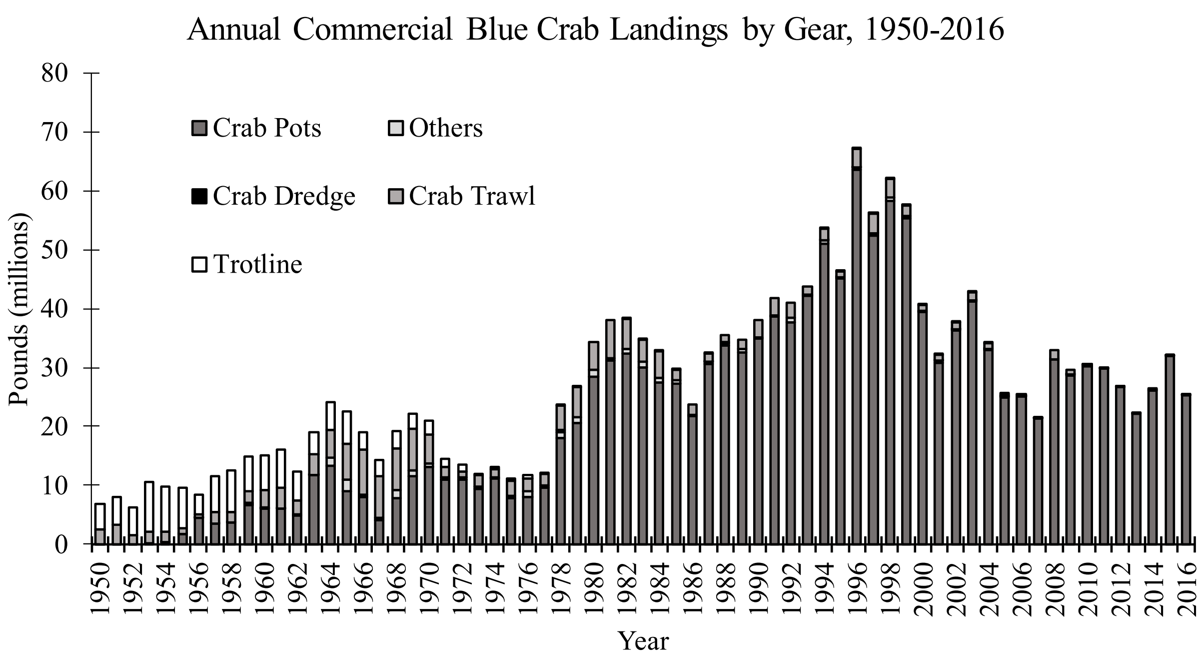


Figure 1.2. Annual commercial fishery landings of blue crabs in North Carolina, by major gear, 1950–2016.

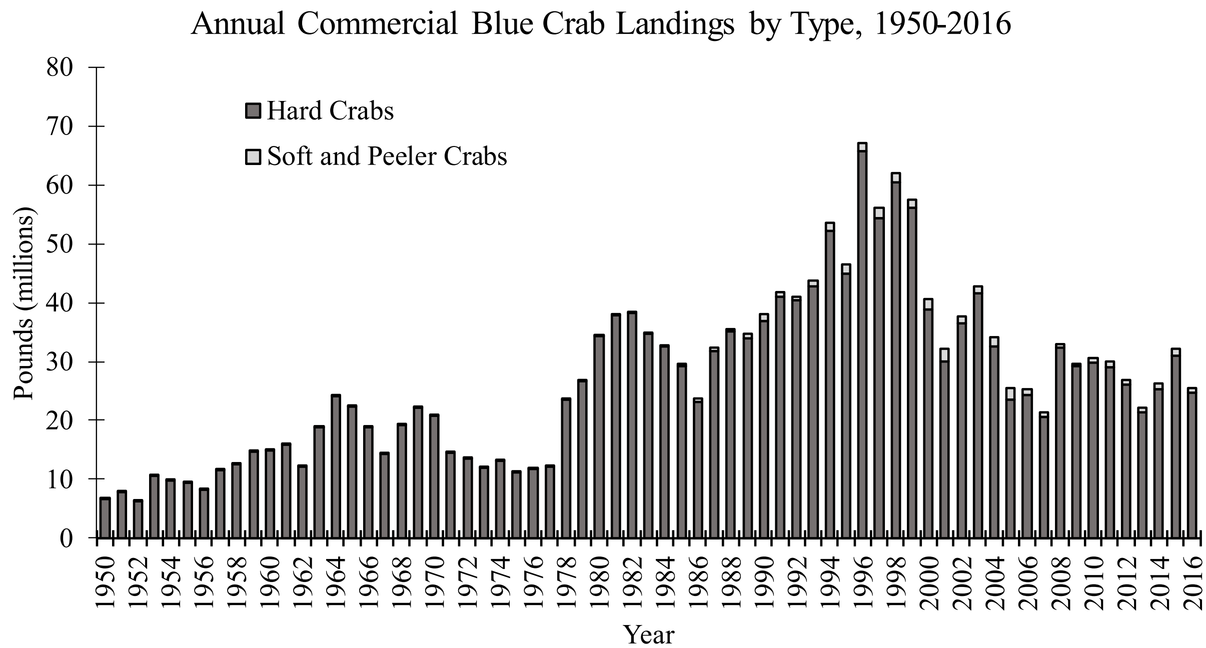


Figure 1.3. Annual commercial fishery landings of blue crabs in North Carolina, by crab type, 1950–2016.

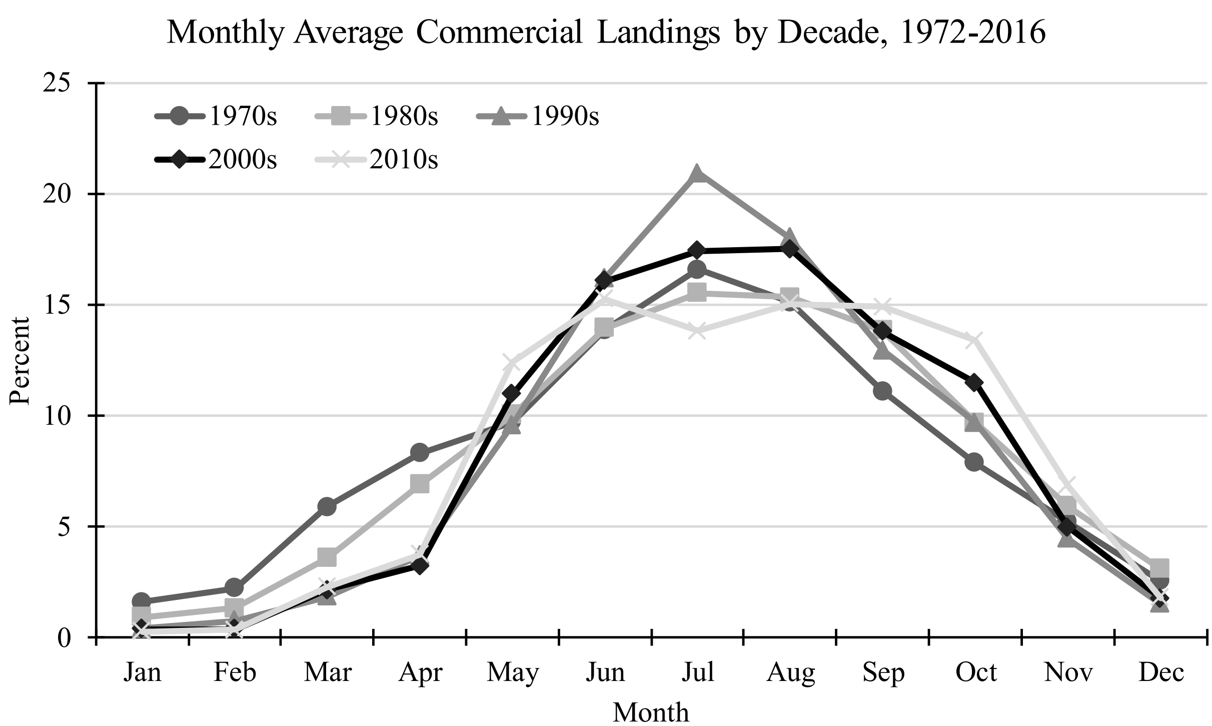


Figure 1.4. Average percent of blue crab commercial landings among months, by decade, 1972–2016.

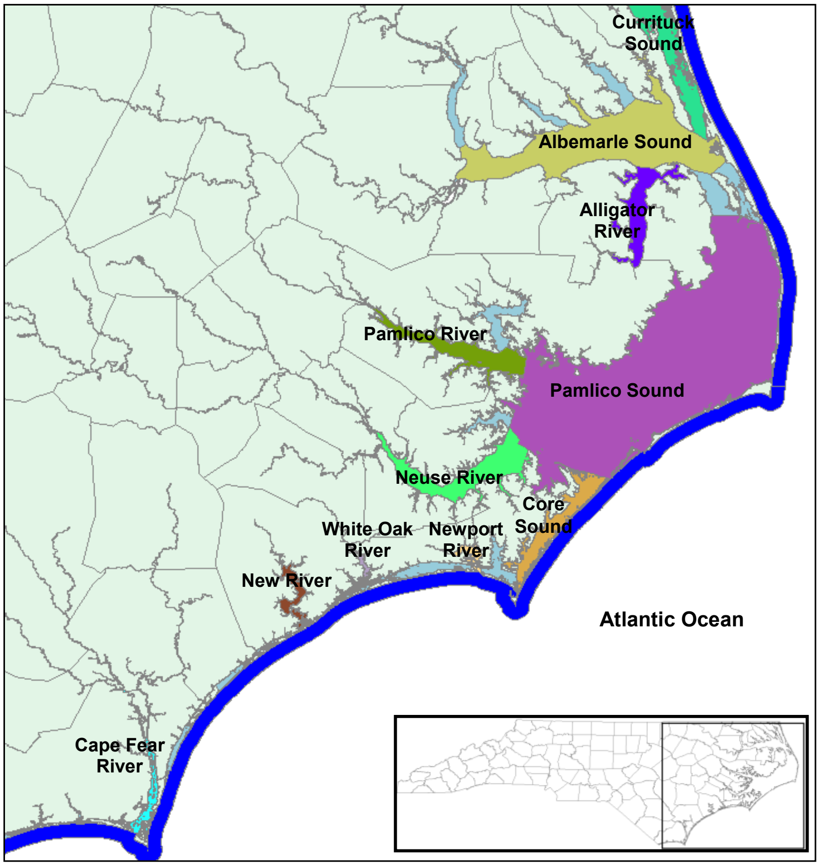


Figure 1.5. Major water bodies within and around North Carolina. The dark blue area represents the extent of the state's coastal fishing waters, which extend to three miles offshore.

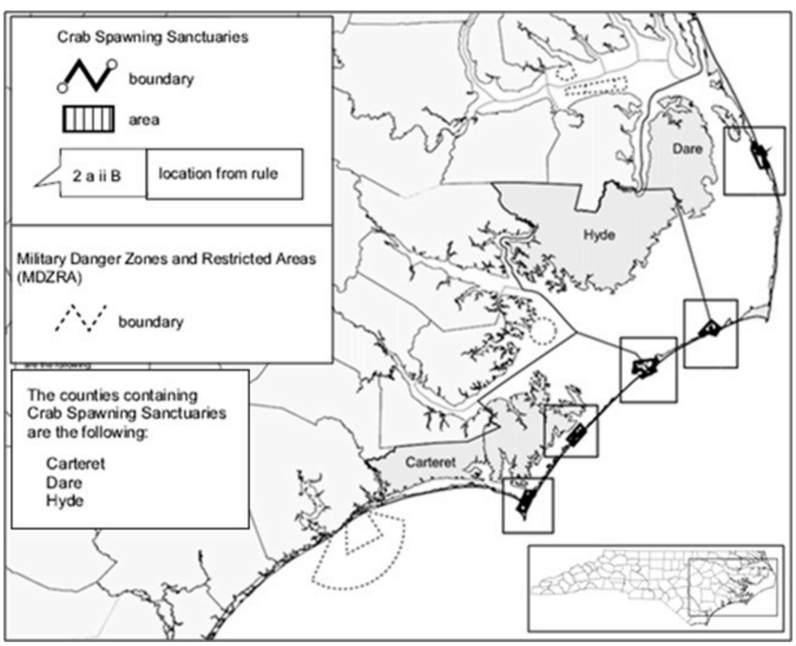


Figure 1.6. General location of blue crab spawning sanctuary areas for the protection of mature female crabs (NCMFC rules 15 NCAC 03L .0205 and 03R .0110).

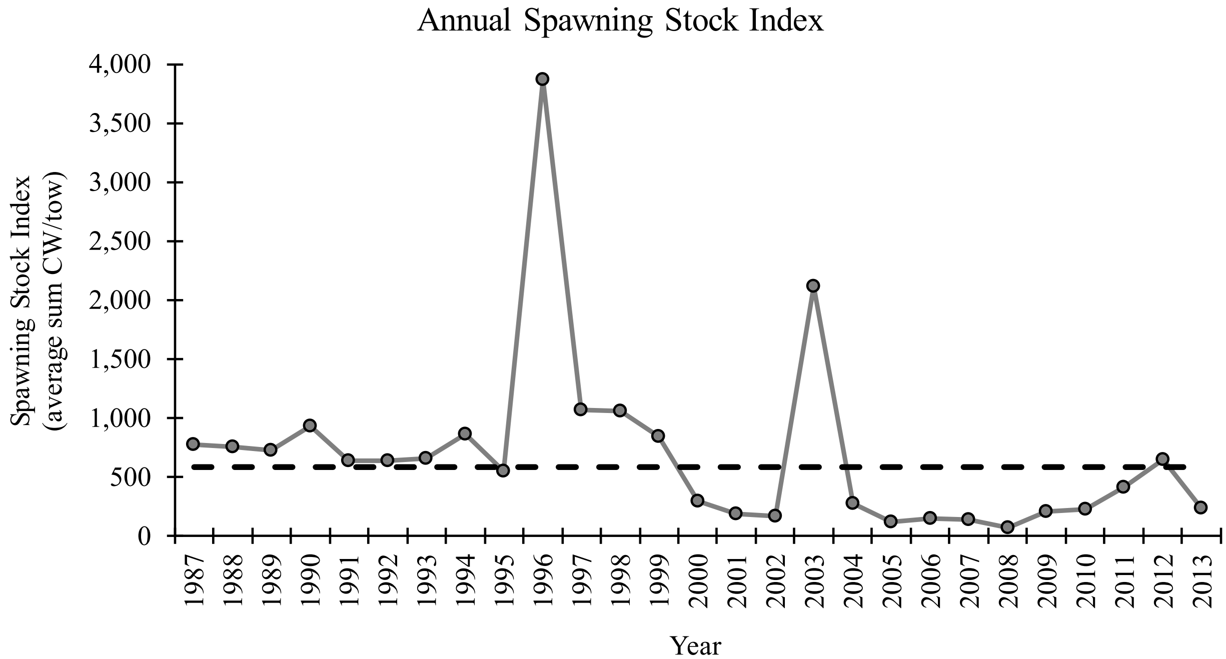
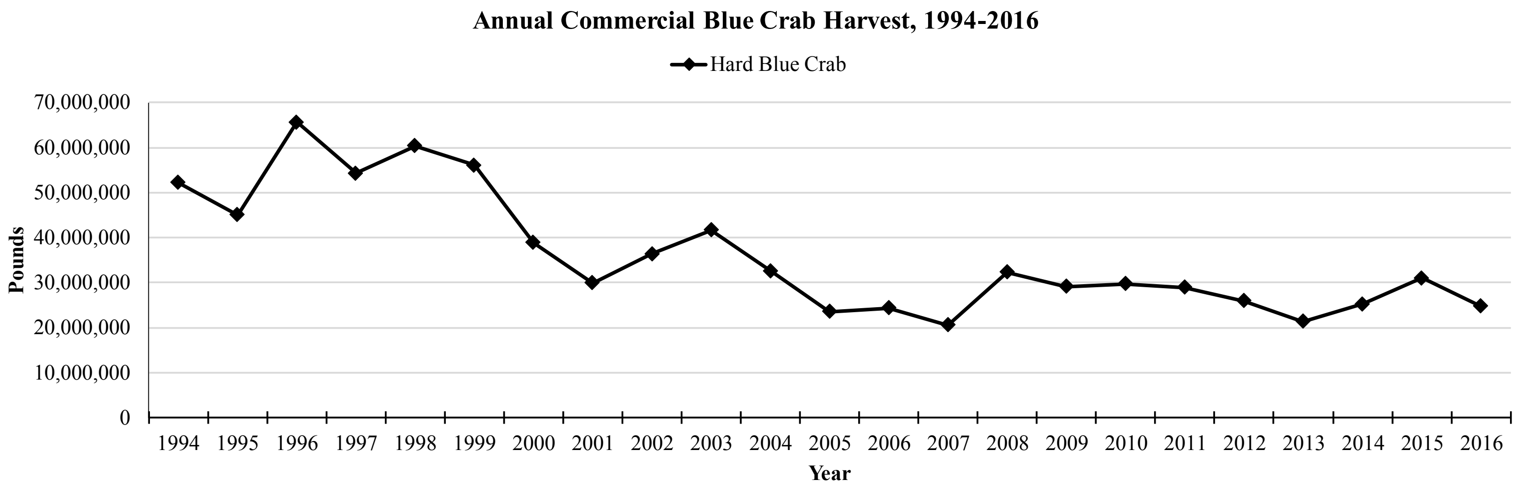


Figure 1.7. Spawning stock index adopted as the management trigger in the 2004 amendment to the North Carolina Blue Crab FMP, 1987-2013. The dashed line represents the lower 90% confidence limit of the reference baseline average (1987–2003). When the spawning stock index falls below this line for two consecutive years, the NCDMF had the proclamation authority to implement spawning stock protection measures.



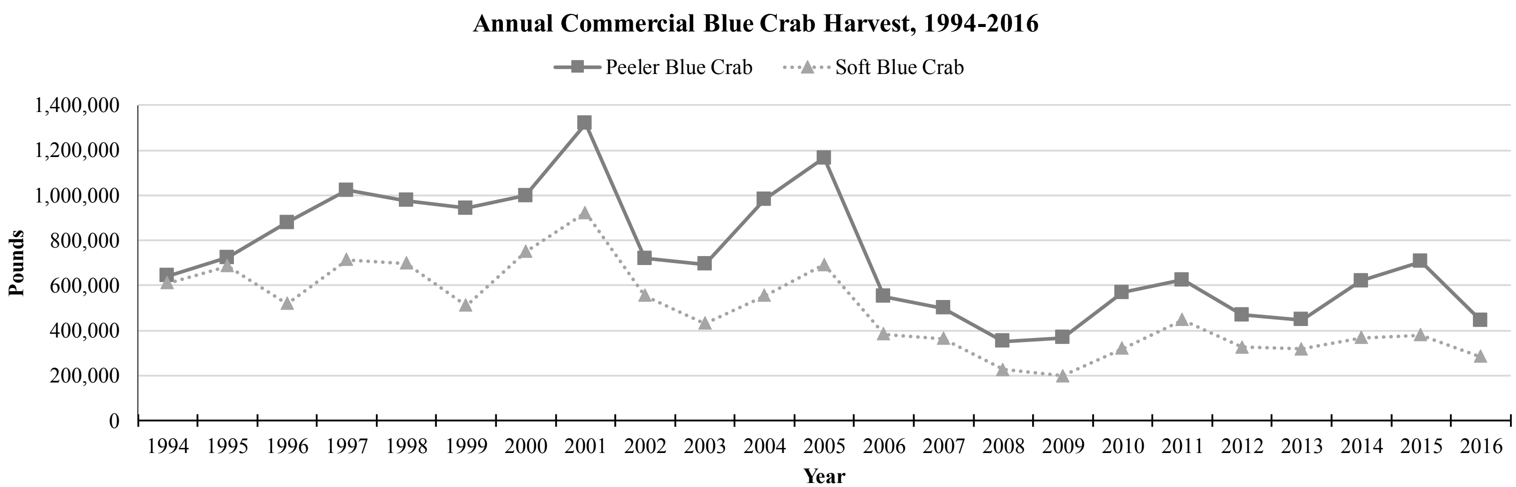


Figure 2.1. Commercial hard, peeler and soft blue crab landings, 1994–2016.

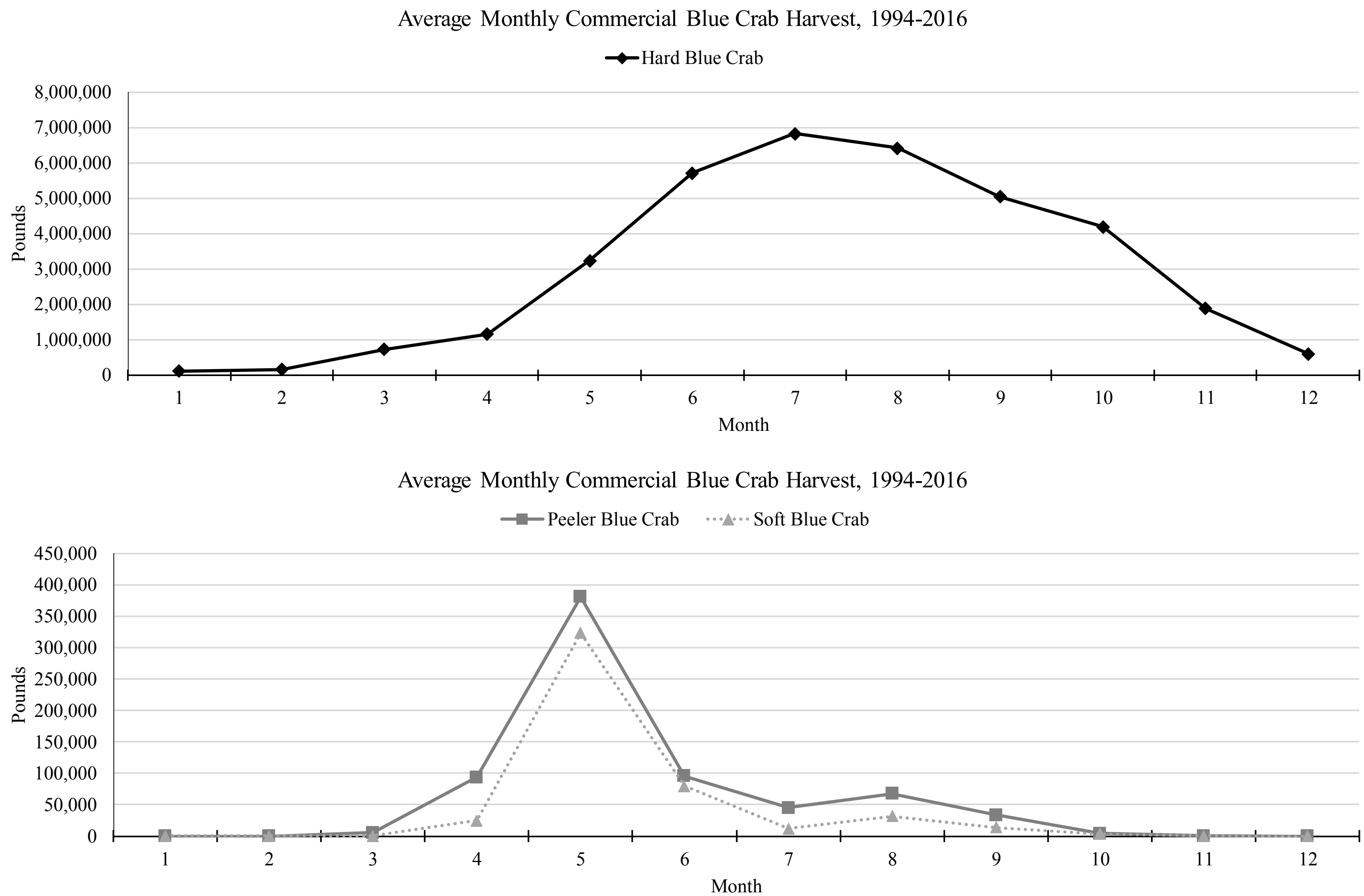
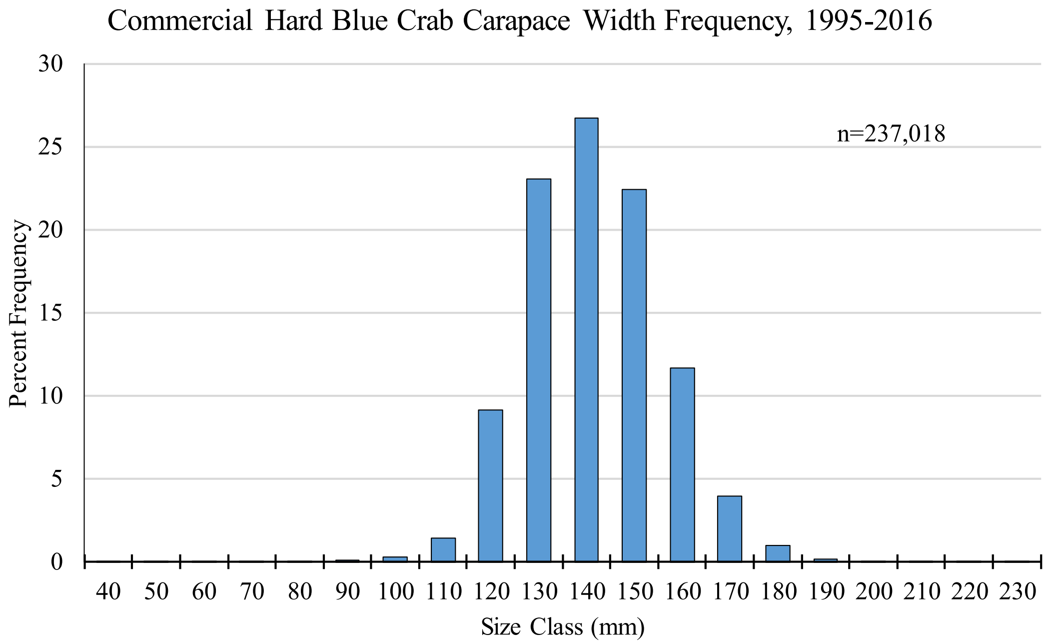


Figure 2.2. Average annual commercial landings of blue crab by type and by month, 1994-2016.



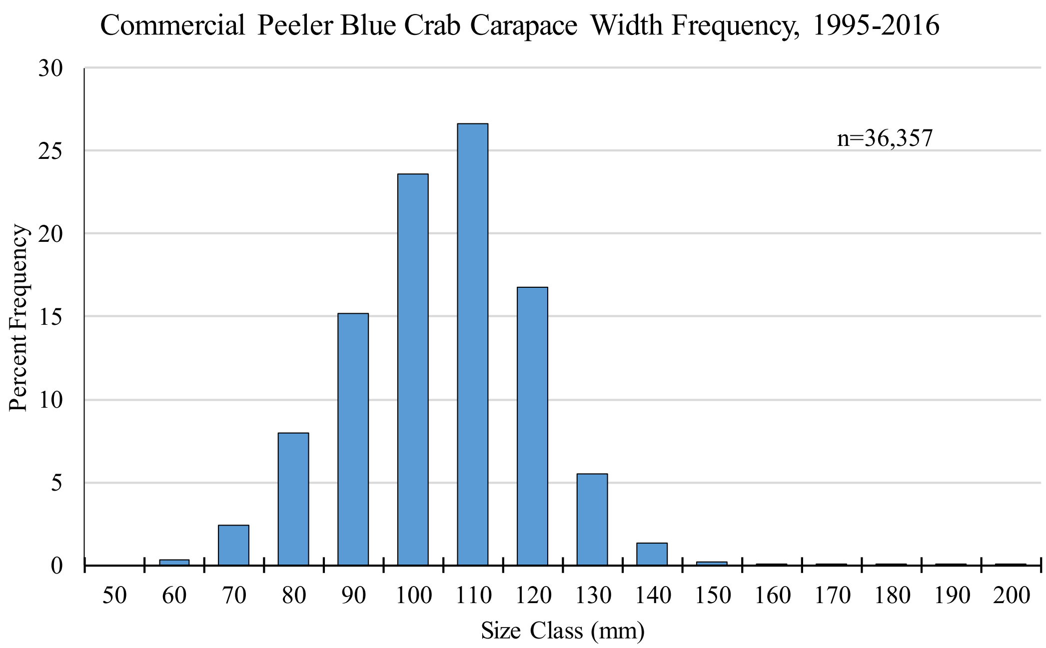


Figure 2.3. Carapace width frequency (10 mm bins) of hard and peeler blue crabs landed by commercial fisheries in North Carolina, 1995-2016. Note: no measurements taken for soft blue crabs.

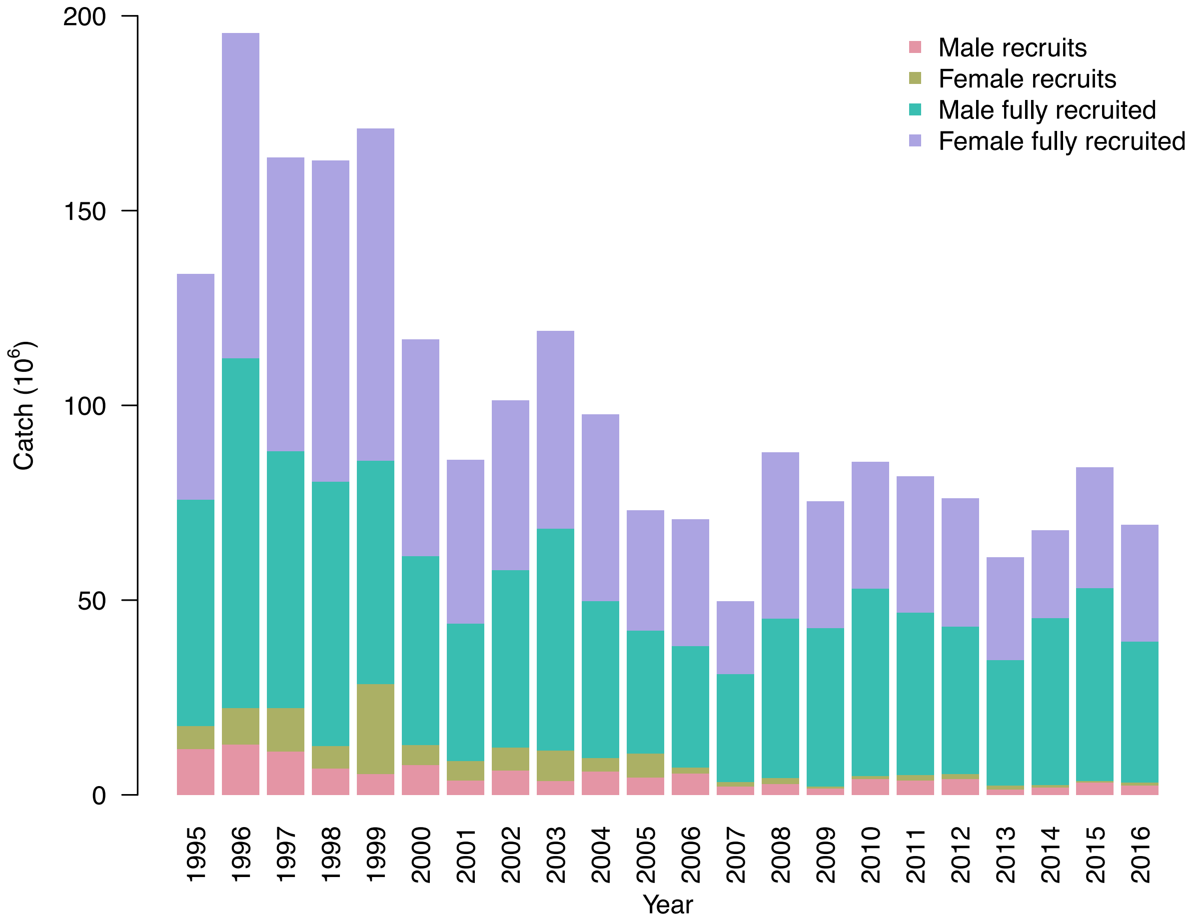
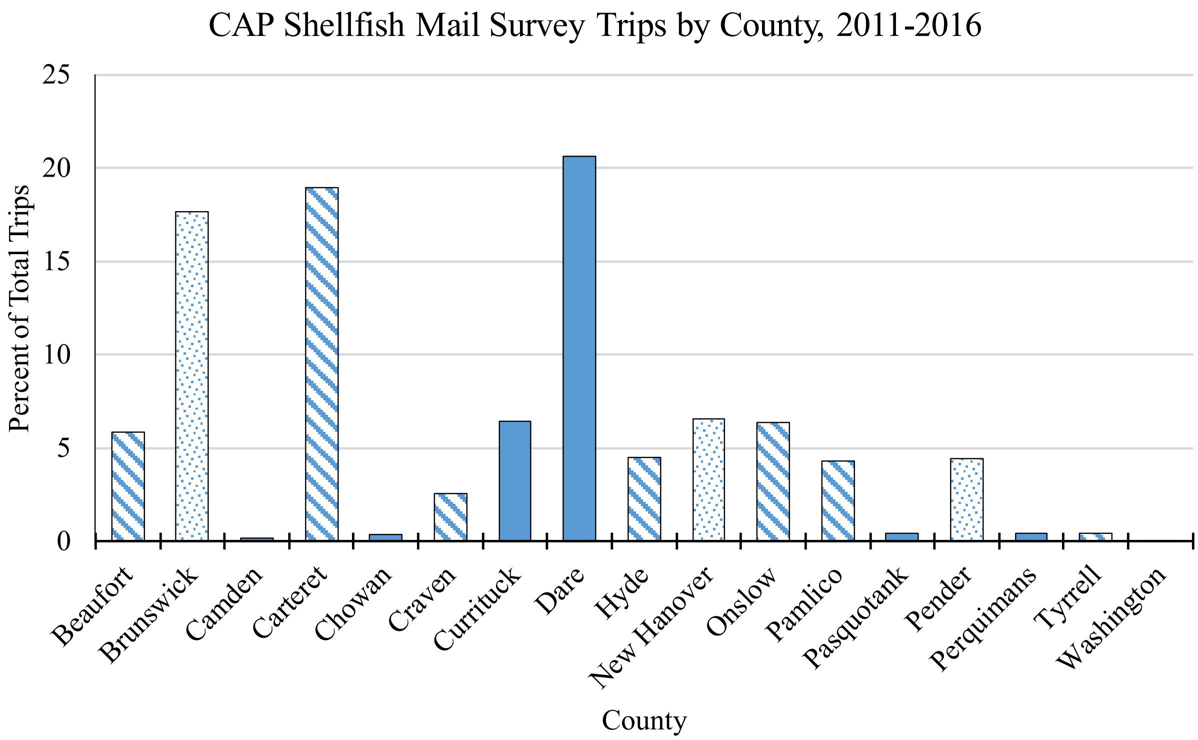


Figure 2.4. Commercial catch data of North Carolina blue crab by sex and stage (< 127 mm CW as recruits and ≥ 127 mm CW as fully recruited crabs) during 1995-2016.



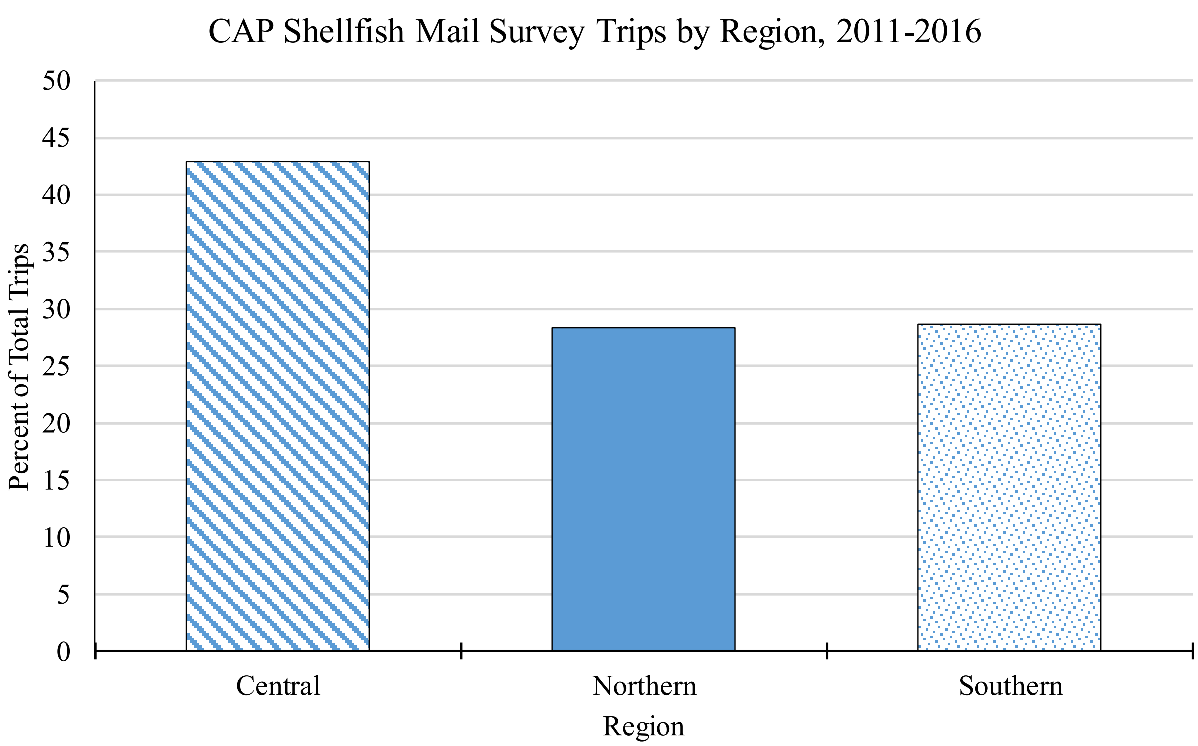


Figure 2.5. Percent crab trips by county and region from CAP shellfish mail survey, 2011-2016.

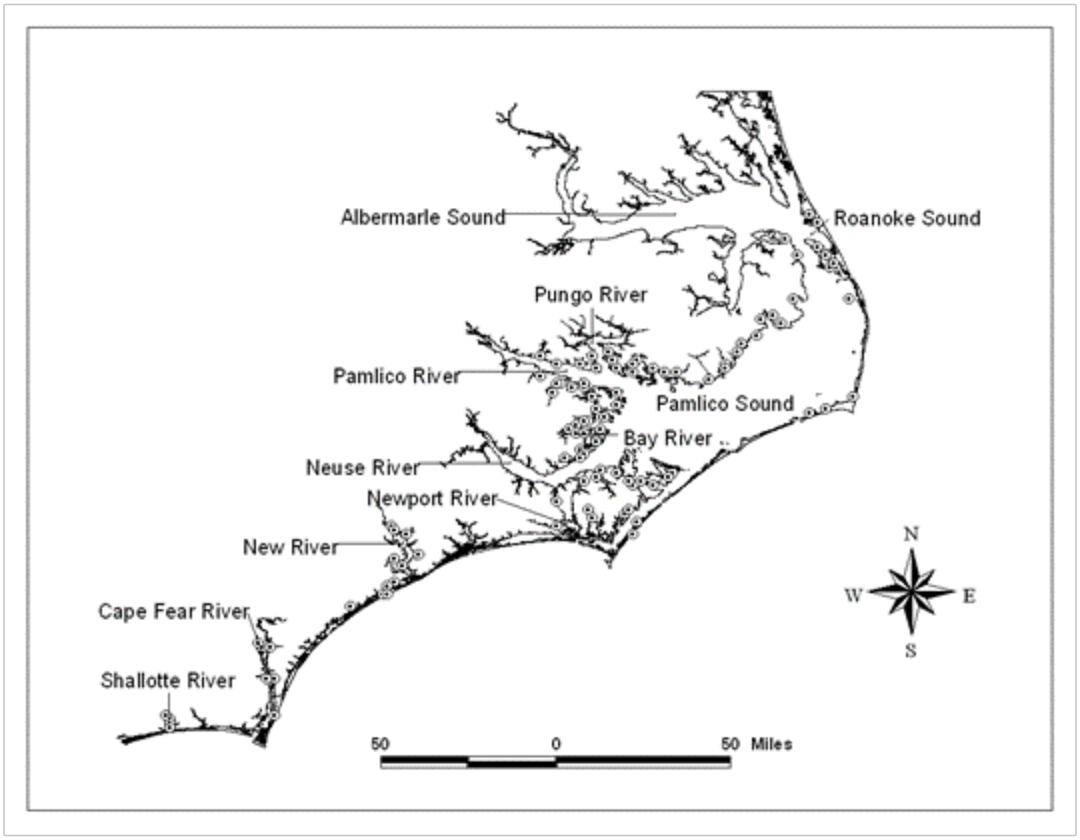
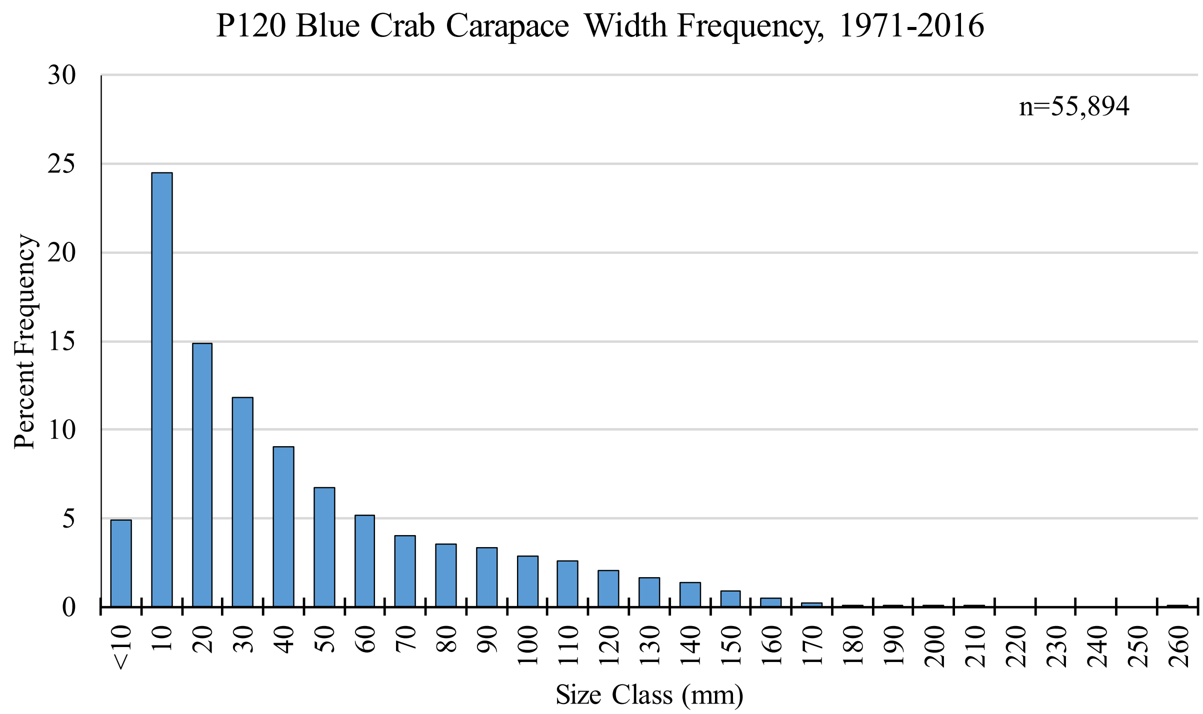


Figure 2.6. Location of all core sample stations in Program 120.



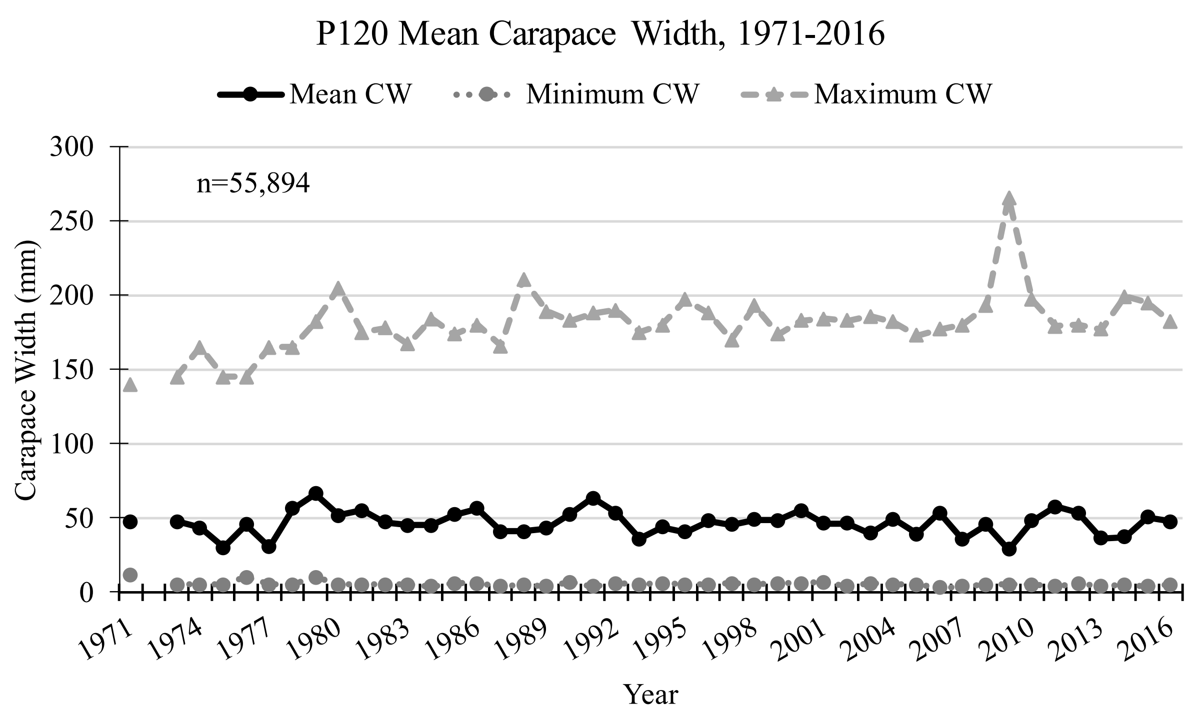
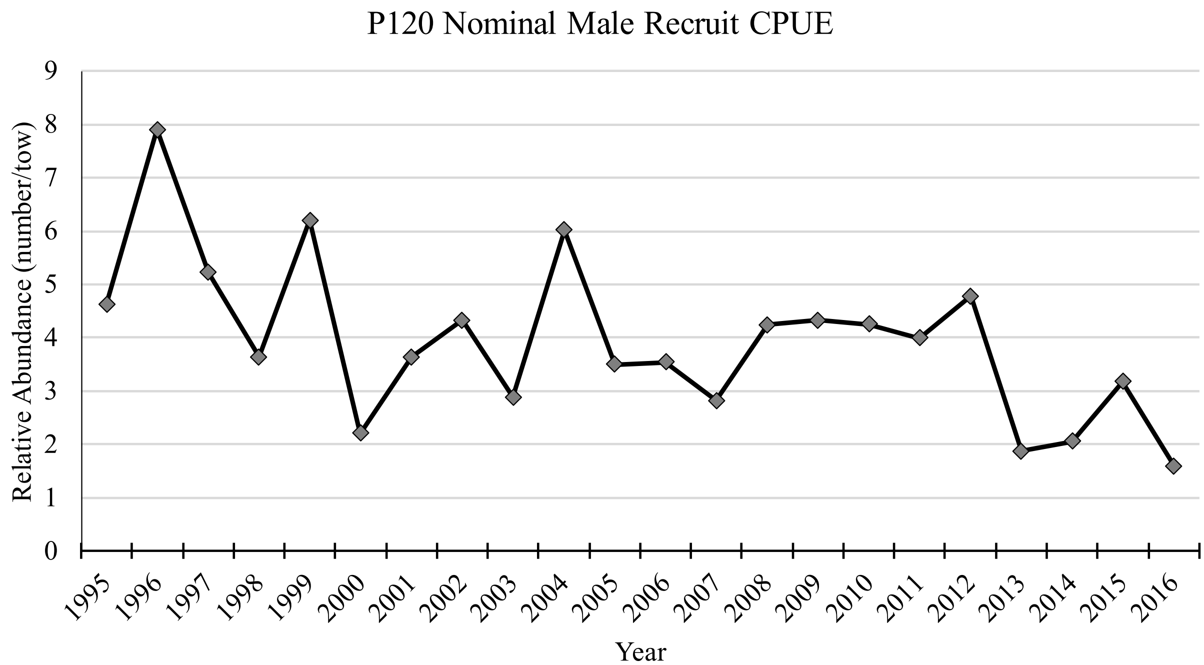


Figure 2.7. Carapace width frequency (10 mm bins), annual mean, minimum, and maximum carapace width (mm) of all blue crab captured in Program 120 core stations in May and June, 1971 – 2016.



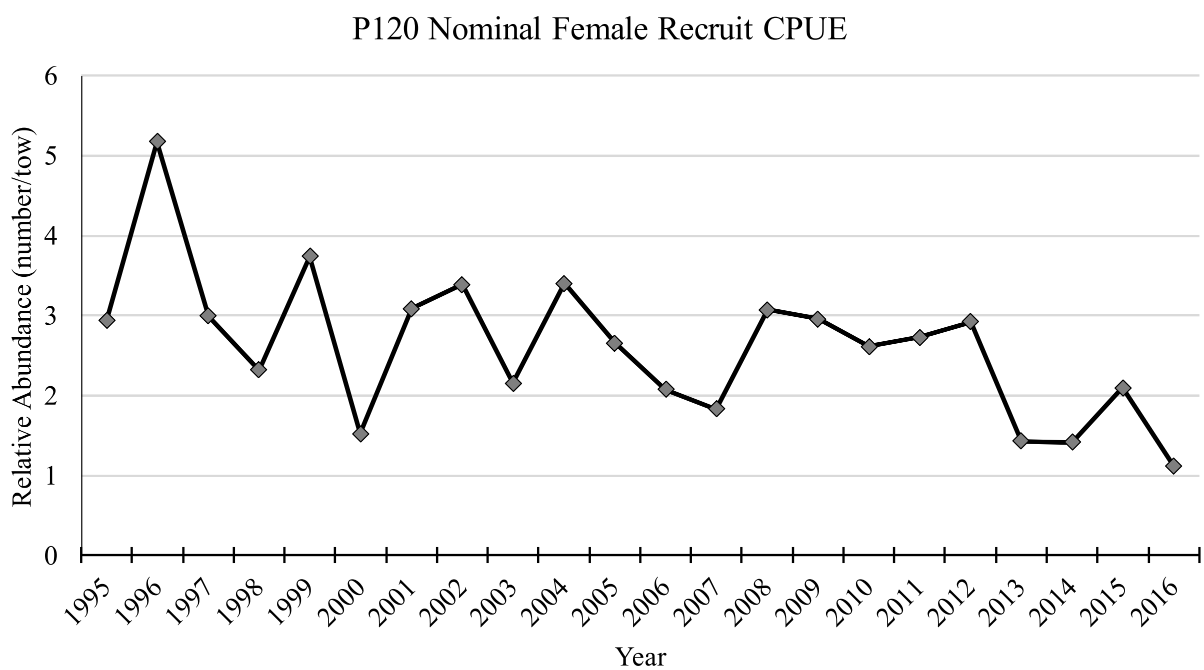


Figure 2.8. Annual nominal catch-per-unit effort (CPUE; number of crab per sample) of recruit (<127 mm CW) blue crabs captured in Program 120 in May and June by sex, 1995 – 2016.

Figure 2.9. Annual standardized catch-per-unit effort (CPUE; number of crab per sample) of recruit (<127 mm CW) blue crabs captured in Program 120 in May and June by sex, 1995 – 2016.

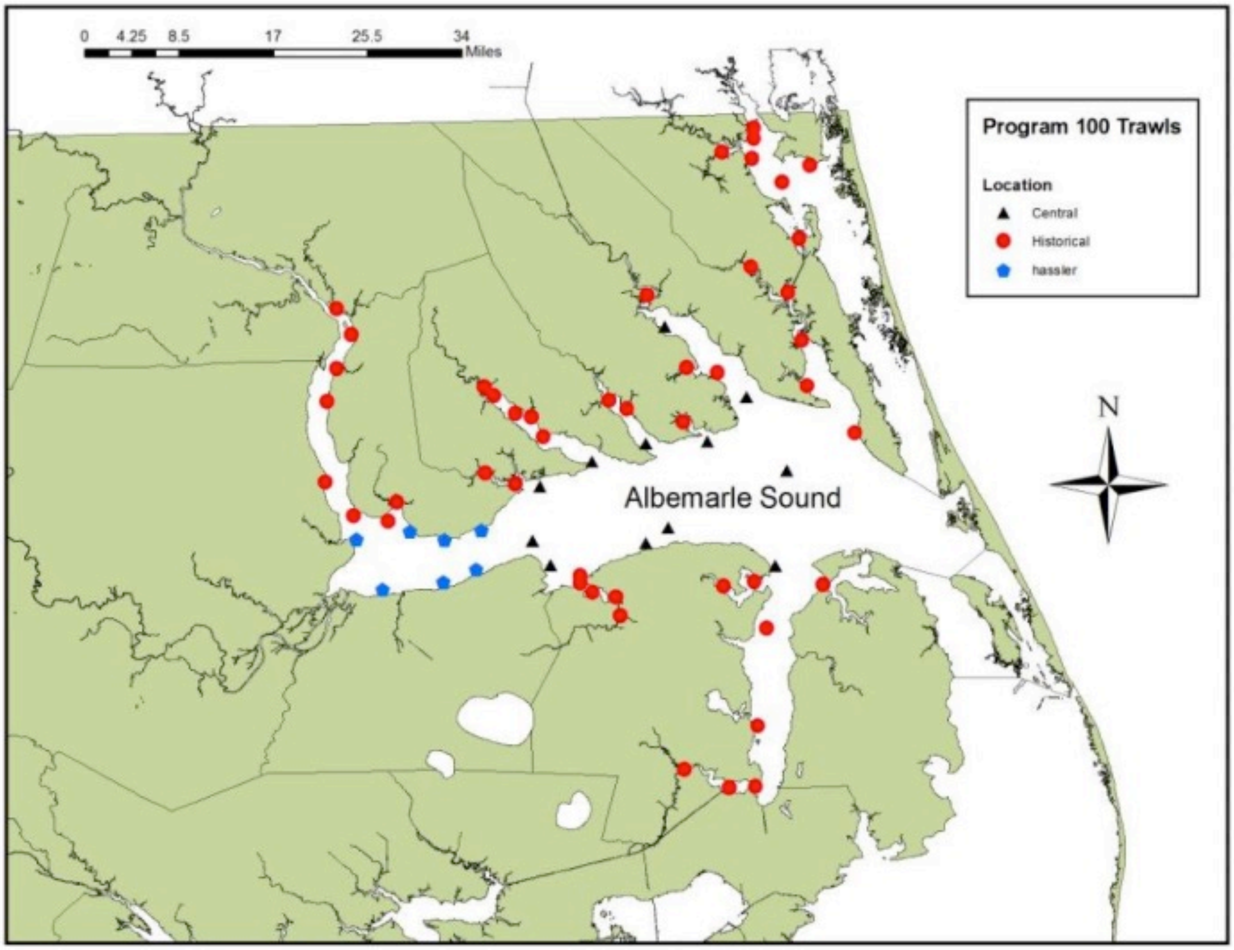
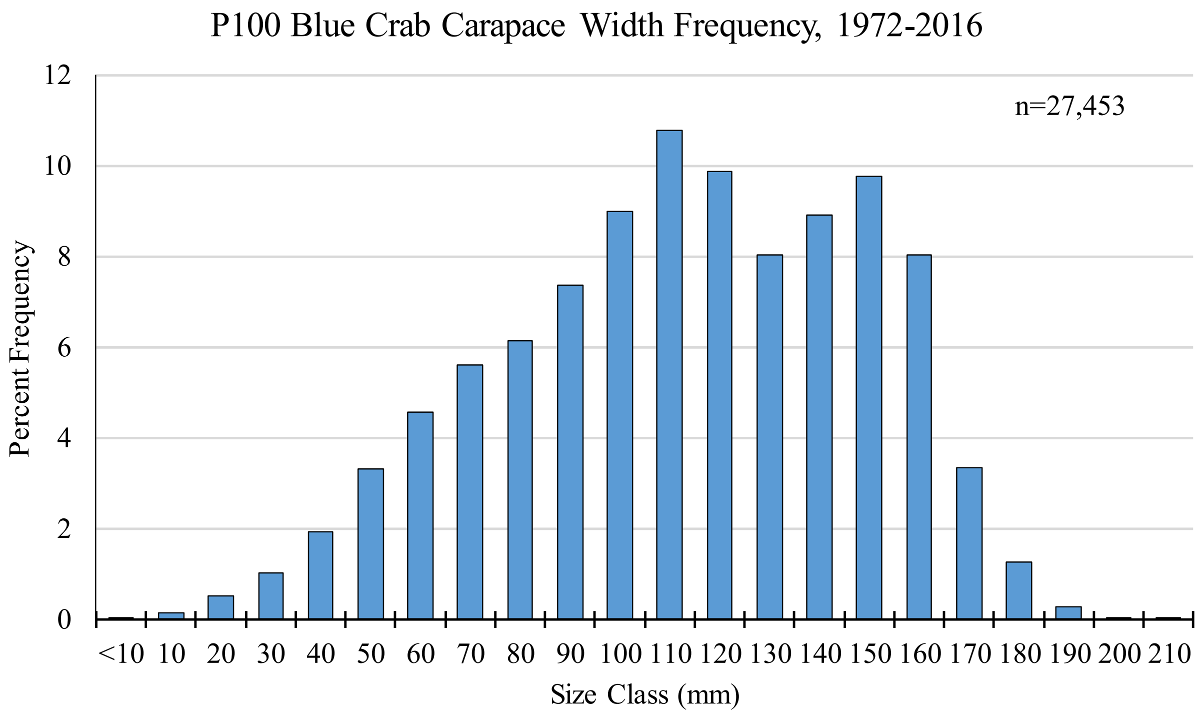


Figure 2.10. Location of all trawl stations in Program 100 by type.



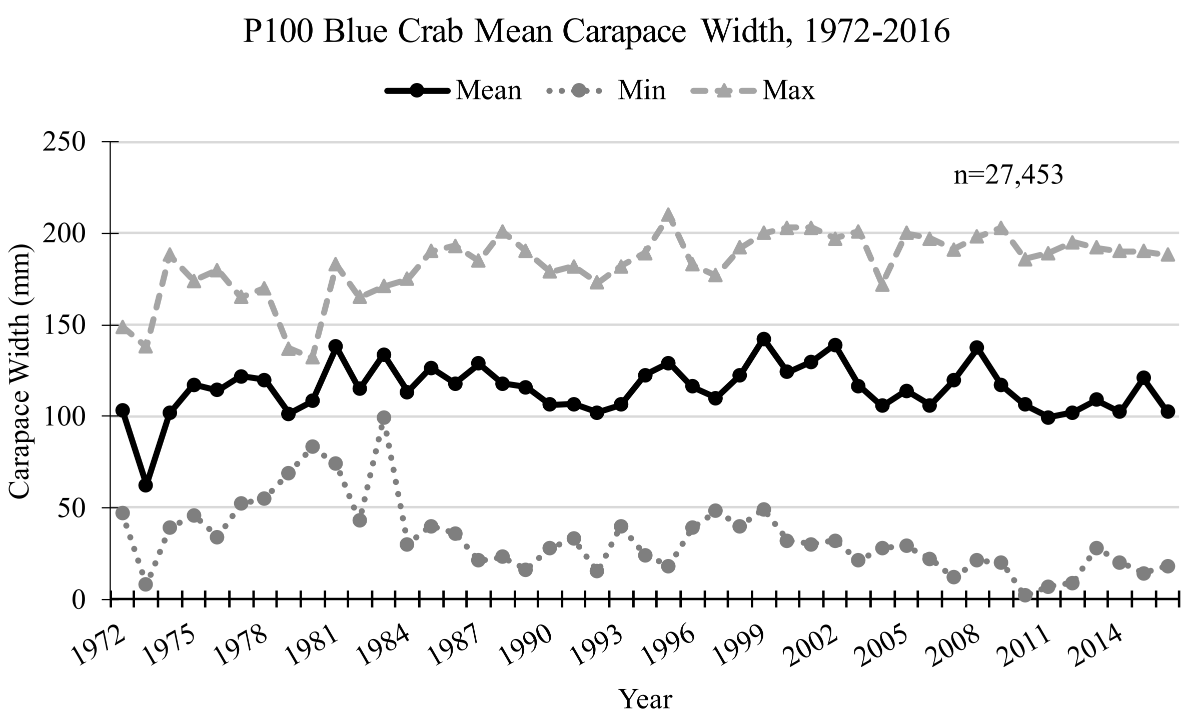


Figure 2.11. Carapace width frequency (10 mm bins), annual mean, minimum, and maximum carapace width (mm) of all blue crabs captured in Program 100 trawl stations, 1972 – 2016.

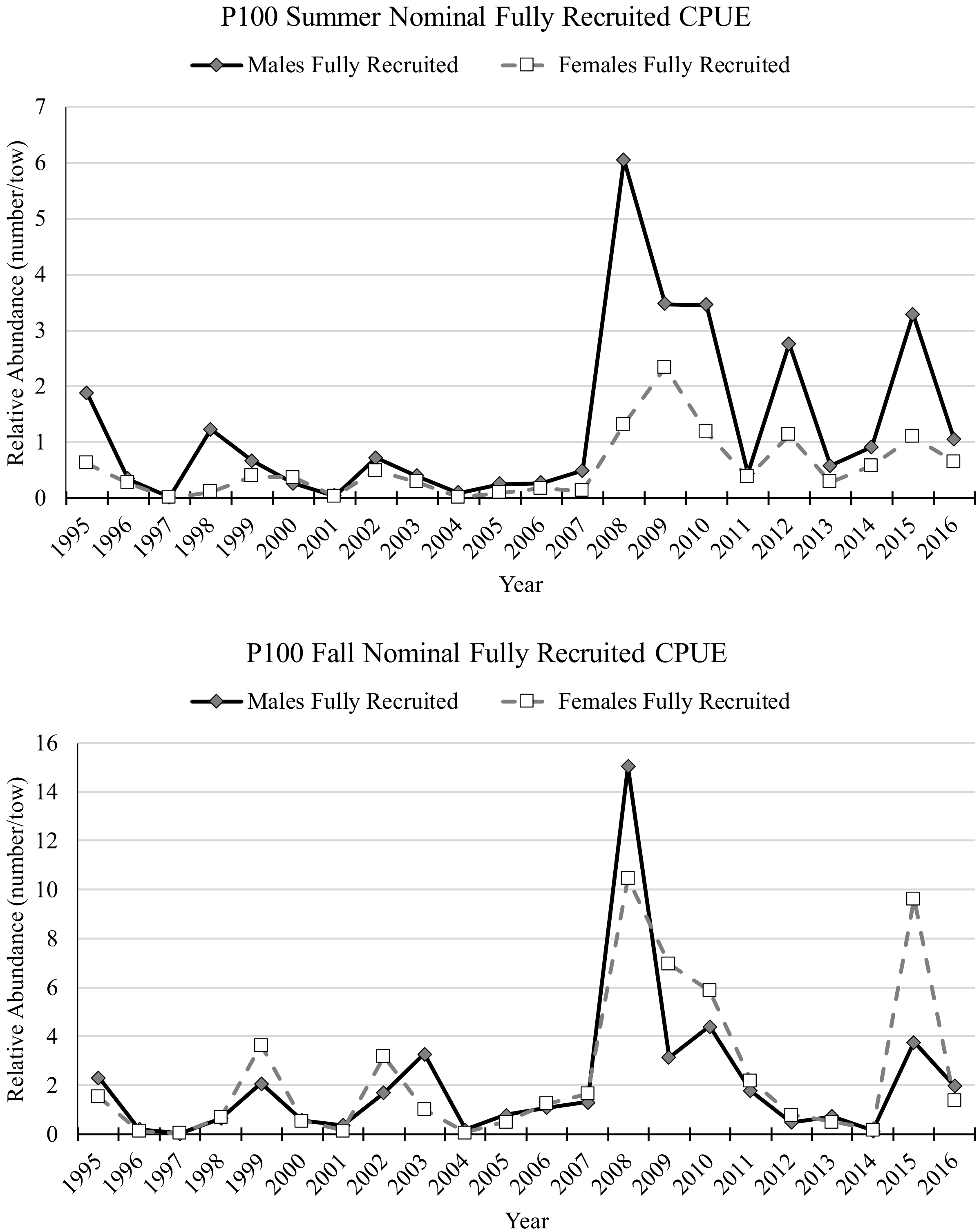


Figure 2.12. Nominal catch-per-unit effort (CPUE; number of crabs per sample) of fully recruited crabs (≥127 mm CW) captured in Program 100 by season and sex, 1995 – 2016.

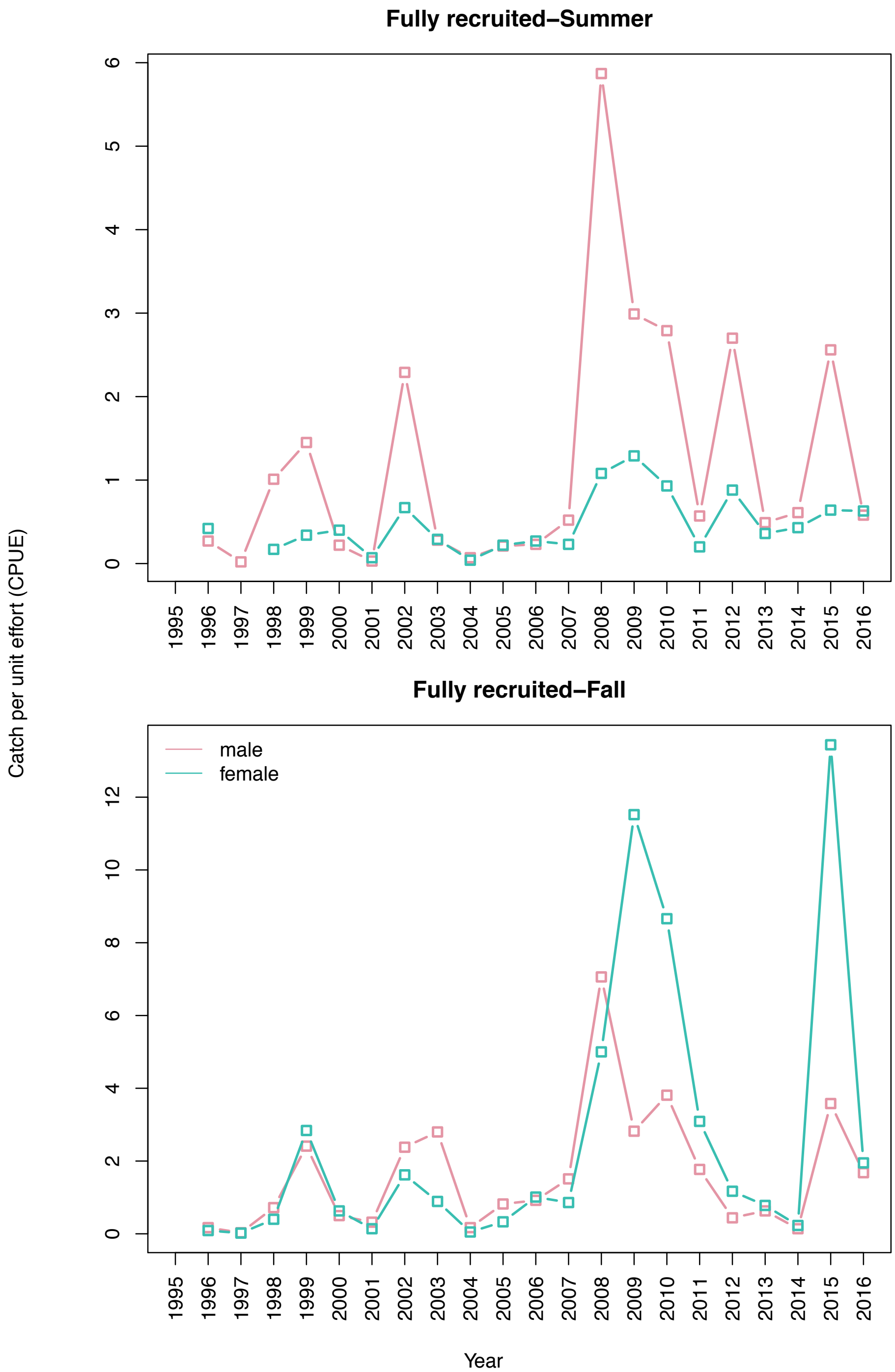


Figure 2.13. Annual standardized catch-per-unit effort (CPUE; number of crabs per sample) of fully recruited crabs (≥127 mm CW) captured in Program 100 by season and sex, 1995 – 2016. Estimated standardized CPUE for female summer indices in 1997 was removed due to large estimated variation.

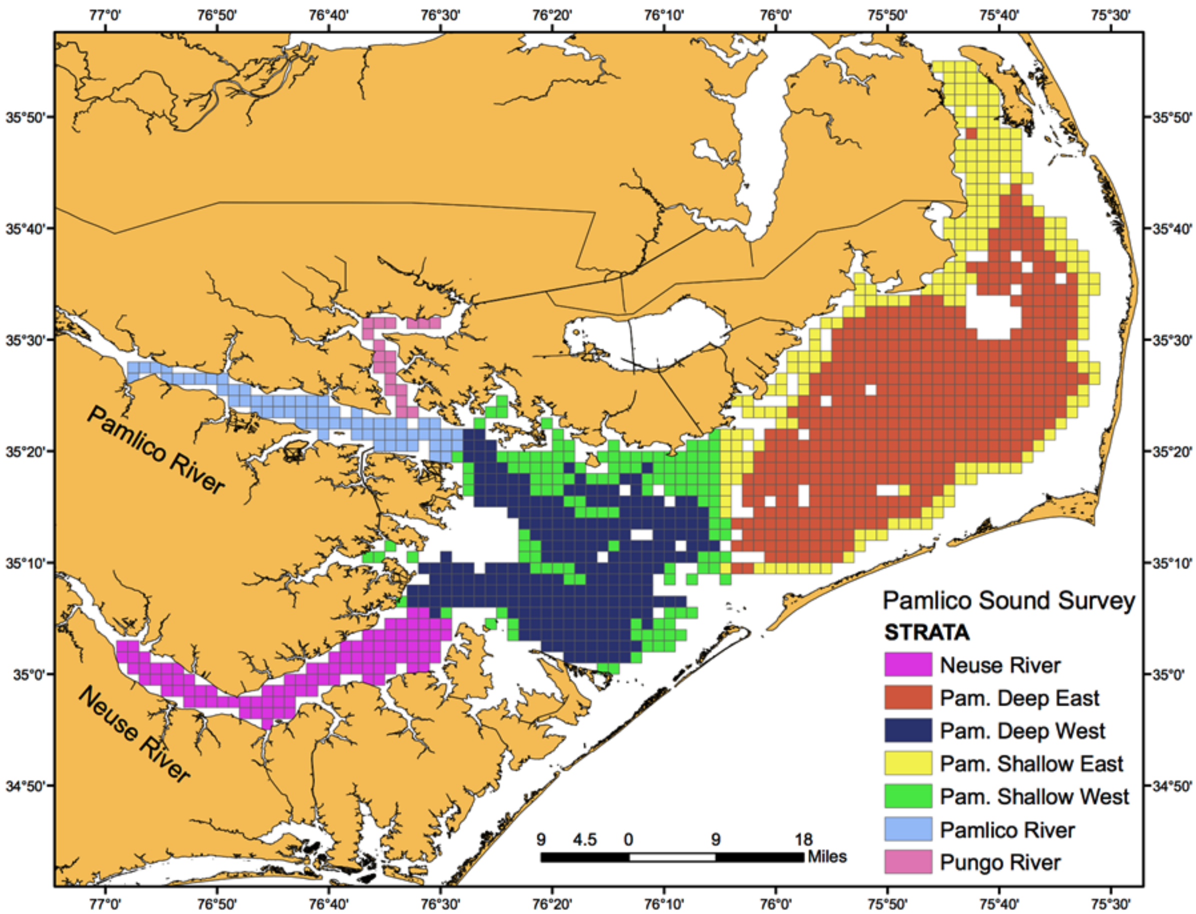
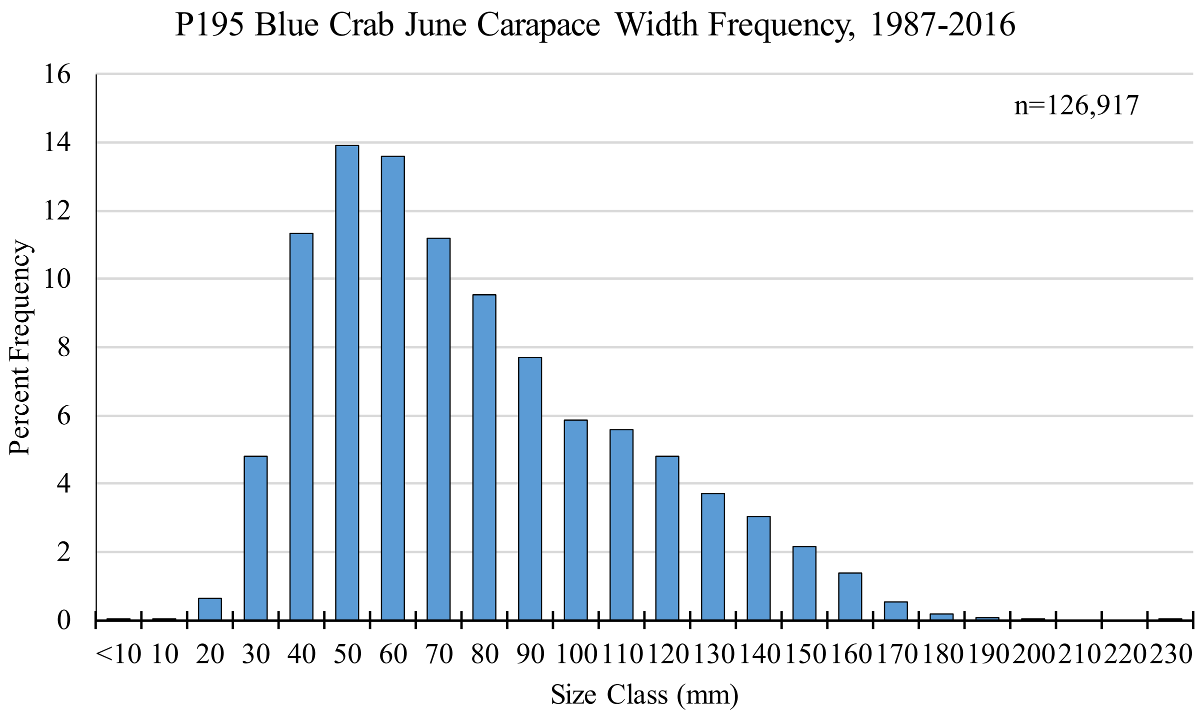


Figure 2.14. Location of all potential sample grids by stratum for the Pamlico Sound Survey (Program 195).



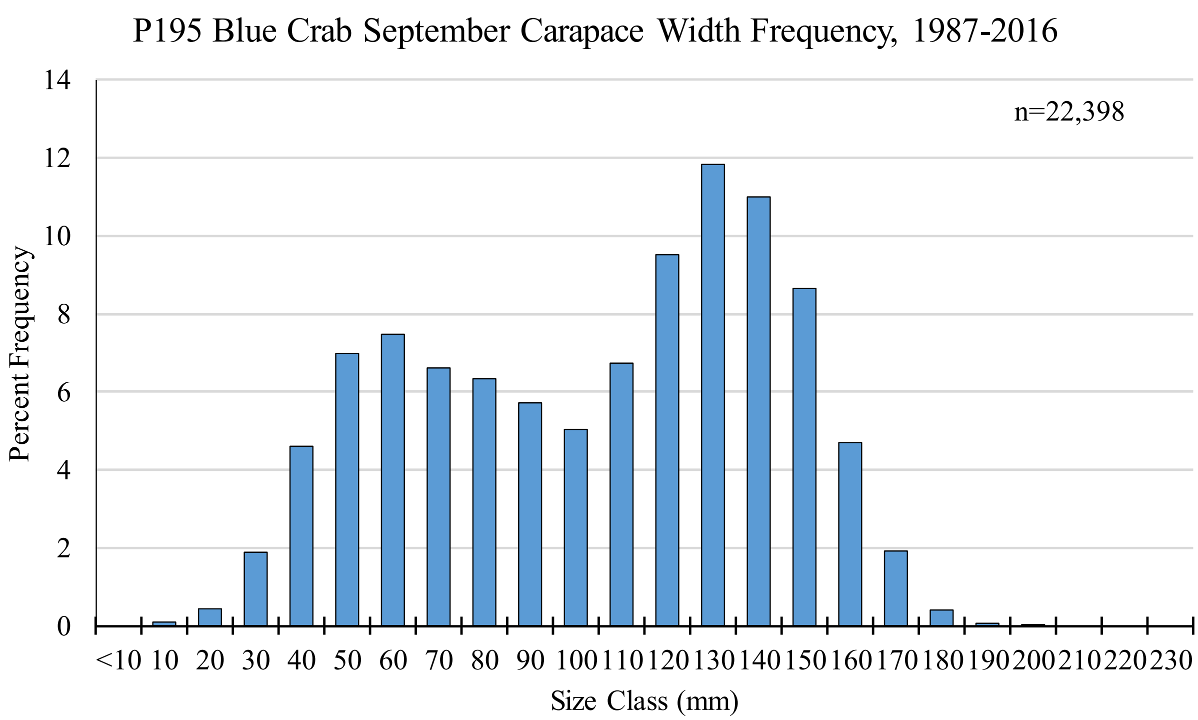
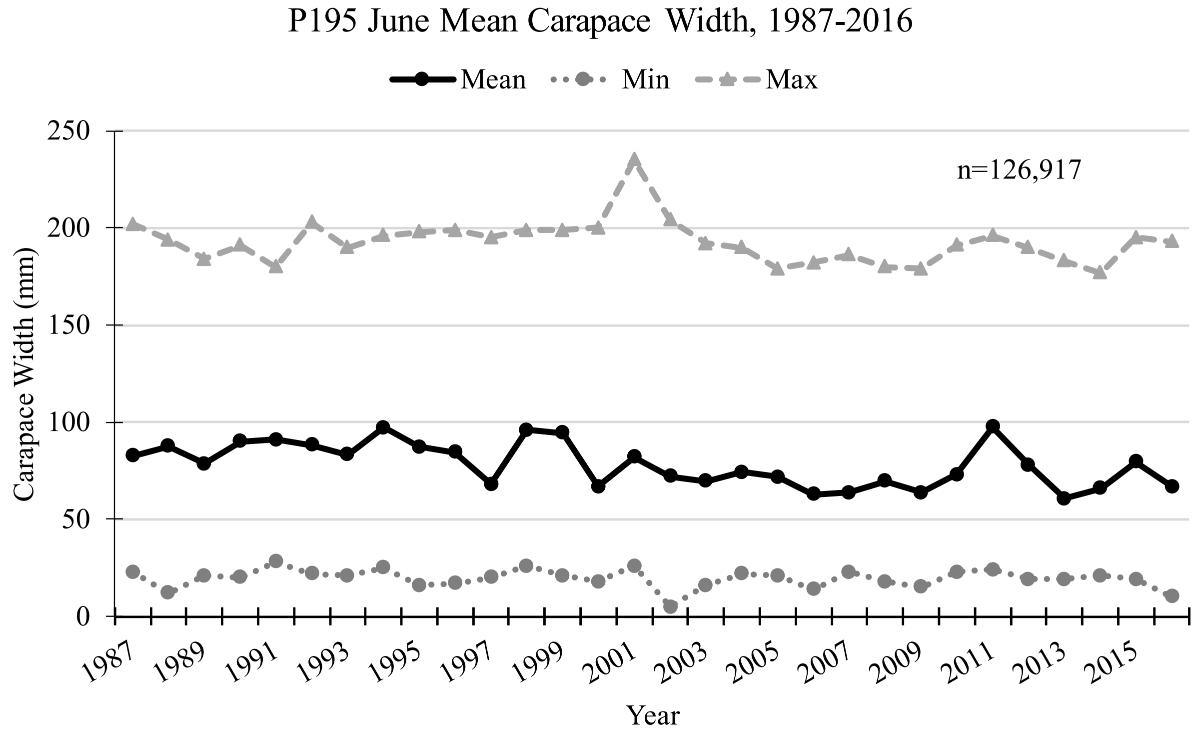


Figure 2.15. Carapace width frequency (10 mm bins) of blue crab captured in program 195 by month, 1987 – 2016 all strata combined.



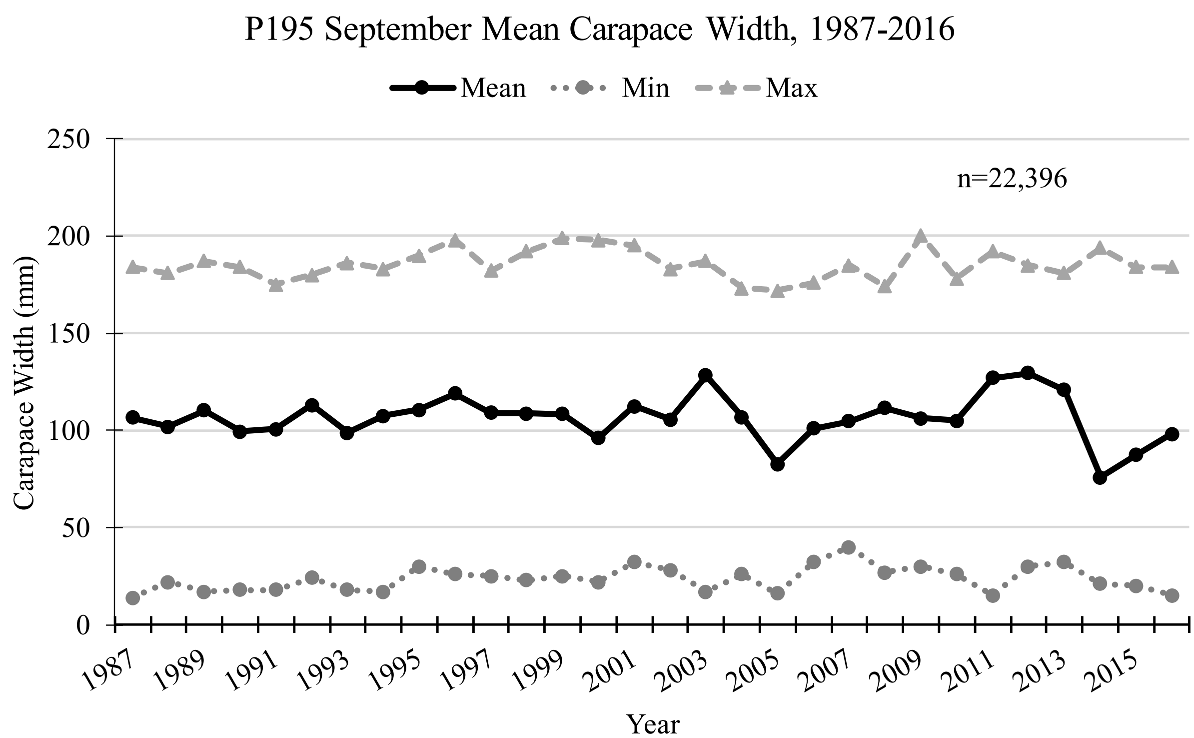


Figure 2.16. Annual mean, minimum, and maximum carapace width (mm) of blue crab captured in Program 195, 1987 – 2016.

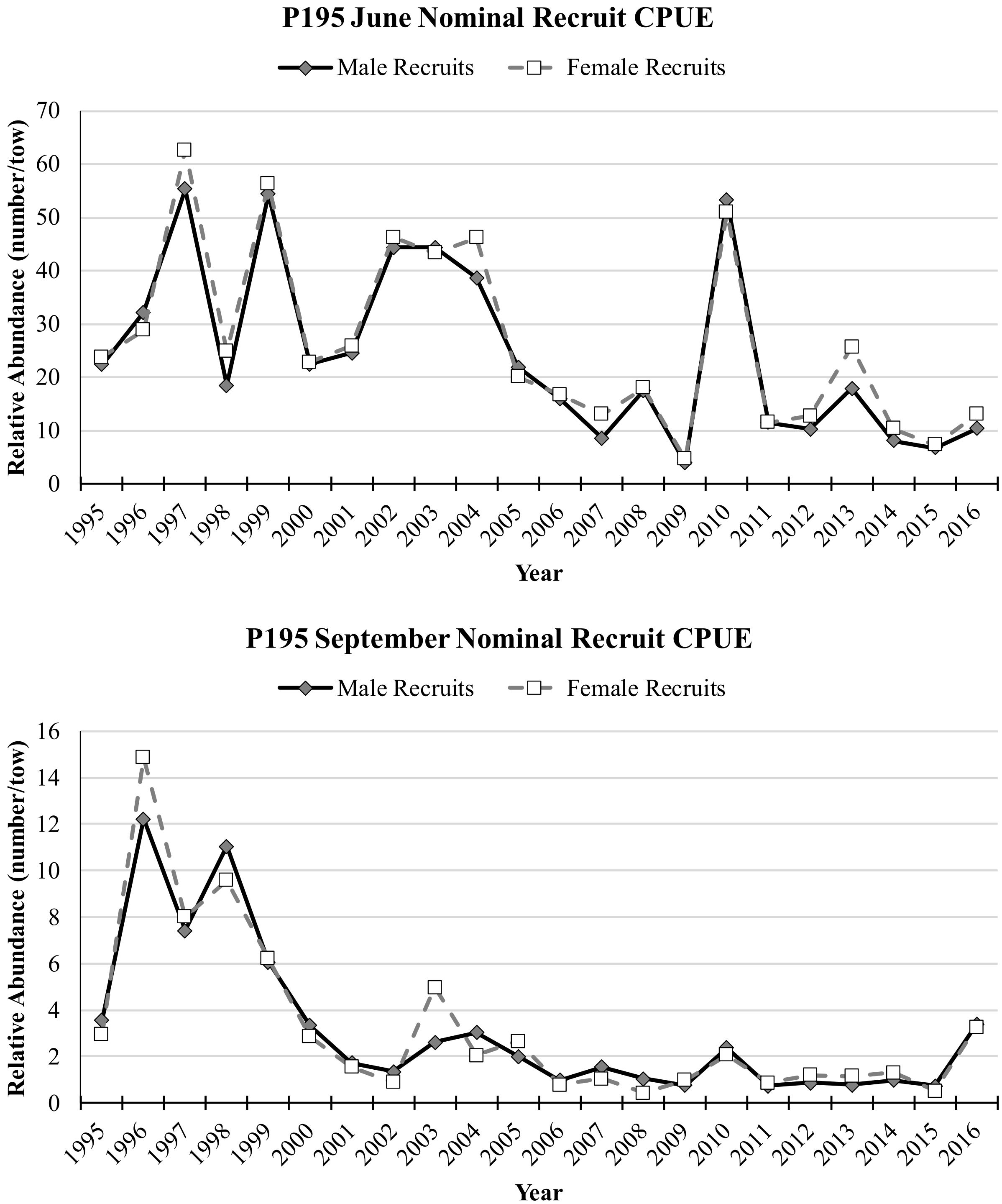
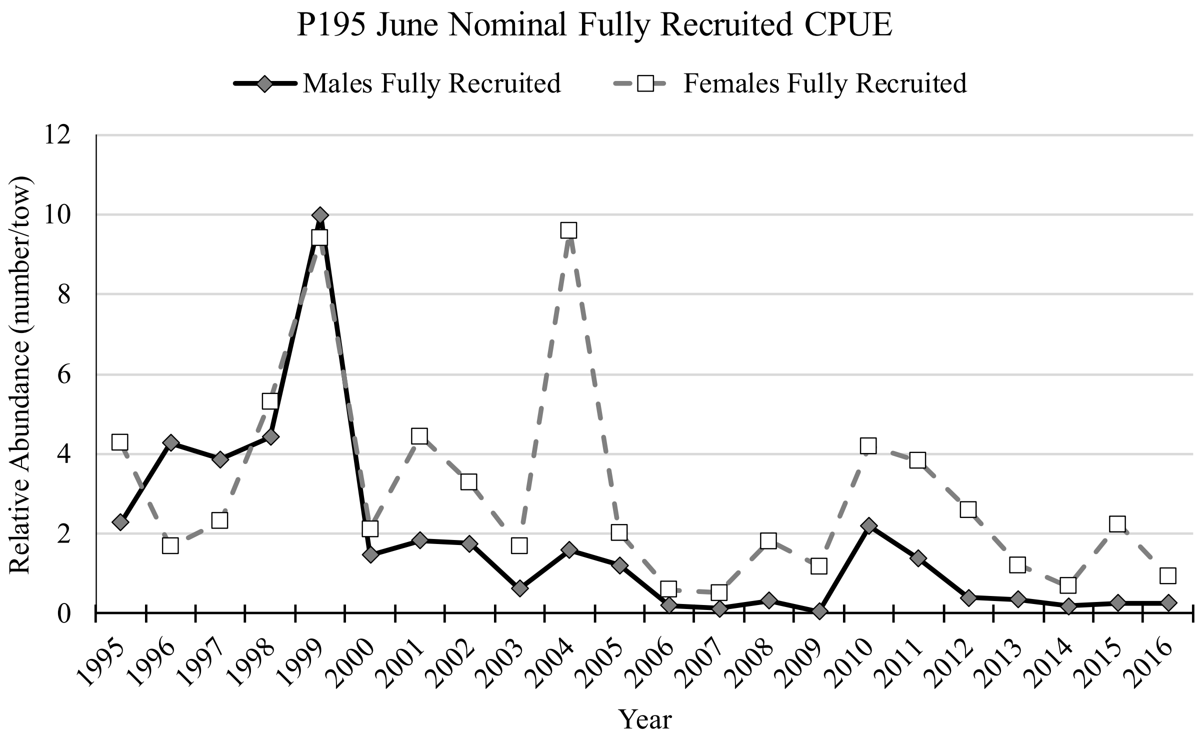


Figure 2.17. Weighted nominal catch-per-unit effort (CPUE; number of crabs per sample) of recruit crabs (<127 mm CW) captured in Program 195 by month and sex, 1995 – 2016 for all strata combined.



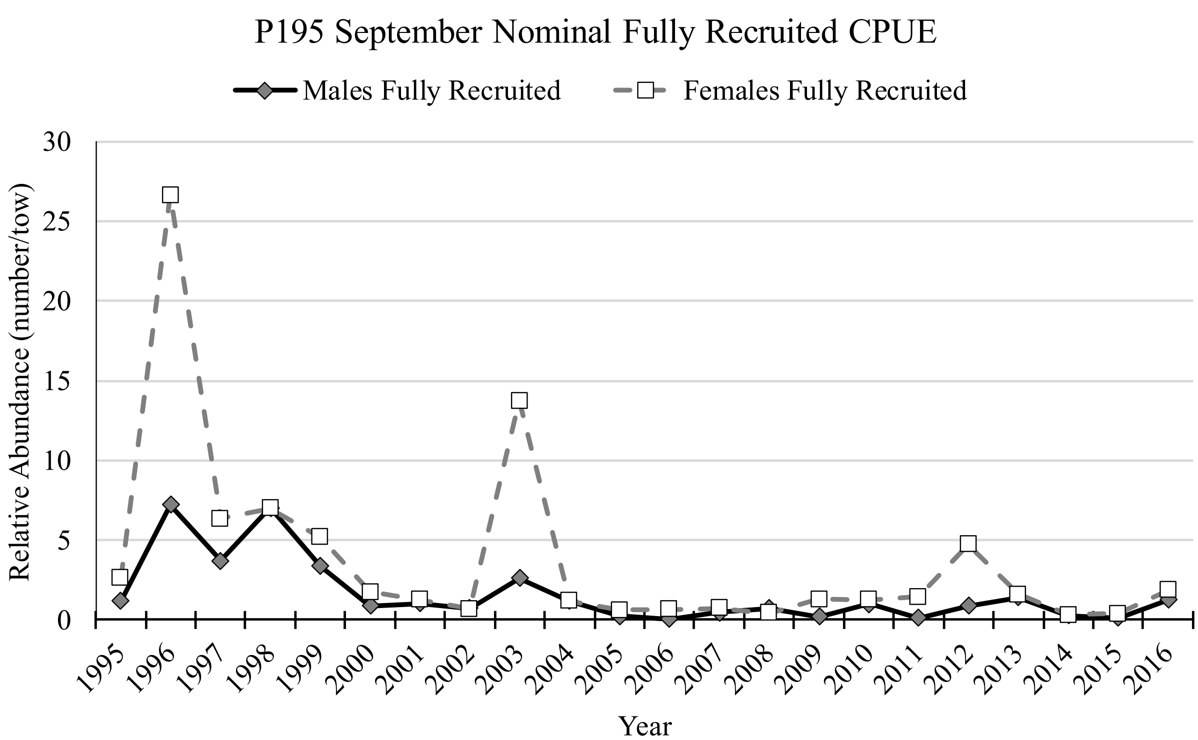


Figure 2.18. Weighted nominal catch-per-unit effort (CPUE; number of crabs per sample) of fully recruited crabs (≥127 mm CW) captured in Program 195 by month and sex, 1995 – 2016 for all strata combined.

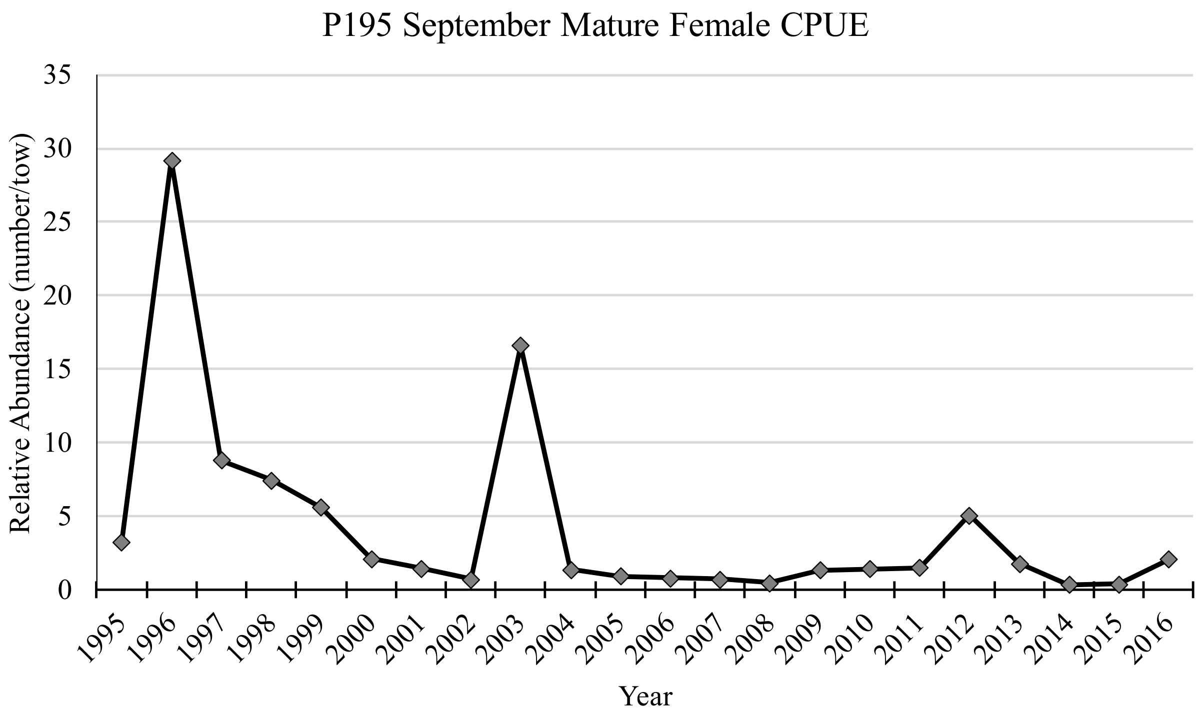


Figure 2.19. Weighted nominal catch-per-unit effort (CPUE; number of crabs per sample) of mature female crabs captured in September in Program 195, 1995 – 2016 for all strata combined.

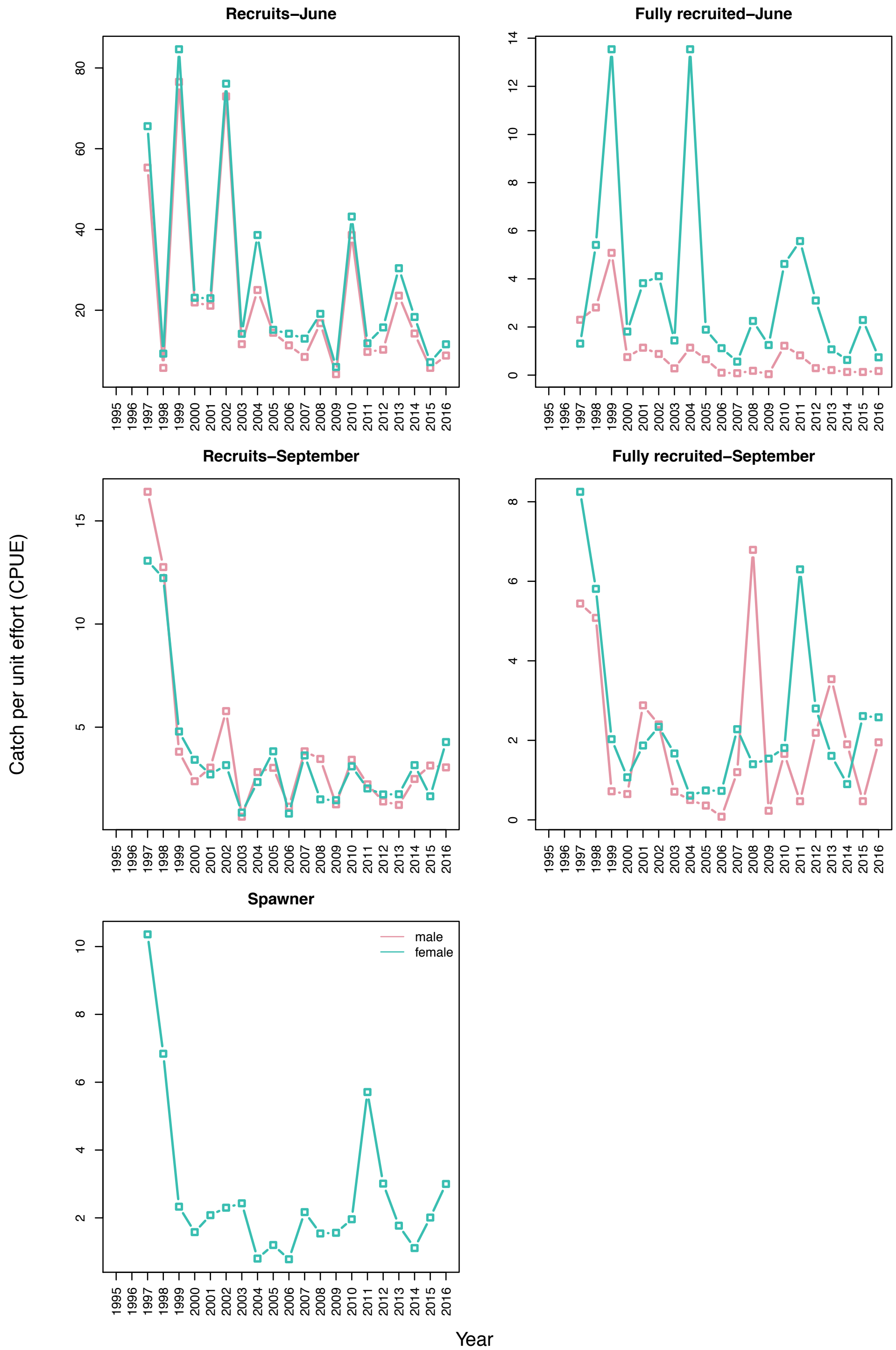


Figure 2.20. Standardized catch-per-unit effort (CPUE; number of crabs per sample) of recruit crabs (<127 mm CW), fully recruited crabs (≥127 mm CW) and mature female crabs (September) captured in Program 195 by month and sex, 1995 – 2016 for all strata combined.

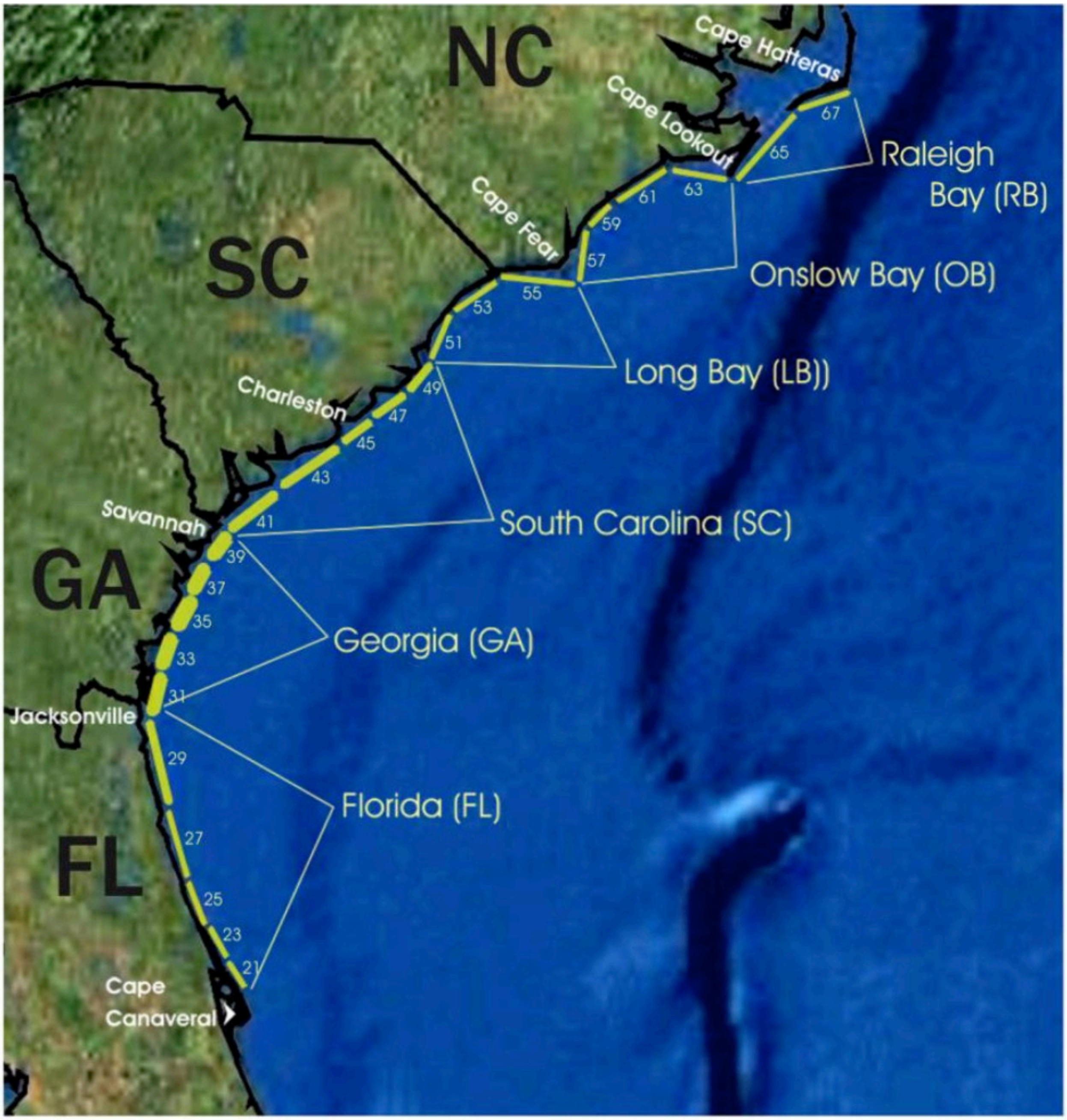


Figure 2.21. Sampling area of the SEAMAP Coastal Survey.

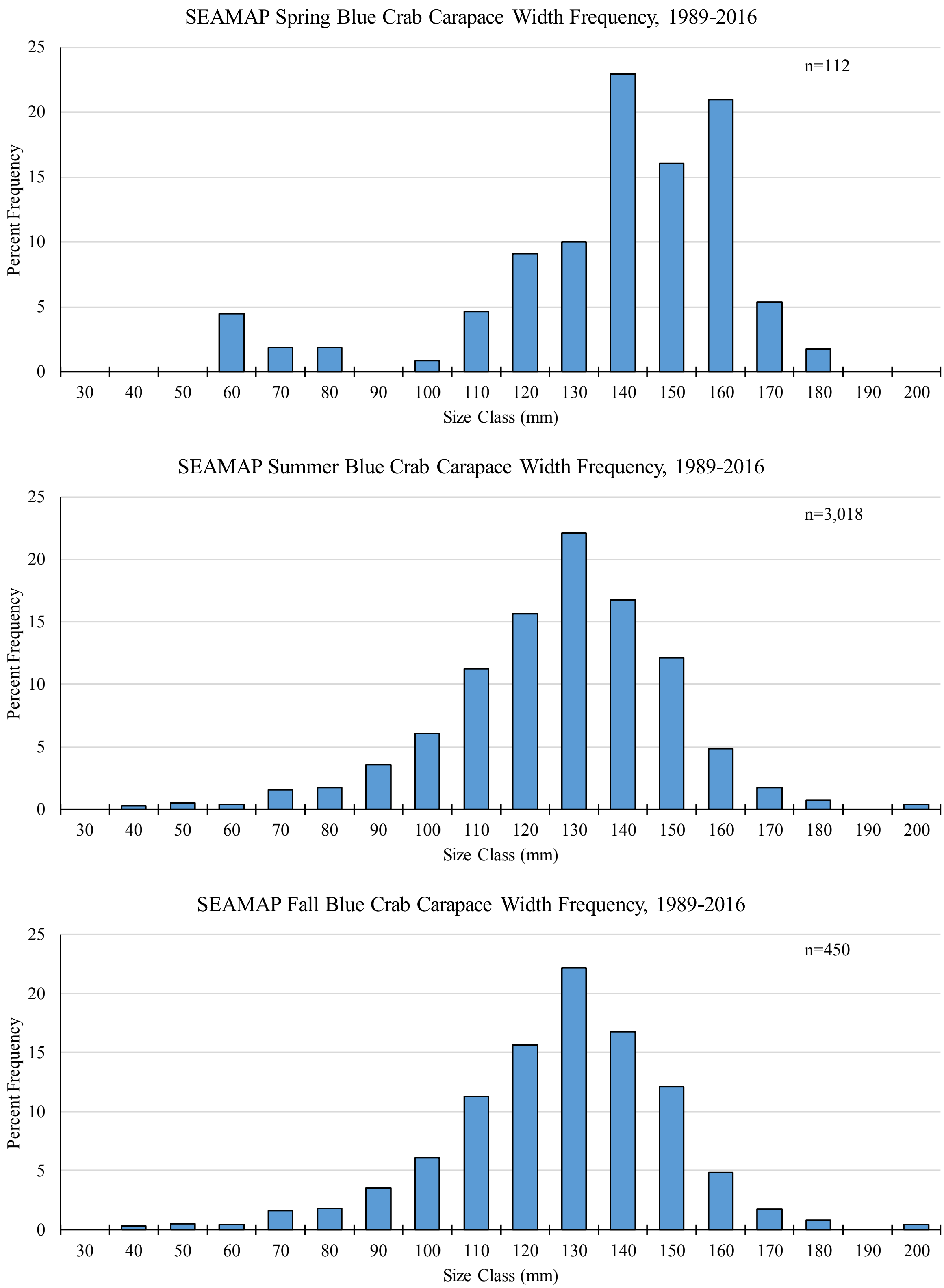


Figure 2.22. Carapace width frequency by season from the SEAMAP Coastal Survey in North Carolina waters, 1989-2016.

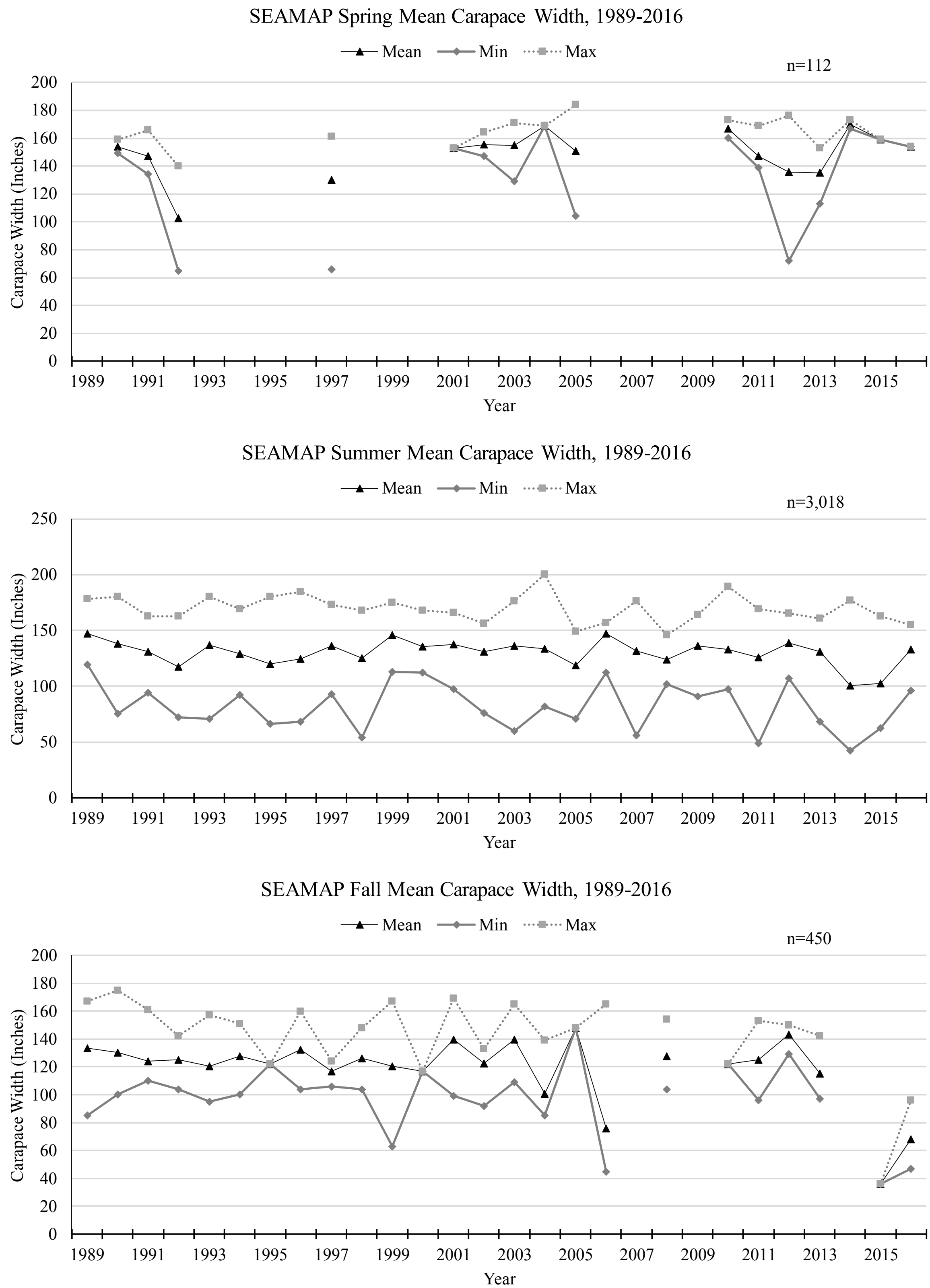


Figure 2.23. Median, minimum, and maximum carapace width by season from the SEAMAP Coastal Survey in North Carolina waters, 1989-2016.

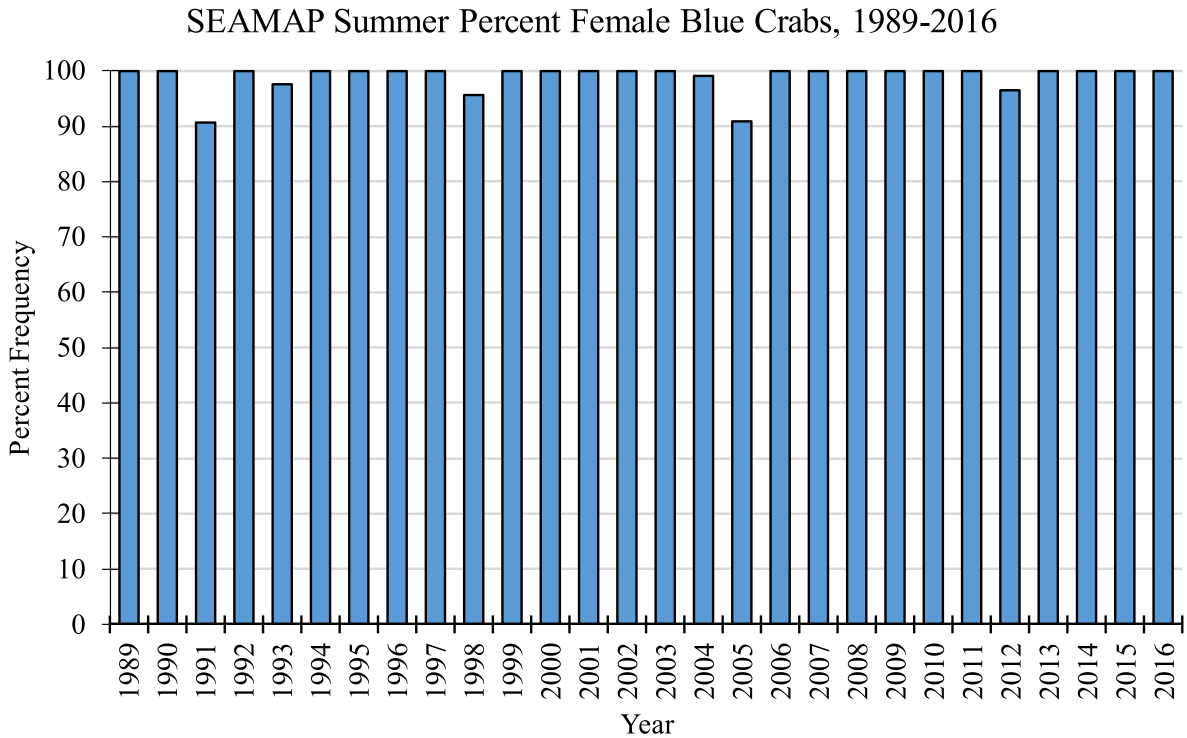


Figure 2.24. Percent of mature female blue crabs in the catch from the summer cruise of the SEAMAP Coastal Survey in North Carolina waters, 1989-2016.

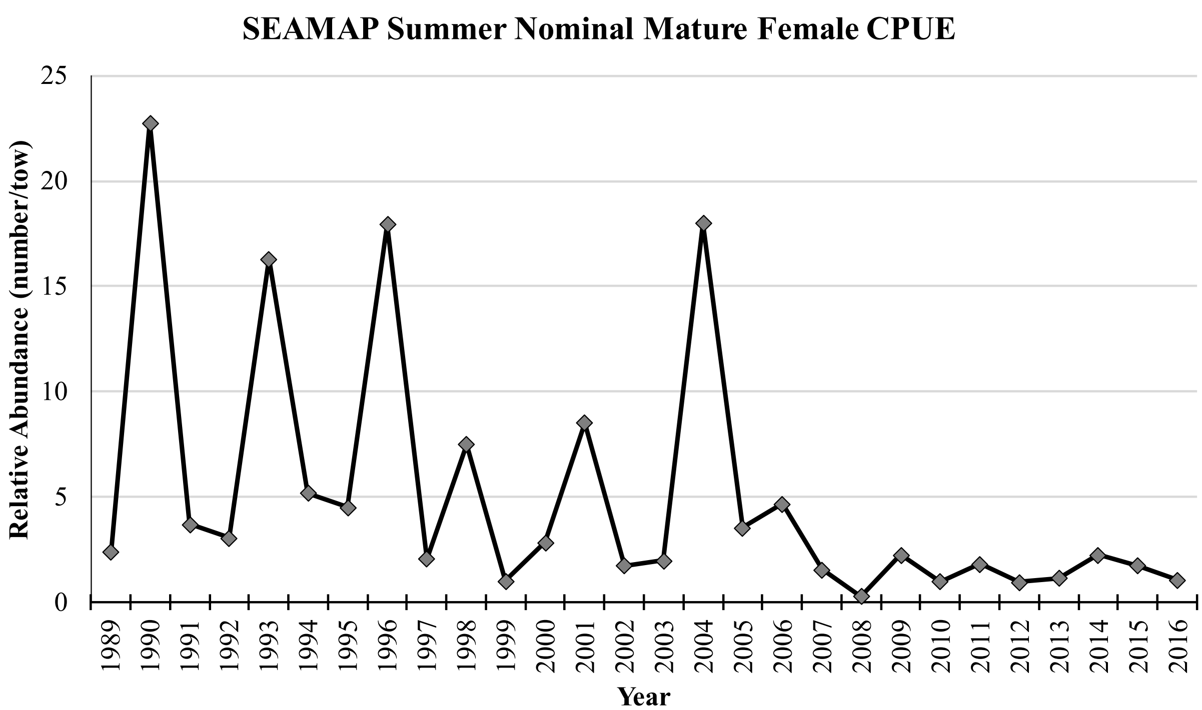


Figure 2.25. Nominal summer CPUE from the SEAMAP Coastal Survey in North Carolina waters, 1989-2016.

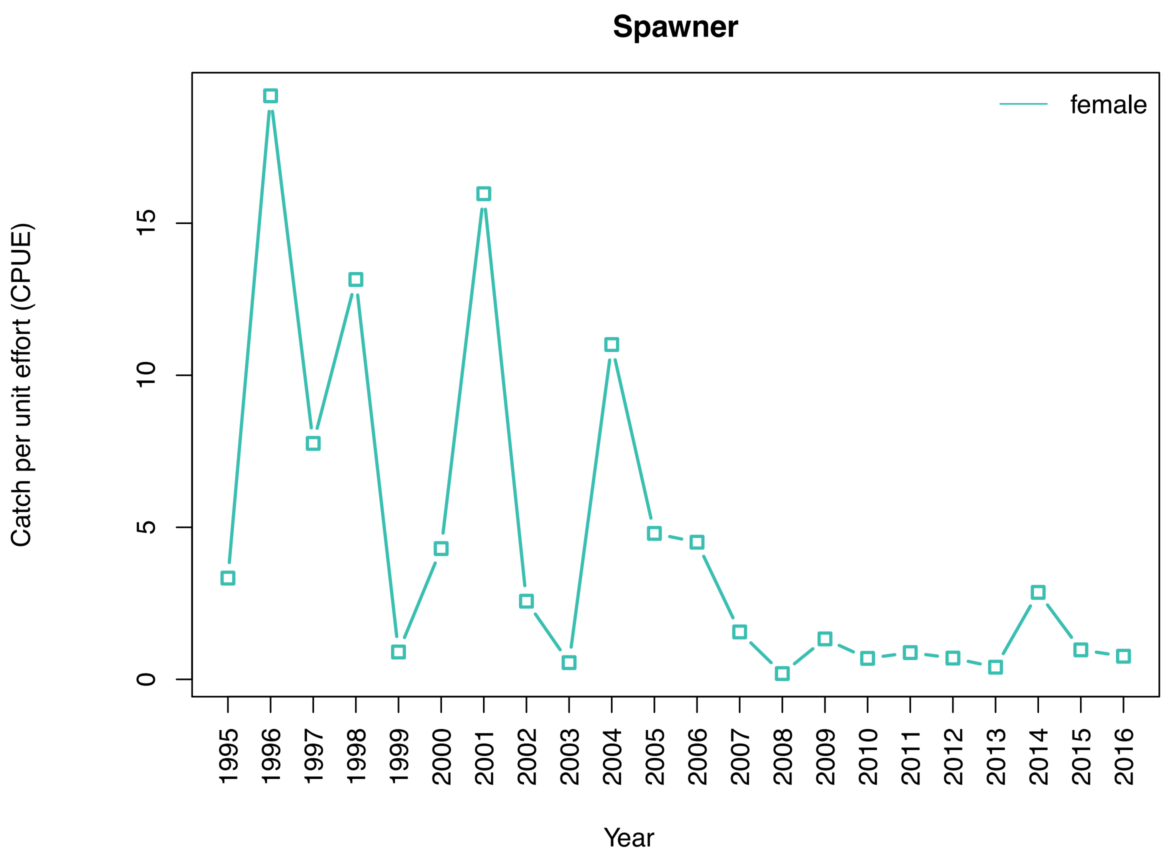


Figure 2.26. Standardized Summer CPUE from the SEAMAP Coastal Survey in North Carolina waters, 1995-2016.

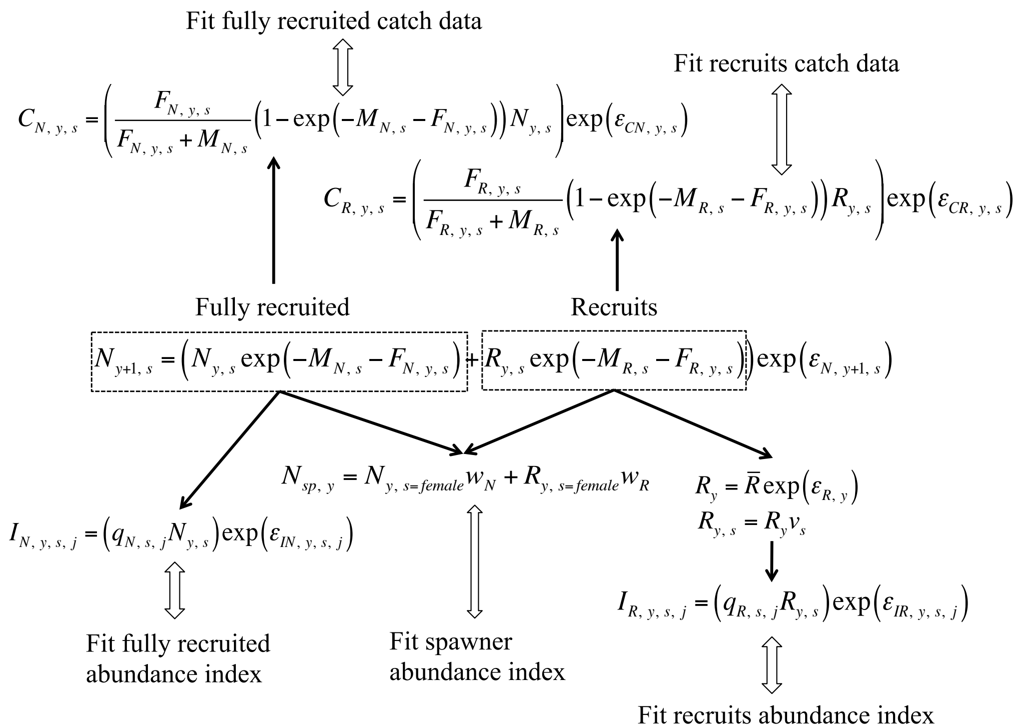


Figure 3.1. Schematic diagram of the two-stage model for North Carolina blue crab stock assessment. Refer to text for symbol explanation.

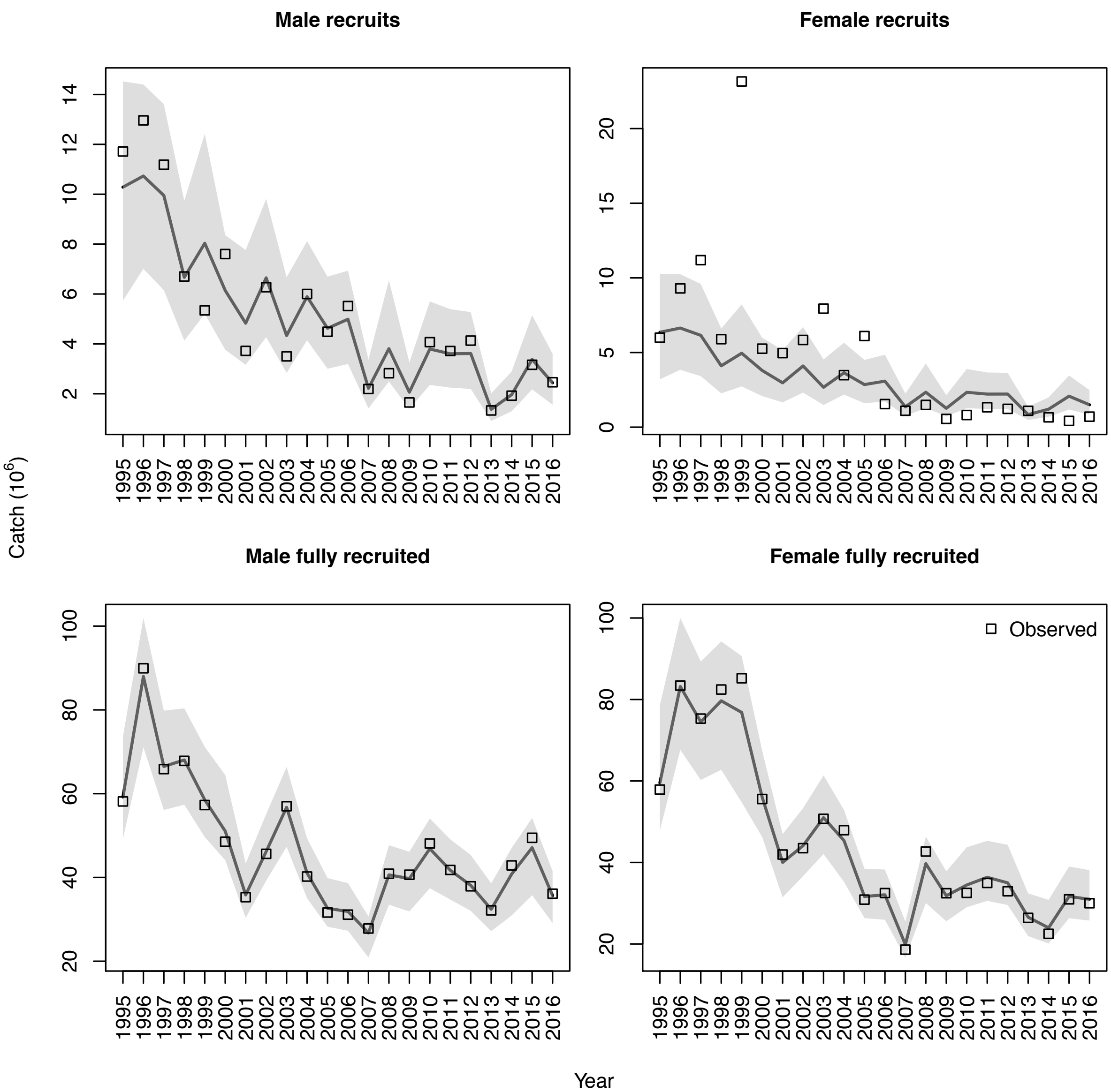


Figure 3.2. Estimated commercial catch of North Carolina blue crab from the baseline model (Model 1), with lines representing posterior mean and shaded area representing 95% credible interval.

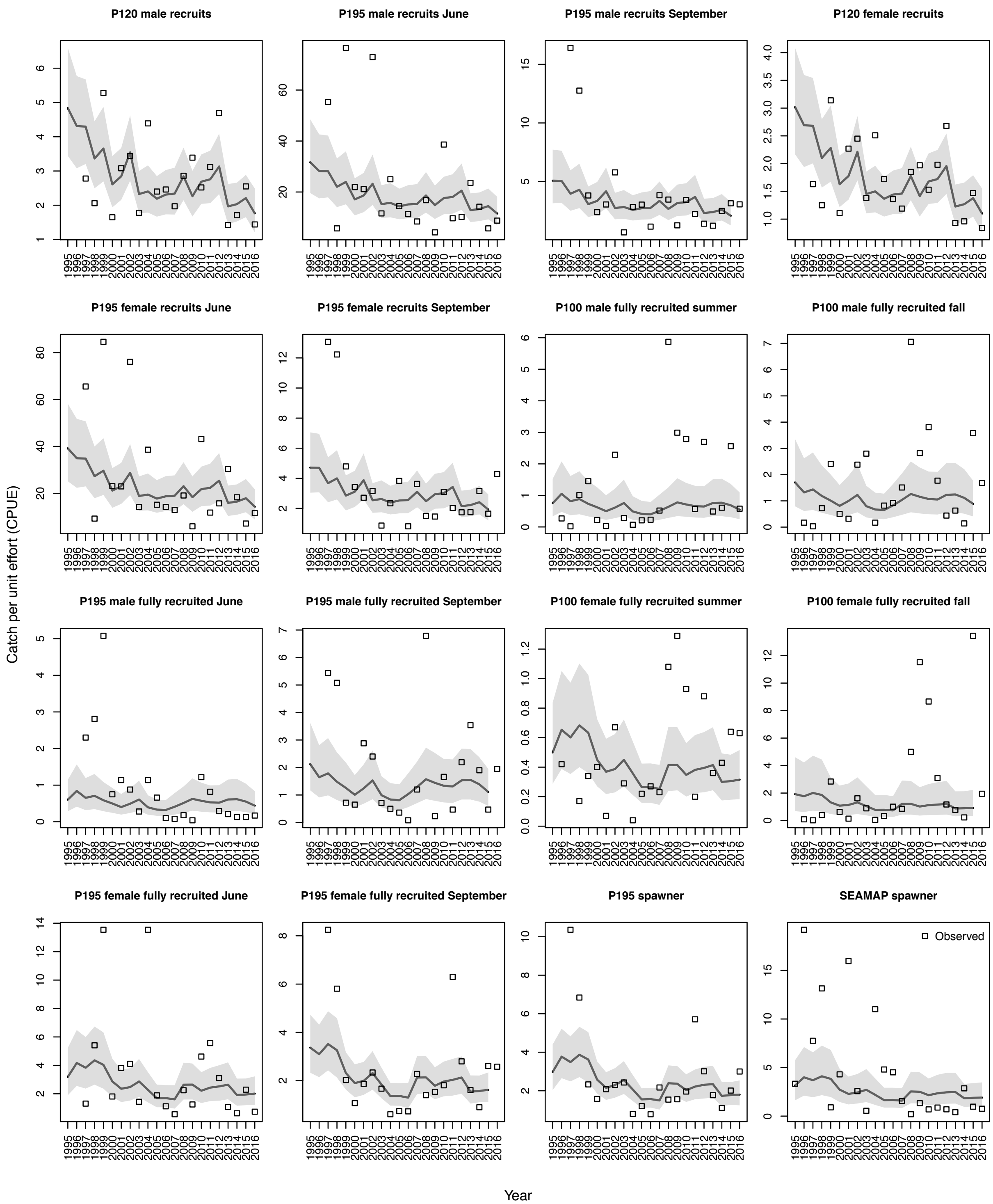


Figure 3.3. Estimated abundance indices of North Carolina blue crab from the baseline model (Model 1), with lines representing posterior mean and shaded area representing 95% credible interval.

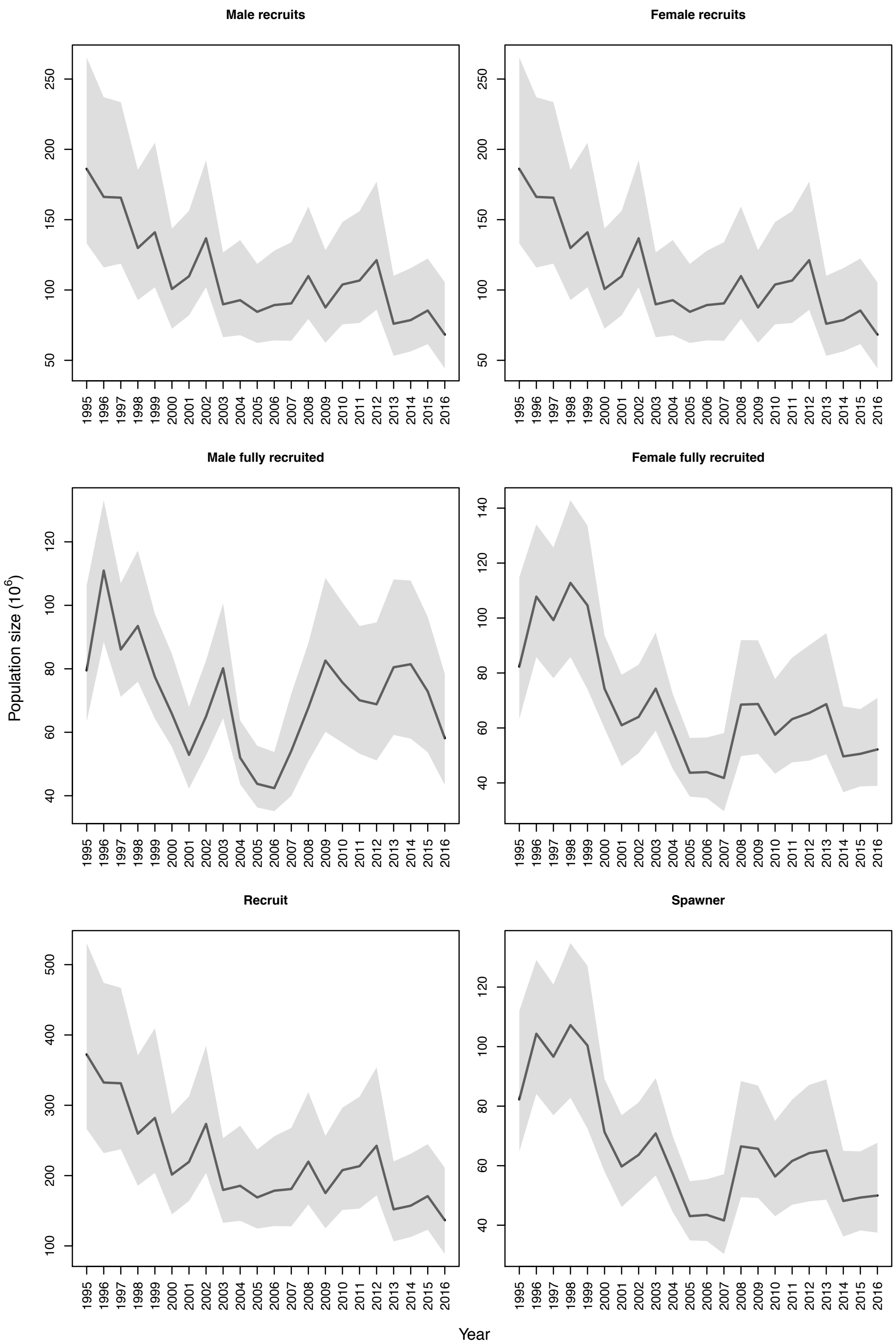


Figure 3.4. Estimated population size of North Carolina blue crab from the baseline model (Model 1), with lines representing posterior mean and shaded area representing 95% credible interval.

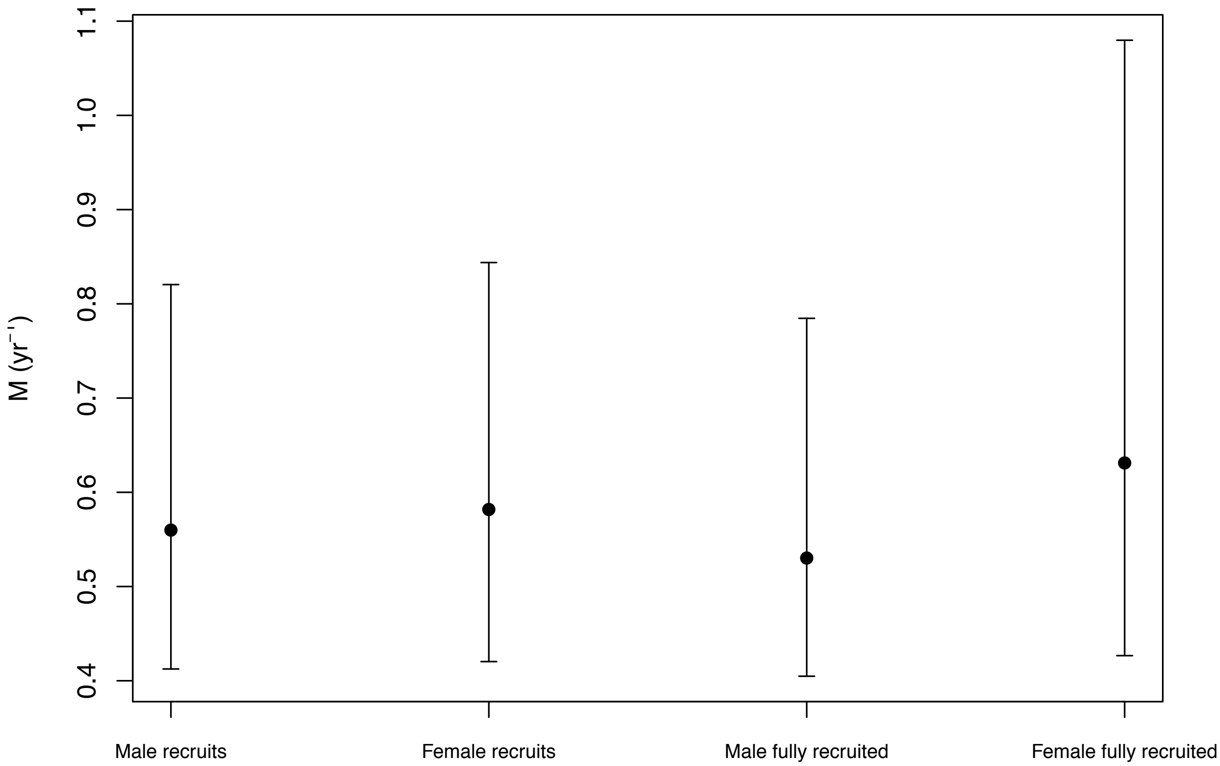


Figure 3.5. Estimated natural mortality (*M*) from the baseline model (Model 1), with dots representing posterior mean and wiskers representing 95% credible interval.

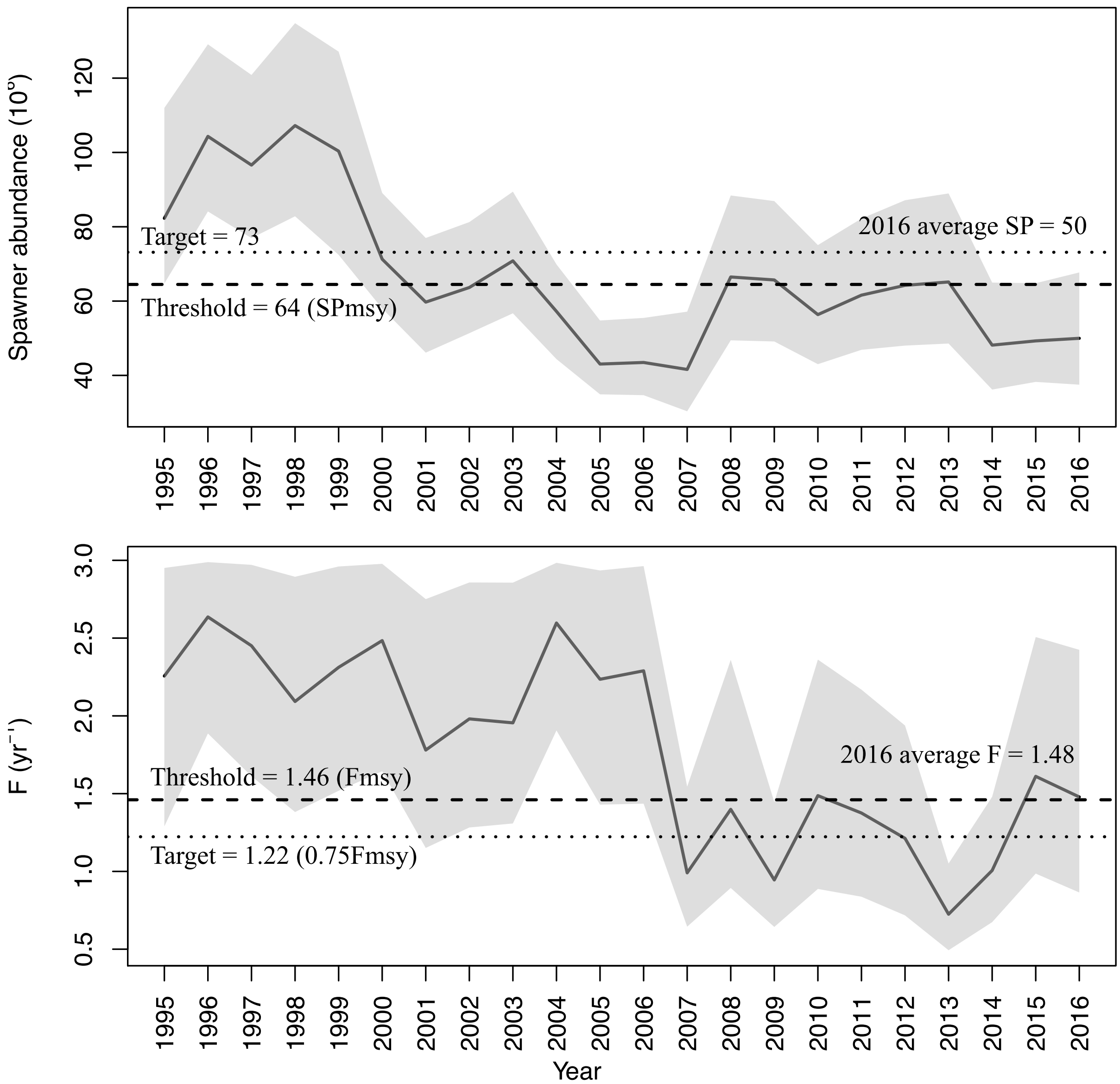


Figure 3.6. Estimated spawner abundance and fishing mortality (*F*) of North Carolina blue crab from the baseline model (Model 1), with lines representing posterior mean and shaded area representing 95% credible interval from the baseline model, Model 1. The threshold and target values are the posterior means.

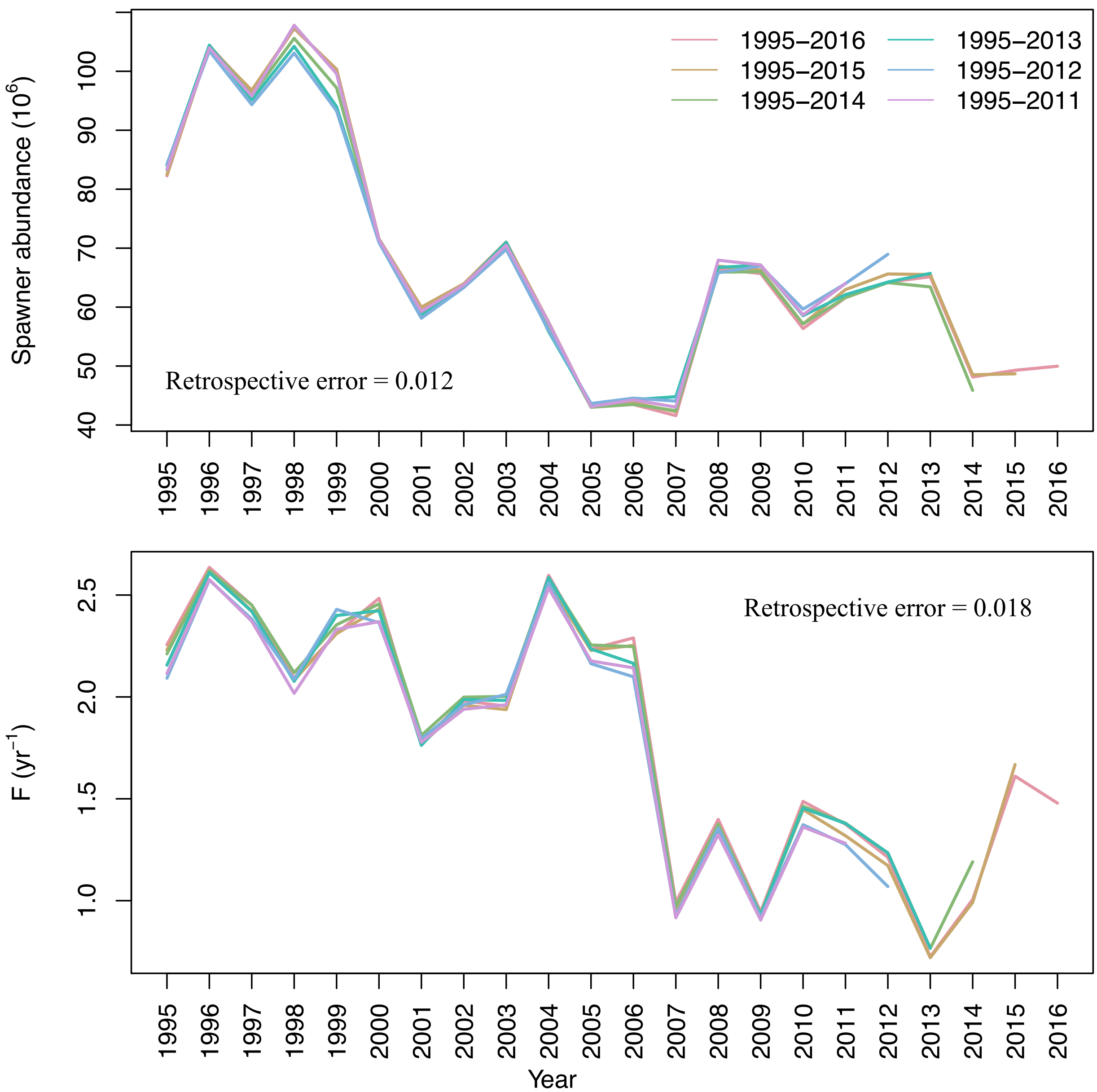


Figure 3.7. Estimated spawner abundance and fishing mortality (*F*) of North Carolina blue crab from a retrospective analysis with additional one year of data added at a time for five years in the baseline model, Model 1. Lines represent posterior mean.

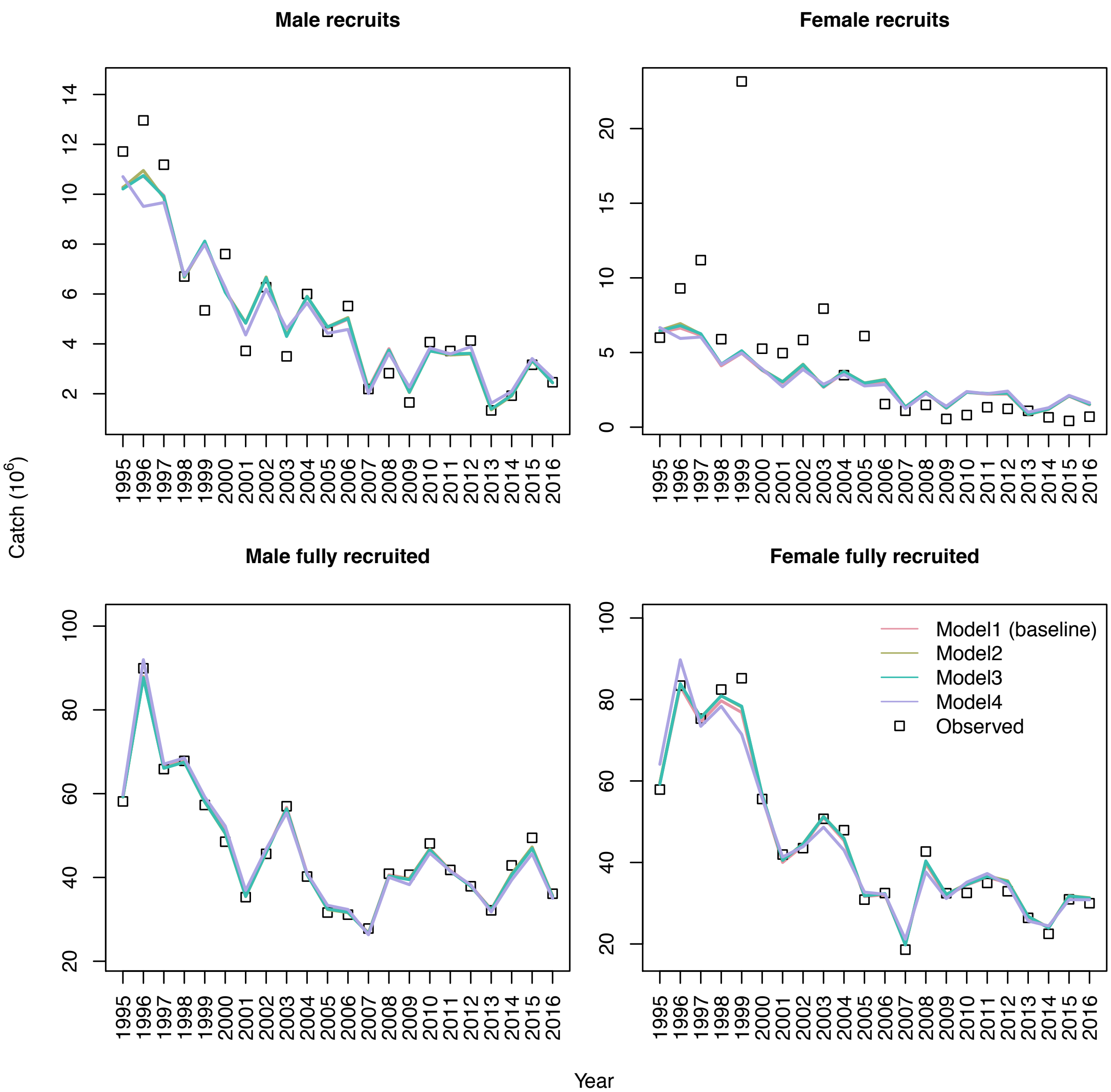


Figure 3.8. Estimated commercial catch of North Carolina blue crab from candidate models, with lines representing posterior mean. The Please refer to Table 3.3 for the explanation of candidate models.

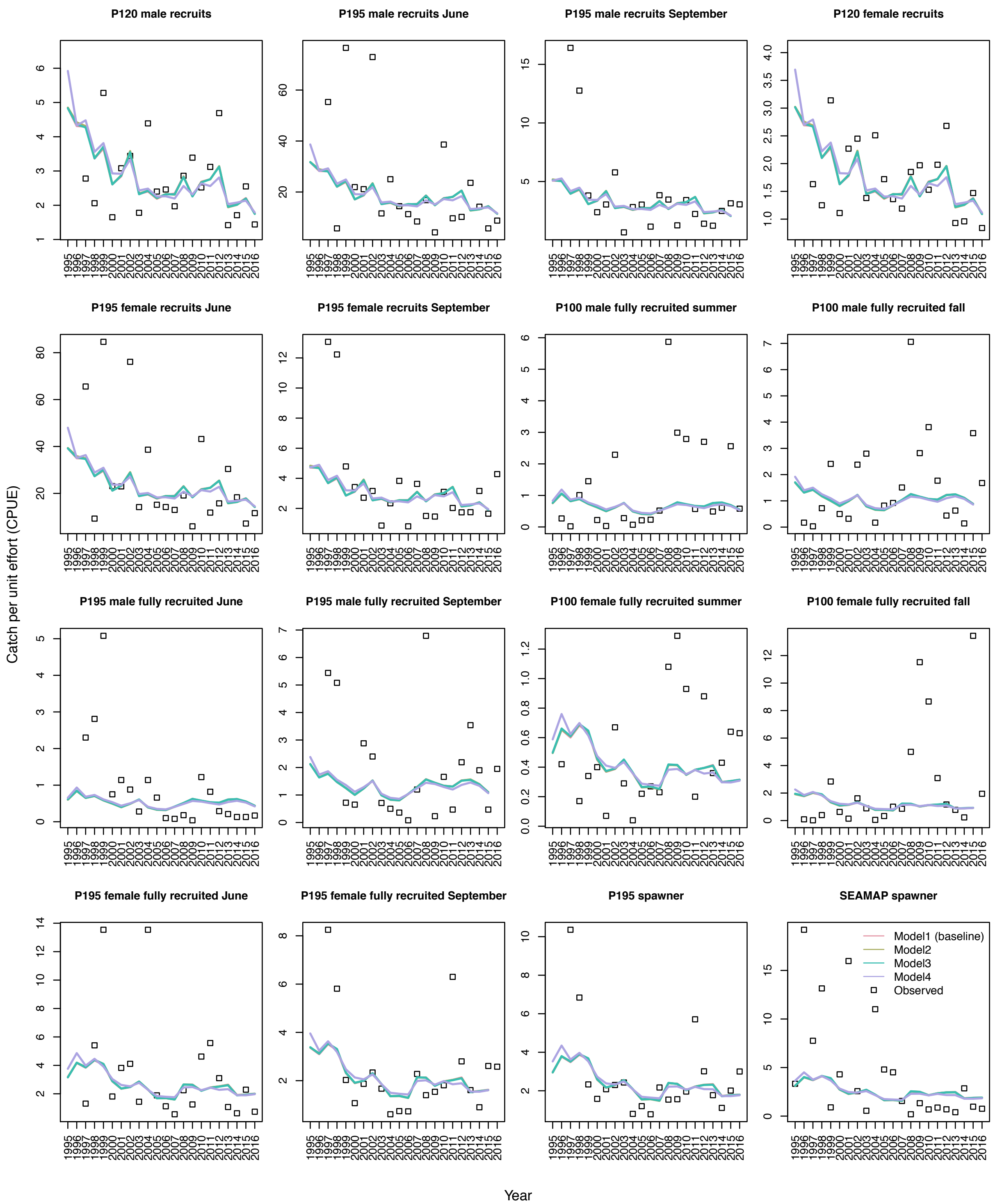


Figure 3.9. Estimated abundance indices of North Carolina blue crab from candidate models, with lines representing posterior mean. Please refer to Table 3.3 for the explanation of candidate models.

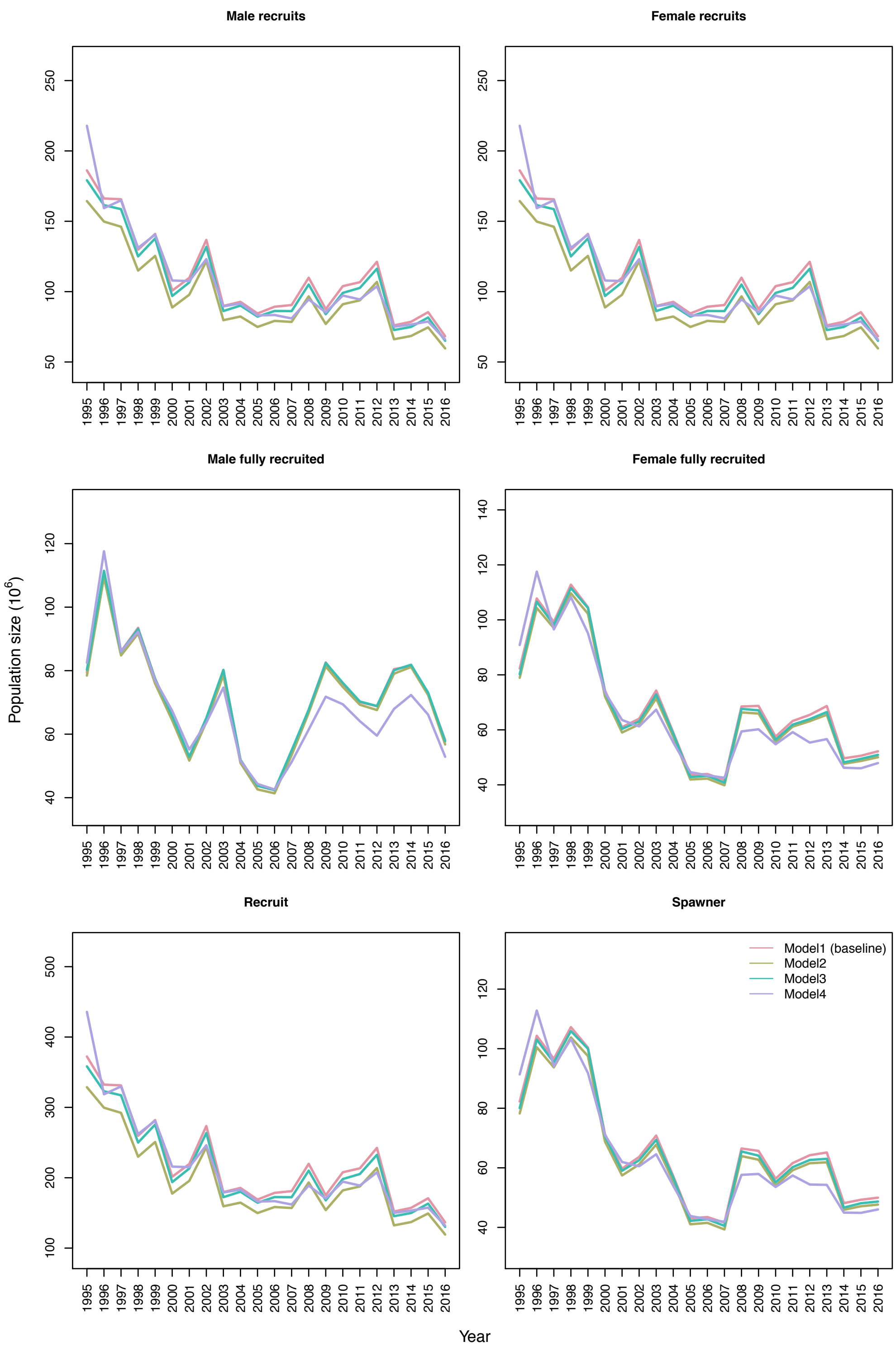


Figure 3.10. Estimated population size of North Carolina blue crab from candidate models, with lines representing posterior mean. Please refer to Table 3.3 for the explanation of candidate models.

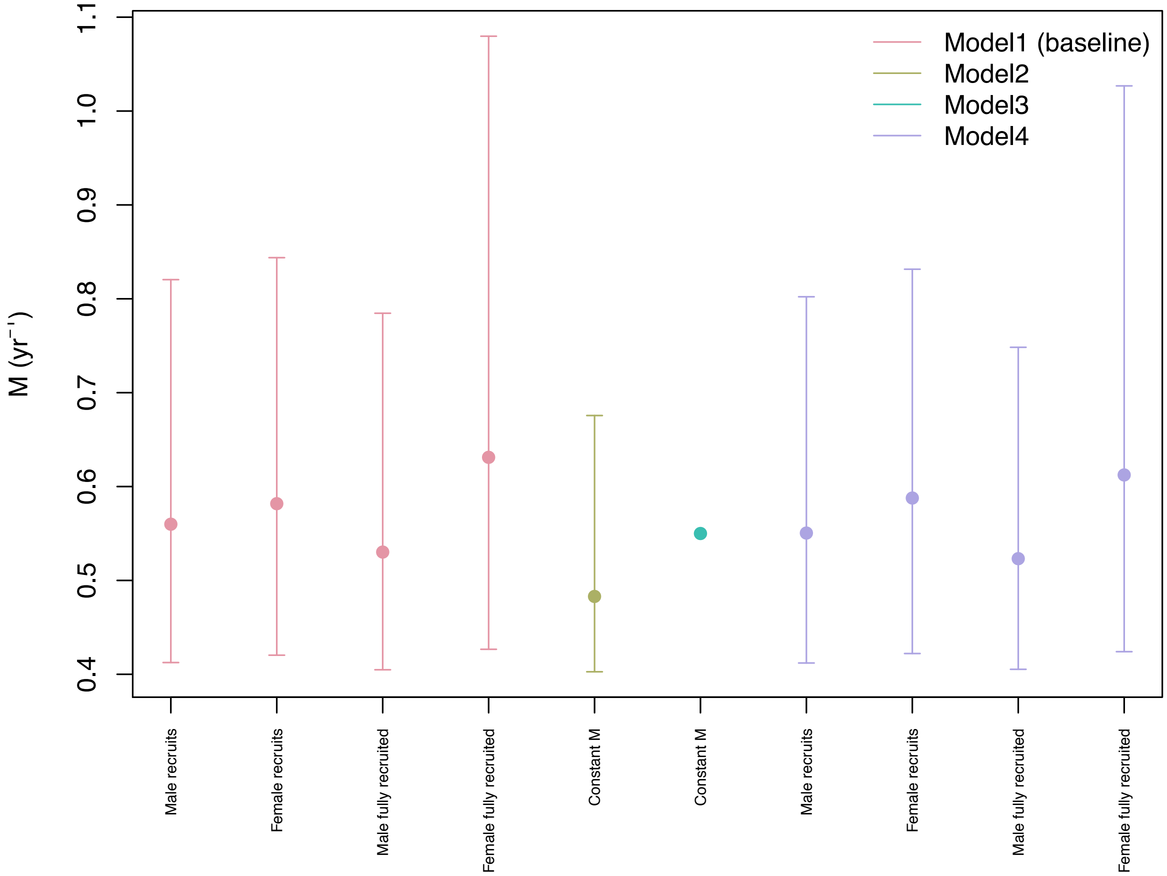


Figure 3.11. Estimated natural mortality (*M*) from candidate models, with dots representing posterior mean and wiskers representing 95% credible interval. Please refer to Table 3.3 for the explanation of candidate models.

Figure 3.12. Estimated fishing mortality (*F*) of North Carolina blue crab from candidate models, with lines representing posterior mean. Please refer to Table 3.3 for the explanation of candidate models.

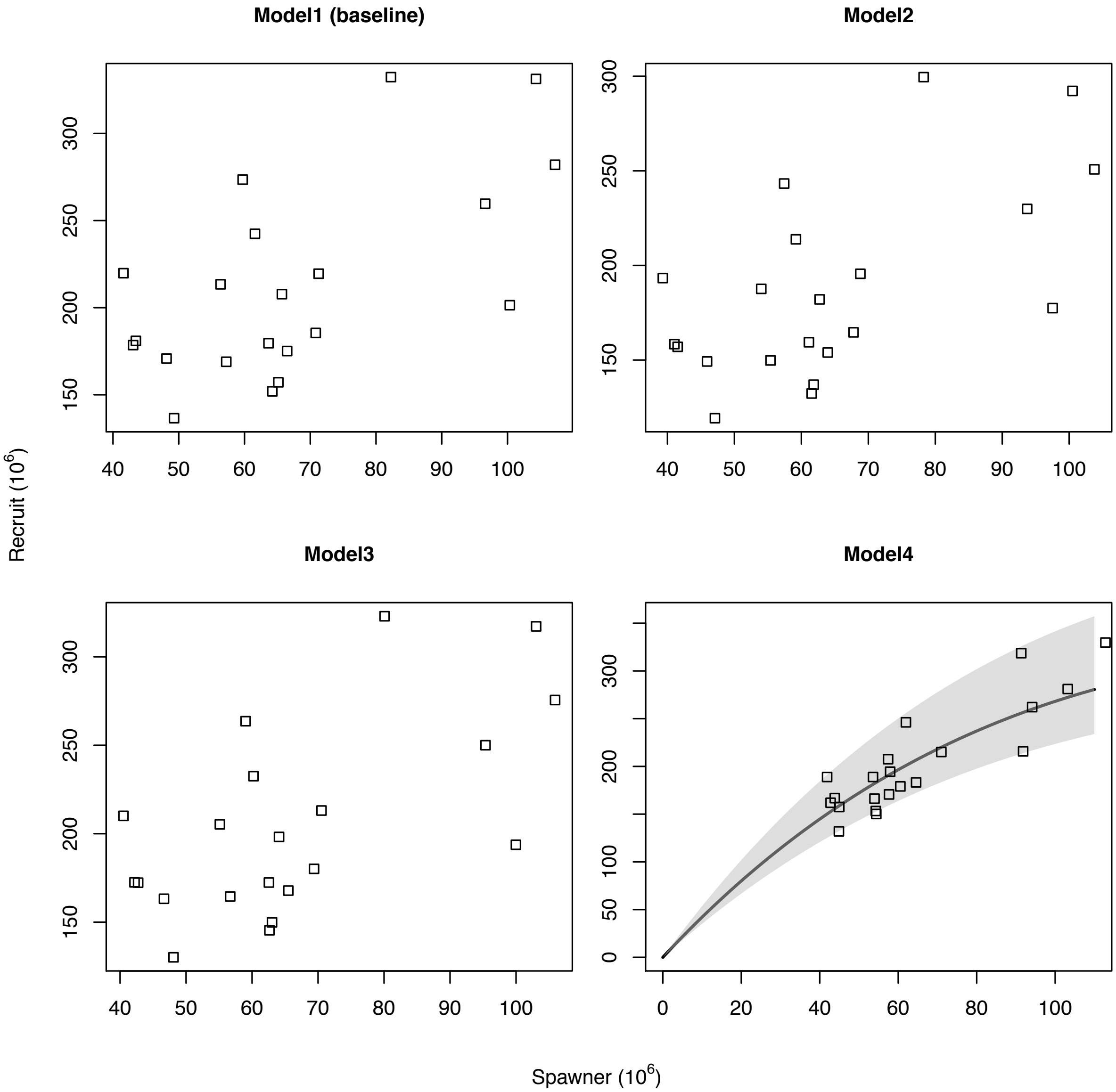


Figure 3.13. Estimated recruitment and spawner relationships from candidate models. Models 1-3 show the estimated annual average of recruits and spawner stock size; Model 4 shows the estimated recruits given a spawner stock size assuming a Ricker curve, with lines representing posterior mean and shaded area representing 95% credible interval. Please refer to Table 3.3 for the explanation of candidate models.

10 APPENDIX

10.1 APPENDIX A: Traffic Light Approach

The blue crab Traffic Light is divided into three separate characteristics: 1) adult abundance, 2) recruit abundance, and 3) production. Each characteristic uses data from several division biological surveys and sampling programs to determine the relative abundance of adult and recruit blue crabs in the population and various production indictors for the stock each year. Under the plan, management measures will be implemented in the blue crab fishery if certain biological triggers are met. To trigger management action, either the adult abundance or production characteristic of the Traffic Light must be at or above the 50% red threshold for three consecutive years to trigger moderate management action and must be at or above the 75% red threshold for two of three consecutive years to trigger elevated management action as established in the plan (Table A1). The recruit abundance indicator, while not used to trigger initial management action, may be used to supplement any management action taken if an adult abundance or production trigger is activated. The three-year period was chosen to prevent taking management action due to annual variability in the blue crab stock and instead base any management response on the observation of a short, but continued declining trend in the population.

As a result of the update with data through 2015, a revision to the Blue Crab Fishery Management Plan was adopted in May 2016 to improve the condition of the blue crab stock. Since management measures were implemented in June 2016, it is too early to tell what effect, if any, they have had on the condition of the blue crab stock.

The most recent update, including data through 2016, indicates the adult abundance characteristic continues to exceed the moderate threshold of 50% red (adult=66% red; Figure A1). This serves as the fourth consecutive year at or above the 50% red threshold for the adult abundance characteristic. The recruit abundance characteristic has exceeded the 75% red threshold for fourth consecutive year (2016=88% red). The production characteristic has met the 50% red threshold (2016=50% red) for the first of three years required before management action must be taken due to the condition of this characteristic.

Table A1. Moderate and elevated management measures under the adaptive management framework for the Blue Crab Traffic Light in Amendment 2 to the Blue Crab Fishery Management Plan.

Characteristic	Moderate management level	Elevated management level
Adult abundance	A1. Increase in minimum size limit for male and immature female crabs	A4. Closure of the fishery (season and/or gear)
	A2. Reduction in tolerance of sub-legal size blue crabs (to a minimum of 5%) and/or implement gear modifications to reduce sublegal catch	A5. Reduction in tolerance of sub-legal size blue crabs (to a minimum of 1%) and/or implement gear modifications to reduce sublegal catch
	A3. Eliminate harvest of v-apron immature hard crab females	A6. Time restrictions
Recruit abundance	R1. Establish a seasonal size limit on peeler crabs	R4. Prohibit harvest of sponge crabs (all) and/or require sponge crab excluders in pots in specific areas
	R2. Restrict trip level harvest of sponge crabs (tolerance, quantity, sponge color)	R5. Expand existing and/or designate new crab spawning sanctuaries
	R3. Close the crab spawning sanctuaries from September 1 to February 28 and may impose further restrictions	R6. Closure of the fishery (season and/or gear)
		R7. Gear modifications in the crab trawl fishery
Production	P1. Restrict trip level harvest of sponge crabs (tolerance, quantity, sponge color)	P4. Prohibit harvest of sponge crabs (all) and/or require sponge crab excluders in pots for specific areas
	P2. Minimum and/or maximum size limit for mature female crabs	P5. Reduce peeler harvest (no white line peelers and/or peeler size limit)
	P3. Close the crab spawning sanctuaries from September 1 to February 28 and may impose further restrictions	P6. Expand existing and/or designate new crab spawning sanctuaries
		P7. Closure of the fishery (season and/or gear)

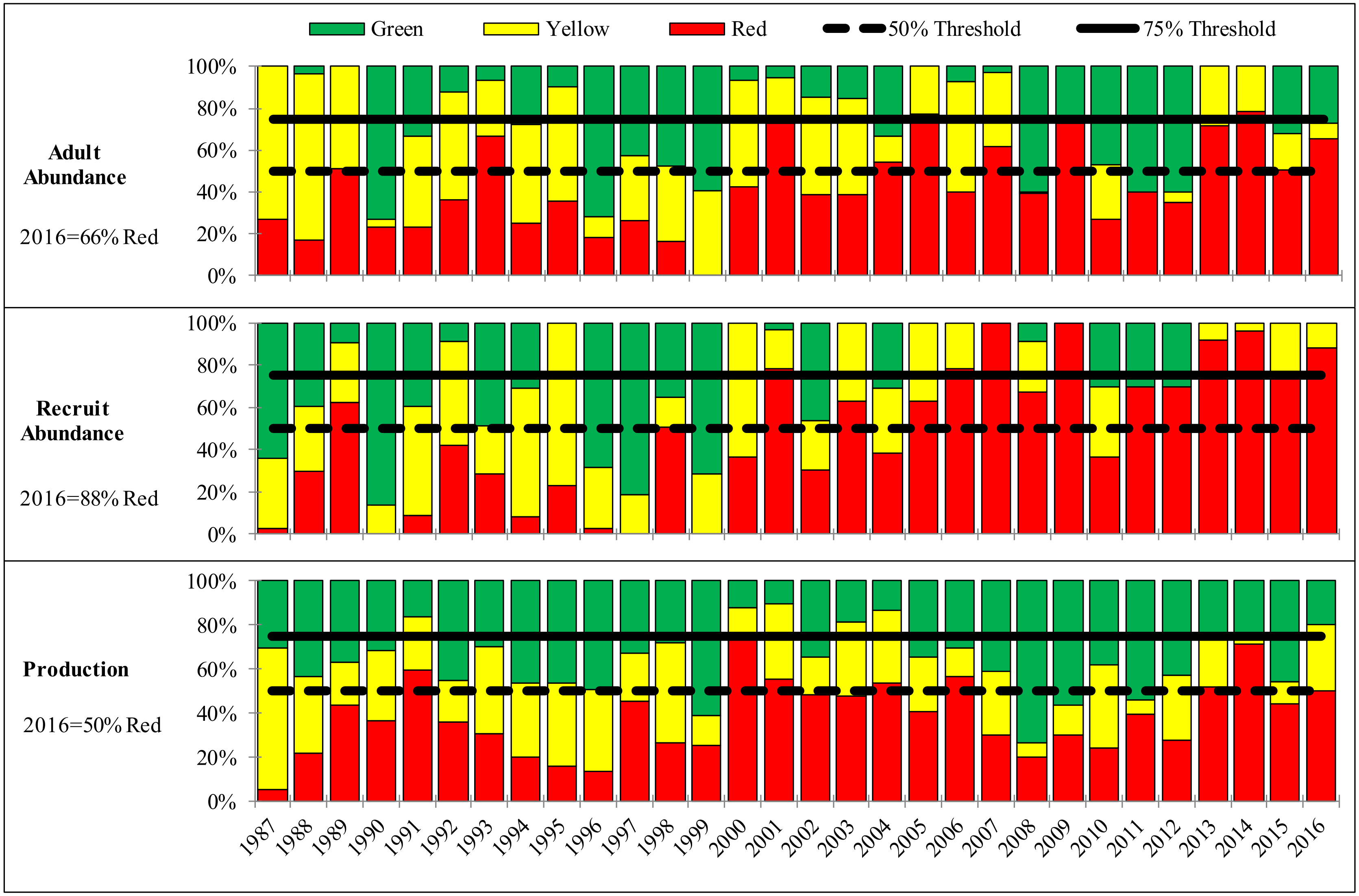


Figure A1. Adult abundance, recruit abundance, and production characteristics for the 2016 Blue Crab Traffic Light update.

10.2 APPENDIX B: External Peer Review Report

External Peer Review Report
for the
2018 Stock Assessment
of
Blue Crab in the North Carolina

Jeffrey Brust (chair), New Jersey Division of Fish and Wildlife

Dr. Edward Hale, Delaware Department of Natural Resources and Environmental Control

Dr. Robert Leaf, University of Southern Mississippi

Genine McClair, Maryland Department of Natural Resources

April 16, 2018

EXECUTIVE SUMMARY

A peer review of the North Carolina blue crab (*Callinectes sapidus*) stock assessment was conducted in New Bern, North Carolina on March 27-29, 2018. The Peer Review Panel (RP) evaluated the data sources and model relative to a set of Terms of Reference provided by the Stock Assessment Team. Based on the information provided in the assessment report and during the peer review workshop, the RP accepts the stage- and sex-structured Catch Survey Analysis model as appropriate for management use.

The fishery dependent and independent data sources, including potential biases in each one, were well described. The data sources used in the model were determined to be appropriate, but the RP suggests additional analyses to further evaluate potential data sources and better justify their inclusion or exclusion. The index standardization process was also well documented, and is consistent with best practices. The panel would have liked to see a list of all covariates available for each index, rather than just those selected. We also recommend further investigation into development of regional indices, and exploration of environmental events or indices to help explain trends in abundance.

The RP is in agreement that the CSA model used in this assessment is a significant improvement over the qualitative traffic light approach used previously. The stage-based structure is appropriate given the life history of blue crabs. We express some concerns about possible overparameterization, inconsistencies between survey and fishing time steps, and model assumptions about life history characteristics (M, growth). Sensitivity runs indicate the model is robust to these uncertainties, but recommendations are provided to address the RP's concerns.

Reference points selected are based on historical performance of spawner per recruit to prevent a "worst case scenario" (*i.e.* falling below a previously observed low point). The RP recognizes the difficulty establishing more quantitative reference points given the available data, but expresses concern over the utility of the reference points selected. It was noted that there was little variability in SPR over time, and the degree of risk in the SPR values selected is unknown (*i.e.* they could be ultra-conservative or ultra-liberal). The RP provides guidance into development of other reference points, such as those used for blue crabs in other areas, or species with similar life histories.

Stock status was determined as overfished and overfishing. This is consistent with the Assessment Team's professional opinion and observations about stock dynamics in recent years, and sensitivity runs indicate that this determination is robust to model assumptions. The RP concurs with this determination, but again encourages investigation into other reference points, which may affect status determination.

The Assessment Team provided a list of research recommendations that address data gaps and other uncertainties. The RP concluded that the list is relevant, but provides guidance on prioritization of the different items.

Overall, the RP is impressed with the amount of research and analysis conducted by the Assessment Team. Prior to and during the review workshop the Assessment Team was very responsive to the RP's questions and request. Further, an external peer review for a state level stock assessment is recognized as being above and beyond the capacity of most states. Staff of the NC Division of Marine Fisheries are commended for their efforts.

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1 INTRODUCTION

The North Carolina Division of Marine Fisheries (NC DMF) held an external peer review workshop on March 27-29, 2018 in New Bern, NC to evaluate the 2018 North Carolina blue crab (*Callinectes sapidus*) stock assessment. Members of the review panel (RP) included fishery biologists and natural resource managers from other state agencies and academia. This assessment of the North Carolina blue crab stock is the second to undergo an in-person peer review workshop; previous assessments had been reviewed through a desk audit process. Overall, the RP is impressed with the State's commitment to treating local assessments with the same level of scrutiny as regional, national and international assessments. In this respect, North Carolina sets a high bar for other states to follow in order to promote science-based management of its marine resources.

The assessment team (AT) provided a draft of the stock assessment report to the RP approximately three weeks prior to the review workshop. At the time, the AT requested that potential sensitivity run suggestions be provided prior to the review workshop since the model took approximately 4-6 hours to run, limiting the number of sensitivity runs that could be performed during the workshop. The RP submitted several ideas, as well as identified some topics that needed additional clarification or discussion during the review workshop.

Prior to the workshop, the AT also provided a set of Terms of Reference (ToR) for the RP to address in order to focus the review and deliberations on relevant aspects of the assessment, including data sources, model choice and parameterization, reference points, stock status, and research recommendations. The RP concludes that the AT addressed each of the ToR adequately, and that the model and model results are suitable for management use. Additional comments on each of the ToR are provided through the remainder of this report.

2 TERMS OF REFERENCE

2.1 Evaluate the thoroughness of data evaluation and presentation including:

Overall, the RP found that the AT adequately addressed this ToR. The individual biological monitoring programs, both fishery dependent and fishery independent, were well documented. Further, the AT acknowledged survey specific limitations and potential biases after a description of each survey, and the application of GLMs to standardize indices was well described. However, the RP did identify several potential strategies that may have helped clarify the data sources used, justify inclusion of data sources, and explain the process for index and model selection. These are described in detail below.

2.1.1 Justification for inclusion or elimination of available data sources

The AT provided thorough descriptions of the multiple monitoring programs considered, including fishery-dependent (Commercial Monitoring-Trip Ticket Program[TTP], Biological Characterization [P436]; Recreational Monitoring-Telephone and Mail-in surveys) and fishery independent surveys (Estuarine Trawl Survey[P120]; Juvenile Anadromous Survey[P100]; Pamlico Sound Survey[P195]; Southeast Area Monitoring and Assessment Program[SEAMAP]). The AT acknowledged survey specific limitations and potential biases after a description of each survey. For example, the AT acknowledged that the TTP fails to capture information on unsuccessful trips, recording only positive catch events. However, the RP notes that the survey response rate was not characterized by region of the recreational monitoring survey despite stratifying the survey design. Also, the AT limited survey participation to recreationally licensed individuals. The P120 survey was reported to potentially inflate the abundance of mature female crabs in Pamlico Sound by including transient females in abundance estimation. Further, the survey has the potential to report fewer crabs than are actually present because of a failure to sample waters deeper than 2 m. Similarly, P100 was described as potentially biased due to a failure to sample a broader depth range, as well as potentially limited in spatial scope which could significantly misrepresent the presence of mature female crabs. Conversely, P195 was described as potentially biased because of an inability to sample shallower waters and navigate complex habitat structure which may act as refugia. SEAMAP was accepted for use by the AT, and it is the only survey that samples the entire stock distribution, but it was largely recognized by the RP to potentially misrepresent trends in statewide or smaller regional patterns in abundance given the offshore sampling design.

The AT described the monitoring programs excellently; however, the RP did identify a few issues that may help clarify the available data sources, index standardization and model parametrization. First, a conceptual presentation of life history dynamics used to inform model input would have been helpful to the RP in order to document significant biological milestones encapsulated within the model parameters. For example, further detail on molt frequency and timing with respect to the model assumption that all crabs would enter the fully recruited stage after one year would help to evaluate the merits of this assumption. Similar discussion on the links between the model and natural mortality (*e.g.* pre- and post-recruitment rates), predation, and environmental tolerances (*e.g.* effects of storm events on recruitment, mortality, and availability to survey gear) would prove useful to justify model structure and parameterization.

The description of the standardization process included in the explanation of the P120 survey was excellent. However, the RP recommends the AT document all available individual covariates (not just those selected) and error structure listed for each standardized survey within the report. This information was provided upon request at the peer review by the AT. Overall, the RP felt that a series of more comprehensive tables and figures, including those developed/presented at the peer review documenting a comprehensive list of the indices considered, model type and error structure of selected standardized indices, a quantitative comparison of surveys (e.g. correlation matrix), as well as corresponding figures (e.g. GLM fit and residual plots) would have helped the RP consider more fully the surveys chosen and methods used to standardize indices prior to the review. Further, both trace plots and marginal density plots would have been helpful in order to consider diagnostics of model convergence and parameter estimation. Similarly, Gelman diagnostics would have been helpful to the RP in assessing differences among chains (Gelman and Rubin, 1992), and plots of the posterior distributions would have helped the RP assess model differences. Finally, the RP would have appreciated the presentation of a continuity run of the traffic light approach within the assessment to compare the preferred model with an updated result from a previously approved management strategy.

The RP found the overall presentation of monitoring programs well documented in the stock assessment. However, several recommendations should be considered to improve the next benchmark stock assessment. In particular, the RP recommends providing additional information and justification on the data sources evaluated, and additional types of data sources should be considered. The RP feels that, although the data sources used in the assessment were appropriate, the assessment report itself lacked sufficient justification for inclusion of specific data sources beyond listing the available monitoring programs. The potential exclusion of data sources from the assessment (e.g. recreational survey, commercial CPUE, total number of commercial licenses sold) should have been made available within the body of the stock assessment report to comparatively assess all available data streams. The RP also recommends that additional evaluation of the data sources with respect to each other should be performed. For example, available surveys, particularly fishery-dependent monitoring programs, should have been examined to determine if significant correlations were present with commercial landings. Correlation matrices of the difference indices (with appropriate time lags) are instrumental in looking for consistent signals. These were provided at the RP's request during the assessment workshop, but should be included in the draft assessment report. Finally, environmental information, including fresh water input, river flow, frequency and intensity of environmental perturbations (*i.e.* hurricanes), as well as large scale climatic indices (*e.g.* AMO/NAO/ENSO) should be explored to determine if any mechanistic physical parameters affecting recruitment or abundance could be identified and potentially included within the assessment model. However, the AT did present a number of comparisons including commercial landings relative to large hurricane events to the RP at the peer review for further consideration.

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

The RP found the description of data bias following each monitoring program helpful in assessing potential weaknesses of individual surveys. However, several recommendations should be considered to improve the next benchmark stock assessment. In particular, the RP recommends that a discussion on comprehensive issues with current sampling methodologies, including the lack of larger-scale, regional information, and whether or not surveys were tracking population abundance. Also, a proportion of positive tows for individual monitoring programs would be helpful in assessing the utility of individual sampling programs within the assessment model. Finally, appropriate comparisons of the different data sources with each other are very useful for evaluating the information content of the different sources. Much of this information was supplied to the RP upon request during the peer review workshop, but should be included in the assessment report.

2.1.3 Calculation and standardization of indices and other statistics

The RP found the calculation and standardization of indices and other statistics consistent with current best scientific practices. Specifically, the RP appreciated the incorporation of environmental variables into index standardizations given the historical information regarding environmental consideration within the assessment report. The application of GLMs to standardize indices was well documented in P120. However, a table of covariates and error structures for individual standardized indices is recommended for all indices in future assessments within the assessment report. Also, environmental indices, including those described in Section 2.1.1 of this report should be considered to examine potential relationships affecting recruitment and/or abundance. Finally, other diagnostics of index and model performance would have helped the RP better understand model parameter selection and comparative performance among models (e.g. GLM fit and residual plots, trace plots and marginal density plots, Gelman diagnostics and posterior distributions).

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

Multiple data sets from throughout the stock range in North Carolina were used as inputs into the Catch Survey Analysis model broken out by stage (recruit < 127mm and fully recruited > 127mm) and sex, including commercial landings and several fishery-independent indices. The commercial landings data were appropriately characterized using biological samples from Program 436, which ran for most of the assessment time-frame. The development and use of standardized indices for the fishery-independent surveys as input for the model was a significant improvement from previous assessments, as a means to address the influence of environmental variability. The GLM approach used was appropriate and well documented, however a list of all available covariates for each index, as well as presentation of additional diagnostics of standardization (e.g. deviance explained, AIC, etc.) would improve the RP's understanding of the effects of standardization.

A limitation for the indices utilized (with the exception of SEAMAP) is that they each cover a small spatial and temporal component of the unit stock. As such, while some of the indices showed similar patterns for the same stage and sex, others did not. There also appeared to be very real differences in regional trends between Pamlico and Albemarle sounds. Since assessment models typically have difficulty reconciling conflicting indices, the RP discussed the merit of developing combined indices by sex and stage outside the model rather than treating each survey as an independent index. Upon request by the RP, the AT ran a sensitivity analysis that incorporated combined indices to provide a more comprehensive stock-wide signal by stage and sex for model input. This model run had minimal impacts on biomass trends, and no effect on stock status. However, the RP recommends further exploration of a means to fully capture stock-wide changes in abundance for future assessments. Combining indices may also benefit the model implementation by reducing the number of parameters that must be fit.

A temporal change in abundance is reflected in some of the datasets after 2007, and it was unclear what caused this drastic change and whether it was explored by the AT. Therefore, the RP requested a sensitivity run that explored a time-block to allow for differences in catchability after 2007. While, this run had better fits to some of the indices, it increased the number of estimated parameters and did not change stock status. This sensitivity run supports the use of a single time-block, but further exploration into the data sets to investigate this temporal change will provide further justification for inclusion/exclusion of these data sets for future assessments.

To evaluate the contribution of each index to the model the RP suggested sensitivity runs that serially removed indices. As time did not allow for this process, the AT ran a sensitivity run that dropped Program 100, the Albemarle Sound juvenile trawl survey, which had the most pronounced change in abundance after 2007, and a run that dropped Program 120, the Estuarine Trawl Survey, which samples south of Albemarle Sound. Both of these sensitivity runs had negligible effects on the results compared to the base model, suggesting the model is robust to these data inputs.

The RP also discussed the appropriateness of SEAMAP as an index of abundance for the model considering the habitat sampled by the survey and unknown coastal mixing of nearby stocks (e.g. Chesapeake Bay). While SEAMAP is the only survey that samples the entire stock range within NC, the RP is concerned that there is limited connectivity between the component of the stock sampled in the ocean and the remainder of the stock in the estuaries.

The start date for the assessment was 1995. While harvest of blue crabs from North Carolina has been occurring for much longer than the assessed timeframe, the start date was adequately justified by reliable commercial landings following the implementation of the TripTicket Program in 1994 and survey data with associated environmental data becoming available in 1997. However, the RP recommends future reports consider the effect of historic harvest levels on starting biomass and evaluation of stock status.

A large data gap for this assessment is unknown recreational harvest. Expert opinion from the AT is that recreational harvest is minimal compared to commercial harvest, and available data are not considered reliable enough to estimate harvest accurately, so recreational harvest was assumed to be zero. However, it is known that recreational harvest is not zero, and data from other states suggest that it may be substantial. A sensitivity run conducted during the review workshop indicated the model results and stock status are robust to this uncertainty. Further, the RP acknowledges the difficulty in estimating recreational harvest based on the available mail surveys and no license requirement to recreationally crab in the state. Regardless, we highly recommend inclusion of recreational harvest in future assessments.

The annual time-step of this model assumes recruits grow to be fully recruited within one year. Some discussion of the accuracy of this growth assumption for all crabs < 127 mm is needed. The RP recommends exploration of a narrower recruit criteria (e.g. 80mm – 127mm) applied to survey data sets. As discussed in Section 2.1.1, a detailed review of the species life history and its implications for the model set up and parameterization would be useful.

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

The assessment integrated three sources of information (life history, fishery-dependent and fishery-independent) into a Catch-Survey Analysis (CSA), specifically catch-multisurvey analysis, that was implemented using a Bayesian parameter estimation method. The use of CSA was initially applied to four groundfish stocks in New England - Georges Bank and Southern New England yellowtail flounder and Georges Bank and NAFO SA 4X haddock stocks (Collie and Sissenwine, 1983). The approach is a stage-based population dynamics model that divides the population into pre- and post-recruits. The population model, involves fitting the time series of observed abundances of pre-recruit and post-recruit individuals to obtain estimates of stage-specific population estimates and fishing mortality rates. The approach has been reviewed and the method is robust to variation in input parameters; however, absolute estimates are sensitive to the ratio of catchabilities for each stage (Mesnil, 2003). CSA has been applied to a variety of crustacean species including northern shrimp in the northwest Atlantic, king crab in Alaska, and blue crab in Delaware Bay, Chesapeake Bay, and the eastern and western Gulf of Mexico (Miller et al., 2011, 2005; VanderKooy, 2013; Wong, 2010; Zheng et al., 2002). Miller et al. (2005, 2011) refined the model to include multiple surveys and relaxed the assumption that catch is known without error.

The RP concluded that the Catch-Multiple Survey Analysis presented in the Stock Assessment of the North Carolina Blue Crab 1995-2016 is appropriate to understand this stock's fishery and biological dynamics. The stage-based modeling approach is necessary given the difficulty of age determination of crustaceans. Stage-based methods are often used for management and conservation when the length-at-age relationship is not well understood (Rogers-Bennett and Leaf, 2006). The sensitivity runs in the assessment report, and those requested by the RP, further indicate that the model is robust to the assumptions used in the model. The use of quantitative stock assessment methods is an improvement over those such as the traffic light methods used previously for this stock.

Although the RP believes the model configuration is adequate, we believe that three aspects of the temporal dynamics of the model should be addressed. The RP advises that each of the input time series included in the model should be on the same temporal scale. Particularly, the commercial harvest should coincide temporally with the life-history of the blue crab stock in North Carolina and coincide with the indices of abundance – August 31 to September 1. The RP agrees with the decision to lag the fall fully recruited indices forward to the next year, but with up to 30% of the harvest occurring after the index is developed, this could create inconsistencies between the index and population. Adjusting the fishing year to be consistent with the index year will alleviate this concern.

Another structural issue in the model that we recommend the AT review and discuss is the time span of the assessment. The stock has been exploited by both the recreational and commercial sectors for a very long time, and identification of the relative magnitude of harvest from each sector is necessary.

The third temporal aspect of the model that we would encourage the AT to review is the temporal scale of the indices of abundance used in the assessment model. We encourage the AT to review the indices of abundance to identify the time period (months) and associated length-class (minimum and maximum carapace lengths) that are representative of the pre- and post-recruit individuals. Such an approach would require censoring the indices of abundance using methods as described in Sections 2.1 and 2.2 of this report.

We would encourage the AT to consider reducing the number of parameters that are estimated in the model. One way this could be accomplished is to aggregate sexes which would result in increased parsimony because the number of catchability parameters would be reduced. Similarly, the aggregation of sex in the model and the reasonable assumption of a 1:1 sex ratio may result in a greater precision of fitted abundance indices.

The review panel was concerned that estimates of some biological characteristics are not consistent with those of the natural stock, particularly the estimated natural mortality rates. We believe that the magnitude of the natural mortality rate estimates for both the pre- and post-recruit stages are unreasonably low – at least when compared with those incorporated into the Chesapeake Bay blue crab stock assessment (Miller et al., 2011, 2005). That the natural mortality rate estimates of the pre-recruit and post-recruit stages are equal does not seem biologically reasonable. We believe that aggregating sexes and using an informed prior on the natural mortality rate is necessary and desirable as it would provide more structure to model and perhaps reduce the problematic boundary condition estimates exhibited by the posterior distribution. Further, the RP is concerned about the ability for natural mortality to be estimated within the model, especially when the estimated values are so different from previously published estimates (*e.g.* those in the Chesapeake Bay).

The *de facto* alternative model used in the assessment was a qualitative "traffic light" approach that made use of a variety of indices to describe the fishery and the biological conditions of the stock (Caddy, 1999). We believe that an alternative model, such as a biomass dynamics model, should be used to support the assessment. The use of an alternative model can be used as a validation of the results of the stage-structured model. Surplus production models of blue crab have been used previously for this purpose, notably for the Chesapeake (Miller 2011) and Gulf of Mexico (VanderKooy, 2013). In these assessments the production model can provide support for the reference point MSY.

2.4 Evaluate the adequacy and appropriateness of recommended stock status determination criteria. Evaluate the methods used to estimate values for stock status determination criteria.

The AT established biomass threshold and target reference points as spawner per recruit (SPR) values 30% and 40% greater than the average of three lowest SPR values observed over the time period of the assessment. Fishing mortality reference points were set at the F values that produced these levels of SPR. The AT indicated that a poor fit to the spawner-recruit relationship and difficulty estimating an unfished (virgin) biomass prevented development of more commonly used maximum sustainable yield (MSY) reference points, or those based on overall spawning potential. The RP notes that there is little variability in SPR over time, and the degree of risk in the SPR values selected is unknown (*i.e.* they could be ultra-conservative or ultra-liberal). Also, it would be useful to present the YPR and SPR surfaces, rather than just the time series, in order to evaluate the selected reference point values relative to alternative values.

The RP recognizes the difficulty establishing more quantitative reference points given the available data, and status determinations appear robust to model assumptions using the reference points selected; however, the RP recommends the AT investigate development of more quantitative reference points. For example, stock assessments for blue crab in the Gulf of Mexico (Vanderkooy 2013) and Chespeake Bay (Miller et al 2011) have similar issues fitting the spawner-recruit relationship, yet both establish MSY-based reference points. We believe that although MSY or MSY proxy reference points, though plagued with considerable uncertainty because of the environmental dynamics that impact the stock, should be explored and discussed. At a minimum these could be used as qualitative references for management (Fogarty and Gendron, 2004).

Blue crab population dynamics are considered to be highly influenced by regional environmental variation (Vanderkooy, 2013). Vanderkooy (2013) notes that for the Gulf of Mexico Blue Crab stock: “Changes in the supply and distribution of rainfall could have significant impacts on estuarine productivity and threaten blue crab fishery sustainability”. Recruitment of Atlantic menhaden (*Brevoortia tyrannus*) is also highly influenced by a number of interacting environmental factors and processes (Buccheister et al. 2016), and management is based on relative spawning potential (ASMFC 2017). We recommend further investigation into methods to estimate unfished biomass, and therefore development of reference points based on spawning potential.

Other possible reference point methods include egg per recruit models, as have been used for both US and Canadian lobster (although this method is not currently used for either stock), or incorporation of environmental parameters to improve understanding of recruitment dynamics. Leaf and Friedland (2014) used environmental indices of stock productivity to identify drivers of recruitment patterns of Georges Bank Haddock.

We reiterate that although status determination appears robust to the model, the RP has concerns about the reference points selected. A number of alternatives are provided above, with a priority on MSY-based reference points. The above guidance should not be considered a comprehensive discussion on the available alternatives, and the AT is encouraged to conduct research into appropriate reference points given the life history and data gaps, and also to further evaluate the risks associated with per recruit reference points selected.

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

The RP is satisfied that the sex- and stage-structured CSA model presented as the base run of the assessment report is suitable for management use for the next five years. A number of uncertainties and possible areas of concern with the available data, model assumptions and structure, and reference points have been identified throughout this report that could be addressed to improve the model in the future; however, sensitivity runs clearly indicate that the model results and status determinations are robust to the RP's primary areas of concern. Further, the results of the assessment are consistent with the lead biologists' perceptions of the fishery and stock dynamics. These two points provide credence to the RP's determination that the model provides a valid basis for management of North Carolina's blue crab stock.

Although the RP approves the use of this model for the next five years, we do not advocate that management decisions over that entire time period be based on the results of a 2018 model run. Because of the short life span of blue crabs, as well as other biological and environmental influences, it is strongly recommended that the model be updated at least once within the approved management time period of 5 years.

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

The RP agrees with many of the research recommendations in the assessment report. However, we advise that the AT prioritize these, categorically at a minimum, to focus primarily on improving the precision and accuracy of those data that address deficiencies in the assessment model and decision-making. For this reason, we recommend categorizing as high priority the development of a state-wide fishery-independent index of abundance for both life-stages, beyond the "continue existing" programs. This would serve to reduce the dimensionality of the input data (and number of parameters) and allow aggregation of the spatial-temporal issues in the indices. Similarly, the review panel would advise that a high priority research item is to characterize the magnitude of recreational harvest. Finally, given the difficulty to understand stock and fishery status, we believe that the evaluation of alternative reference points should be a top priority. We suggest that the assessment and management group in the agency review the options of fishery-reference points for invertebrate stocks (crustacean and molluscan stocks) that exhibit similar life history and stock recruitment dynamics.

Of medium priority, the RP would recommend evaluating ecosystem and environmental effects on the blue crab stock. Blue crab are a common prey item of many benthivores (Oshima and Leaf, 2018), and patterns in predator abundance likely influence stock dynamics. Further, the influence of environmental events, such as rainfall/freshwater influx, temperature anomalies, or major storms could be evaluated with respect to abundance, or even just availability to surveys and the fishery. We would also recommend investigation of alternative model types, such as a biomass dynamic model. Alternative models could provide corroboration in model results, but may also provide more quantitative reference points. Finally, we believe that exploring genetic stock structure and age and growth determination of blue crab to be of relatively low priority.

3 ADDITIONAL COMMENTS

Overall, we would like to commend the AT for their innovative approach to the assessment of blue crab in the State of North Carolina. The RP does have a few suggestions that might help improve this assessment as well as future assessments. The traffic light approach should have been included within the body of the assessment report to consider a continuity run of a previously established management method alongside the newly developed assessment model. However, it should be noted that the AT did provide the results of a continuity run in comparison to the new model during the peer review. Also, the RP would have appreciated if the model was made available in print and digital form prior to the review workshop in order to evaluate the code, understand mechanics of the analyses, and perform sensitivity runs independently. Finally, the RP would have preferred more time prior to the review in order to allow for a longer period of review.

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10.3 APPENDIX C: Additional Sensitivity Analyses

Per the peer reviewers' request, the working group explored eight candidate models (Model 5 – Model 12), additional to the baseline model (Model 1) and the three ones (Model 2 – Model 4) that are included in the report (Table C1). The fitting to catch data (Figures C1-C3), estimated population size (Figures C7-C8), estimated natural mortality (Figures C9-C10) and fishing mortality (Figures C11-C12) by the two-stage model were quite robust to the assumptions that have been explored, such as natural mortality assumptions, recruitment-spawner relationship, dropping spawner indices, higher catch to account for recreational catch. One exception occurred in Model 8 in which a high input value of natural mortality (M=1.2) resulted in relatively high population size estimates (Figure C8).

Assumption of time-block catchability and the use of combined indices slightly improved the model fitting to abundance indices (Figures C4-C6). Estimated spawner abundance and recruitment showed weak relationship in all candidate models except the Model 4 where a Ricker curve was assumed (Figures C13-C14). Comparing the stock status from all candidate models based on biological reference points that are commonly used (including the maximum sustainable yield based, yield-per-recruit based), an overfished stock and overfishing were suggested in most cases (Table C2).

Tables

Table C1. Additional sensitivity runs (bolded) that have been explored during peer-review workshop.

Model	Features
Model 1 (baseline)	Sex- and stage-specific natural mortality Recruitment free parameter to estimate (lognormal distribution) Time-constant catchability All abundance indices Initial year when catch data start (1995) Sex-specific recruits selectivity to estimate
Model 2	Same as Model 1 except a constant natural mortality to estimate
Model 3	Same as Model 1 except a constant natural mortality to input (*M*=0.55)
Model 4	Same as Model 1 except recruitment follows a Ricker mode
Model 5	**Same as Model 1 except a time-block catchability (2007)**
Model 6	**Same as Model 1 except dropping P100 indices**
Model 7	**Same as Model 1 except dropping P120 recruit indices**
Model 8	**Same as Model 3 except *M*=1.2**
Model 9	**Same as Model 1 except using the combined indices**
Model 10	**Same as Model 1 except increasing catch by 15% to account for recreational catch**
Model 11	**Same as Model 1 except dropping all spawner indices (P195 and SEAMAP)**
Model 12	**Same as Model 1 except using fishing year catch data (September 1-August 31)**

Table C2. Stock status determination from sensitivity analysis.

Scenario ID	$N_{SP,\ 2016}$ (10^6)	F_{2016}	$N_{SP,\ MSY}$ (10^6) - threshold	F_{MSY} - threshold	Overfished	Overfishing
Model 1 (baseline)	49.98	1.48	64.48	1.46	Y	Y
Model 2	47.66	1.49	68.54	1.37	Y	Y
Model 3	48.68	1.49	65.1	1.52	Y	N
Model 4	46.03	1.71	79.78	0.94	Y	Y
Model 5	49.47	1.5	63.02	1.46	Y	Y
Model 6	46.22	1.67	67.47	1.32	Y	Y
Model 7	53.5	1.34	71.11	1.31	Y	Y
Model 8	62.13	1.54	59.86	1.84	N	N
Model 9	50.57	1.64	147.63	1.13	Y	Y
Model 10	56.99	1.5	74.41	1.42	Y	Y
Model 11	50.7	1.49	61.38	1.55	Y	N
Model 12	56.57	1.84	74.24	1.39	Y	Y

Figures

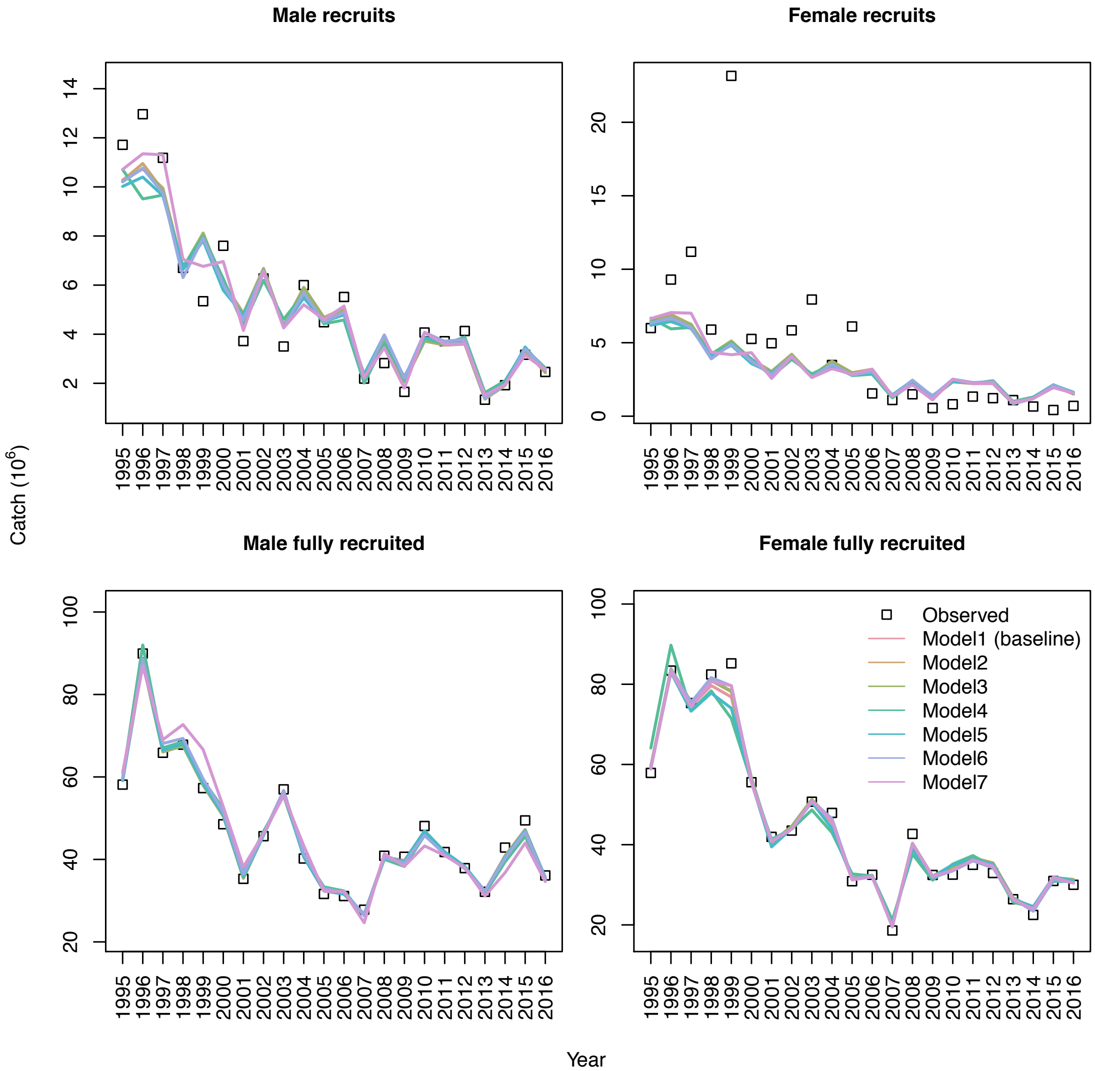

Figure C1. Estimated commercial catch of North Carolina blue crab from candidate models M1-M7, with lines representing posterior mean. The Please refer to Table 1 for the explanation of candidate models.

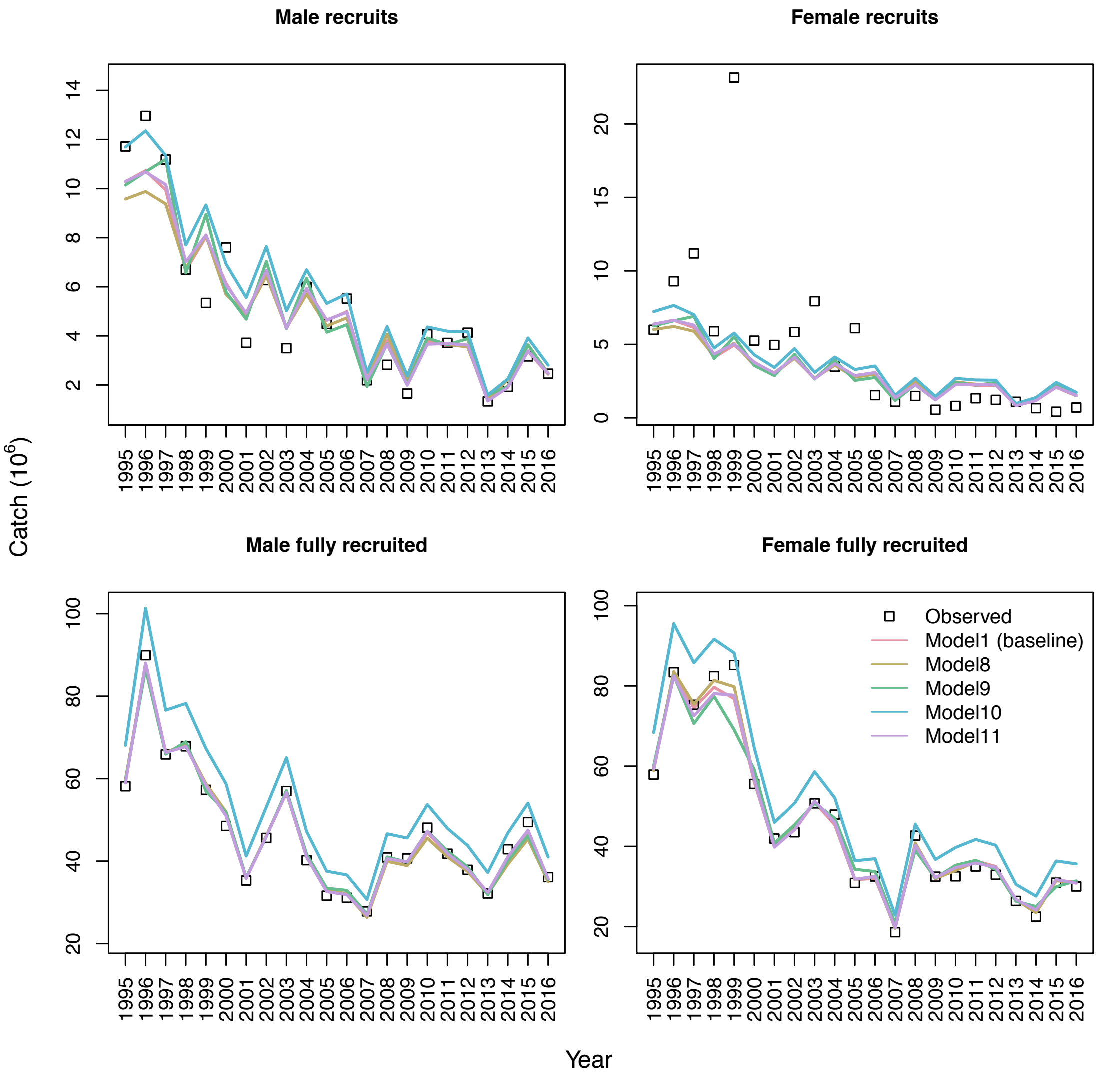

Figure C2. Estimated commercial catch of North Carolina blue crab from candidate models M8-M11, with lines representing posterior mean. The Please refer to Table 1 for the explanation of candidate models.

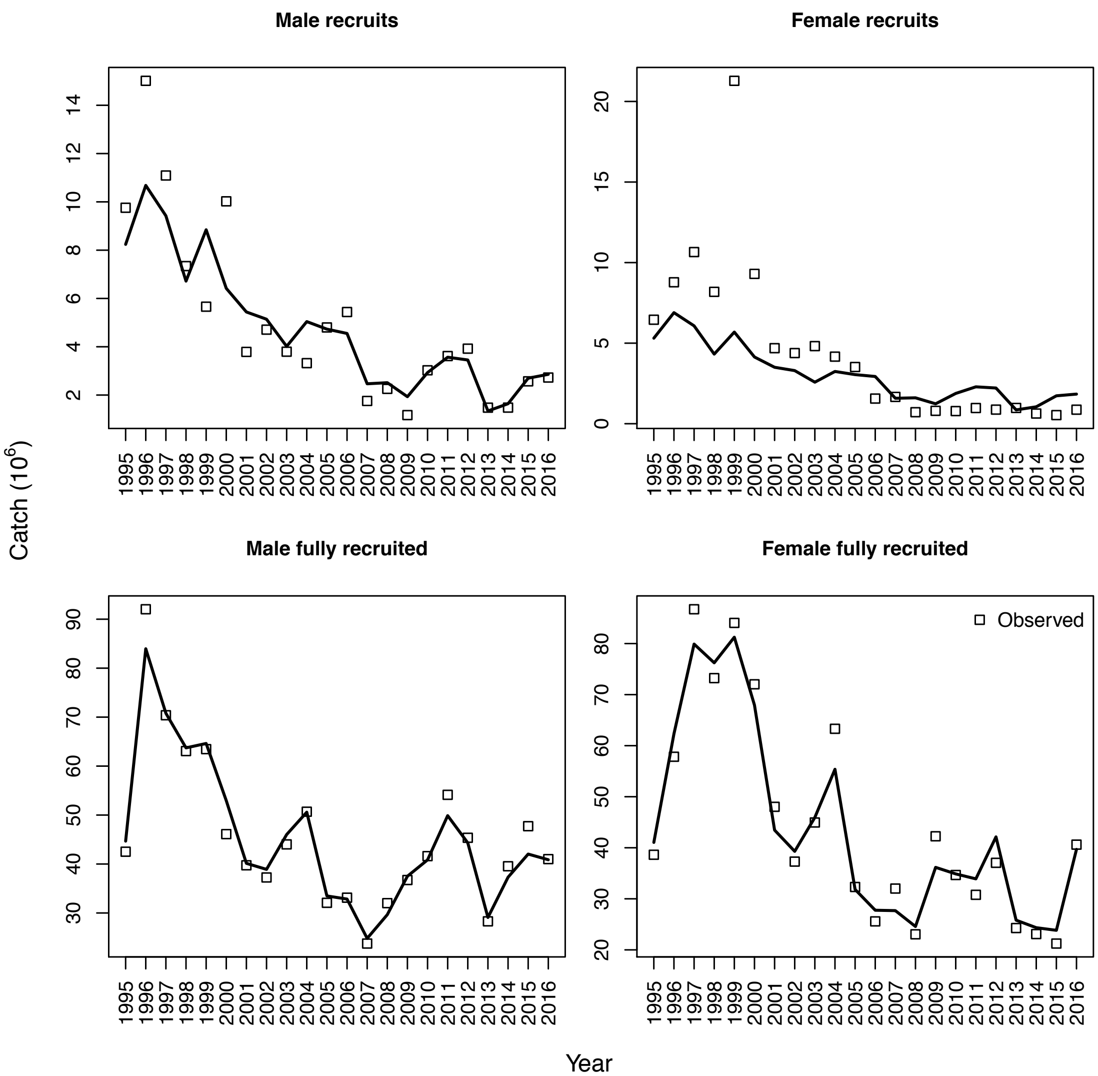

Figure C3. Estimated commercial catch of North Carolina blue crab from candidate models M12, with lines representing posterior mean. The Please refer to Table 1 for the explanation of candidate models.

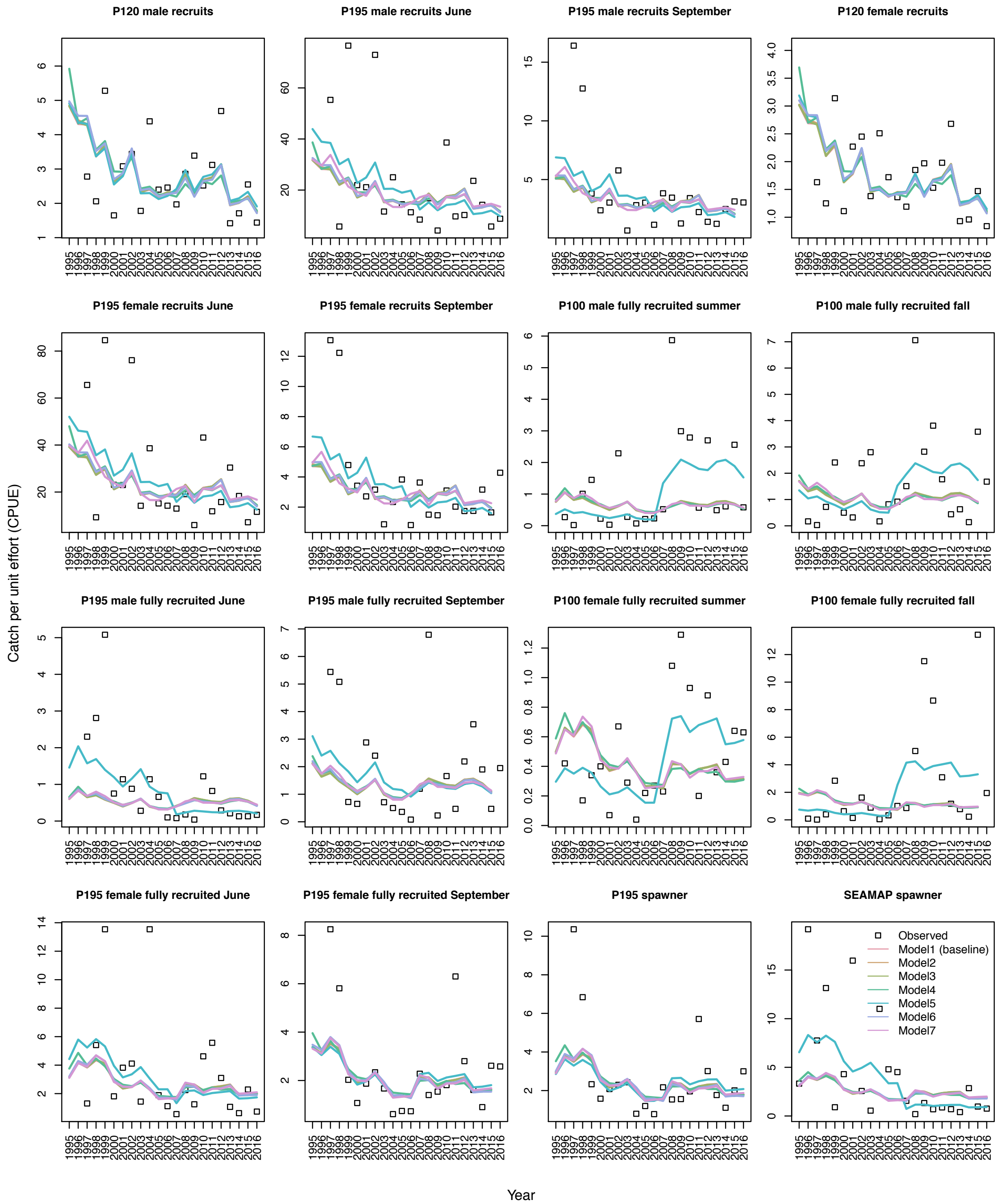

Figure C4. Estimated abundance indices of North Carolina blue crab from candidate models M1-M7, with lines representing posterior mean. Please refer to Table 1 for the explanation of candidate models.

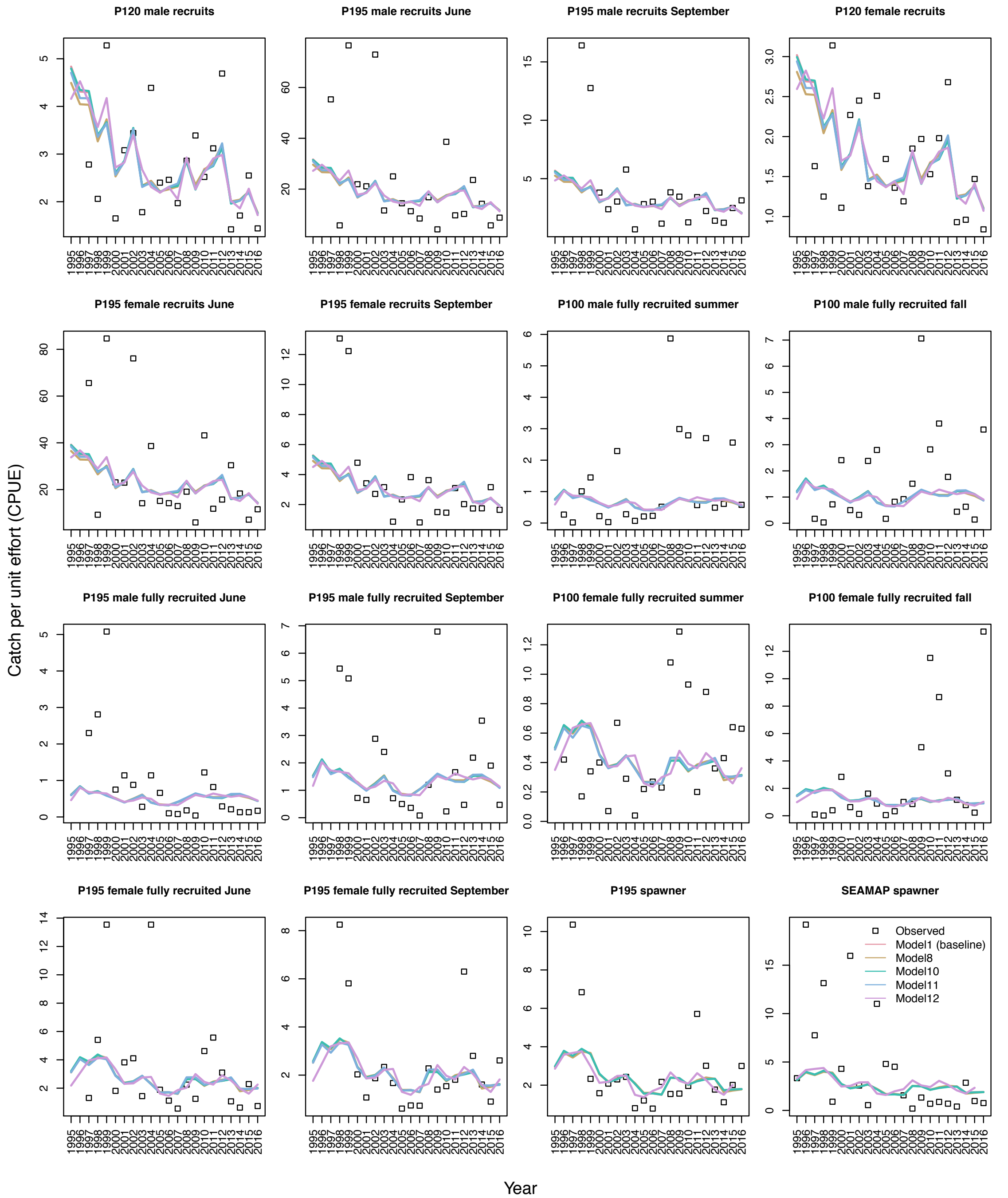

Figure C5. Estimated abundance indices of North Carolina blue crab from candidate models M8, M10-M12, with lines representing posterior mean. Please refer to Table 1 for the explanation of candidate models.

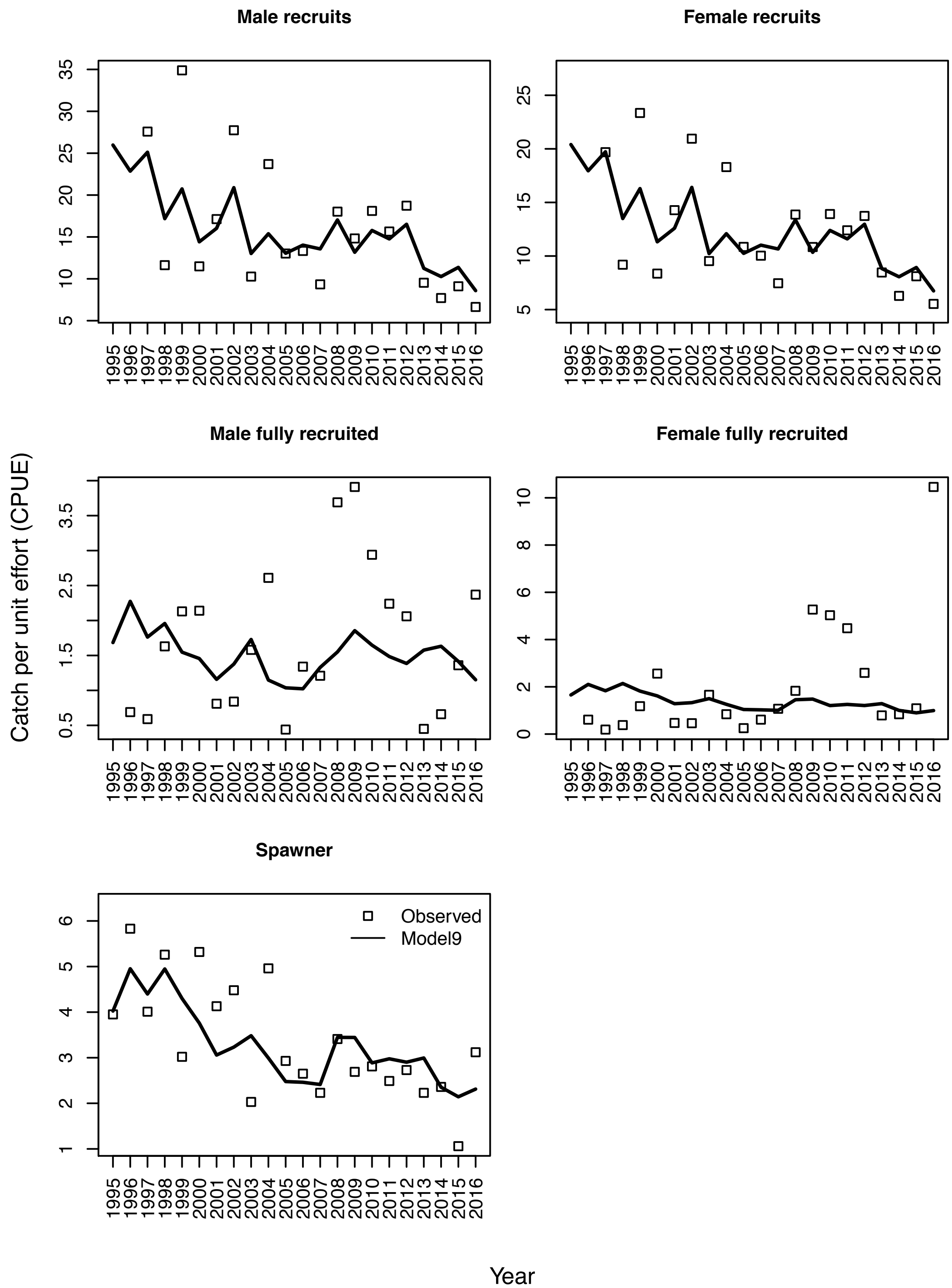

Figure C6. Estimated abundance indices of North Carolina blue crab from candidate models M9, with lines representing posterior mean. Please refer to Table 1 for the explanation of candidate models.

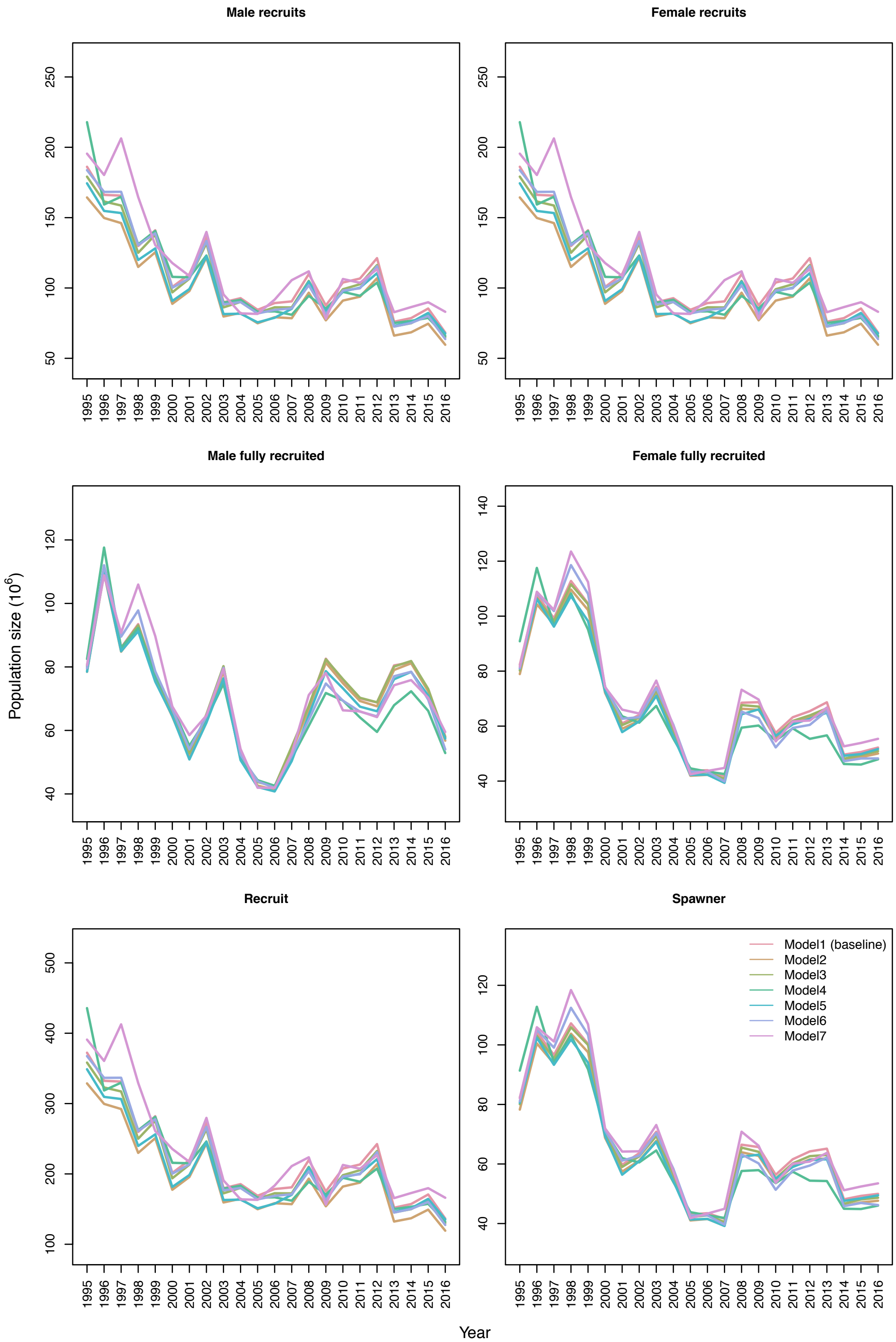

Figure C7. Estimated population size of North Carolina blue crab from candidate models M1-M7, with lines representing posterior mean. Please refer to Table 1 for the explanation of candidate models.

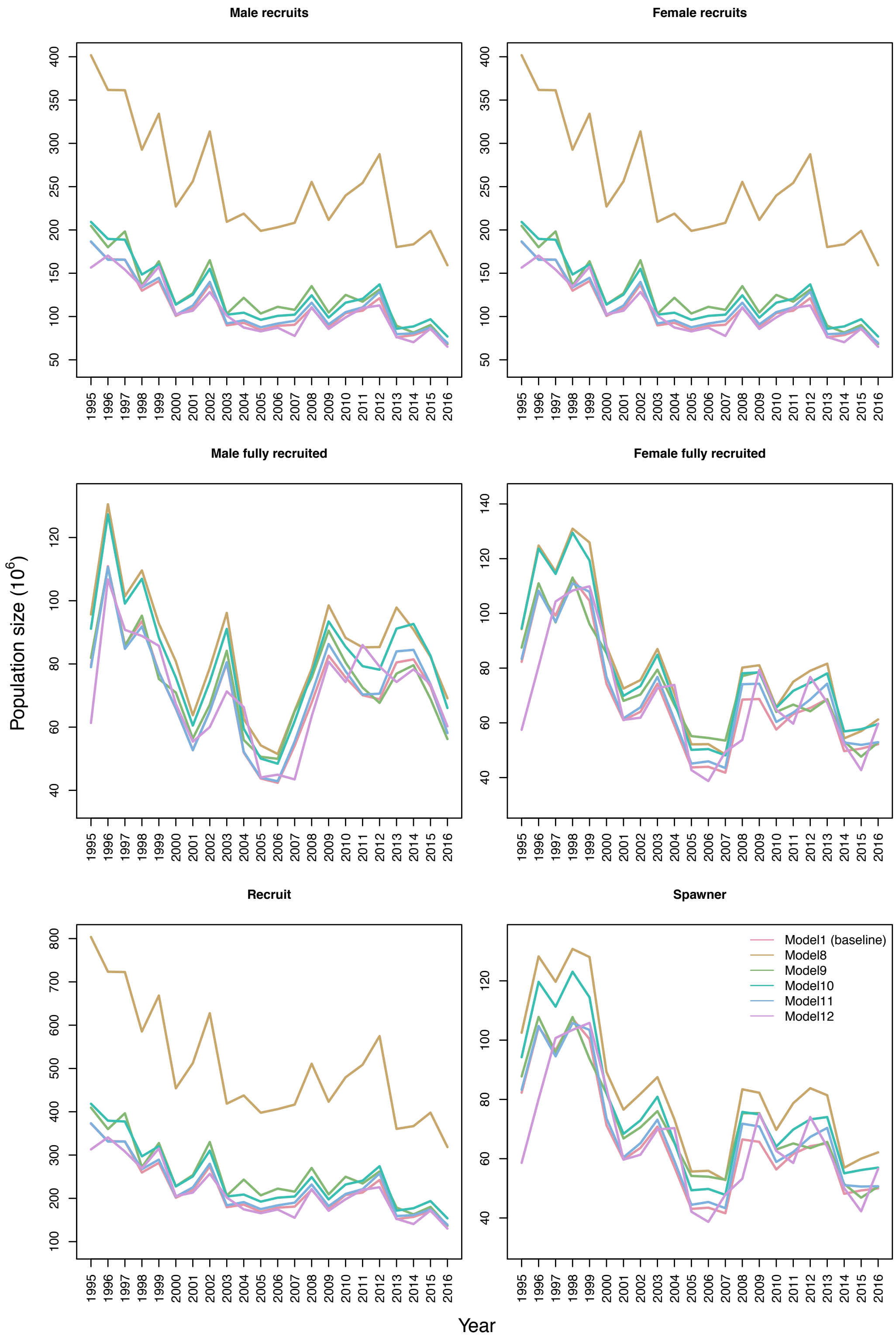

Figure C8. Estimated population size of North Carolina blue crab from candidate models M8-M12, with lines representing posterior mean. Please refer to Table 1 for the explanation of candidate models.

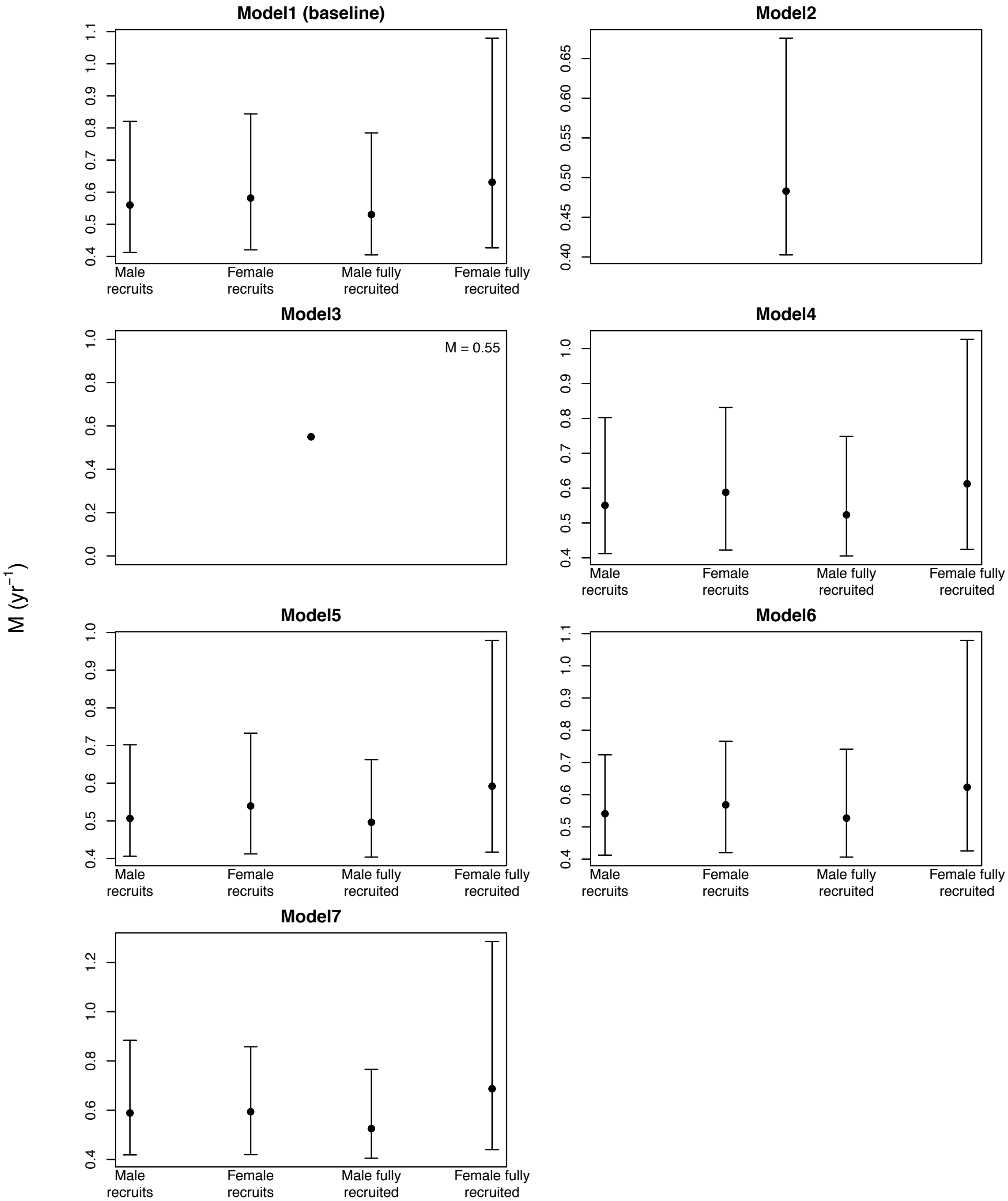

Figure C9. Estimated natural mortality (*M*) from candidate models M1-M7, with lines representing posterior mean. Please refer to Table 1 for the explanation of candidate models.

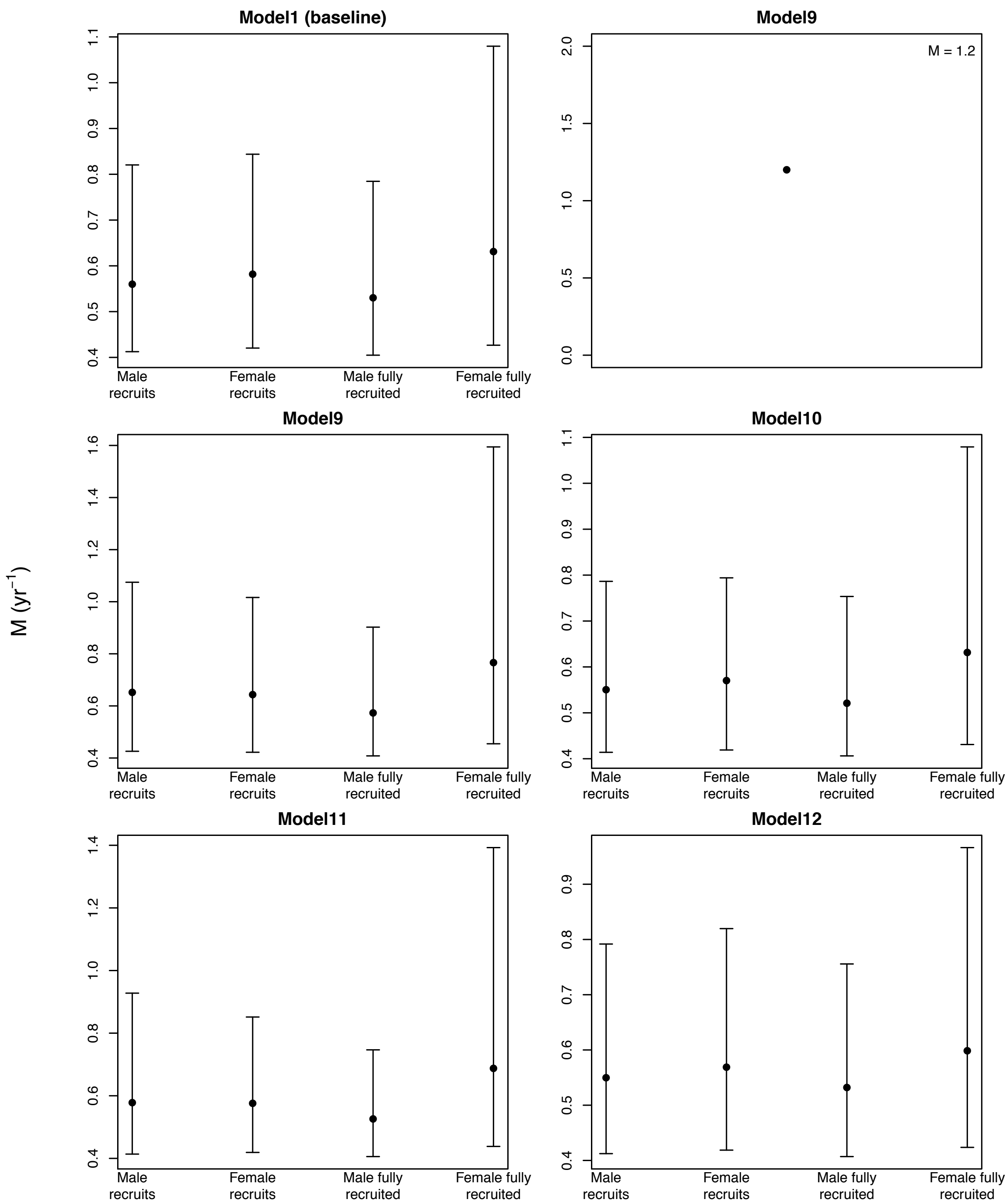

Figure C10. Estimated natural mortality (*M*) from candidate models M8-M12, with lines representing posterior mean. Please refer to Table 1 for the explanation of candidate models.

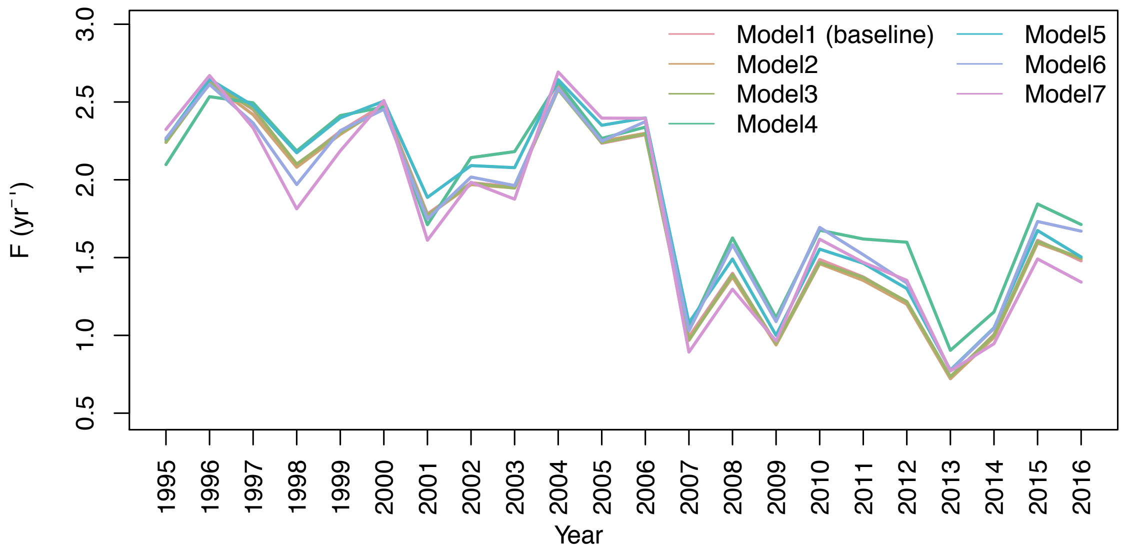

Figure C11. Estimated fishing mortality (*F*) of North Carolina blue crab from candidate models M1-M7, with lines representing posterior mean. Please refer to Table 1 for the explanation of candidate models.

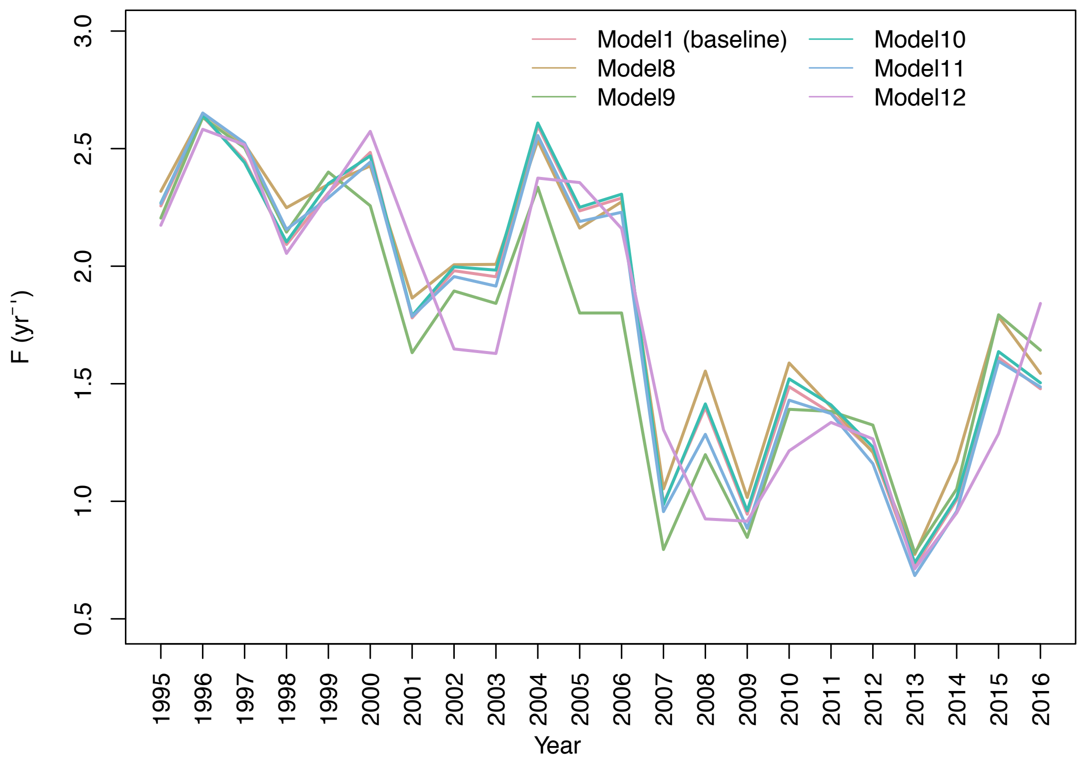

Figure C12. Estimated fishing mortality (*F*) of North Carolina blue crab from candidate models M8-M12, with lines representing posterior mean. Please refer to Table 1 for the explanation of candidate models.

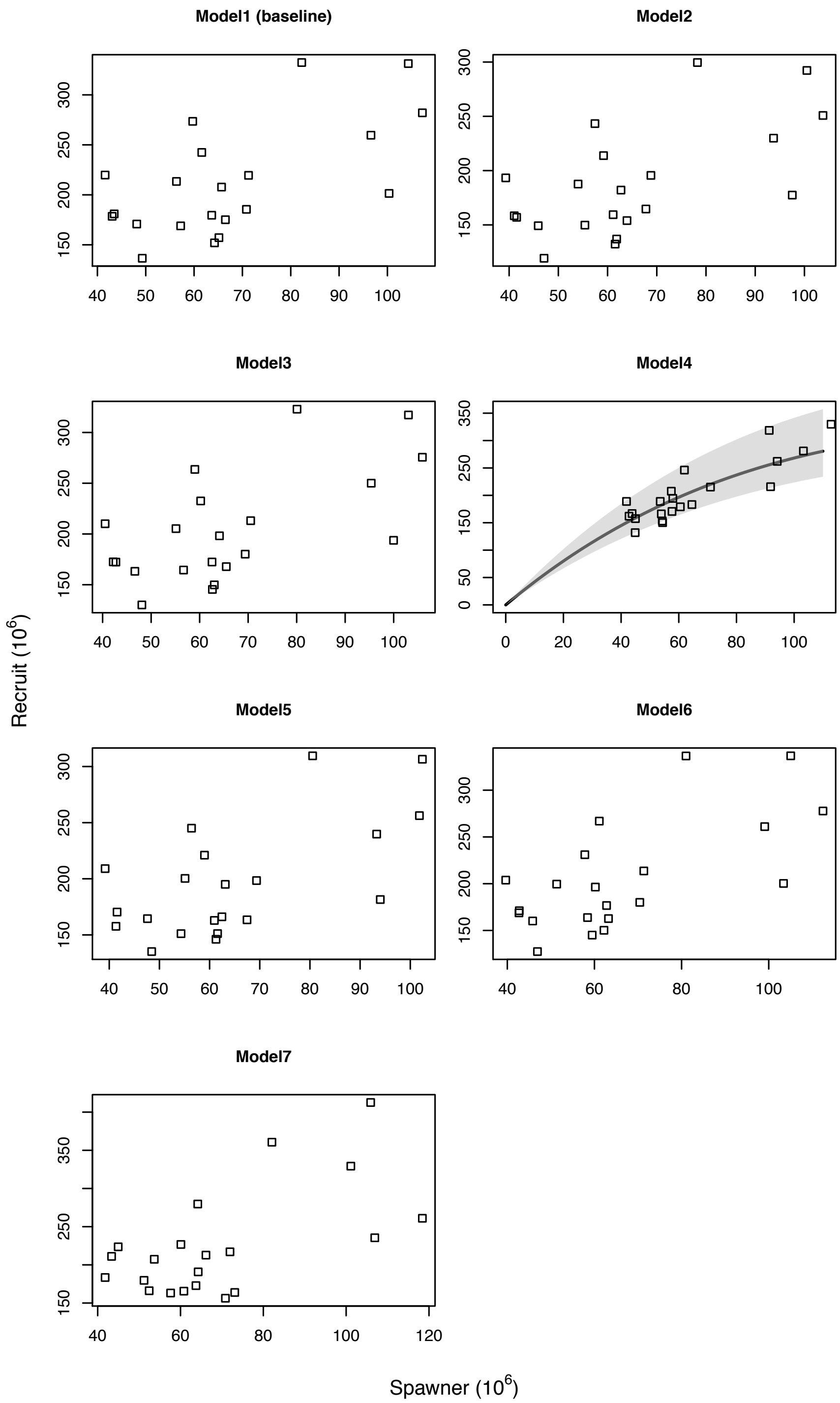

Figure C13. Estimated recruitment and spawner relationships from candidate models M1-M7. Models show the estimated annual average of recruits and spawner stock size except Model 4 which shows the estimated recruits given a spawner stock size assuming a Ricker curve, with lines representing posterior mean and shaded area representing 95% credible interval. Please refer to Table 1 for the explanation of candidate models.

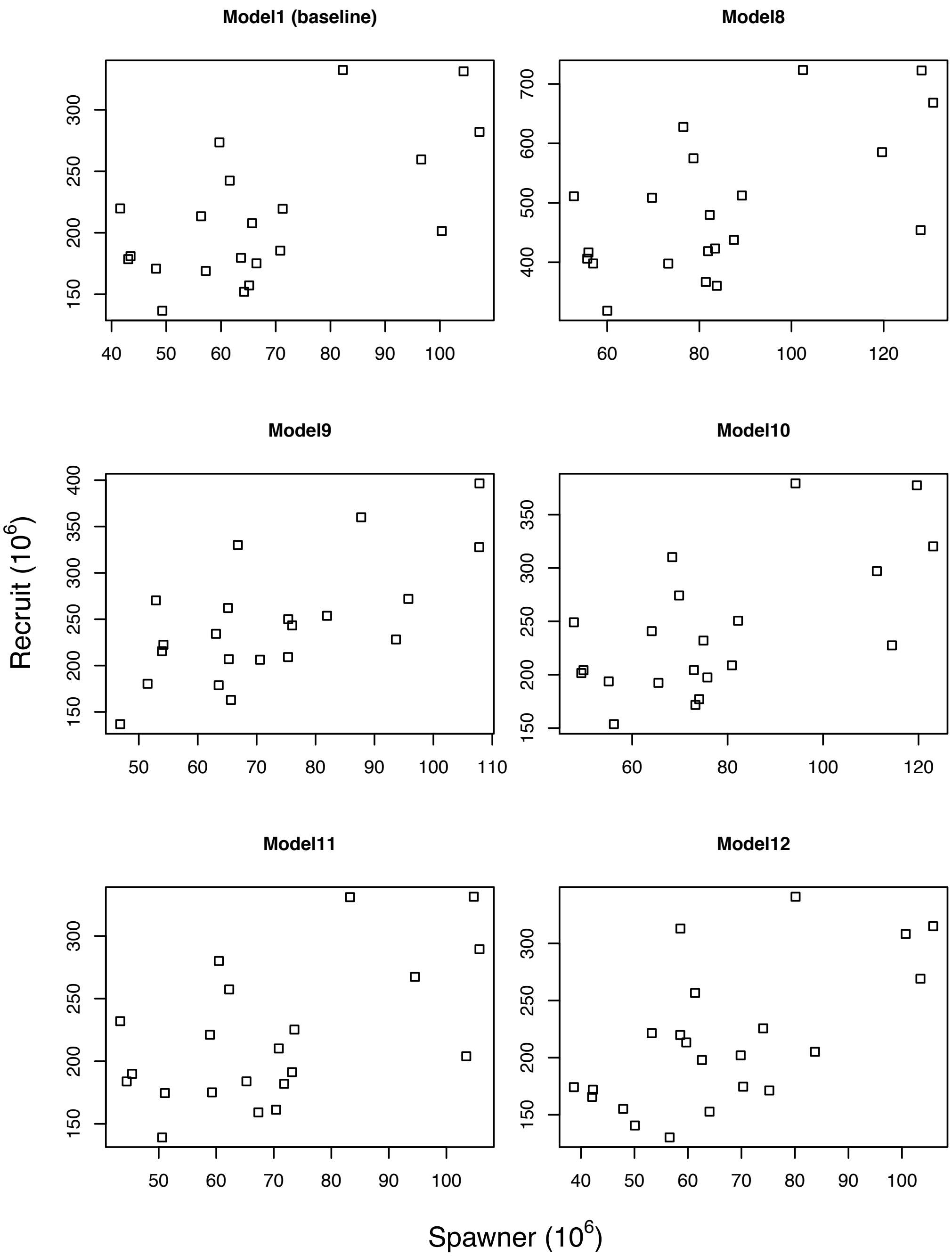

Figure C14. Estimated recruitment and spawner relationships from candidate models M8-M12. Models show the estimated annual average of recruits and spawner stock size Please refer to Table 1 for the explanation of candidate models.