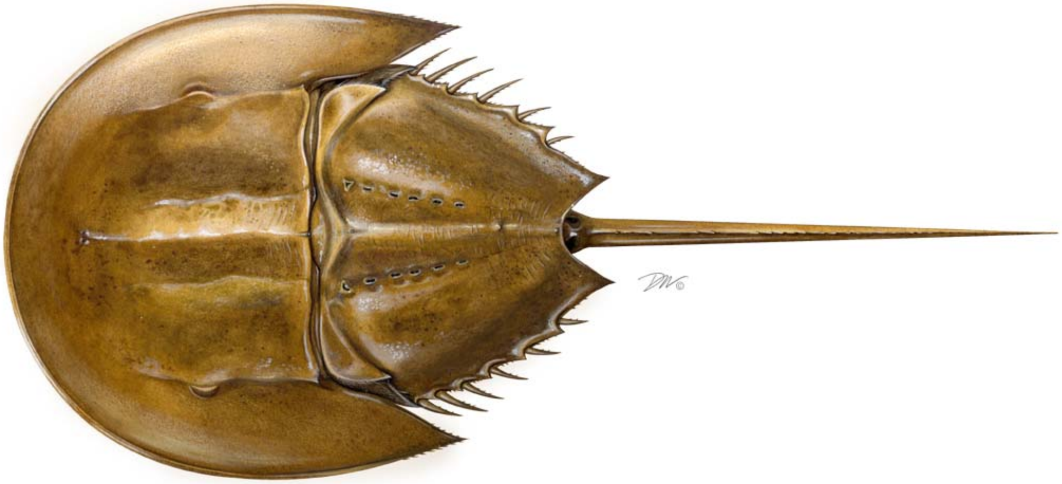
Stock Assessment Report No. 09-02 (Supplement A)
of the

Atlantic States Marine Fisheries Commission

Horseshoe Crab Stock Assessment for Peer Review



November 2009

Healthy, self-sustaining populations for all Atlantic coast fish species or successful restoration well in progress by 2015

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Horseshoe Crab Stock Assessment for Peer Review

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Preface

This is the third assessment of the coastwide horseshoe crab stock. The first assessment in 1998 grew from a rapid response to rising bait harvest and declining stocks of horseshoe crab and shorebirds in Delaware Bay. Between the first and second assessment a single-species framework was developed that proposed relying on index-based analyses until data to support catch-survey model became available. Monitoring programs that targeted horseshoe crabs, particularly in Delaware Bay, were designed and first implemented in 1999 and 2001.

The second assessment in 2004 regionalized the assessment and continued the index-based analyses. Although focus remained on Delaware Bay because of the heightened inter-specific issues, the 2004 assessment clearly indicated that stock definition and management needed to be regionalized. Data were not yet sufficient to support a catch-survey model for the Delaware Bay population, but simultaneous with the 2004 assessment several modeling efforts were underway using age(stage)-based or surplus production model structures.

During the time between the 2004 and present assessment, data availability and modeling efforts have improved. Application of the surplus production model to the Delaware Bay population has been refined. For the first time data are sufficient to fit the catch-survey model for the Delaware Bay population, although some technical issues remain. Most importantly, out of recognition that management of horseshoe crabs in Delaware Bay requires a multi-species assessment, an adaptive management framework has been developed over the past two years to support management of horseshoe crab harvest constrained by shorebird conservation. While this assessment report retains a single-species focus, a companion report describes the multi-species adaptive management framework.

Considerable progress has been made in assessing the Delaware Bay horseshoe crab population. However, assessment of populations in regions other than the Delaware Bay continues to rely on index-based analyses. This is happening while harvest pressure is redirected from Delaware Bay to other regions and embayments. A goal for future assessments should be to improve monitoring and analyses in all regions to support sustainable harvest management.

Terms of Reference for the Horseshoe Crab Stock Assessment

1. Evaluate precision and accuracy of fishery-dependent and fishery-independent data used in the assessment, including the following but not limited to:
    a. Discuss the effects of data strengths and weaknesses (e.g. temporal and spatial scale, gear selectivities, determining age class, sample size, standardization of indices) on assessment inputs and outputs.
    b. Justify weighting or elimination of available data sources.
2. Determine most appropriate assessment analysis or analyses given management objectives, available data, and species life history.
3. Evaluate methods used to evaluate population dynamics and determine stock status.
    a. Have the strengths and limitations of these methods been clearly and thoroughly explained?
4. Evaluate the current practice of conducting assessments, including methods and data used, at a regional or sub-regional (estuary-specific) level rather than coastwide.
5. State and evaluate assumptions made for all methods and explain the likely effects of assumption violations on results. Assumptions include, but are not limited to:
    a. Population is at equilibrium.
    b. Constant ecosystem (abiotic and trophic) conditions.
6. Evaluate biological or empirical reference points.
7. Evaluate the status of each sub-stock as related to reference points, and summarize the relative status of the horseshoe crab stock throughout its range. State uncertainties associated with this evaluation.
8. Develop detailed short and long-term prioritized recommendations for needed research, data collection, and assessment methodology. Highlight improvements to be made by next benchmark review.

1.0 Introduction

The status of the horseshoe crab, *Limulus polyphemus*, population along the Atlantic coast is of great concern for a number of different interests (Berkson and Shuster 1999; Walls et al. 2002; Odell et al. 2005). Horseshoe crabs play an important role in marine and estuarine ecosystems, and their eggs are a critical food source for many migratory shorebirds. In addition, the species serves as a primary bait source for several important commercial fisheries and is the backbone of a major biomedical process. Despite its importance, little is known about horseshoe crab abundance and stock dynamics. However, with each new year of data comes better understanding.

1.1 Brief Overview and History of Fisheries

Historically, horseshoe crabs were harvested commercially for fertilizer and livestock feed. Between the mid-1800s and mid-1900s harvest ranged from approximately 1 to 5 million crabs annually (Shuster 1960; Shuster 1982; Shuster and Botton 1985; Finn et al. 1991). Harvest numbers dropped to between 250,000 and 500,000 crabs annually in the 1950s (Shuster 1960) and 42,000 crabs were reported annually by the early 1960s (Finn et al. 1991). Early harvest records should be viewed with caution due to probable under-reporting. The period between 1950 and 1960 is considered the nadir of horseshoe crab abundance. The substantial commercial-scale harvesting of horseshoe crabs ceased in the 1960s (Shuster 1996).

Since the mid to late 1900s, horseshoe crabs have been commercially harvested primarily for use as bait and to support a biomedical industry. Horseshoe crabs are commercially harvested primarily for use as bait in the conch (*Busycon spp*.) pot and American eel (*Anguilla rostrata*) pot fisheries, although they are also harvested to a lesser extent for use as bait in the catfish (*Ictalurus spp.*) and killifish (*Fundulus spp*.) fisheries. The biomedical fishery harvests the crabs for the manufacture of Limulus Amebocyte Lysate (LAL), a product used to test pharmaceuticals for the presence of gram-negative bacteria.

The increase in harvest of horseshoe crabs during the 1990s was largely due to increased use as whelk bait. According to National Marine Fisheries Service (NMFS) records, landings by the whelk pot fishery increased during the 1990s and was positively correlated with horseshoe crab landings (Spearman $r = 0.76$, $P = 0.01$). In contrast, commercial landings by the American eel pot fishery in Atlantic states declined from 544 mt in 1990 to 252 mt in 1998 during the period when horseshoe crab landings increased. Eel and horseshoe crab landings were negatively correlated during that time (Spearman $r = -0.83$, $P = 0.002$).

Between 1970 and 1990, commercial harvest ranged from less than 20,000 pounds to above 2 million pounds annually (Table 1, Figure 1). Reported harvest increased during the late 1990s to nearly 6 million pounds in 1997 (Table 1, Figure 1) and above 2.5 million crabs in 1998. Since state-by-state quotas took effect in 2001 through Addendum I to the Horseshoe Crab Fishery Management Plan (FMP) and wide-spread use of bait saving devices, reported bait landings have continued to drop to around 660,000 crabs in 2008 (Table 2, Figure 2).

1.1.1 Bait Fishery

The horseshoe crab fishery supplies bait for the American eel, conch (whelk) and, to a lesser degree, catfish (*Ictaluridae*) fisheries. The American eel pot fishery prefers egg-laden female horseshoe crabs, while the conch pot fishery uses both male and female horseshoe crabs.

Most fishing effort for horseshoe crabs is concentrated within the mid-Atlantic coastal waters and adjacent federal waters. However, Massachusetts has also supported a significant fishery. The hand, trawl and dredge fisheries accounted for over 85% of the 2008 reported commercial horseshoe crab bait landings by gear type (ASMFC 2009). This is consistent with the distribution of landings by gear since 1998. Although the hand fishery accounted for most of the coastwide harvest and was typically the most prominent method of take in most states, the trawl fishery accounted for almost 25% of the reported landings by gear in 2009 (ASMFC 2009).

Commercial landings for horseshoe crab are collected by the NMFS by state, year, and gear type. Data is obtained from dealers, logbooks, and state agencies that require fishermen to report landings; however, NMFS records are often incomplete. In addition, the conversion factor used to convert numbers landed to pounds landed has been quite variable among the states and NMFS. Despite the inaccuracies in the data, all reported landings data show that commercial harvest of horseshoe crabs increased substantially from 1990 to 1998 and have generally declined since then (Table 1, Figure 1). Since 1998, states have been required to report annual landings to ASMFC through the compliance reporting process. These data are reliable and are shown in Table 2 and Figure 2.

1.1.2 Biomedical Fishery

Research on horseshoe crabs for use in the biomedical industry began in the early 1900s (Shuster 1962). Scientists have used horseshoe crabs in eye research, surgical suture wound dressing development, and detection of bacterial endotoxins in pharmaceuticals (Hall 1992). Horseshoe crab blood has recently been found to be useful in cancer research. The current major biomedical use of horseshoe crabs is in the production of Limulus Amebocyte Lysate (LAL). LAL is a clotting agent in horseshoe crab blood that makes it possible to detect human pathogens such as spinal meningitis and gonorrhea in patients, drugs, and all intravenous devices. The LAL test was commercialized in the 1970s (J. Cooper, pers. comm), and is currently the worldwide standard for screening medical equipment for bacterial contamination.

There are four companies along the Atlantic Coast that process horseshoe crab blood for use in manufacturing LAL: Associates of Cape Cod (MA), Lonza (MD, formerly Cambrex Bioscience), Wako Chemicals (VA), and Charles River Endosafe (SC). In addition, Limuli Labs (NJ) bleeds horseshoe crabs but does not manufacture LAL.

Blood from horseshoe crabs is obtained by collecting adult crabs, extracting a portion of their blood, and releasing them alive. Crabs collected for LAL production are typically collected by hand or trawl. Crabs are inspected to cull out damaged or moribund animals, and transported to the bleeding facility. Following bleeding, most crabs are returned to near the location of capture; however, since 2004, states have the ability to enter bled crabs into the bait market and count those crabs against the bait quota (ASMFC 2004).

Prior to 2004, no records were kept on biomedical harvest, although several sources estimate harvest during the 1990s around 200,000 to 250,000 crabs per year (D. Hochstein, pers. comm.; B. Swan, pers comm; Manion et al. 2000). Harvest records beginning in 2004 indicate an increase in biomedical harvest to more than 510,000 crabs in 2008, of which 402,000 crabs were bled (Table 3). ASMFC assumes a constant 15% mortality rate for bled crabs that are not returned to the bait fishery.

1.2 Management Unit Definition

The fishery management unit includes the horseshoe crab stock(s) of the Atlantic Coast of the United States (Maine to eastern Florida). The coastwide stock is currently managed on state by state, multi-state (e.g., DE Bay region), and embayment levels. See section 2.1 Stock Definition for more information.

1.3 Regulatory History

Prior to 1998, horseshoe crab harvest was unregulated in most states. The Horseshoe Crab Management Board approved the Horseshoe Crab FMP in October 1998. The goal of the FMP was "management of horseshoe crab populations for continued use by: current and future generations of the fishing and non-fishing public (including the biomedical industry, scientific and educational research) migratory shorebirds; and other dependent fish and wildlife (including federally listed sea turtles)" (ASMFC 1998a). The FMP outlined a comprehensive monitoring program and maintained controls on the harvest of horseshoe crabs put in place by New Jersey, Delaware, and Maryland prior to the approval of the FMP. These measures were necessary to protect horseshoe crabs within and adjacent to the Delaware Bay, which is the epicenter of spawning activity along the Atlantic Coast. However, subsequent increased landings in other states largely negated these conservation efforts.

In April 2000, the Management Board approved Addendum I to the Horseshoe Crab FMP (ASMFC 2000a). This Addendum established a coastwide, state-by-state annual quota system to further reduce horseshoe crab landings. Through Addendum I the Board recommended to the federal government the creation of the Carl N. Schuster Jr. Horseshoe Crab Reserve, an area of nearly 1,500 square miles in federal waters off the mouth of Delaware Bay that is closed to horseshoe crab harvest. In May 2001, the Management Board approved Addendum II, which established criteria for voluntary quota transfers between states (ASMFC 2001).

In March 2004, the Board approved Addendum III to the FMP (ASMFC 2004). The addendum sought to further the conservation of horseshoe crab and migratory shorebird populations in and around the Delaware Bay. It reduced harvest quotas, implemented seasonal bait harvest closures in New Jersey, Delaware, and Maryland, and revised monitoring components for all jurisdictions.

Addendum IV was approved in May 2006 (ASMFC 2006a). It further limited bait harvest in New Jersey and Delaware to 100,000 crabs (male only) and required a delayed harvest in Maryland and Virginia. Addendum V, adopted in September 2008, extends the provisions of Addendum IV through October 31, 2009 (ASMFC 2008a). Through a vote, the Board extended the provisions of Addendum IV through October 31, 2010.

1.4 Assessment History

The Atlantic States Marine Fisheries Commission's (ASMFC) *Stock Assessment Peer Review Process* (ASMFC 2002) states that each species' stock assessments should be externally peer reviewed at least every five years. The initial stock assessment for horseshoe crab was completed in late 1998 and peer reviewed (ASMFC 1999; ASMFC 1998b). The five-year trigger necessitated that work begin on the current assessment in 2003. This assessment, however, was not externally reviewed. The Horseshoe Crab Management Board decided instead to internally review the current assessment because the structure of the assessment has changed little since the initial assessment in 1998. A stock assessment framework using a catch-survey method was developed by the Horseshoe Crab Stock Assessment Subcommittee (SAS) and peer reviewed (ASMFC 2000b). Generally, the peer review panel concluded the framework is an appropriate method for assessing the stock once sufficient data become available (ASMFC 2006b). In the meantime, it recommended continuation of trend analyses and development of less data-intensive models (e.g. surplus production and modified DeLury models).

Figure 3 shows the timeline of analyses starting from the proposed stock assessment framework in 2000 to the present. The proposed framework envisioned trend analyses continuing as data became available to support application of assessment models. Regional trend analyses were the basis for the 2004 coast-wide assessment and continue in the present assessment. Since the 2004 assessment, surplus-production modeling has been applied to the Delaware Bay population (Davis et al. 2006). Recently, the catch-survey model has been applied to the Delaware Bay population, and multi-species models have been developed to support an adaptive resource management framework for horseshoe crabs and shorebirds in Delaware Bay.

2.0 Life History

Horseshoe crabs are characterized by high fecundity, high egg and larval mortality, and low adult mortality (Botton and Loveland 1989; Loveland et al. 1996). They breed in late spring on low-energy coastal beaches along the Atlantic coast, laying eggs in nests buried in the sand. Planktonic larvae hatch from the eggs within 2-4 weeks, although some larvae may overwinter within nests and hatch out the following spring (Botton et al. 1992). Larvae settle within a week of hatching and begin molting. Juvenile crabs remain in the intertidal flats, usually near breeding beaches. Older individuals move out of intertidal areas to deeper waters (Botton and Ropes 1987). Crabs are thought to mature around 10 years of age, and may live up to 20 years.

2.1 Stock Definitions

The horseshoe crab stock, for the purpose of this assessment, is defined as the horseshoe crabs ranging from the coasts of Maine to Florida seaward. However, data suggests there may be a regional or sub-regional population structure. Tag release and recapture data from the United States Fish and Wildlife horseshoe crab tagging database was used to examine if there were any trends in release and recapture location (Table 4). Tag recaptures after >3 months at large were examined by release state and location versus recapture state and location. Results showed that releases in Massachusetts (MA) and Rhode Island (RI) were almost exclusively caught in MA or RI; releases from CT were recaptured in CT with a small percentage from non-coastal NY; releases from coastal NY were recaptured in coastal NY or coastal NJ; releases from New Jersey (NJ), Delaware (DE), Maryland (MD), and Virginia (VA) were almost exclusively caught in those states (many in DE Bay); releases from within Delaware Bay were recaptured largely within Delaware Bay and some from coastal NJ, DE, MD, VA, and NC; and releases from South Carolina (SC) were caught in SC and Georgia. These results suggest regional horseshoe crab populations. Rutecki et al. (2004) conclude that management of individual populations, possibly down to the embayment level, needs to consider harvest rates and population structures and abundances present.

Botton and Loveland (2003) examined abundance and dispersal of horseshoe crab larvae in Delaware Bay. They found a strong tendency for larvae to stay close to spawning beaches. This finding suggests that larvae dispersal is not the mechanism for mixing populations (Botton and Loveland 2003). Widener and Barlow (1999) studied a population of horseshoe crabs that appeared to be a local one. They concluded, "Harvesting large numbers of animals from such a local population would have significant impact on its size" (Widener and Barlow 1999).

Genetic structure indicates that males disperse at higher rates than females, and female-mediated gene flow among embayments is limited (Pierce et al. 2000, King et al. 2005). King et al. (2005) suggested that the distribution of the American horseshoe crab is comprised of multiple population units divided among large geographic regions: Gulf of Maine, mid- mid-Atlantic, Atlantic Florida, Gulf Florida, and Mexico. Also, tagging data indicate that a majority of adult crabs remain within local regions and some overwinter in local embayments (ASMFC 2004; James-Pirri et al. 2005; Swan 2005; Smith et al. 2006; Moore and Perrin 2007). These data are further supported by stable isotope analyses, which indicate adult crabs are loyal to local feeding grounds (Carmichael et al. 2004, O'Connell et al. 2003).

Trends in horseshoe crab abundance and population dynamics differ among regions (ASMFC 2004). In particular, smaller sized populations such as those in Cape Cod waters may be localized based on spawning densities, size structure, and movement patterns (Carmichael et al. 2003; James-Pirri et al. 2005). Since different types of harvest (bait, biomedical, or scientific) select for different size and sex segments of the population, different populations may experience different harvest pressures due to their location-specific population dynamics (Rutecki et al. 2004).

Finally, different embayments and regions are subject to different types and levels of harvest for different purposes. In Delaware Bay waters, commercial harvest is conducted by hand and dredge (Kraemer and Michels 2009), while in areas such as Cape Cod most harvest is conducted by hand from local beaches (Rutecki et al. 2004). In Delaware Bay, the majority of harvested crabs are collected for bait. In contrast, among Cape Cod populations, the primary purpose for which crabs are harvested (bait, biomedical, or scientific) varies by embayment (Rutecki et al. 2004) with bait harvest predominating except in Pleasant Bay where only biomedical harvest is permitted (A. Leschen, pers. comm.). Since mortality associated with each harvest type varies, the extent of harvest pressure and depletion by overharvest also necessarily varies among embayments (Widener and Barlow 1999; Rutecki et al. 2004). Hence, there is strong support for local management based on regional or sub-regional population structure and harvest pressures.

2.1.1 Genetics

King et al. (2003 and 2005) found that the correlation of genetic and geographic distance between horseshoe crab populations sampled along the Atlantic coast suggests isolation by distance as the driving force behind population structure. Their genetic analysis points to the possibility of four regional stocks within the United States: Northeast (Gulf of Maine), mid-Atlantic, Florida-Atlantic, and Florida-Gulf. A separate study showed possible subdivision between collections from the upper Chesapeake Bay and near the entrance of Delaware Bay (Pierce et al. 2000). However, this is in contrast to what King et al. found. Pierce et al. (2000) also suggest that the samples from the upper Chesapeake Bay show a resident population.

In addition, based on electrophoretic evidence, gene flow does occur between widely separated populations, although considerable genetic variation exists within and between populations of horseshoe crabs (Selander et al. 1970). Saunders et al. (1986) found no evidence for genetic divergence between New England and middle Atlantic populations based on mitochondrial DNA analysis.

2.1.2 Morphometric Information

Shuster (1979) suggested that each major estuary along the coast had a discrete horseshoe crab population, which could be distinguished from one another by adult size, carapace color and eye pigmentation. Differences between the morphologic characteristics of discrete populations were seen among geographically distinct populations (Riska 1981). Larger animals and populations are reported in the middle of the species' distribution (Maryland to New York), while smaller animals and populations are found in the southern and northern extent of its range (Shuster 1982). However, based on morphometric data collected in South Carolina the greatest mean adult size occurs in the South Atlantic Bight and decreases in size north and south (Shuster 1950; Thompson 1998). Thompson (1998) hypothesized that larger individuals occur in the South Atlantic Bight due to optimal temperature and salinity for horseshoe crab development in this region.

2.2 Migration Patterns

The general migratory pattern of horseshoe crabs is believed to be that (1) juveniles move to deeper bay water as they mature, (2) juveniles either reach sexual maturity in the estuary or migrate to and mature in the ocean, and (3) adults migrate annually from the ocean or deep bay waters to spawn on estuarine beaches (Baptist et al. 1957; Shuster 1979; Shuster and Botton 1985; Botton and Ropes 1987; Botton and Loveland 2003; Smith et al. 2009a). There is considerable evidence, however, that migratory patterns may be more complex. Smith et al. (2009a) suggested horseshoe crabs in Delaware Bay exhibit sex-specific migratory patterns. Until about age 8 years, juveniles of both sexes remain within the bay. After age 8 years, females begin to migrate to the continental shelf as older juveniles and mature in the ocean. In contrast, males tend to remain within the bay to mature. After reaching maturity, both sexes migrate from the ocean or deep bay waters to spawn on the estuarine beaches. Evidence from Delaware Bay and New England waters suggest some adults overwinter in local embayments (Widener and Barlow 1999; Smith et al. 2006; Moore and Perrin 2007). For example, Botton and Ropes (1987) concluded that horseshoe crabs in estuaries north of Long Island, NY, remained within the estuaries or close to shore in the ocean. In fact, Moore and Perrin (2007) and Watson et al. (2009) found that horseshoe crabs remained within local embayments year-round in Maine and New Hampshire, respectively. In contrast, the greatest proportion of the Delaware Bay horseshoe crabs appears to migrate to the continental shelf (Botton and Ropes 1987, Hata 2008). The annual migration from deep waters to spawn on estuarine beaches appears to be triggered, at least in part, by rising water temperature (Smith and Michels 2006, Watson et al. 2009).

2.3 Age

No reliable method is available to directly age horseshoe crabs. Botton and Ropes (1988) and Grady et al. (2001) used epifaunal *Crepidula fornicata* (shell length / shell weight) on the crab's prosoma to indirectly determine age. Shuster developed criteria for assigning approximate age based on carapace color and the extent of carapace wear (Shuster 2000). Hata and Berkson (2003) used shell wear, color and structural changes of the pedipalps (males) to stage horseshoe crabs by maturity in conjunction with the Virginia Polytechnic Institute and State University's horseshoe crab trawl survey. Smith et al. (2009a) used shell wear, color, size, structural changes of pedipalps and egg presence to characterize maturity and approximate age. Several researchers have proposed the use of ommatidia (units that compose the compound eye) to age juvenile horseshoe crabs, but funding sources are necessary to more formally investigate this possibility (R. Weber pers. comm.). Research using lipofuscin for aging has not been shown to be reliable (Smith et al. 2009a). Estimating age by length/width measurements, at least over a wide geographical range, is complicated by the apparent latitudinal differences in size (Shuster 1954; Botton and Loveland 1992).

Indirect aging methods have provided estimates of longevity. Botton and Ropes (1988) estimated that Delaware Bay horseshoe crabs live at least 17 to 19 years using *C. fornicata*. Swan (2005) found a similar range for Delaware Bay horseshoe crabs based on tagging data. Grady et al. (2001) estimated that Pleasant Bay crabs live at least 17 years using *C. fornicata*. Ropes (1961) estimate longevity at 14 to 19 years using tagging data from Pleasant Bay. Shuster and Sekiguchi (2003) reported that horseshoe crabs may live for 20 years in the northern part of their range.

2.4 Growth

Horseshoe crabs undergo stepwise growth, with females typically attaining larger sizes than males. Smith et al. (2009a), reviewing several studies, reported the average prosomal width growth increment for all instars was 1.28 (range: 1.15 – 1.52). Growth is relatively rapid during the first several years progressing through stages I-V in the first year, stages VI – VII the second year, stages VII – IX the third year, with a single molt per year until reaching maturity (Shuster 1982). Shuster (1950) citing "different" sources and a series of exuviae from a captive specimen, approximated that it took 9 to 12 years for horseshoe crabs to reach sexual maturity. Sekiguchi et al. (1982) concluded crabs molt 16 times and mature in their ninth year; females molt 17 times and mature in their tenth year. Smith et al. (2009a) found that males in Delaware Bay tended to mature at age 10 and 11, while females tended to mature at ages 10, 11 and 12.

Carmichael et al. (2003) concluded that male and female horseshoe crabs continue to molt upon maturation and that males and females had differential growth rates with females also molting more times than males. Female exuviae from crabs of a mature size with amplexus scars have been encountered (G. Breese, G. Gauvry, and C. Shuster, pers. comms.), further supporting the conclusions of Carmichael et al (2003). However, Smith et al. (2009a) examined the hypotheses of differential maturity, differential growth and indeterminate molting and concluded that females did not grow at a faster rate than males, but rather underwent an additional molt.

Although they could not rule out post-amplexus molting, they did find that it is uncommon (<1% of population) and has no population-level effect within the Delaware Bay population.

2.5 Reproduction

Adult horseshoe crabs move from deep bay and shelf waters in the spring to spawn in the intertidal zone of beaches. In Florida, spawning occurs between March and November, with peak spawning occurring between June and August (Rudloe 1980). Spawning in South Carolina was reported from March to July, peaking in May (Thompson 1998). In the Delaware Bay area the crabs spawn from April through at least July, with peak spawning in May and June (Shuster and Botton 1985, Michels et al. 2009). Carmichael et al. (2003) reported the spawning season in Pleasant Bay, Massachusetts may span from late March through mid-July based on amplexused pairs. Barlow et al. (1986), Widener and Barlow (1999) and James-Pirri et al. (2005) reported spawning at Cape Cod, Massachusetts from May through July with apparent peaks in May and June.

Peak spawning is associated with the new and full moons which correspond with the highest tides (Shuster 1954, Rudloe 1980, Shuster and Botton 1985, Barlow et al. 1986, Smith et al. 2002a). Leschen et al. (2006) and James-Pirri et al. (2005) found a similar level of spawning during all daytime high tides regardless of lunar phase in the vicinity of Cape Cod. Female crabs typically arrive at the spawning beach with a male attached to the opisthosoma. Often several satellite males accompany the attached pair. The males externally fertilize the eggs as they are being deposited. Although a single attached male can fertilize all of a female's eggs, when satellite males are present (two to four) they may fertilize an average of 74 percent of the female's eggs (Brockmann 2003).

Horseshoe crabs appear to prefer well-drained sandy beaches that are protected from surf; although, it is not uncommon to observe crabs spawning in cobble, mud, and peat. On a single tide, females deposit from two to five clusters of about 1000 – 4000 eggs at depths from 5 to 20 cm (Rudloe 1979, Brockmann 1990, Leschen et al. 2006, Brockmann 2003). However, estimates of eggs per cluster vary: Shuster and Botton (1985) reported 3,650 to 4,000 eggs per cluster and Weber and Carter (2009) reported an average of 5,786 ± 2,834 eggs per cluster. On average, female crabs spawn over one tidal cycle (5 days of high tide around new or full moon) in Florida, whereas males returned over two tidal cycles (Brockmann and Penn 1992). Brockmann (1990) reported that a female nests on average 3.4 times on a tide, laying a cluster of eggs at each nest. Female horseshoe crabs in Delaware Bay were shown to spawn over two to five consecutive nights, remaining within 50 to 715m of their established spawning beach before moving away from the beaches several days after the new moon (Brousseau et al. 2004). Significant beach fidelity over successive years has not been demonstrated.

Horseshoe crabs are highly fecund. Shuster (1982) reported 88,000 eggs per female for the Delaware Bay. Leschen et al. (2006) found a correlation between female size and the number of eggs in horseshoe crabs in Pleasant Bay, Massachusetts. Average fecundity ranged from 14,500 eggs at 201mm prosomal width (PW) to 63,500 eggs at >261mm PW.

Egg development is dependent on temperature, salinity, moisture and oxygen. The eggs hatch in two to four weeks or longer (Shuster 1950; Shuster 1954). Botton et al. (1992) demonstrated that trilobite larvae can overwinter to hatch the following spring. Upon hatching larvae spend about 6 days swimming before settling to the bottom (Shuster 1982).

2.6 Natural Mortality

Factors contributing to natural mortality include age and excessive energy expenditure during spawning, which can result in stranding, desiccation, and predation. Loveland et al. (1996) believe that the natural mortality rate in adults is probably low. Botton and Loveland (1989) concluded that stranding mortality, which they estimated to be about 10% of the total population in Delaware Bay in the mid 1980s, is likely to vary among estuaries because it is affected by population density, weather and tidal conditions, and beach geomorphology. The condition of the individual, which is probably age related, is also a factor in stranding-related mortality (Penn and Brockmann 1995). Carmichael et al. (2003) found in Pleasant Bay, Massachusetts, adults had a lower estimated mortality rate than juveniles, and there was no significant difference in estimated mortality rate between adult males and females. Horseshoe crab mortality due to predation from sea turtles and other marine animals remains unknown. Shorebirds feed on horseshoe crab eggs in areas of high spawning densities such as the Delaware Bay. Horseshoe crab eggs are considered essential food for several shorebird species in the Delaware Bay, which is the second largest migratory staging area for shorebirds in North America. Despite significant shorebird predation on horseshoe crab eggs, such activity probably has little impact on the horseshoe crab population (Botton et al. 1994). Horseshoe crabs place egg clusters at 5-25 cm deep (Weber and Carter 2009), which is deeper than most short-billed shorebirds can penetrate. Many eggs are brought to the surface by wave action and burrowing activity by spawning horseshoe crabs. These surface eggs consumed by birds would not survive, due to desiccation (Botton et al. 1994).

Adult and juvenile horseshoe crabs make up a portion of the loggerhead sea turtle's (*Caretta caretta*) diet in the Chesapeake Bay (Musick et al. 1983; Keinath 2003; Seney and Musick 2007). Horseshoe crab eggs and larvae are also a seasonally preferred food item of a variety of invertebrates and finfish, including sharks (Squaliformes) (Shuster 1982).

2.7 Sex Ratio

There are two sex ratios to keep track of in horseshoe crab ecology and management. The population sex ratio is the ratio of males to females among individuals in the population. The operational sex ratio is the ratio of males to females among adults that are actively spawning.

While juveniles show a balanced population sex ratio (Shuster and Sekiguchi 2003; Smith et al. 2009a), the population sex ratio among adults has been observed to be somewhat skewed toward males in Delaware Bay (2.2:1 M:F; Smith et al. 2006) and Pleasant Bay, MA(2.3:1 M:F; Carmichael et al. 2003). This difference has been attributed to higher fishing or natural mortality among adult females compared to males, but also might be due to males maturing earlier than females and living as long as females (Smith et al. 2009a).

The operational sex ratio of horseshoe crabs on the spawning beaches is highly skewed toward males because of behavior and population demographics (Brockmann and Smith 2009). One male attaches to a female in amplexus prior to spawning. However, during fertilization the amplexed pair is often surrounded by unattached males (Brockmann and Penn 1992). Hence, the operational sex ratio on spawning beaches is expected to be male biased compared to the population sex ratio among adults.

A population sex ratio over 1 male to 1 female is likely to be required among adults to ensure that reproduction is not limited by sex ratio. Although Brockmann (1990) found that satellite males (i.e., males not in amplexus) are not needed to fertilize eggs, females will tend not to nest unless they are in amplexus with a male. Some males (approximately 30%) are not capable of amplexus because of their condition (Brockmann and Smith 2009). Thus, there needs to be an excess of males in the population to ensure a sufficient number of males capable of amplexus to pair with the females ready to spawn. In the Delaware Bay population, the operational sex ratio averaged 3.8 M:F (SD = 0.51) over 1999 to 2008 (Michels et al. 2009). In contrast, the population sex ratio averaged 2.0 M:F (SD = 0.19) over 2002 to 2008 (Hata 2008). Thus, the operational sex ratio averaged 1.88 times (SD = 0.19) the population sex ratio in the Delaware Bay population (Michels et al. 2009, Hata 2008).

In unharvested populations, the operational sex ratio has been lower than in Delaware Bay. In Tauton Bay, ME, the operational sex ratio averaged 1.9 M:F (SD = 0.46) over 2001 to 2005 (S. Schaller, unpubl. data). In Seahorse Key, FL, the operational sex ratio averaged 2.2 (SD = 0.46) over 1993 to 2009 (J. Brockmann, unpubl. data). Estimates of population sex ratio are not available for these populations. However, if the operational sex ratio is 1.88 times the population sex ratio, as in the Delaware Bay population, then we would expect that population sex would be 1.05 M:F (51% males) in Tauton Bay and 1.17 M:F (54% males) in Seahorse Key.

3.0 Habitat Description

3.1 Brief Overview Habitat Requirements

Essential habitat is defined as those waters and substrate necessary for fish spawning, breeding, feeding, or growth to maturity. Habitat requirements change throughout the horseshoe crab life cycle, extending from intertidal beach fronts and tidal flats in coastal embayments for eggs and larvae, to the edge of the continental shelf for adults. *Limulus* has been described as an ecological generalist (Shuster and Sekiguchi 2009) able to tolerate a wide range of environmental parameters throughout its distribution. Various environmental tolerances have been documented for horseshoe crabs in several areas; however, Sekiguchi and Shuster (2009) suggest that individual sub-populations may have a narrower tolerance than the species as a whole.

3.1.1 Spawning, Egg, and Larval Habitat

Spawning adults prefer sandy beach areas within bays and coves that are protected from wave energy (Shuster and Botton 1985; Smith et al. 2002b; Jackson et al. 2002). Nests are primarily located between the low tide terrace (tidal flat) and the extreme high tide water line. Weber and Carter (2009) found that 85% of nests were deposited between the tidal flat and the nocturnal high tide wrack line on the western shore beaches of Delaware Bay. Penn and Brockmann (1994) found similar results in Delaware Bay, but noted that nest deposition occurred in a narrower band within the beach front on Seashore Key, Florida. The differences in nest site selection between Florida and Delaware can be explained by differences in beach morphology, particularly sediment grain size, and its effect on interstitial conditions (Penn and Brockmann

1994). In Massachusetts, New Jersey, and Delaware, beaches are typically coarse-grained and well drained, as opposed to Florida beaches which are typically fine-grained and poorly drained.

Beach habitat also must include a sufficient depth of porous, well-oxygenated sediments to provide a suitable environment for egg survival and development (Botton et al. 1988). Nest depth on the western shore of Delaware Bay generally ranged between 3.5 and 25.5 cm (mean 15.5, SD 3.5), although nest depth may be affected by wave energy, bioturbation, or other factors after deposition (Weber and Carter 2009). These results are similar to those found by previous investigators on Delaware Bay beaches (e.g., Hummon et al 1976, Penn and Brockmann 1994, Botton et al 1994).

Rate of egg development is dependent on interstitial environmental parameters including temperature, moisture, oxygen, and salinity (French 1979, Jegla and Costlow 1982, Laughlin 1983, Penn and Brockmann 1994) and disturbance (bioturbation) from external forces (Jackson et al 2008). Placement of nests in the intertidal zone subjects horseshoe crab eggs to a wide range of environmental parameters, making it necessary for eggs and larvae to have wide tolerance ranges; however optimum egg development occurs within a much narrower range of conditions. Studies have shown that optimal development occurs at salinities between 20 and 30 ppt (Jegla and Costlow 1982, Laughlin 1983), although populations from microtidal lagoon systems that often experiences high salinities (>50 ppt) had an optimal range of 30 to 40 ppt, with hatching occurring at salinities as high as 60 ppt (Ehlinger and Tankersly 2004). Egg development occurs most readily at temperatures ranging from 25 to 30 C (Jegla and Costlow 1982; Laughlin 1983; Penn and Brockmann 1994; Ehlinger and Tankersly 2004), with temperatures of 20 and 40 C showing little to no development (Laughlin 1983; Ehlinger and Tankersly 2004). Penn and Brockmann (1994) found optimal development of horseshoe crab eggs from Delaware and Florida to occur at oxygen concentrations between 3 and 4 ppm and moisture content between 5 and 10%.

In addition to the influences of interstitial microhabitat on nest site selection, Thompson (1998) found that preferentially selected spawning sites were located adjacent to large intertidal sand flat areas, which provide protection from wave energy and an abundance of food for juveniles.

Optimal horseshoe crab spawning areas are limited by the availability of suitable sandy beach habitat. For example, based on geomorphology Botton et al. (1992) estimated that only 10 percent of the New Jersey shore adjacent to Delaware Bay provided optimal horseshoe crab spawning habitat. However, spawning may occur along peat banks if there is sand in the upper intertidal regions and along the mouths of salt marsh creeks (Botton 1995). Shuster (1996) states that spawning may occur along muddy tidal stream banks, but not on peat banks because adults are sensitive to hydrogen sulfide and anaerobic conditions. Subtidal spawning has been reported, but the extent to which this occurs is unknown. A Habitat Suitability Index model was developed for horseshoe crab spawning habitat within the Delaware Bay (Brady and Schrading 1996).

After hatching, some larvae delay emergence and overwinter within beach sediments, emerging the following spring (Botton et al. 1992). Larvae typically settle in shallow water areas to molt (Shuster 1982). Nearshore, shallow water, intertidal flats are considered essential habitats for development of juvenile horseshoe crabs (Botton 1995). Juveniles usually spend their first two years on intertidal sand flats (Rudloe 1981). Thompson (1998) also found significant use of sand flats by juvenile horseshoe crabs in South Carolina.

3.1.2 Juvenile and Adult Habitats

Prime spawning habitat is widely distributed throughout Maryland's Chesapeake and coastal bays, including tributaries. Horseshoe crabs are restricted to salinities that exceed 7 parts per thousand. In the Chesapeake Bay, spawning habitat generally extends to the mouth of the Chester River, but can occur farther north during years of above normal salinity levels. Prime spawning beaches within the Delaware Bay consist of sand beaches between Maurice River and the Cape May Canal in New Jersey and between Bowers Beach and Lewes in Delaware.

Older juveniles and adults are exclusively subtidal, except during spawning. Second and third year instars remain in the vicinity of the spawning beach but move just offshore into shallow subtidal water (Shuster and Sekiguchi 2009), with each succeeding stage moving toward deeper water. In the Delaware Bay, females begin to leave the Bay and move to continental shelf waters around age 7 to 8 to mature in the ocean (Hata and Hallerman 2009; Smith et al. 2009b). Smith et al. (2009b) provide evidence that males remain in the Bay until maturity (age 9), but Hata and Halllerman (2009) found evidence of significant numbers of immature males on the shelf one to two years prior to reaching maturity (Hata and Hallerman 2009).

Delaware Division of Fish and Wildlife's 16-foot bottom trawl survey data indicated that over 99 percent of juvenile horseshoe crabs (<16 cm prosomal width) were taken at salinities >5 parts per thousand (DE DFW 1998).

As ecological generalists living in a shallow water environment over a wide geographic range, *Limulus* are subject to, and therefore adapted to, a wide range of environmental conditions. Specific requirements for adult habitat are not known, but it has been suggested that individual sub-populations may have a narrower tolerance than the species as a whole (Sekiguchi and Shuster 2009). Adult horseshoe crabs range from 21 N to 44 N and 68 W to 90 W (Sekiguchi and Shuster 2009), and have been found as far as 35 miles offshore at depths greater than 200 meters; however, Botton and Ropes (1987) found that 74 percent of the horseshoe crabs caught in bottom trawl surveys conducted by the National Marine Fisheries Service (NMFS), Northeast Fisheries Science Center were taken in water shallower than 20 meters. They are observed in a wide range of salinity regimes, from low salinity (< 10 pp) areas such as the upper Chesapeake Bay, to the hypersaline (>50 ppt) environments of the Indian River Lagoon in Florida. During the spawning season, adults typically inhabit bay areas adjacent to spawning beaches. In Delaware Bay, horseshoe crabs are active in the Bay area at temperatures above 15 C (Shuster and Sekiguchi 2009), while crabs in Great Bay, NH increase activity at temperatures above 10.5 C (Watson et al 2009). In the fall, adults may remain in bay areas or migrate into the Atlantic Ocean to overwinter on the continental shelf.

Sekiguchi and Shuster (2009) have identified four possible large-scale factors that limit horseshoe crab distribution and habitat, including geomorphology, thermal tolerance, tidal regimes, and currents. Indo-Pacific species of horseshoe crab span the equator, but *Limulus* does not, perhaps due to limited availability of embayments with suitable spawning habitat, or the lack of a broad continental shelf to provide a migratory route. The northern extent of all horseshoe crab species may be limited by duration and severity of winter temperatures. The lack of horseshoe crab populations in the western Gulf of Mexico, which has suitable beach spawning habitat, is thought to be a result of the local tidal regime. Nearly all horseshoe crab populations occur in areas with semi-diurnal tides of moderate amplitude, but tides of this type are not observed in the western Gulf of Mexico.

Habitat degradation is likely an important component of the population dynamics of horseshoe crabs. Groins and bulkheads may adversely impact horseshoe crab spawning habitat. Bulkheads may block access to intertidal spawning beaches, while groins and seawalls intensify local shoreline erosion and prevent natural beach migration. An estimated 10 percent of the New Jersey shoreline adjacent to the Delaware Bay has been severely disturbed by shoreline protection structures (Botton et al 1988). Rip-rap and revetments also adversely impact horseshoe crabs by minimizing potential spawning sites and by entrapping and stranding them. A contributing factor in the decline of horseshoe crabs in the Delaware Bay between 1871 and 1981 may be the increased number of jetties and residential development (Shuster and Botton 1985).

Shoreline erosion combined with shoreline development results in the loss of potentially suitable spawning beaches. Beach migration is a coastwide phenomenon, where beaches move landward associated with erosional events. However, hard structures (e.g., bulkheads, seawalls, revetments) associated with beach development interfere with the natural beach migration causing habitat loss. Beaches along the New Jersey shore of the Delaware Bay have generally eroded at varying rates ranging from 1 to 12 feet per year for the last 100 years (U.S. Army Corps of Engineers 1997). Erosion rates from 1 to 26 feet per year, averaging approximately 3 to 5 feet per year and the existence of hard structures limiting beach migration have resulted in a decline in Delaware beaches (U.S. Army Corps of Engineers 1991). McCormick and McCormick (1998) report the annual rate of erosion in the Chesapeake Bay averages 1 foot per year. Shoreline areas with high concentrations of silt or peat are less favorable to horseshoe crabs because the anaerobic conditions reduce egg survivability. Horseshoe crabs may detect hydrogen sulfide (which is produced in the anaerobic conditions of peat substrates) or low oxygen conditions, and actively avoid such areas (Botton et al 1988). Erosion affects spawning by influencing beach characteristics that are most important in site selection, such as beach topography, sediment texture, and geochemistry (Botton et al 1988).

The diet of juveniles is varied including particulate organic matter from algal and animal sources (Carmichael et al. 2004). As horseshoe crabs mature, the diet composition shifts to larger prey, and horseshoe crabs are known to be important bivalve predators (Botton 2009). Primary prey for adult horseshoe crabs are blue mussels (*Mytilus edulis*) and surf clams (*Spisula solidissima*) (Botton and Haskin 1984; Botton and Ropes 1989). Recent declines in surf clam in the mid-Atlantic are being attributed to climate-change induced increases in water temperatures during late-summer and fall (E. Powell, pers. comm.). The effects of a declining prey base, in general, and of surf clam populations, in particular, on horseshoe crab population carrying capacity is unknown.

4.0 Fishery Dependent Data Sources

Commercial fisheries for horseshoe crab consist primarily of directed trawls and hand harvest fisheries for use as bait and are the major source of fishery-dependent data for the stock. Landings for horseshoe crabs have been reported since 1970 and fishery-dependent data of the catches have been collected since 1998. Crabs are also commercially collected for use in the biomedical industry. While fishery-dependent data have been collected from this fishery, landings data is not well documented. Fishery-independent data sources for horseshoe crab exist primarily as trawl survey data collected by various states and the federal government where horseshoe crab is not the target species.

4.1 Commercial Bait Fishery

The commercial bait fishery consists primarily of trawl, hand harvest, and dredge fisheries. State and federal governments collected the fishery-dependent data included in this summary. Since 1998, ASMFC has compiled landings by state in the annual FMP review report.

4.1.1 Data Collection and Treatment

4.1.1.1 Survey Methods

Commercial horseshoe crab landings data collection is a joint state and federal responsibility. The cooperative state-federal fishery data collection systems obtain landings data from state-mandated fishery or mollusk trip-tickets, landing weighout reports provided by seafood dealers, federal logbooks of fishery catch and effort, shipboard and portside interview and biological sampling of catches. State fishery agencies are usually the primary collectors of landings data, but in some states NMFS and state personnel cooperatively collect the data.
Statistics for each state represent a census of the horseshoe crabs landed, rather than an expanded estimate of landings based on sampling data. Although the NMFS reports landings in pounds, adoption of the Interstate Fishery Management Plan for Horseshoe Crab (FMP) in 1998 required states to collect and report all horseshoe crab harvest by numbers, pounds, sex and harvest method (ASMFC 1998a). All states with an operating fishery require mandatory reporting. Horseshoe crab landings reported after 1997 were expressed as numbers of crabs and were obtained directly from the states.

Commercial sampling intensity varies from state to state. Most jurisdictions have implemented mandatory monthly or weekly reporting. Though reporting compliance has substantially improved since adoption of the FMP, some states do not currently provide landings by sex.

4.1.1.2 Biological Sampling Methods

Under the 1998 FMP states are required to characterize a portion of the commercial catch based on prosomal width and sex. Though many states implemented this compliance component, sampling intensity was inconsistent between states and between years. Some states used spawning survey data to characterize their shore-based fishery. The SAS agreed to use such information if it can be shown that this strategy would yield the same quality information.

Under the proposed framework for a horseshoe crab stock assessment states will be required to characterize their landings by sex and maturity (identification of new recruits to the spawning population). Development of a technique for determining maturity is underway.

Prosomal width measurements were available from the Delaware horseshoe crab hand fishery, the Georgia whelk/crab fishery (bycatch, 2000-2006), the Maryland horseshoe crab biomedical harvest, the Massachusetts horseshoe crab bait fishery, the New York horseshoe crab trawl fishery, and the South Carolina biomedical landings.. Concern was expressed that with quotas being monitored by number, harvesters may select for larger horseshoe crabs or that harvesters would begin landing immature crabs if adult numbers declined and demand remained high.

4.1.1.3 Ageing Methods

There are currently no direct methods to reliably age horseshoe crabs. According to Smith et al. (2009a), the ageing of horseshoe crabs using lipofuscin accumulation has not yet been shown to be reliable. Shuster (2000) developed a method for assigning general age based on shell wear and appearance. Botton and Ropes (1988) indirectly aged horseshoe crabs using slipper shells attached to the horseshoe crab to establish a minimum age. Researchers at the Virginia Tech Horseshoe Crab Research Center distinguish sex and maturity (immature, newly mature, and multiparous) in horseshoe crabs using genital papillae, modified pedipalps, rub marks and presence/absence of eggs.

4.1.1.4 Catch Estimation Methods

Reference period landings (RPL) were based on each state's best estimate of their commercial horseshoe crab bait landings (in numbers of crabs) for the period between 1995 and 1997. Some states used a single year's landings while other states used an average of landings within that timeframe (ASMFC 2000a). The Horseshoe Crab Technical Committee reviewed and approved each state's RPL.

The ASMFC quota is based on a 25% reduction in state-by-state RPL. Quotas were based on numbers of horseshoe crabs landed (not pounds).

Mean prosomal widths were obtained from various fisheries. Width measurements were segregated by gender since mature females are generally larger than males.

4.1.2 Commercial Bait Landings

NMFS reported commercial horseshoe crab landings increased to record levels in the mid to late 1990s (Table 1, Figure 1). Though the NMFS coastwide landings database suffers inadequacies (See Section 4.1.6), state-specific landings data support increased landings and effort in the horseshoe crab fishery during this period (ASMFC 1999). Reported NMFS landings since 1998 substantially declined. These landings include all harvest types (i.e. biomedical, bait fishery, marine life) reported to NMFS. The adoption of the FMP in 1998 improved harvest monitoring through mandatory reporting. The adoption of Addendum I to the FMP established reference period landings for the bait fishery that allowed for the implementation of quotas and served as a benchmark to evaluate subsequent bait landings. Addenda III (2004), IV (2006), and V (2008) further reduced harvest quotas, implemented seasonal bait harvest closures, and mandated male-only fisheries in some or all of the states in which harvest impacted the Delaware Bay population of horseshoe crabs (DE, MD, NJ, and VA).

4.1.3 Commercial Bait Discards/Bycatch

Horseshoe crabs are taken as bycatch in a number of fisheries. However, if landed, these crabs must be reported under the requirements of the FMP and are included in the coastwide horseshoe crab landings.

Commercial discard has not been quantified. Discard mortality is known to occur in various dredge fisheries. This mortality may vary seasonally with temperature/crab activity and impacts both mature and immature horseshoe crabs.

4.1.4 Commercial Bait Catch Rates (CPUE)

Commercial catch rates are available for the states of Delaware and Georgia (Table 5, Figure 4). Delaware commercial catch rates were calculated by dividing the number of horseshoe crabs landed in the dredge and hand fishery by the respective number of trips for each fishery. Georgia provided catch rates on horseshoe crabs taken as bycatch by their whelk/crab dredge fishery up until 2006.

Commercial catch rates in the Delaware horseshoe crab dredge fishery peaked in 1996 and were lowest in 2003. Since 2003, the dredge fishery CPUE has risen steadily. No dredge trips were made in 2008. Catch rates in the Delaware horseshoe crab hand fishery peaked in 1997 and were lowest in 1991 and 2004. CPUE in the hand fishery tracks well with the dredge fishery (Table 6, Figure 4).

Interpretation of these catch rates are complicated by the imposition of regulations after 1997. For example, after 1997 trip limits were established on the dredge fishery of 1,500 crabs per day and the hand fishery was restricted to 300 ft^3 per day. In addition, the dredge fishery, which was capped at five permits issued annually to fishermen that had traditionally harvested using this gear became subject to a lottery that included non-traditional participants. These non-traditional fishermen tended to be less efficient while they learned various gear nuisances and locations of horseshoe crab concentrations. Further harvest restrictions were imposed from 2004 and on.

Commercial catch rates of horseshoe crabs taken as bycatch by Georgia whelk/crab dredgers from 2000 thru 2006 were highest in 2000 (w/o TEDs) and 2005(w/ TEDs). CPUE was lowest in 2003 (Table 6, Figure 4). The Georgia catch rates were complicated by the addition of turtle excluder devices (TEDs) after 2000. Observers indicated that some crabs escape through the TEDs upon net retrieval (Haymans 2003).

4.1.5 Commercial Bait Prosomal Widths

Mean prosomal width data from various fisheries are presented in Table 6 and Figures 5 and 6. There were some significant ($P \leq 0.05$) declines in the mean prosomal widths of harvested males and females (Table 7).

Georgia has provided prosomal width data on both sexes of crabs sampled as bycatch from commercial whelk trawling from 1999-2006. Declines in mean prosomal width are seen in both sexes from GA. The maximum prosomal width has not changed; max PW for males was 285 mm in 2001 and 302 in 2006. However, the minimum prosomal width for males has declined from 187 mm in 2001 to 115 mm in 2006 with minimums of 92 mm and 82 mm ins 2004 and 2005. A male with a prosomal width of <190 mm is likely to be a juvenile (Smith et al. 2009). A similar pattern is seen in females. This indicates that juveniles are being caught in the whelk bycatch. Georgia has not had a commercial harvest since 1999, and the same declines in prosomal width are not as evident in fishery independent data.

In the case of Delaware males, this may be attributed to low sample sizes in 1999(3) and 2000(5). The 227 mm averages for males in 1999 and 2000 are suspect. A 227mm male would be in the upper 90% from the Del Bay population (Smith et al. 2009). In contrast, a 207 mm male is right at the median size. The measurements for males in 1999 and 2000 were collected from harvesters targeting females, and the atypically large males might have mistakenly been included in the catch, possibly due to their larger size. The median size female is 265mm, which is what is observed from 1999 to 2006. So, the PW of 231mm in 2007 is suspect. A female with a 231 mm PW would be in the lower 10% from the Delaware Bay population (Smith et al. 2009).

The declines in Maryland's mean male and female prosomal widths between 1993 and 2008 are noteworthy and may be an indication of size selection in the fishery or changes in the size of animals in the population. Commercially harvested female horseshoe crabs in Massachusetts also show a slight decrease in prosomal width over time (2000 – 2008).

A prediction based on the hypothesis that horseshoe crab populations have been dramatically over-fished during the past 10 to 20 years is that the size distribution of females will shift to smaller sized individuals and that large females will be removed from the populations. To evaluate this prediction, we compared size (prosomal width) distributions of Delaware Bay female and male horseshoe crabs from data collected in 1980s (Botton and Loveland 1992) to data collected in 2003-2005 (Smith et al. 2009). These data are presented in the in text table below:

	1986-1987				2003-2005			
	Mean (mm)	SD	Min/Max	n	Mean (mm)	SD	Min/Max	n
Females	258	14	208/316	216	266	19	125/385	9749
Males	201	14	154/256	447	208	16	90/340	26525

Size distributions of horseshoe crabs in Delaware Bay have not changed from the mid 1980s to the present. Of particular note, the largest females in the mid 1980s are not larger than the largest females in the current population.

4.1.6 Potential biases, Uncertainty, and Measures of Precision

NMFS reported horseshoe crab landings are difficult to reliably interpret. These landings may include biomedical, live trade and bait fishery harvest. Prior to passage of the FMP few states required horseshoe crab reporting. Further, harvesters generally reported landings in pieces or baits (1 female or 2 males = 1 bait) and it was unclear whether consistent or adequate conversion factors were used to convert these landings to pounds.

4.2 Commercial Biomedical Fishery

Blood from horseshoe crabs is obtained by collecting adult crabs, extracting a portion of their blood, and releasing them alive. Crabs collected for LAL production are typically collected by hand or trawl. Crabs are inspected to cull out damaged or moribund animals, and transported to the bleeding facility. Following bleeding, most crabs are returned to near the location of capture; however, since 2004, states have the ability to enter bled crabs into the bait market and count those crabs against the bait quota (ASMFC 2004).

Estimates of biomedical harvest prior to 2004 are uncertain due to lack of standardized reporting; however, estimates from several sources are consistent, lending some credence to the estimates. The FDA estimated medical usage increased from 130,000 crabs in 1989 to 260,000 in 1997 (D. Hochstein, pers. comm.). This was consistent with other estimates ranging between 200,000 and 250,000 crabs per year on the Atlantic coast (Swan, pers. comm.; Manion et al. 2000). A survey of biomedical companies conducted by the Horseshoe Crab Technical Committee in 2001 indicated that about 280,000 crabs were bled in 1998 and 2000. Annual reported harvest of crabs for biomedical use in South Carolina has increased over 300% since reporting requirements were established in 1991 (Thompson 1998).

Since 2004, ASMFC has required states to monitor the biomedical use of horseshoe crabs to determine the source of crabs, track total harvest, characterize pre- and post-bleeding mortality, and determine fate (bait or release) of crabs used for biomedical purposes. The total number of crabs delivered to biomedical facilities has increased roughly 50%, from approximately 340,000 crabs in 2004 to 511,000 crabs in 2008 (Table 3). However, the proportion of bled crabs coming from the bait market has increased slightly, so the increase in harvest of crabs for biomedical use only was 44%. Actual use of crabs for bleeding increased 46% from 275,000 to 402,000 crabs.

Mortality in the biomedical fishery is computed in two steps. First, pre-bleeding mortality is determined from harvest and use reports provided by the biomedical harvesters. Second, a 15% mortality rate is applied to all bled crabs to determine the post-bleeding mortality. The two values are summed to provide a coastwide estimate of mortality from the harvest, transport, handling, and bleeding of horseshoe crabs used for biomedical purposes. Pre-bleeding mortality has declined approximately 33% since 2004, to less than 3,000 crabs in 2008 (Table 3). However, total mortality has increased by 38% over the same time period assuming a constant rate (15%) of post-bleeding mortality. Even so, biomedical mortality was less than 10% of total (bait and biomedical) coastwide mortality in 2008.

The 1998 FMP (ASMFC 1998a) establishes a biomedical mortality threshold of 57,500 crabs which, if exceeded, triggers the Management Board to consider action. The threshold was exceeded in 2007 and 2008 with biomedical mortality estimated at 63,000 crabs. At the Management Board’s request, the Horseshoe Crab Technical Committee reviewed available literature and other information on mortality associated with the biomedical fishery (ASMFC 2008b). Despite limitations in study methodology and regional differences in results, the Technical Committee endorsed the use of a constant 15% mortality rate. The Technical Committee also provided suggestions for future research areas and discussed the potential for developing “best practice” guidelines for storage and handling of horseshoe crabs to minimize mortality.

4.3 Recreational

There is no recreational fishery for horseshoe crabs. Some states allow a minimal number of crabs to be retained for personal use. Landings of this type are not quantified.

5.0 Fishery-Independent Data

Many states and the federal government conduct surveys encounter horseshoe crabs. Since 1999 several surveys have been developed to target horseshoe crabs. Data sets are listed in Table 8. Details of the fishery independent surveys are summarized in Appendix B.

6.0 Methods

The current assessment reflects an expanding analytical approach as more data have become available and as a multiple-species assessment has been developed under an adaptive resource management framework. Trend analyses have been retained from the 2004 assessment to examine regional changes in relative abundance. In addition to the previous meta-analyses of regional trends, autoregressive integrated moving averages (ARIMA) models have been applied to all indices to assess current levels relative to variation within each index.

Single-species models in the current assessment include the surplus production and catch-survey models (Collie and Sissenwine 1983, Prager 1994). These models have been applied only to the Delaware Bay population, but could be applied in other regions and populations depending on data. The initial assessment framework for horseshoe crabs identified the catch-survey model as the primary assessment tool (ASMFC 2000b). However, data have not been sufficient to fit the model until recently. The surplus production model has been viewed as a stop-gap approach until data became sufficient to apply the catch-survey model (Davis et al. 2006). The current assessment is the first to include the catch-survey model.

Multi-species models have been developed to support adaptive management of horseshoe crab harvest and recovery of the migratory shorebird populations that rely on horseshoe crab eggs in Delaware Bay. The predictive horseshoe crab models are a stage-based model based on Sweka et al. (2007) and a logistic-growth model based on Davis et al. (2006). The adaptive management framework is described in a separate report.

6.1 Background

6.1.1 Regional Trend Analyses

The objective of the regional trend analyses was to determine change in horseshoe crab populations since the development of the ASMFC Interstate Management Plan. The trend analysis involved fitting a linear regression to the standardized index over the years 1998 to the present. Indices were standardized by subtracting the mean and dividing by the standard deviation.

Population decline is of particular concern. Because the indices were standardized, trend analysis results could be combined using meta-analysis techniques. To do this we used the meta-analysis techniques described by Manly (2001:123-125).

1) Fisher's method addresses the hypothesis that at least one of the indices shows a significant decline. The test statistic is calculated by $S_1 = -2\sum \ln(p_i)$, where p_i is the one-tailed p-value that tests for a significantly negative regression slope for the i^{th} index.

2) Stouffer's method addresses the hypothesis that there is a consensus for a decline supported by the set of indices. Here the individual one-tailed p-values are converted to z-scores, which under the null hypothesis are distributed as a Normal random variable with mean of zero and a variance of $1/\sqrt{n}$, where n is the number of datasets. The test statistic is $S_2 = \bar{z}/\left(1/\sqrt{n}\right)$. A version of the Stouffer's method incorporates weighting into the calculation of the test statistic. We used a measure of precision (the inverse of the root mean square error, i.e., the RMSE) as the weight (w_i). The weighted test statistic is $S_3 = \left(\sum w_i z_i\right)/\sqrt{\sum w_i^2}$.

3) A weighted standardized slope along with confidence intervals addresses the hypothesis that the datasets show a significant decline on average. We used a measure of precision as the weight (inverse of the RMSE) so that the datasets with the higher precision received greater weight. The calculation of the weighted slope is $\bar{b}_w = \sum w_i b_i / \sum w_i$, where b_i is the slope for the i^{th} dataset. The standard error is $se\left(\bar{b}_w\right) = \sqrt{\sum w_i \left(b_i - \bar{b}_w\right)^2 / \left(\sum w_i (n-1)\right)}$. The t-distribution is used to calculate confidence intervals.

6.1.2 Autoregressive Integrative Moving Average Description

Fishery independent surveys for horseshoe crabs can be quite variable, making inferences about population trends uncertain. Observed time series of abundance indices represents true changes in abundance, within survey sampling error, and varying catchability over time. One approach to minimize measurement error in the survey estimates is by using autoregressive integrated moving average models (ARIMA, Box and Jenkins 1976). The ARIMA approach derives fitted estimates of abundance over the entire time series whose variance is less than the variance of the observed series (Pennington 1986). This approach is commonly used to gain insight in stock assessments where enough data for size or age-structured assessments (e.g. yield per recruit, catch at age) is not yet available.

Helser and Hayes (1995) extended Pennington's (1986) application of ARIMA models to fisheries survey data to infer population status relative to an index-based reference point. This methodology yields a probability of the fitted index value of a particular year being less than the reference point [P(index_t<reference)]. Helser et al. (2002) suggested using a two-tiered approach when evaluating reference points whereby not only is the probability of being below (or above) the reference point is estimated, the statistical level of confidence is also specified. The confidence level can be thought of as a one-tailed *a*-probability from typical statistical hypothesis testing. For example, if the P(index_t<reference) = 0.90 at an 80% confidence level, there is strong evidence that the index of the year in question is less than the reference point. This methodology characterizes both the uncertainty in the index of abundance and in the chosen reference point. Helser and Hayes (1995) suggested the lower quartile (25th percentile) of the fitted abundance index as the reference point in an analysis of Atlantic wolfish (*Anarhichas lupus*) data. The use of the lower quartile as a reference point is arbitrary, but does provide a reasonable reference point for comparison for data with relatively high and low abundance over a range of years.

The purpose of this analysis was to fit ARIMA models to time series of horseshoe crab abundance indices to infer the status of the population(s).

6.1.3 Surplus Production Model Description

Surplus production models assume a relatively simple stock system, in which population biomass is increased by growth and recruitment. When biomass levels are high, some of this production is not necessary to maintain the population; this surplus can be removed from the population through harvest or natural mortality. This approach assumes that a population produces more recruits than is necessary to maintain the population, so fisheries should be able to harvest the surplus without negatively impacting the population. Surplus production models assess a population in its entirety, with no age-, size-, or stage-structure. Accordingly, all individuals in the population have the same natural mortality rate and growth rate. It is one of the more simplistic stock assessment methods and requires only a time series of harvest and a time series of catch-per-unit-effort from a survey or fishery.

The surplus production modeling approach is useful for horseshoe crabs because we do not yet have the information on stage-structure required for the catch-survey model. This method allows us to aggregate all stages and assess the population as a whole.

We used the most simplistic form of the surplus production model: the Graham-Schaefer, or logistic, form. This form assumes that population growth is maximized when population abundance is half of the carrying capacity (B=K/2). It is typically used when dealing with abundance data, as opposed to biomass data. We did not assume that equilibrium conditions existed in the population.

Surplus production modeling involves the following assumptions:

- Abundance indices are proportional to the true population abundance.
- The stock reacts instantaneously to changes in conditions.
- The biotic and abiotic environments are constant.
- No interspecific interactions are affecting population dynamics.
- The population is closed; any loss of individuals is due to mortality.

6.1.4 Catch Survey Analysis Description

A catch survey analysis was conducted by Dr. Rich Wong, Delaware Division of Fish and Wildlife. He is not a member of the Horseshoe Crab Technical Committee but his work was accepted by the committee and included in this assessment as Appendix C.

6.2 Configuration

6.2.1 Regional Trend Analyses

Fishery independent datasets and subsequent analyses were organized by region. The regions were the Southeast Region, the Delaware Bay Region, the New York Region, and the New England Region. Detailed descriptions of the surveys within each region are provided in Appendix B. The NMFS trawl survey data were grouped in the Delaware Bay Region because the data requested from NMFS corresponds to tows taken south of Long Island and north of Albermarle Sound.

6.2.2 Autoregressive Integrative Moving Average

Relative abundance indices included in this analysis are shown in Table 8. The ARIMA model fitting procedure of Pennington (1986) and bootstrapped estimates of the probability of being less than an index-based reference point (Helser and Hayes 1995) and corresponding levels of confidence (Helser et al. 2002) were coded in R (R code developed by Gary Nelson, Massachusetts Division of Marine Fisheries). An 80% confidence level was chosen for evaluating P(index_t<reference). Four index-based reference points were considered: 1) the lower quartile of the fitted abundance index (q25) as proposed by Helser and Hayes (1995); 2) the median (q50); 3) the upper quartile (q75); and 4) the fitted abundance index from 1998 – the time of development of the ASMFC Interstate Management Plan for horseshoe crabs. The use of four reference points allowed evaluation of the status of the horseshoe crabs with respect to historic levels, and just prior to the implementation of harvest restrictions to determine if such restrictions have resulted in an increase in abundance. Index values were ln (or ln + 1 in cases where "0" values were observed) transformed prior to ARIMA model fitting.

6.2.3 Surplus Production Model

Data used in the surplus production models:

Fishery-independent surveys: All survey indices were weighted equally in the models.

- Delaware 30-ft trawl, 1991-2008 (mid-year index)
- Delaware 16-ft trawl, crabs > 160-mm, April-July 1992-2008 (mid-year index)
- Delaware Bay Spawning Survey, 1999-2008 (mid-year index)
- New Jersey Delaware Bay trawl, 1998-2008 (mid-year index)
- NMFS Fall trawl, 1991-2008 (beginning of year index, advanced 1 calendar year to coincide with subsequent spring)
- Virginia Tech Offshore Trawl, 2002-2008 (end-of-year index)

We conducted model simulations for both sexes combined, females only, and males only. NMFS fall trawl and Delaware 16-ft 160 mm data were only available with both sexes combined, but we still used these data in the single-sex models. For all other indices and the harvest, we were able to use female-only or male-only data for the single-sex models.

Landings: We calculated regional landings in numbers of crabs from 1991-2008 as the total landings of Delaware, New Jersey, Maryland, and Virginia (Figure 7). For 1991-1997, regional landings were assumed to equal 3.2 times Delaware landings, with a 1:1 sex ratio. For 1998-2008, we assumed a sex ratio for unsexed crabs equal to the observed sex ratio of sexed crabs.

6.2.4 Catch Survey Analysis

See Appendix C for the configuration of the Catch Survey Analysis.

7.0 Results

7.1 Regional Trend Analysis

Regional populations have responded differently since 1998, which was the year preceding the implementation of the Interstate Fisheries Management Plan.

- In the Southeast region, there was no evidence of declines, and 3 out of 4 indices increased significantly (Table 9). This was a continuation of the conclusions from the 2004 assessment.
- In the Delaware Bay region, there was no evidence of declines, and the demographic pattern of significant increases matched the expectations for a recovering population (Table 10). Significant increases were most evident in juveniles and adult males; significant increase in adult females was observed only in the VT benthic trawl survey. This was an improvement from the 2004 assessment.
- In the New York region, there was evidence for declines. Significant declines were observed in 3 out of 6 indices (Table 11). The evidence for declines was a reversal from the 2004 assessment where the consensus was stable and positive trends.
- In the New England region, there was evidence for declines. Significant declines were observed in 3 out of 9 indices (Table 12). The evidence for declines was a continuation and a possible worsening of the trends reported in the 2004 assessment.

7.2 Autoregressive Integrative Moving Average

The ARIMA models provided adequate fits to the majority of horseshoe crab indices. In a few cases (Table 13), residuals from the ARIMA model fits were not normally distributed and thus, subsequent bootstrapped probabilities of being below reference point values should be considered unreliable. The surveys whose residuals were not normally distributed included Rhode Island Division of Fish and Wildlife trawl, Rhode Island – Providence River trawl, Connecticut Long Island Sound – Spring trawl, and Delaware Bay 16 ft trawl – YOY. Two of these surveys, Rhode Island – Providence River trawl and Delaware Bay 16 ft trawl – YOY, had “0” values in some years and needed the ln + 1 transformation as opposed to the ln transformation.

Trends in fitted abundance indices from ARIMA models showed much variation among surveys (Figures 8 – 13). Surveys with time series extending back into the to the mid-1990’s generally show a decreasing trend through the early 2000’s, but show mixed results from the mid 2000’s through 2008 with some indices increasing (e.g. SEAMAP Trawl Survey), remaining stable (e.g. Delaware Bay 30 ft. trawl), or continuing to decrease (e.g. University of Rhode Island –

Graduate School of Oceanography). Within the Delaware Bay region, Virginia Tech Trawl Surveys increased from 2004 – 2007, but then decreased in 2008 (Figure 12). New Jersey trawl surveys have shown mixed results with the New Jersey Surf Clam and New Jersey Delaware Bay trawls showing consistent increases since 2000, but the New Jersey Ocean Trawl decreased since 2004 (Figure 10). Delaware's trawl surveys remain stable in recent years (Figure 11).

Bootstrapped probabilities that 2008 indices were below reference points (q25, q50, q75, and 1998) also varied greatly among surveys (Table 14). To generalize the probabilities of 2008 indices being below reference points, we consider a probability of ≥50% as being "likely" to be below reference points. We also consider only those surveys whose residuals from fitted ARIMA indices were normally distributed. Coast wide, 4 out of 34 surveys (12%) had 2008 indices that were likely less than q25, 10 out of 34 surveys (29%) were likely less than q50, 12 out of 34 (35%) surveys were likely less than q75, and 8 out of 22 (36%) were likely to be less than the 1998 reference point. (The number of surveys available to compare to the 1998 reference point is less than the number available to compare to the other reference points because several surveys were not initiated until after 1998.) Within the Delaware Bay region, 1 out of 19 surveys (5%) had 2008 indices that were likely less than q25, 4 out of 19 surveys (21%) were likely less than q50, 6 out of 19 surveys (32%) were likely less than q75, and 5 out of 11 (45%) were likely less than the 1998 reference point. These results indicated that the majority of survey indices, both coast wide and within the Delaware Bay region, increased over their lower quartile by 2008, but many are still below 1998 levels. However, it appears that New England indices have generally shown a decline with 2 out 5 surveys (40%) likely less than q25, 5 out of 5 surveys (100%) likely less than q50 and q75, and 2 out of 3 surveys (67%) likely less than the 1998 reference point.

The use of ARIMA models for horseshoe crab assessment is an advancement in determining the status of the species. Fitted indices from ARIMA models minimize measurement error and give more precise estimates of the indices. However, the computation of reference points is still rather arbitrary and may change as more years of data are added to the time series. Likewise, the bootstrapped probabilities of being below a reference point in a given year will also change as the reference point changes and the confidence level used to evaluate these probabilities changes (80% confidence was used in this analysis). Despite these shortcomings, the use of the bootstrapped probabilities of being less than the reference points provides a characterization of the uncertainty in the reference point which is not available when viewing raw index values alone. Also, as more years are added to the time series, fitted index based reference points stabilize.

7.3 Surplus Production Model

7.3.1 Goodness of Fit

Model fits of the survey indices are shown for both sexes combined (Figure 14), females only (Figure 15), and males only (Figure 16). For the model with both sexes combined, the Delaware 30 ft trawl survey and the Delaware 16 ft 160 mm survey were negatively correlated ($\rho = -0.223$). In the female-only model, multiple surveys were negatively correlated: the Delaware 30 ft trawl survey and the Delaware 16 ft 160 mm survey ($\rho = -0.237$); the Delaware Bay spawning survey and the Delaware 16 ft 160 mm survey ($\rho = -0.087$); the Delaware 30 ft trawl survey and the New Jersey Delaware Bay trawl survey (ρ = -0.051); and the Delaware 30 ft trawl survey and the NMFS fall trawl survey (ρ = -0.024). In the male-only model, the Delaware 30 ft trawl survey and the Delaware 16 ft 160 mm survey were negatively correlated (-0.243).

7.3.2 Parameter Estimates

The surplus production models estimated that relative biomass decreased from 1991-2000 for both sexes combined and females only (Figure 17 and 18); male relative biomass decreased from 1991-2001 (Figure 18). From this point, relative biomass increased steadily to the present, with the models estimating current (2009) relative biomass to be approximately equal to relative biomass in 1996-1997.

Production model estimates of relative fishing mortality peaked in 1998-1999 at approximately 2-3 times F_{MSY} levels (Figure 17-19). Since then, relative fishing mortality has declined; current (2008) relative fishing mortality is approximately equal to the 1991 level.

7.3.5 Projection Estimates

We projected the population forward for 6 years (2009-2014) at a harvest level equal to 2008 landings of 94,000 females and 240,000 males (334,000 total crabs). We also evaluated scenarios with no harvest from 2009-2014. In surplus production model projections, relative biomass increased under both management scenarios (no harvest and harvest equal to 2008 landings) for all segments of the Delaware Bay population (Figure 20-22).

7.4 Catch Survey Analysis

See Appendix C for results of the Catch Survey Analysis.

8.0 Stock Status

8.1 Current Overfishing, Overfished/Depleted Definitions

No overfishing or overfished definitions have been adopted by the Management Board.

8.2 Stock Status Determination

Results infer the following findings and recommendations. Table 16 provides a summary of population trends and stock status by region.

a) As stated in the 2004 assessment, the coastwide horseshoe crab population is subdivided into regional/local populations. Genetic studies have identified multiple isolated subpopulations. Tagging studies have supported the presence of subpopulations, and also showed a finer, regional/local structure. Observed movement rates at larger scales allow for genetic mixing, but do not coincide with large-scale population shifts. Population indices show unique trends between some regional/local populations, suggesting dynamics might result from regional/local factor(s). Factors could include regional/local differences in harvest, habitat quality, prey availability, pollution, or other stressors. The regional/local differences highlight the potential for localized overharvesting. *Management regulations and population assessment should be implemented on a regional or localized scale. Monitoring and research should reflect the regional/local differences.*

b) Horseshoe crab abundance trends varied regionally/sub-regionally. Positive trends were observed in the Southeast and Delaware Bay regions. In the Southeast region there was evidence that abundance has increased over the past decade. In Delaware Bay, there was evidence for demographic-specific increases in abundance. Increases were most evident among juvenile indices followed by indices of adult males. A significant increase in adult females was observed in the VT benthic trawl survey. These demographic patterns are consistent with a recovery population since horseshoe crabs have a long time to maturity and males mature before females (Shuster and Sekiguchi 2003).

Declining abundance was evident in the New York and New England regions. Declines in the New England region had been evident in the 2004 assessment. However, declines in New York represent a downturn from the 2004 assessment.

In this assessment, ARIMA modeling of indices was introduced to allow comparisons of indices to empirical reference points. The ARIMA model was applied to all indices and assessed whether recent values were likely to be above the lower quartile or above the 1998 value. Coastwide, 4 out of 34 surveys (12%) had 2008 indices that were likely to be above the lower quartile reference point and 8 out of 22 (36%) were likely to be above the 1998 reference point.

The region-specific trends reinforce the importance of management, regulations, and monitoring on a regional or localized scale. Decreased harvest of the Delaware Bay population has redirected harvest to other regions, particularly New York and New England. While the recent evidence from the Delaware Bay population is positive, the evidence from New York and New England suggest that current harvest within those regions is not sustainable. *Continued precautionary management is therefore recommended coastwide to anticipate effects of redirecting harvest from Delaware Bay to outlying populations.*

c) The 2004 assessment indicated that future assessments would incrementally progress towards a stock assessment framework as sufficient data become available. This assessment presents the application and results from two modeling approaches focused on the Delaware Bay population where the most data are available.

The surplus production model was fit to the Delaware Bay indices. Based on the production model simulations, current fishing mortality on horseshoe crabs appears to be sustainable, and it is unlikely that overfishing is occurring (i.e., $F_{2008}/F_{MSY} < 1$; Table 15 and Figure 23). Relative fishing mortality was highest for male horseshoe crabs, but was still significantly less than 1. There is greater uncertainty surrounding estimates of relative biomass. Although point estimates of B_{2009}/B_{MSY} show a population that is not overfished (where $B_{2009}/B_{MSY} > 1$; Table 15 and Figure 23), the 80% confidence intervals all identify a possibility that the population is overfished. Female horseshoe crab relative biomass shows the highest degree of uncertainty and lowest relative biomass.

The catch survey model was fit to the VT benthic trawl data (Appendix C). This was the first instance that the catch survey model was successfully fit to available data; in previous attempts data were not sufficient for the model to converge on a solution. The catch survey model was the assessment framework initially proposed for horseshoe crabs.

Although there are remaining technical concerns, this assessment represents a considerable advance. *Application of assessment models should continue to be evaluated for the Delaware Bay data sets and explored for assessment of other regional populations.*

d) The 2004 assessment suggested that adaptive resource management should be explored as a potential framework to link management of horseshoe crab harvest to multiple species objectives, particularly shorebird recovery. Since the 2004 assessment, considerable progress has been made. In 2007, the Horseshoe Crab and Shorebird Technical Committees met jointly and formed an Adaptive Resource Management (ARM) working group. With funding from National Fish and Wildlife Foundation and USGS/FWS, a post-doc was hired to coordinate development of an ARM framework. Multi-species models have been developed and evaluated. The ARM framework, which has been developed through good-faith input from stakeholders, incorporates uncertainty in model predictions and a process for finding optimal harvest strategies. *Although the single species assessment continues (as reported herein), it is the intention of the stock assessment committee to continue to link data, modeling, and monitoring to the ARM framework, especially for assessment of the Delaware Bay population.*

9.0 Research Recommendations

As determined by the current assessment, the following research recommendations are the highest priorities (in no particular order) along the Atlantic coast and around Delaware Bay:

- Expand or implement fishery-independent surveys (e.g., spawning, benthic trawl, tagging) to target horseshoe crabs throughout their full range including estuaries. Highest priority should be given to implementing directed surveys in the New England and New York regions.
- Estimate the proportion of the Delaware Bay population that is available in time and space within existing VT benthic trawl survey area. This estimation should take into account age class (i.e., primiparous, multiparous).
- Assess the selectivity of gear used in the VT benthic trawl survey. This assessment should take into account age class (i.e., primiparous, multiparous).
- Estimate survival of early life stages (e.g., age zero) and growth rate by instar within Delaware Bay.
- Further develop catch-survey analysis and apply assessment modeling beyond the Delaware Bay region.
- Characterize the proportion of states' landings that comprise crabs of Delaware Bay origin. This can be done through a directed tag/release study, genetics/microchemistry study, or both.

It is expected that other high research and monitoring priorities will be recommended as a result of the peer review process of the Stock Assessment Framework (see Section 6.1.1).

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11.0 Tables

Table 1. Reported Atlantic coast horseshoe crab landings and value, 1970 – 2008 (NMFS Commercial Fishery Landings Database 2009)

Year	Metric tons	Pounds	Value ($)
1970	7.2	15,900	2,383
1971	5.4	11,900	970
1972	19.1	42,000	880
1973	40.2	88,700	1,960
1974	7.6	16,700	2,656
1975	28.5	62,800	7,974
1976	926.7	2,043,100	28,524
1977	214.6	473,000	7,859
1978	330.4	728,500	23,251
1979	551.4	1,215,630	81,977
1980	256.9	566,447	47,731
1981	148.2	326,695	36,885
1982	238.9	526,700	46,647
1983	212.6	468,600	37,901
1984	102.1	225,112	22,834
1985	278.9	614,939	54,903
1986	288.4	635,823	69,773
1987	232.1	511,758	77,058
1988	312.5	688,839	86,706
1989	502.0	1,106,645	140,889
1990	235.4	519,057	61,878
1991	174.9	385,487	39,674
1992	146.1	321,995	34,730
1993	372.5	821,205	85,808
1994	531.4	1,171,571	131,175
1995	1,096.0	2,416,168	309,467
1996	2,340.3	5,159,326	1,542,092
1997	2,713.9	5,983,033	1,182,375
1998	3,100.5	6,835,305	2,109,723
1999	2,379.8	5,246,598	1,338,922
2000	1,703.9	3,756,475	960,117
2001	1,059.9	2,336,645	667,018
2002	1,257.4	2,772,010	540,037
2003	1,190.4	2,624,248	695,338
2004	442.0	974,425	432,702
2005	645.0	1,421,957	514,418
2006	702.6	1,548,900	821,017
2007	791.0	1,743,934	1,110,188
2008	606.3	1,336,671	697,914

Table 2. State by state Atlantic coast horseshoe crab landings reported through ASMFC, 1998 – 2008 (ASMFC 2009) [Note: The ASMFC Quota was initiated in 2001 through Addendum I and has since been adjusted in 2003 through Addendum III and in 2006 through Addendum IV.]

State	ASMFC Quota	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
ME	13,500	13,500	1,500	1,391	100	150	98	0	0	0	0	0
NH	350	200	350	180	0	120	0	0	0	0	5	0
MA	330,377	400,000	545,715	272,930	134,143	138,613	125,364	69,436	73,740	171,906	150,829	103,963
RI	26,053	-	26,053	13,809	3,490	3,886	5,824	6,030	8,260	15,274	15,564	15,549
CT	48,689	34,583	45,050	15,921	12,175	32,080	15,186	23,723	15,311	26,889	25,098	32,535
NY	366,272	352,462	394,026	628,442	129,074	177,271	134,264	142,279	155,108	172,381	298,222	148,719
NJ	100,000	241,456	297,680	398,629	261,239	281,134	113,940	46,569	87,250	3,444	0	0
PA	0	75,000	0	0	0	0	0	0	0	0	0	0
DE	100,000	479,634	428,980	248,938	244,813	298,318	356,380	127,208	154,269	147,813	76,663	102,113
MD	170,653	114,458	134,068	152,275	170,653	278,211	168,865	161,928	169,821	136,733	172,117	163,495
VA	152,495	1,015,700	650,640	145,465	48,880	42,954	106,577	94,713	97,957	155,704	79,570	68,149
NC	24,036	21,392	28,094	14,973	9,130	12,988	24,367	9,437	7,713	10,331	9,300	26,191
SC	0	-	0	0	0	0	0	0	0	0	0	0
GA	29,312	-	29,312	0	0	0	0	0	0	0	0	0
FL	9,455	200	19,446	10,462	0	200	1,628	0	0	469	186	0
Total	1,371,192	2,748,585	2,600,914	1,903,415	1,013,697	1,265,925	1,052,493	681,323	769,429	840,944	827,554	660,714

Table 3. Coastwide annual harvest, use, and mortality of horseshoe crabs used for biomedical purposes.

	2004	2005	2006	2007	2008
Number of crabs brought to biomedical facilities (bait and biomedical crabs)	343,126	323,149	367,914	500,251	511,478
Number of biomedical-only crabs harvested (not counted against state bait quotas)	292,760	283,720	309,289	428,872	423,614
Estimated mortality of biomedical-only crabs prior to bleeding	4,391	4,256	4,639	3,599	2,973
Number of biomedical-only crabs bled	275,194	270,496	296,958	398,844	402,080
Estimated mortality of biomedical-only crabs during or after bleeding	41,279	40,574	44,543	59,833	60,312
Total estimated mortality on biomedical crabs not counted against state bait quotas	45,670	44,830	49,182	63,432	63,285

Table 4. Coastwide Horseshoe Crab Tagging Data: Release and Recapture Summary (1999-2008)

		RECAPTURE REGION	Northeast						Coast NY	Coast NJ-NC					
RELEASE REGION	RELEASE STATE	RECAPTURE STATE	RI	MA	CT	NY	UNK	Total	NY	NJ	DE	MD	VA	NC	Total
Northeast	RI (1,666)		**65.6% (59)**	25.6% (23)			5.6% (5)	96.7% (87)							
	MA (3,076)		5.2% (5)	**92.7% (89)**			1% (1)	99% (95)							
	CT (5,672)				**96.9% (31)**			96.9% (31)	3.1% (1)						
	NY (257)					**100% (1)**		100% (1)							
	TOTAL (10,671)		29.2% (64)	51.1% (112)	14.2% (31)	0.5% (1)	2.7% (6)	**97.7% (214)**	0.5% (1)						
Coast NY	NY (2,271)			1.8% (1)		5.5% (3)		7.3% (4)	**74.5% (41)**	16.4% (9)					16.4% (9)
Coast NJ-NC	NJ (1,396)								7.1% (2)	**50% (14)**					50% (14)
	DE (1,169)										**36% (18)**	10% (5)	2% (1)		48% (24)
	MD (28,795)		0.1% (1)	0.1% (1)	0.1% (1)			0.3% (3)	0.2% (2)	0.5% (4)	8.% (72)	**26.7% (233)**	7.9% (69)	0.5% (4)	43.7% (382)
	VA (15,298)					0.3% (1)		0.3% (1)	0.8% (3)	2.9% (11)	4.7% (18)	8.2% (31)	**18.7% (71)**	0.3% (1)	34.7% (132)
	NC (276)												14.3% (1)	**57.1% (4)**	71.4% (5)
	TOTAL (46,934)		0.1% (1)	0.1% (1)	0.07% (1)	0.1% (1)	0.0%	0.3% (4)	0.5% (7)	2.2% (29)	8.1% (108)	20.1% (269)	10.6% (142)	0.7% (9)	**41.6% (557)**
Delaware Bay	NJ (19,738)					0.1% (1)		0.1% (1)		2% (25)	1.4% (17)	0.4% (5)	0.1% (1)	0.1% (1)	4% (49)
	DE (29,371)				0.1% (1)			0.1% (1)		1.1% (22)	3.8% (73)	2% (39)	0.9% (17)	0.1% (2)	8% (153)
	TOTAL (49,109)				0.03% (1)	0.03% (1)		0.1% (2)		1.5% (47)	2.9% (90)	1.4% (44)	0.6% (18)	0.1% (3)	6.4% (202)
Chesapeake Bay	MD (93)														
Southeast	SC (2,525)														
Total Recaps			65	114	33	6	6	224	49	85	198	313	160	12	768

* Table includes all recaptures of animals at large for 3 months or more.

** % Recaptured (actual # of animals)

*** Release State (# of tags released)

Table 4. Continued

		RECAPTURE REGION	Delaware Bay			Chesapeake Bay			Southeast			UNK	Total Recaps
RELEASE REGION	RELEASE STATE	RECAPTURE STATE	NJ	DE	Total	MD	VA	Total	GA	SC	Total		
Northeast	RI (1,666)		1.1% (1)	2.2% (2)	3.3% (3)								90
	MA (3,076)			1% (1)	1% (1)								96
	CT (5,672)												32
	NY (257)												1
	TOTAL (10,671)		0.5% (1)	1.4% (3)	1.8% (4)								219
Coast NY	NY (2,271)			1.8% (1)	1.8% (1)								55
Coast NJ-NC	NJ (1,396)		35.7% (10)	7.1% (2)	42.9% (12)			0.0%					28
	DE (1,169)		12% (6)	40% (20)	52% (26)								50
	MD (28,795)		12% (105)	42.9% (375)	54.9% (480)		0.5% (4)	0.5% (4)				0.3% (3)	874
	VA (15,298)		16.8% (64)	45.8% (174)	62.6% (238)	0.3% (1)	1.1% (4)	1.3% (5)				0.3% (1)	380
	NC (276)		14.3% (1)		14.3% (1)		14.3% (1)	14.3% (1)					7
	TOTAL (46,934)		13.9% (186)	42.6% (571)	56.5% (757)	0.1% (1)	0.7% (9)	0.7% (10)				0.3% (4)	1339
Delaware Bay	NJ (19,738)		**46.7% (571)**	49.1% (600)	95.7% (1171)							0.2% (2)	1223
	DE (29,371)		18.5% (355)	**72.7% (1398)**	91.2% (1753)		0.2% (4)	0.2% (4)				0.6% (11)	1922
	TOTAL (49,109)		29.4% (926)	63.5% (1998)	**93% (2924)**		0.1% (4)	0.1% (4)				0.4% (13)	3145
Chesapeake Bay	MD (93)					**100% (1)**		**100% (1)**					1
Southeast	SC (2,525)								0.9% (5)	**99.1% (525)**	**100% (530)**		530
Total Recaps			1113	2573	3686	2	13	15	5	525	530	17	5289

* Table includes all recaptures of animals at large for 3 months or more.

** % Recaptured (actual # of animals)

*** Release State (# of tags released)

Table 5. Commercial catch rates (CPUE) of horseshoe crabs in Delaware and Georgia

	Delaware						**Georgia**		
Year	**Hand Harvest**	**Trips**	**Hand CPUE**	**Dredge Harvest**	**Trips**	**Dredge CPUE**	**Bycatch**	**Net Hrs**	**CPUE**
1991	17,457	62	281.6	22,158	16	1384.9			
1992	24,355	71	343.0	16,665	9	1851.7			
1993	29,867	44	678.8	20,466	17	1203.9			
1994	74,899	93	805.4	26,173	12	2181.1			
1995	133,586	172	776.7	38,515	30	1283.8			
1996	245,889	211	1165.4	50,470	14	3605.0			
1997	374,379	318	1177.3	53,052	33	1607.6			
1998	389,566	629	619.3	90,068	137	657.4			
1999	336,232	393	855.6	92,748	84	1104.1			
2000	192,993	301	641.2	55,945	51	1097.0	293	20.86	14.05
2001	160,028	420	381.0	84,785	157	540.0	543	55.89	9.72
2002	191,343	403	474.8	101,387	172	589.5	147	42.226	3.48
2003	302,101	845	357.5	54,279	220	246.7	13	36.45	0.36
2004	66,210	197	336.1	60,244	152	396.3	133	40.95	3.25
2005	96,832	161	601.4	57,437	117	490.9	754	89.49	8.43
2006	72,477	160	450.5	75,336	94	801.4	561	42	2.73
2007	59,429	124	566.0	17,234	19	907.1			
2008	102,113	131	779.5						

Table 6. Trends in female and male horseshoe crab prosomal width (millimeters) from fishery dependent surveys

	DE-Hand		GA-Trawl Bycatch			MD			MA-Bait Fishery		NY-Bait Fishery(Trawl)		SC-Biomedical		VA-Dredge/Pound	
Year	Female	Male	TEDs ?	Female	Male	Source	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male
1993						COMM	317	251								
1994						COMM	235	223								
1995						COMM	245	211								
1996						COMM	248	202								
1997						COMM	243	204								
1998						COMM	242	207								
1999	265	227	w/o TEDs	267	269	COMM	254	211					308	237		
2000	260	227	w/o TEDs	275	235	COMM	239	199	265	201			314	241	264	224
2001	267	208	w/ TEDs	291	232	COMM	251	208	259	195			311	235	253	220
2002	266	206	w/ TEDs	281	218	COMM	234	212	264	200			301	235	267	222
2003	269	206	w/ TEDs	268	204	COMM	272	207	255	198			312	240	274	223
2004	266	207	w/ TEDs	197	177	COMM	263	217	250	199	284	219	314	240		
2005	262	208	w/ TEDs	229	212	BIO	204	170	254	191	260		306	236	287	223
2006	264	207	w/ TEDs	187	175	BIO	207	171	253	197	271		307	236	258	222
2007	231	207	w/ TEDs			BIO	221	180	255	198	236	214	302	233	265	222
2008		207	w/ TEDs			BIO	217	170	250	198	255	210	304	234	247	214

TED = Turtle Excluder Device

Table 7. Statistical analyses of changes in mean prosomal widths of males and females

Data Series	a	b	R^2	F	P
DE female (1999-2007)	-2.2333	4734.5	0.2779	2.6939	0.145
DE male (1999-2008)	-1.9273	4072.3	0.4758	7.2623	0.027
GA female (1999-2006)	-13.008	26297	0.6365	10.504	0.018
GA male (1999-2006)	-11.299	22841	0.7966	23.49567	0.003
MA female (2000-2008)	-1.5533	3368.9	0.6023	10.599	0.014
MA male (2000-2008)	-0.295	788.69	0.0754	0.571	0.475
MD female (1993-2008)	-3.3218	6888.6	0.337	7.115	0.018
MD male (1993-2008)	-3.5339	7272	0.618	22.64712	0.000
NY female (2004-2008)	-8.15	16610	0.5176	3.2187	0.171
SC female (1999-2008)	-0.7204	1751.3	0.2203	2.26	0.171
SC male (1999-2008)	-0.4965	1231.3	0.2799	3.109	0.116
VA female (2000-2008 x05)	-0.617	1500.18	0.021	0.129	0.732
VA male (2000-2008 x05)	-0.567	1356.85	0.277	2.301	0.180

Table 8: Fishery independent data used to develop relative abundance indices included in the ARIMA analysis

Survey	Index Type	Stage	Sex	Years
New England Region				
New Hampshire habitat monitoring survey - May-September	Stratified mean per length of beach	Adult	All	2001 - 2008
New Hampshire habitat monitoring survey - May-June	Stratified mean per length of beach	Adult	All	2001 - 2008
Massachusetts DMF bottom trawl - Fall	Stratified mean	Adult	All	1978 - 2008
Massachusetts DMF bottom trawl - Spring	Stratified mean	Adult	All	1978 - 2009
Rhode Island Division of Fish and Wildlife	Arithmetic mean catch per tow	All	All	1998 - 2008
University of Rhode Island - Graduate School of Oceanography	Arithmetic mean catch per tow	All	All	1959 - 2008
Rhode Island - Marine Research Inc.	Arithmetic mean catch per tow	All	All	1988 - 2008
Rhode Island - Providence River	Arithmetic mean catch per tow	All	All	1992 - 2008
New York Region				
Connecticut Long Island Sound Trawl - Fall	Geometric Mean	All	All	1992 - 2008
Connecticut Long Island Sound Trawl - Spring	Geometric Mean	All	All	1992 - 2008
NYSDEC Long Island Sound Seine - Little Neck Bay	Geometric Mean	All	All	1987 - 2008
NYSDEC Long Island Sound Seine - Manhassett Bay	Geometric Mean	All	All	1987 - 2008
NYSDEC Peconic Bay small mesh trawl survey	Geometric Mean	All	All	1987 - 2008
NYSDEC Long Island Seine - Jamaica Bay	Geometric Mean	All	All	1987 - 2008
Delaware Bay Region				
New Jersey Surf Clam Index	Geometric Mean	All	All	1998 - 2008
New Jersey Ocean Trawl	Geometric Mean	All	All	1988 - 2008
New Jersey Delaware Bay Trawl	Geometric Mean	All	All	1998 - 2008
New Jersey Delaware Bay Trawl - Females	Geometric Mean	Adult	Female	1998 - 2008
New Jersey Delaware Bay Trawl - Males	Geometric Mean	Adult	Male	1998 - 2008
New Jersey Delaware Bay Trawl - Juveniles	Geometric Mean	Juvenile	All	1998 - 2008
Delaware Bay 16 ft trawl - YOY	Geometric Mean	YOY	All	1992 - 2008
Delaware Bay 16 ft trawl - Juvenile	Geometric Mean	Juvenile	All	1992 - 2008
Delaware Bay 30 ft trawl	Geometric Mean	All	All	1990 - 2008
Delaware Bay 30 ft trawl - Females	Geometric Mean	All	Female	1990 - 2007
Delaware Bay 30 ft trawl - Males	Geometric Mean	All	Male	1990 - 2007
Delaware Bay spawning survey - Females	Stratified mean	Adult	Female	1999 - 2008

Table 8: Continued

Survey	Index Type	Stage	Sex	Years
Delaware Bay spawning survey - Males	Stratified mean	Adult	Male	1999 - 2008
Virginia Tech Trawl Survey	Stratified mean	Adult	All	2002 - 2008
Virginia Tech Trawl Survey - Females	Stratified mean	Adult	Female	2002 - 2008
Virginia Tech Trawl Survey - Males	Stratified mean	Adult	Male	2002 - 2008
Virginia Tech Trawl Survey - core DB area	Stratified mean	Adult	All	2001 - 2008
Virginia Tech Trawl Survey - core DB area Females	Stratified mean	Adult	Female	2001 - 2008
Virginia Tech Trawl Survey - core DB area Males	Stratified mean	Adult	Male	2001 - 2008
Maryland Coastal Bay Trawl	Geometric Mean	All	All	1989 - 2008
NMFS/NEFSC Spring Trawl Survey	Geometric Mean	All	All	1988 - 2008
NMFS/NEFSC Fall Trawl Survey	Geometric Mean	All	All	1988 - 2008
Southeast Region				
SEAMAP Trawl Survey	Geometric Mean	All	All	1995 - 2008
North Carolina multimesh gill net	Geometric Mean	All	All	2001 - 2008
South Carolina Trawl	Geometric Mean	All	All	1995 - 2008
Georgia Shrimp Trawl survey	Arithmetic mean	All	All	1999 - 2009
Florida Seahorse Key (Gulf) Spawning Survey[1]	Mean number per tide	Adult	All	1993 - 2009

[1] Missing years 1998, 1999, 2001,2002, and 2003

Table 9. Trend analyses for Southeast region from 1998 to present. Description of datasets is in Appendix B. S1, S2, S3 and weighted slope are components of a meta-analysis. S1 tests whether at least on dataset shows a decline. S2 tests whether there is a consensus for decline among datasets. S3 is similar to S2, weights incorporates weights inverse to the RMSE (root mean square error). The weighted slope estimates and overall standardized slope using weights inverse to the RMSE. Significant trends for individual datasets are highlighted.

Dataset	time series duration	standardized RMSE	weight	standardized slope	se_slope	t	df	p	p (1-tailed)	log(p)	z|p
SEAMAP	1998-2008	0.3252	3.07503075	0.08795	0.03101	2.84	9	0.0195	0.99023779	-0.00981	2.33536
SC trawl	1998-2008	0.55958	1.787054577	0.07437	0.05335	1.39	9	0.1968	0.90161331	-0.10357	1.2908
GA trawl	1999-2009	0.55912	1.788524825	0.2401	0.05331	4.50	9	0.0015	0.99925963	-0.000741	3.17843
FL SS	1997-2009	142.81395	0.007002117	31.22305	13.81711	2.26	4	0.0015	0.95664721	-0.044321	1.71304

S1	df	Pr(X2>S1 | df)	z-bar	S2	Pr(Z<S2)	wt z-bar	S3	Pr(Z<S3)	weighted slope	var(wt_slope)	se_wt_slope	LCL 90	UCL 90
0.31688194	8	0.99997686	2.129407972	4.258815944	0.99999	2.28080896	3.9505	0.999961002	0.15792516	0.34031	0.58336	-1.545479	1.86132965

Table 10. Trend analyses for Delaware Bay region for 1998 to present. Description of datasets is in Appendix B. S1, S2, S3 and weighted slope are components of a meta-analysis. S1 tests whether at least on dataset shows a decline. S2 tests whether there is a consensus for decline among datasets. S3 is similar to S2, weights incorporates weights inverse to the RMSE (root mean square error). The weighted slope estimates and overall standardized slope using weights inverse to the RMSE. Significant trends for individual datasets are highlighted.

Dataset	time series duration	standardized RMSE	weight	standardized slope	SE_slope	t	df	p	p (1-tailed)	log(p)	z|p
Combined Sex/Age											
NMFS spring	1998-2008	0.04907	20.37905	0.00227	0.00468	0.49	9	0.639	0.68207168	-0.38262052	0.473499807
NMFS fall	1998-2008	0.06223	16.06942	0.00564	0.00593	0.95	9	0.3671	0.81653801	-0.20268181	0.902250202
NJ ocean	1998-2008	0.16276	6.144016	-0.02165	0.01552	-1.4	9	0.1964	0.0975143	-2.32775622	-1.295845832
NJ surf clam	1998-2009	0.85604	1.16817	0.31109	0.08162	3.81	9	0.0041	0.99792344	-0.00207872	2.866290877
MD coastal bays	1998-2009	0.07163	13.96063	-0.00033045	0.00683	-0.05	9	0.9625	0.48060723	-0.73270491	-0.04862962
NC gillnet	2001-2008	0.0227	44.05286	0.00881	0.0035	2.52	6	0.0456	0.97726888	-0.02299345	2.000352283
Juveniles											
NJ DelBay juv	1998-2008	0.12611	7.929585	0.02298	0.01202	1.91	9	0.0883	0.9557692	-0.04523882	1.70356919
DE 16ft lt160mm	1998-2008	0.27703	3.609717	0.07079	0.02641	2.68	9	0.0252	0.98739697	-0.01268313	2.238229893
VT trawl juv	2002-2008	14.38634	0.06951	3.45357	2.71876	1.27	5	0.2599	0.87001158	-0.13924875	1.126445892
VT trawl juv core	2001-2008	18.80063	0.05319	7.37024	2.901	2.54	6	0.044	0.97795954	-0.02228698	2.013320615
Males											
NJ DelBay males	1998-2008	0.11514	8.685079	0.02265	0.01098	2.06	9	0.0691	0.96525993	-0.03535786	1.815284855
DE 30ft males	1998-2008	0.36903	2.709807	0.02272	0.04063	0.56	9	0.5913	0.70542798	-0.3489506	0.540076832
DelBay SS male	1999-2008	0.60084	1.664337	0.09861	0.06615	1.49	8	0.1744	0.91272227	-0.09132364	1.35771081
VT trawl admale	2002-2008	10.07993	0.099207	4.88929	1.90493	2.57	5	0.0502	0.97498234	-0.02533592	1.959661937
VT trawl admale core	2001-2008	45.34038	0.022055	20.40357	6.99617	2.92	6	0.0268	0.98668435	-0.0134051	2.216879804
Females											
NJ DelBay fem	1998-2008	0.07728	12.93996	-0.0002755	0.00737	-0.04	9	0.971	0.4844832	-0.72467252	-0.038904659
DE 30ft females	1998-2008	0.34531	2.895949	-0.00403	0.03802	-0.11	9	0.9183	0.45741157	-0.7821717	-0.106956934
DelBay SS fem	1999-2008	0.09942	10.05834	-0.00030303	0.01095	-0.03	8	0.9786	0.48840099	-0.71661852	-0.029078512
VT trawl adfem	2002-2008	4.56809	0.21891	2.46286	0.86329	3.06	5	0.0281	0.98594899	-0.01415066	2.195859323
VT trawl adfem core	2001-2008	28.19258	0.03547	13.0333	4.35021	3	6	0.0241	0.9879959	-0.01207673	2.256998048

S1	df	Pr(chisq>S1 | df)	z-bar	S2	Pr(Z<S2)	wt z-bar	S3	Pr(Z<S3)	weighted slope	var(wt_slope)	se_wt_slope	LCL 90	UCL 90
13.30871311	40	0.999977732	1.207351	5.399436657	1	0.39053842	1.7023	0.955652068	0.0191869	0.003666486	0.060551513	-0.085813	0.124187073

Table 11. Trend analyses for New York region for 1998 to present. Description **of datasets is in Appendix B. S1, S2, S3 and weighted slope are components of a meta-analysis. S1 tests whether at least on dataset shows a decline. S2 tests whether there is a consensus for decline among datasets. S3 is similar to S2, weights incorporates weights inverse to the RMSE (root mean square error). The weighted slope estimates and overall standardized slope using weights inverse to the RMSE. Significant trends for individual datasets are highlighted.**

Dataset	time series duration	standardized RMSE	weight	standardized slope	se_slope	t	df	p	p (1-tailed)	log(p)	z|p
Peconic Bay	1998-2008	0.17099	5.848295222	-0.04473	0.0163	-2.74	9	0.0227	0.01134608	-4.47888331	-2.27857818
Jamaica Bay	1998-2008	0.22939	4.359387942	0.02835	0.02187	1.30	9	0.2271	0.88643754	-0.12054461	1.207798158
Little Neck Bay	1998-2008	0.64609	1.547771982	-0.16283	0.0616	-2.64	9	0.0268	0.01338332	-4.31374616	-2.21490423
Manhassett	1998-2008	0.74328	1.34538801	-0.15367	0.07087	-2.17	9	0.0583	0.02913557	-3.53579543	-1.89365254
CT LIS spring	1998-2008	0.3053	3.275466754	-0.01618	0.02911	-0.56	9	0.5918	0.29593954	-1.21760012	-0.536115
CT LIS fall	1998-2008	0.37632	2.657312925	0.041	0.02588	1.58	9	0.2827	0.9261996	-0.07666552	1.448058115

S1	df	Pr(X2>S1 | df)	z-bar	S2	Pr(Z<S2)	wt z-bar	S3	Pr(Z<S3)	weighted slope	var(wt_slope)	se_wt_slope	LCL 90	UCL 90
27.48647029	12	0.006572161	-0.71123228	-1.74215617	0.040741	-0.627546564	-1.5372	0.06212598	-0.028414	0.000819287	0.028623186	-0.086091	0.02926305

Table 12. Trend analyses for New England region for 1998 to present. Description of datasets is in Appendix B. S1, S2, S3 and weighted slope are components of a meta-analysis. S1 tests whether at least on dataset shows a decline. S2 tests whether there is a consensus for decline among datasets. S3 is similar to S2, weights incorporates weights inverse to the RMSE (root mean square error). The weighted slope estimates and overall standardized slope using weights inverse to the RMSE. Significant trends for individual datasets are highlighted.

Dataset	time series duration	standardized RMSE	weight	standardized slope	se_slope	t	df	p	p (1-tailed)	log(p)	z|p
MA Fall All Regions	1998-2008	0.23802	4.20132762	0.00827	0.02269	0.36	9	0.7239	0.63804102	-0.449352703	0.35322741
MA Spring All Regions	1998-2008	0.06147	16.26809826	-0.00675	0.00514	-1.31	9	0.2185	0.1107992	-2.200035759	-1.222288908
URIGSO	1998-2008	1.18351	0.844944276	-0.30375	0.11284	-2.69	9	0.0247	0.01236045	-4.393253392	-2.245736346
RI MRI	1998-2008	0.24245	4.124561765	-0.01236	0.02312	-0.53	9	0.6057	0.30293897	-1.194223919	-0.515966314
RI Provr	1998-2008	9.03439	0.110688159	0.05455	0.8614	0.06	9	0.9509	0.52455491	-0.645205172	0.061588939
RI Stout	1998-2008	3.80789	0.262612628	1.5	1.20416	1.25	9	0.3013	0.87783333	-0.130298533	1.164223768
RI DFW	1998-2008	0.14713	6.796710392	0.01905	0.01403	1.36	9	0.2075	0.89620549	-0.10958555	1.260222751
NH MayJune	2001-2008	0.01739	57.50431282	-0.00907	0.00268	-3.38	6	0.0149	0.00738932	-4.907719035	-2.437758395
NH MaySept	2001-2008	0.00652	153.3742331	-0.00329	0.00101	-3.26	6	0.0171	0.00865226	-4.749934789	-2.380172852

S1	df	Pr(X2>S1 | df)	z-bar	S2	Pr(Z<S2)	wt z-bar	S3	Pr(Z<S3)	weighted slope	var(wt_slope)	se_wt_slope	LCL 90	UCL 90
37.5592177	18	0.00442801	-0.662517772	-1.98755332	0.023431	-2.130650869	-6.392	8.18903E-11	-0.0036118	0.0003473	0.018635983	-0.038266	0.03104271

Table 13: Results of autoregrisive integrated moving average (ARIMA) models for horseshoe crab surveys. W is the Shapiro-Wilk test statistic for normality of residuals (p value in parentheses); n is the number of years in the time series; r_1, r_2, and r_3 are the first three autocorrelations; θ is the moving average parameter, SE is the standard error of θ (standard error in parentheses); and σ^2_c is variance of the index.

Survey	W	p	n	r_1	r_2	r_3	θ	SE	σ^2_c
New England Region									
New Hampshire habitat monitoring survey - May-September	0.89	0.25	8	-0.18	-0.60	0.10	0.17	0.45	0.24
New Hampshire habitat monitoring survey - May-June	0.93	0.55	8	-0.17	-0.55	0.13	0.11	0.47	0.26
Massachusetts DMF bottom trawl - Fall	0.97	0.42	31	-0.31	-0.24	-0.11	0.86	0.1	0.69
Massachusetts DMF bottom trawl - Spring	0.88	0.00	32	-0.44	0.05	-0.13	0.67	0.17	0.01
Rhode Island Division of Fish and Wildlife	0.79	0.01	11	-0.08	-0.21	-0.39	0.03	0.36	0.14
University of Rhode Island - Graduate School of Oceanography	0.97	0.33	50	-0.38	0.00	0.03	0.34	0.11	1.14
Rhode Island - Marine Research Inc.	0.95	0.34	21	-0.53	0.38	0.29	0.34	0.18	0.67
Rhode Island - Providence River	0.89	0.05	17	-0.44	-0.17	0.25	0.78	0.22	2.56
New York Region									
Connecticut Long Island Sound Trawl - Fall	0.93	0.18	17	-0.12	-0.47	0.05	0.66	0.23	0.20
Connecticut Long Island Sound Trawl - Spring	0.84	0.01	17	-0.51	0.06	-0.03	0.71	0.24	0.35
NYSDEC Long Island Sound Seine - Little Neck Bay	0.97	0.69	22	-0.65	0.46	-0.53	0.87	0.36	0.38
NYSDEC Long Island Sound Seine - Manhasset Bay	0.99	1.00	22	-0.58	0.3	-0.36	0.83	0.19	0.73
NYSDEC Peconic Bay small mesh trawl survey	0.92	0.10	22	-0.23	0.39	-0.03	0.14	0.17	0.18
NYSDEC Long Island Seine - Jamaica Bay	0.97	0.65	22	-0.57	-0.08	0.32	0.79	0.12	0.33
Delaware Bay Region									
New Jersey Ocean Trawl	0.97	0.81	21	0.12	-0.34	-0.24	0.39	0.30	0.05
New Jersey Surf Clam Index	0.97	0.91	11	-0.69	0.63	-0.46	0.35	0.22	0.48
New Jersey Delaware Bay Trawl	0.98	0.96	11	-0.59	0.11	0.00	0.61	0.21	0.17
New Jersey Delaware Bay Trawl - Females	0.93	0.44	11	-0.68	0.36	-0.07	1.00	0.31	0.32
New Jersey Delaware Bay Trawl - Males	0.94	0.51	11	-0.68	0.42	-0.13	0.58	0.26	0.18
New Jersey Delaware Bay Trawl - Juveniles	0.97	0.93	11	-0.45	-0.08	0.18	0.66	0.24	0.99
Delaware Bay 16 ft trawl - YOY	0.78	0.00	17	-0.29	-0.13	0.02	1.00	0.20	0.20
Delaware Bay 16 ft trawl - Juvenile	0.98	0.98	17	-0.33	0.35	-0.41	0.26	0.24	0.58

Table 13: Continued.

Survey	W	p	n	r_1	r_2	r_3	θ	SE	σ^2_c
Delaware Bay Region									
Delaware Bay 30 ft trawl	0.96	0.54	19	-0.47	0.02	-0.03	0.60	0.20	1.18
Delaware Bay 30 ft trawl - Females	0.96	0.59	18	-0.48	0.06	0.04	0.58	0.21	1.22
Delaware Bay 30 ft trawl - Males	0.96	0.69	18	-0.41	-0.06	0.13	0.63	0.21	1.58
Delaware Bay spawning survey - Females	0.98	0.98	10	-0.30	-0.08	-0.17	1.00	0.30	0.01
Delaware Bay spawning survey - Males	0.89	0.18	10	-0.14	-0.15	-0.07	0.70	0.34	0.05
Virginia Tech Trawl Survey	0.97	0.89	7	0.31	-0.49	-0.49	1.00	0.51	0.05
Virginia Tech Trawl Survey - Females	0.92	0.48	7	0.36	-0.44	-0.45	1.00	0.46	0.04
Virginia Tech Trawl Survey - Males	0.98	0.97	7	0.28	-0.50	-0.49	1.00	0.63	0.06
Virginia Tech Trawl Survey - core DB area	0.90	0.28	8	0.06	-0.66	-0.11	0.78	0.50	0.09
Virginia Tech Trawl Survey - core DB area Females	0.92	0.47	8	0.15	-0.61	-0.23	0.71	0.44	0.09
Virginia Tech Trawl Survey - core DB area Males	0.89	0.25	8	0.01	-0.67	-0.05	0.85	0.72	0.08
Maryland Coastal Bay Trawl	0.89	0.02	20	-0.48	-0.04	0.29	0.84	0.15	0.32
NMFS/NEFSC Spring Trawl Survey	0.89	0.02	21	-0.58	0.18	0.08	1.00	0.16	0.63
NMFS/NEFSC Fall Trawl Survey	0.93	0.13	21	-0.47	-0.06	0.12	1.00	0.39	0.13
Southeast Region									
SEAMAP Trawl Survey	0.97	0.87	14	-0.4	0.9	-0.27	0.44	0.29	1.47
North Carolina multimesh gill net	0.91	0.36	8	-0.61	0.03	0.21	0.51	0.29	0.04
South Carolina Trawl	0.96	0.68	14	-0.10	-0.12	-0.41	0.19	0.43	0.20
Georgia Shrimp Trawl survey	0.94	0.50	11	-0.25	-0.33	0.05	0.10	0.36	0.13
Florida Seahorse Key (Gulf) Spawning Survey	0.96	0.84	10	-0.07	-0.59	0.10	0.17	0.31	0.37

Table 14: Reference points from the ARIMA model for each survey and the probability of the 2008 fitted index being below the reference point. The 2008 percentile represents the percentile of the fitted index relative to the entire time series. Reference points were the lower quartile (q25), median (q50), upper quartile (q75) of the fitted indices and the fitted 1998 indices (1998) from the ARIMA models. Values for q25, q50, q75 and 1998 represnt ln tranformed index values.

Survey	2008 percentile	q25	P(< q25)	q50	P(<q50)	q75	P(<q75)	1998	P(< 1998)
New England Region									
New Hampshire habitat monitoring survey - May-September	0.00	-4.62	0.49	-4.04	0.97	-3.65	1.00	*	*
New Hampshire habitat monitoring survey - May-June	0.14	-3.64	0.48	-2.98	0.91	-2.56	1.00	*	*
Massachusetts DMF bottom trawl - Fall	0.03	-1.58	0.31	-1.47	0.60	-1.19	0.85	-1.57	0.37
Massachusetts DMF bottom trawl - Spring[12]	0.16	0.10	0.58	0.14	0.90	0.19	0.96	0.16	0.94
Rhode Island Division of Fish and Wildlife[2]	0.20	-1.05	0.08	-1.00	0.81	-0.94	0.81	-1.88	0.00
University of Rhode Island - Graduate School of Oceanography	0.06	1.34	1.00	2.37	1.00	3.66	1.00	0.93	1.00
Rhode Island - Marine Research Inc.	0.00	-1.10	0.83	-0.78	1.00	0.57	1.00	-1.10	0.86
Rhode Island - Providence River[12]	0.25	0.93	0.24	1.21	0.42	1.66	0.58	1.75	0.61
New York Region									
Connecticut Long Island Sound Trawl - Fall	1.00	-0.06	0.02	0.21	0.09	0.33	0.23	0.06	0.04
Connecticut Long Island Sound Trawl - Spring[2]	0.63	-0.81	0.07	-0.51	0.20	-0.44	0.32	-0.62	0.12
NYSDEC Long Island Sound Seine - Little Neck Bay	0.48	0.54	0.05	0.62	0.15	0.68	0.32	0.68	0.32
NYSDEC Long Island Sound Seine - Manhassett Bay	0.67	-0.15	0.01	0.11	0.11	0.15	0.22	0.19	0.29
NYSDEC Peconic Bay small mesh trawl survey	0.10	-0.83	0.65	-0.27	0.91	0.23	1.00	-0.11	0.91
NYSDEC Long Island Seine - Jamaica Bay	1.00	-0.86	0.05	-0.73	0.26	-0.69	0.48	-0.83	0.19
Delaware Bay Region									
New Jersey Ocean Trawl	0.00	-0.36	0.90	-0.20	0.99	-0.03	1.00	-0.03	1.00
New Jersey Surf Clam Index	1.00	-0.46	0.00	-2.05	0.00	0.52	0.03	-0.21	0.00
New Jersey Delaware Bay Trawl	0.90	-0.70	0.01	-0.55	0.05	-0.39	0.16	-0.70	0.01
New Jersey Delaware Bay Trawl - Females	0.50	-2.21	0.24	-2.18	0.37	-1.96	0.65	-1.58	0.94
New Jersey Delaware Bay Trawl - Males	0.90	-1.44	0.00	-1.35	0.01	-1.11	0.12	-1.29	0.04
New Jersey Delaware Bay Trawl - Juveniles	1.00	-1.95	0.02	-1.64	0.10	-1.44	0.23	-1.81	0.06
Delaware Bay 16 ft trawl - YOY[12]	0.50	0.39	0.02	0.44	0.10	0.47	0.25	0.47	0.21
Delaware Bay 16 ft trawl - Juvenile	0.81	-1.46	0.01	-0.77	0.09	-0.54	0.28	-1.24	0.21
Delaware Bay 30 ft trawl	0.33	-0.34	0.24	0.05	0.66	0.64	0.95	0.18	0.74

Table 14: Continued.

Survey	**2008 percentile**	**q25**	**P(< q25)**	**q50**	**P(<q50)**	**q75**	**P(<q75)**	**1998**	**P(< 1998)**
Delaware Bay 30 ft trawl - Females	0.35	-0.98	0.31	-0.47	0.73	0.08	0.96	-0.41	0.80
Delaware Bay 30 ft trawl - Males	0.35	-1.18	0.32	-0.67	0.71	-0.04	0.97	-0.60	0.77
Delaware Bay spawning survey - Females	0.89	-0.20	0.01	-0.20	0.06	-0.19	0.18	*	*
Delaware Bay spawning survey - Males	0.67	1.03	0.05	1.09	0.14	1.13	0.23	*	*
Virginia Tech Trawl Survey	0.83	3.44	0.00	3.71	0.01	4.03	0.03	*	*
Virginia Tech Trawl Survey - Females	0.83	2.31	0.00	2.64	0.03	2.94	0.07	*	*
Virginia Tech Trawl Survey - Males	0.83	3.06	0.00	3.30	0.00	3.60	0.02	*	*
Virginia Tech Trawl Survey - core DB area	0.86	3.57	0.00	3.73	0.00	4.03	0.01	*	*
Virginia Tech Trawl Survey - core DB area Females	0.86	2.53	0.00	2.61	0.00	2.97	0.01	*	*
Virginia Tech Trawl Survey - core DB area Males	0.86	3.14	0.00	3.33	0.00	3.60	0.01	*	*
Maryland Coastal Bay Trawl[2]	0.26	-1.82	0.28	-1.74	0.52	-1.57	0.86	-1.71	0.55
NMFS/NEFSC Spring Trawl Survey[2]	0.75	-2.94	0.03	-2.83	0.12	-2.76	0.27	-2.78	0.16
NMFS/NEFSC Fall Trawl Survey	0.55	-1.60	0.17	-1.56	0.30	-1.45	0.53	-1.65	0.01
Southeast Region									
SEAMAP Trawl Survey	0.77	-2.16	0.00	-1.96	0.00	-0.53	0.17	-1.86	0.00
North Carolina multimesh gill net	1.00	-1.99	0.00	-1.91	0.00	-1.83	0.09	*	*
South Carolina Trawl	0.92	0.14	0.05	0.59	0.14	0.71	0.34	-0.33	0.00
Georgia Shrimp Trawl survey	0.90	-0.01	0.00	0.20	0.00	0.64	0.00	*	*
Florida Seahorse Key (Gulf) Spawning Survey	0.33	4.48	0.00	5.12	0.00	6.06	0.19	4.66	0.37

* Indicates that the survey time series began after 1998.

[1] Indicates surveys where a ln +1 transformation was used due to "0" values in the time series.

[2] Indicates that the probabilities of being less than the reference point may not be valid because the the residuals from the ARIMA model were not normally distributed.

Table 15. Relative biomass and relative fishing mortality (and 80% bias-corrected confidence intervals) for Delaware Bay horseshoe crabs, as estimated by surplus production models.

	B_{2009}/B_{MSY}			F_{2008}/F_{MSY}		
	Point est.	**80% LCI**	**80% UCI**	**Point est.**	**80% LCI**	**80% UCI**
Both sexes combined	1.440	0.881	1.733	0.232	0.165	0.399
Females only	1.123	0.498	1.685	0.230	0.130	0.421
Males only	1.444	0.890	1.707	0.298	0.221	0.496

Table 16. Summary of population trends and stock status by region

	Meta analysis: post-FMP trends	**ARIMA**				**Surplus Production**	**Catch-Survey Analysis**
		25%	**50%**	**75%**	**1998**		
New England	Consensus for declines; Negative slopes in 3 of 9 surveys	2 of 5 surveys likely below reference point	5 of 5 surveys likely below reference point	5 of 5 surveys likely below reference point	2 of 3 surveys likely below reference point		
New York	Consensus for declines; Negative slopes in 3 of 6 surveys	1 of 5 surveys likely below reference point	1 of 5 surveys likely below reference point	1 of 5 surveys likely below reference point	1 of 5 surveys likely below reference point		
Delaware Bay	No evidence for declines; Positive slopes: Combined sex/age 2 of 6; Juveniles 3 of 4; Adult males 3 of 5; Adult females 2 of 5	1 of 19 surveys likely below reference point	4 of 19 surveys likely below reference point	6 of 19 surveys likely below reference point	5 of 11 surveys likely below reference point	$F<F_{MSY}$ and decreasing; $B>B_{MSY}$ and increasing; 80% CIs extend above (F) and below (B) reference points	Stock increase more than 3-fold from 2001 to 2008; estimated F < 0.05 in recent years
South Atlantic	No evidence for declines; Positive slopes in 2 of 3 surveys	0 of 5 surveys likely below reference point	0 of 5 surveys likely below reference point	0 of 5 surveys likely below reference point	0 of 3 surveys likely below reference point		

12.0 Figures

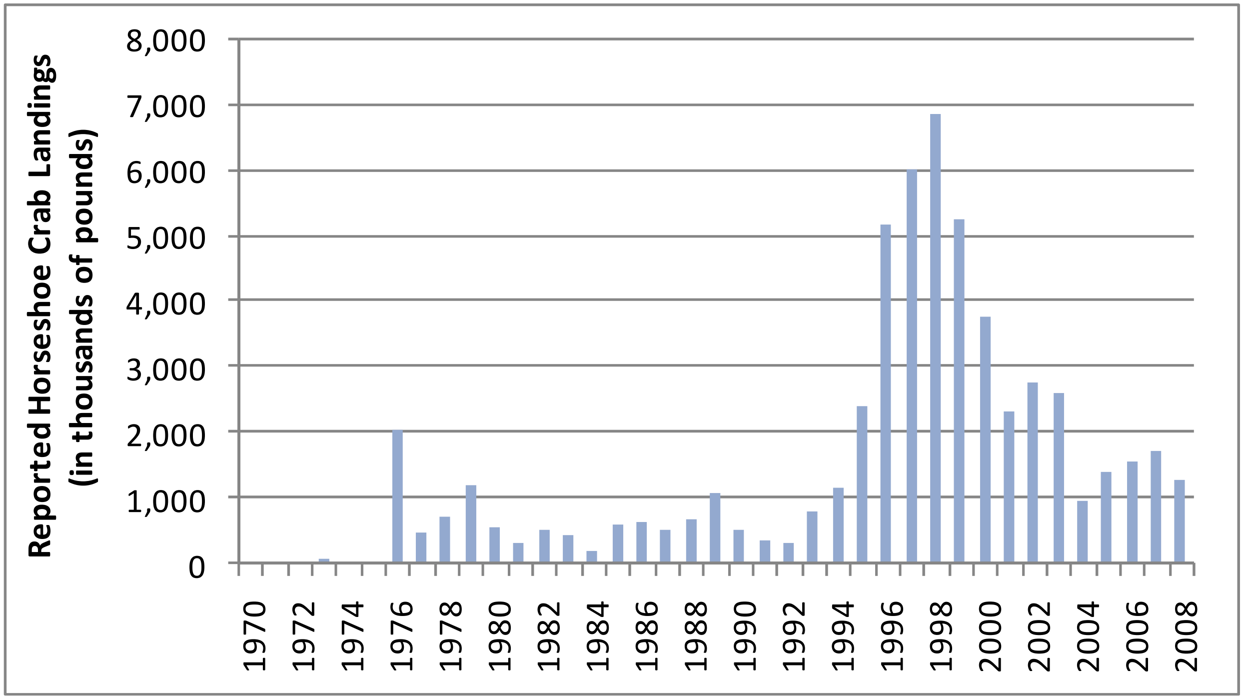


Figure 1. Reported Atlantic coast horseshoe crab landings (in pounds), 1970 – 2008. (NMFS Commercial Fishery Landing Database 2009)

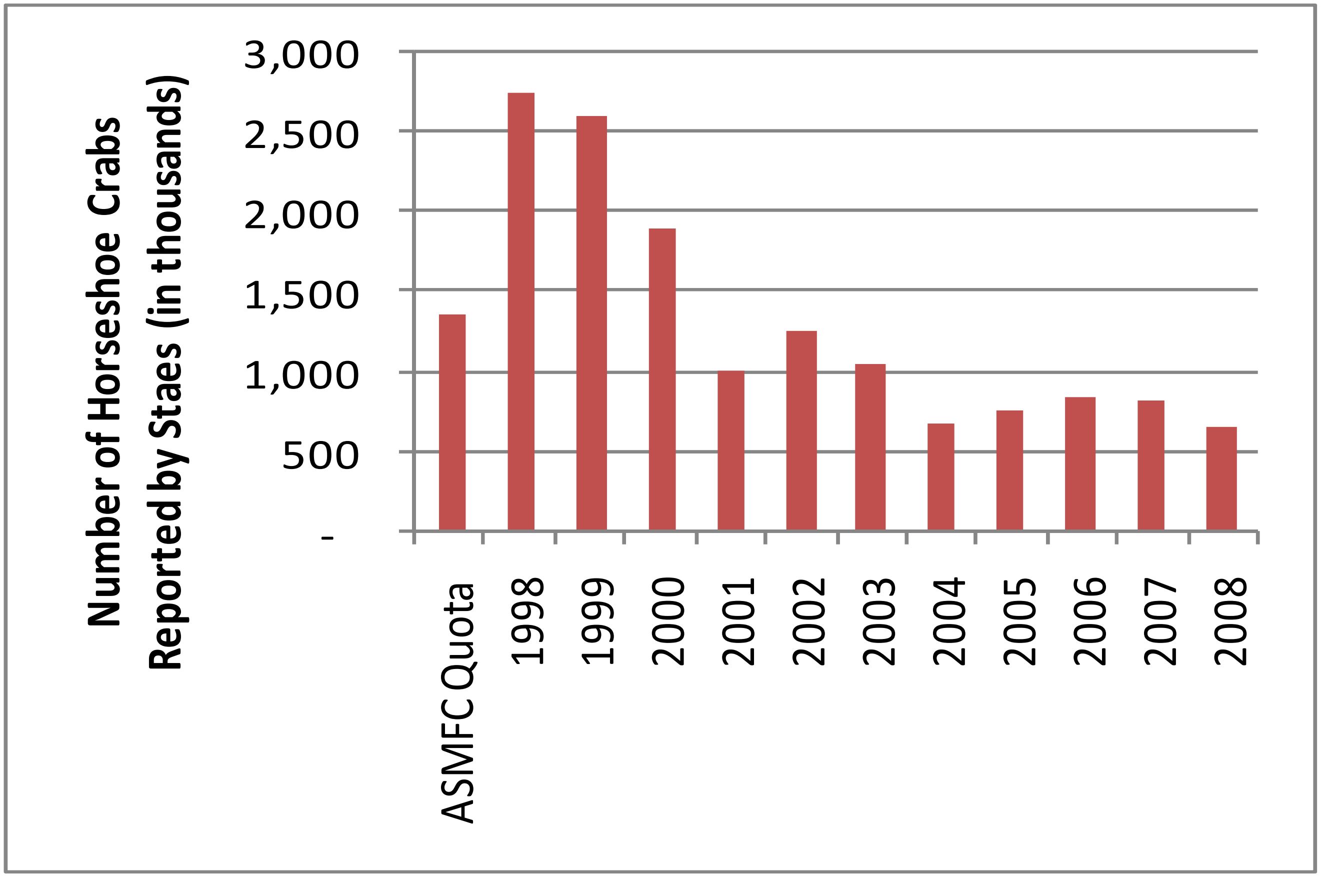
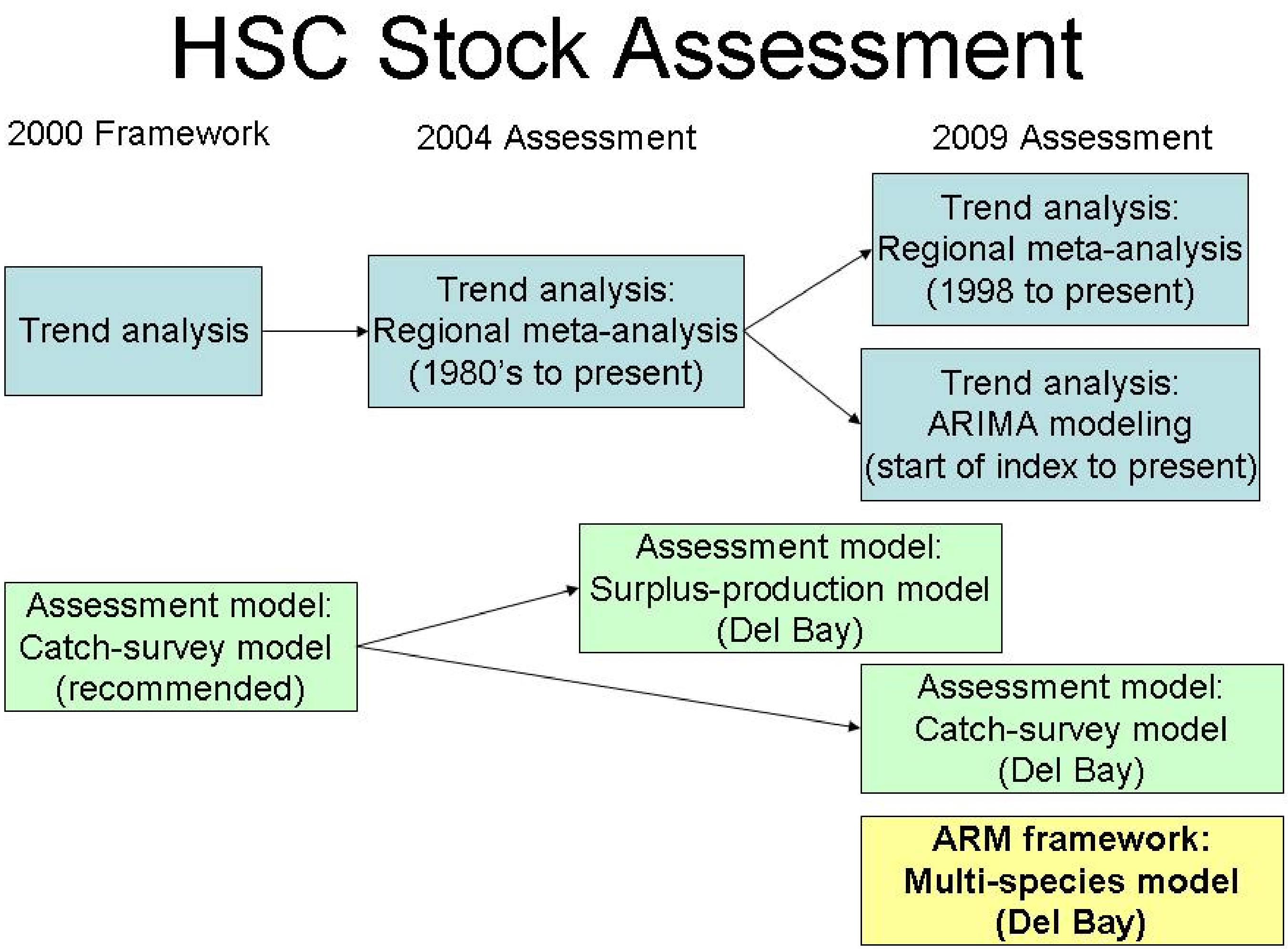


Figure 2. Atlantic Coastwide horseshoe crab landings reported by states through ASMFC, 1998 – 2008 (ASMFC 2009) [Note: The ASMFC Quota was initiated in 2001 through Addendum I and has since been adjusted in 2003 through Addendum III and in 2006 through Addendum IV.]



HSC Stock Assessment

2000 Framework

2004 Assessment

2009 Assessment

Trend analysis

Trend analysis: Regional meta-analysis (1980's to present)

Trend analysis: Regional meta-analysis (1998 to present)

Trend analysis: ARIMA modeling (start of index to present)

Assessment model: Catch-survey model (recommended)

Assessment model: Surplus-production model (Del Bay)

Assessment model: Catch-survey model (Del Bay)

ARM framework: Multi-species model (Del Bay)

Figure 3. Timeline of introduction of analyses in relation to past and present assessments.

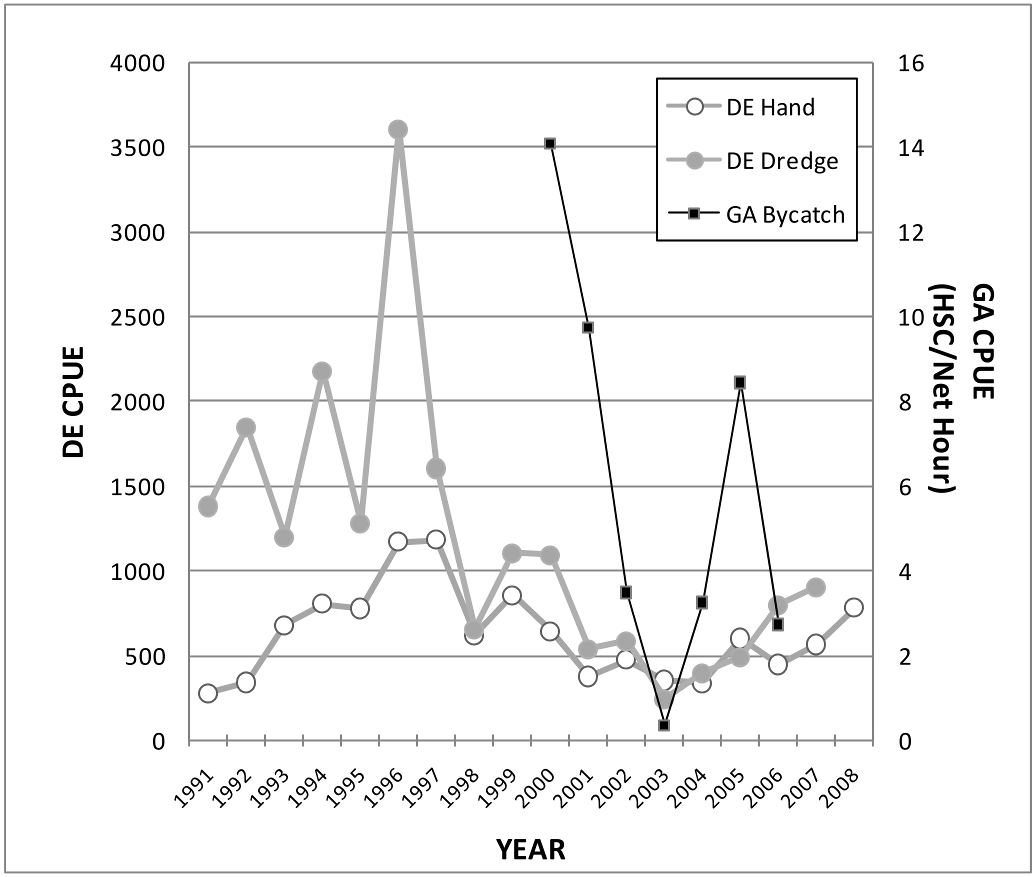


Figure 4. Commercial catch rates (CPUE) of horseshoe crabs in Delaware and Georgia

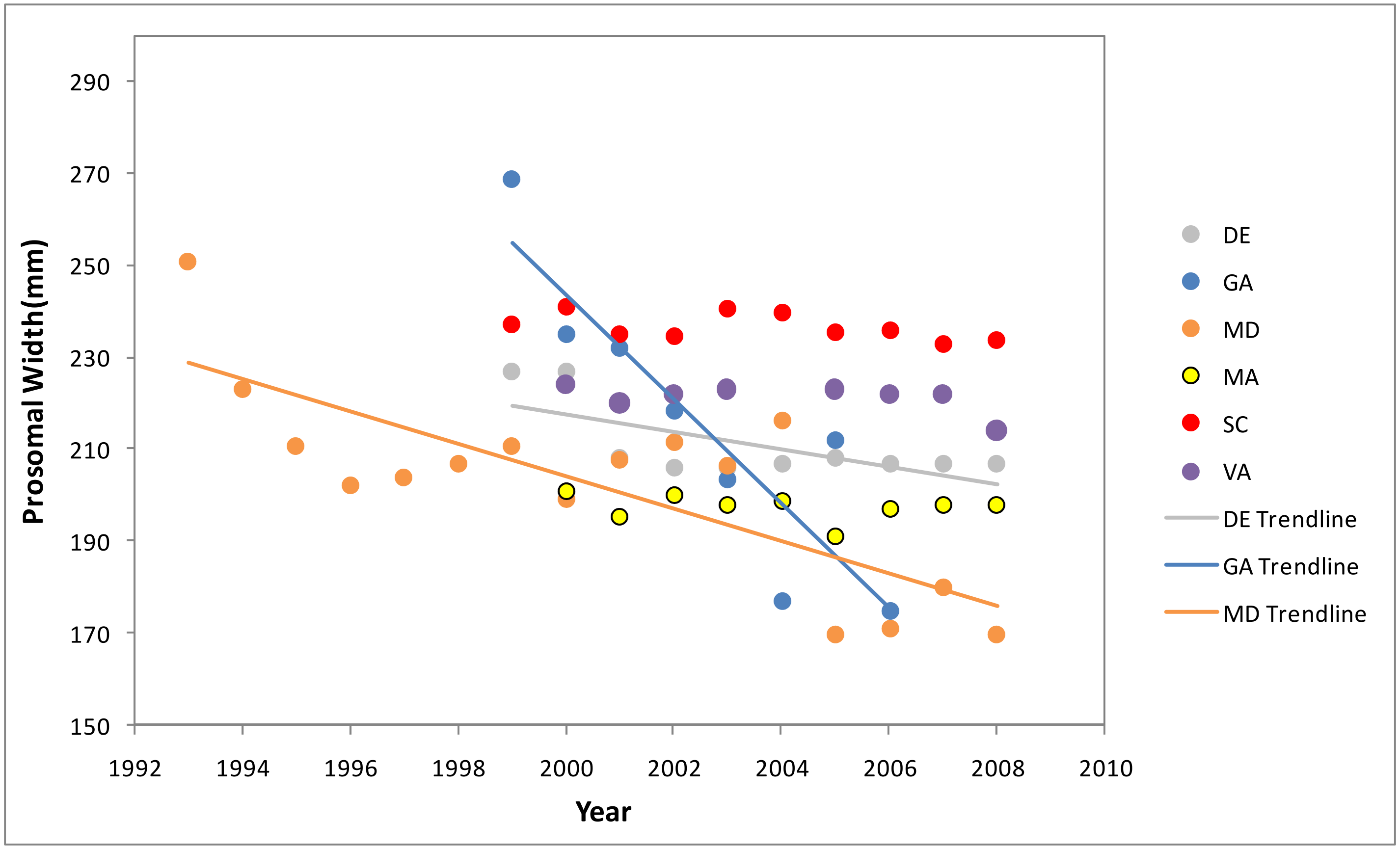


Figure 5. Trends in male horseshoe crab prosomal width from fishery dependent surveys

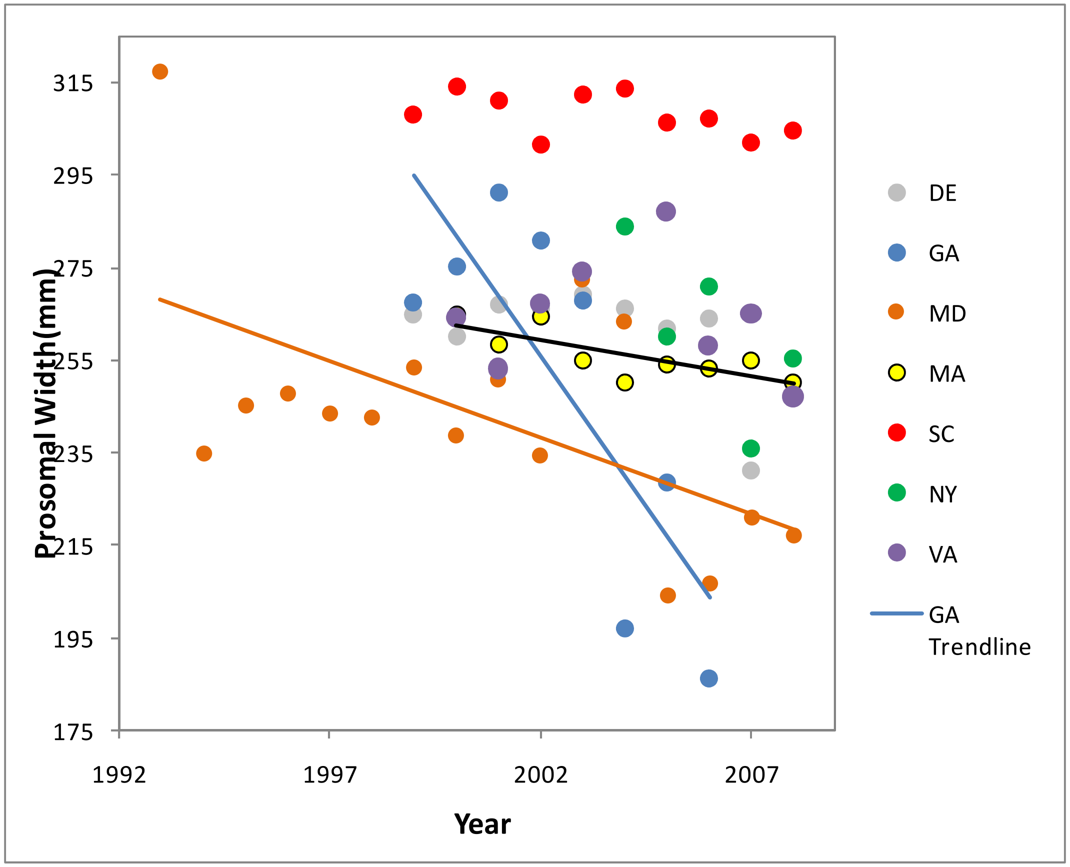


Figure 6. Trends in female horseshoe crab prosomal width from fishery dependent surveys

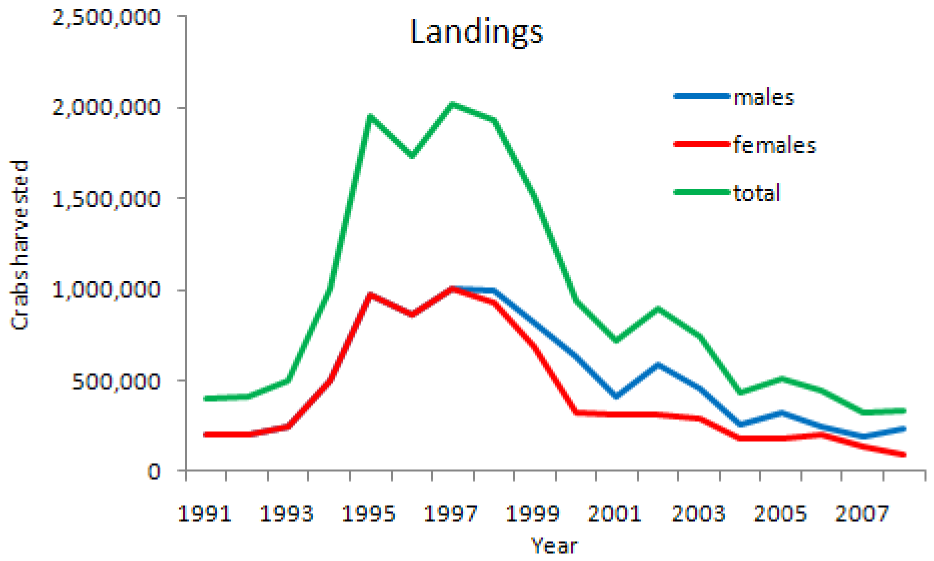


Figure 7. Landings of horseshoe crabs used in surplus production modeling, for males, females, and both sexes combined.

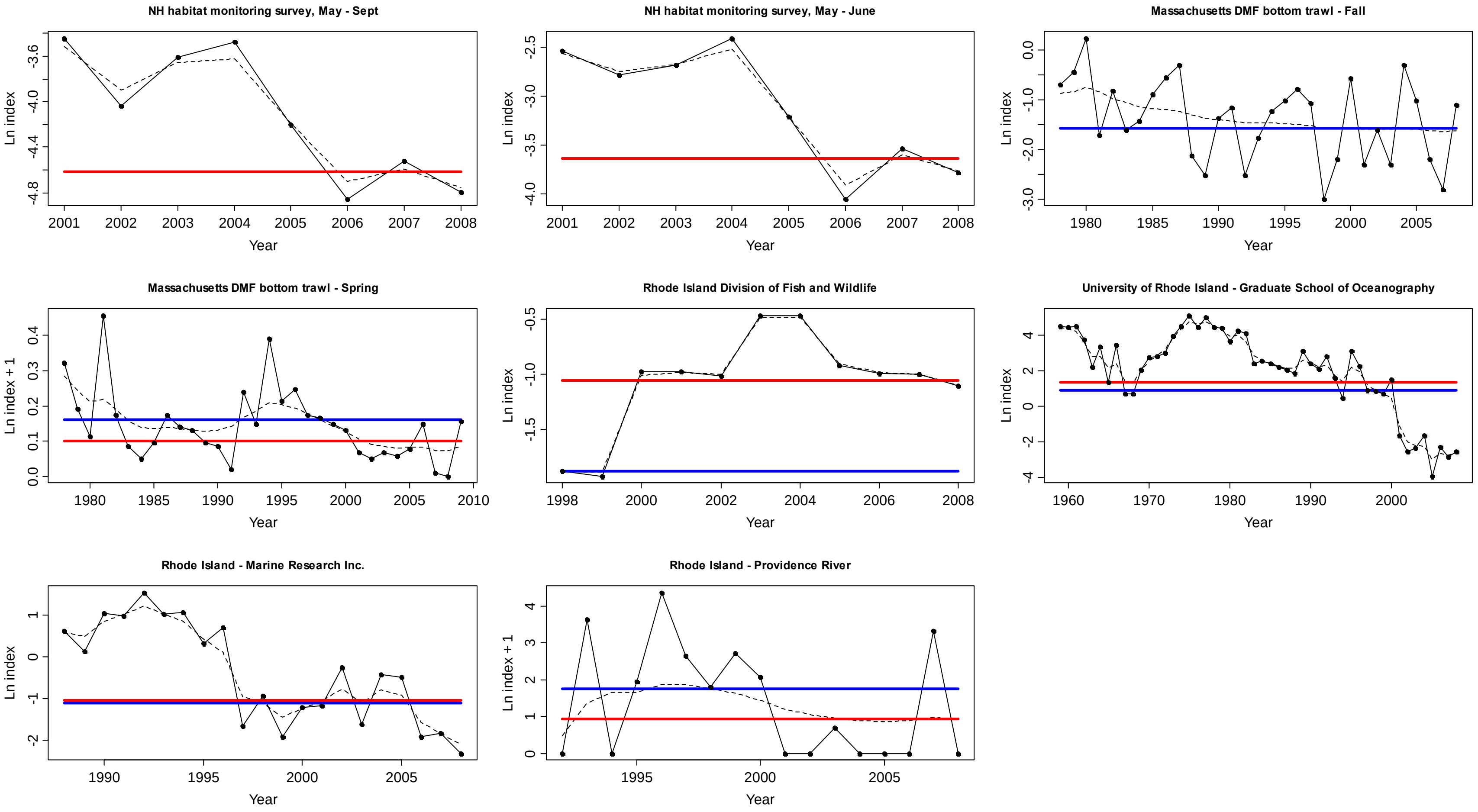


Figure 8: New England horseshoe crab ARIMA models. The solid line represents the observed indices and the dashed line represents the fitted indices. The red horizontal line represents the q25 reference point and the horizontal blue line represents the 1998 reference point.

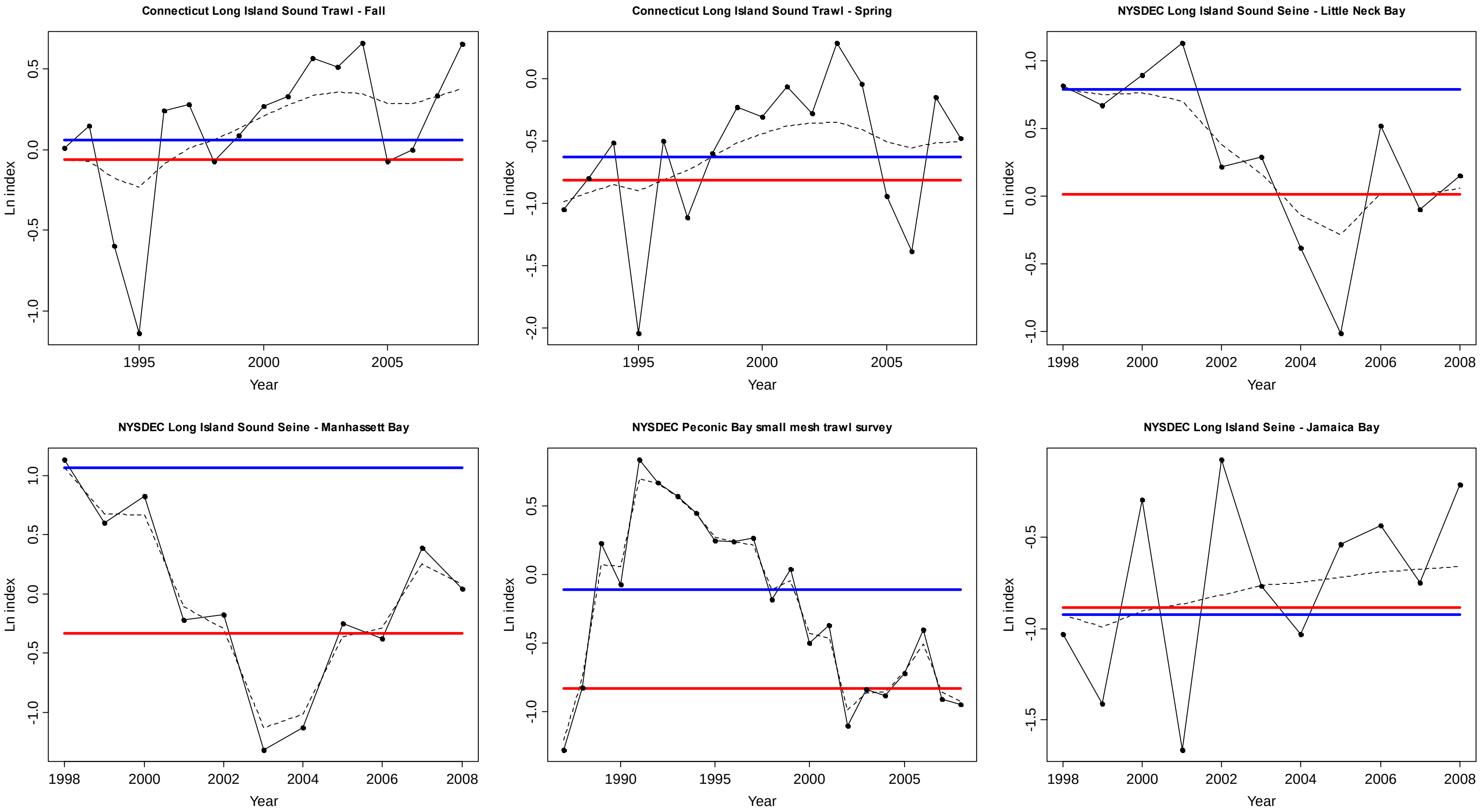


Figure 9. New York Region horseshoe crab ARIMA models. The solid line represents the observed indices and the dashed line represents the fitted indices. The red horizontal line represents the q25 reference point and the horizontal blue line represents the 1998 reference point.

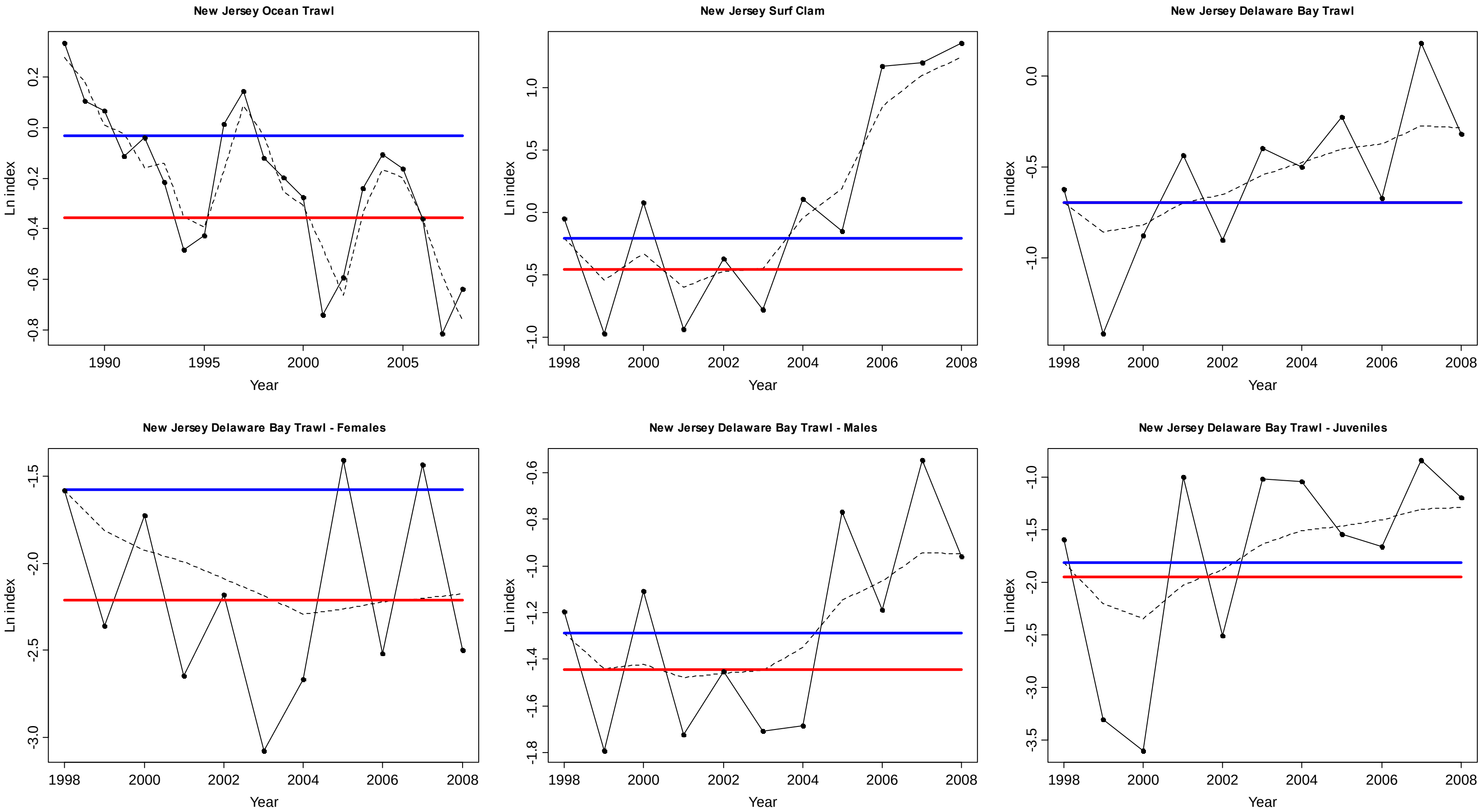


Figure 10. New Jersey horseshoe crab ARIMA models. The solid line represents the observed indices and the dashed line represents the fitted indices. The red horizontal line represents the q25 reference point and the horizontal blue line represents the 1998 reference point.

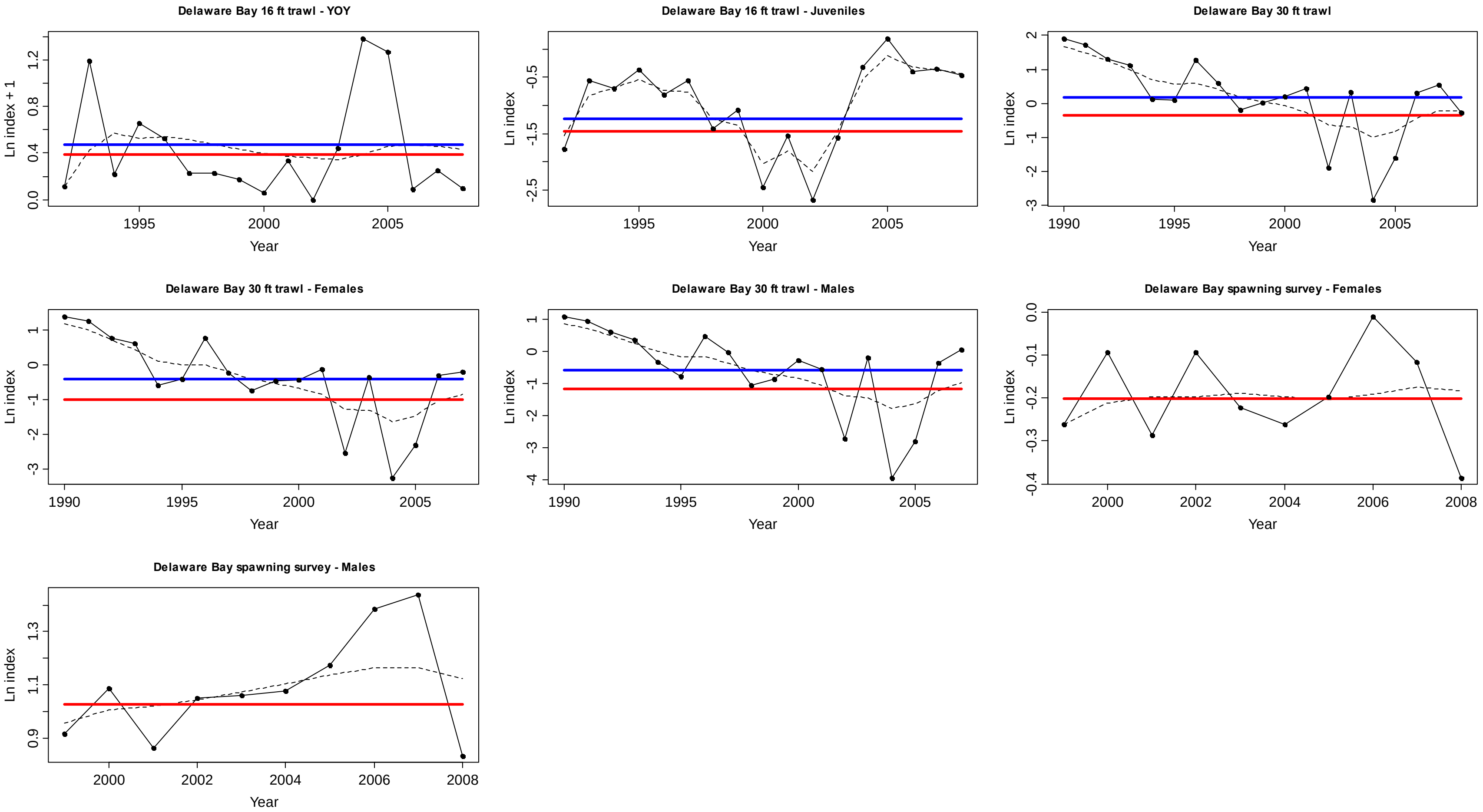


Figure 11. Delaware horseshoe crab ARIMA models. The solid line represents the observed indices and the dashed line represents the fitted indices. The red horizontal line represents the q25 reference point and the horizontal blue line represents the 1998 reference point.

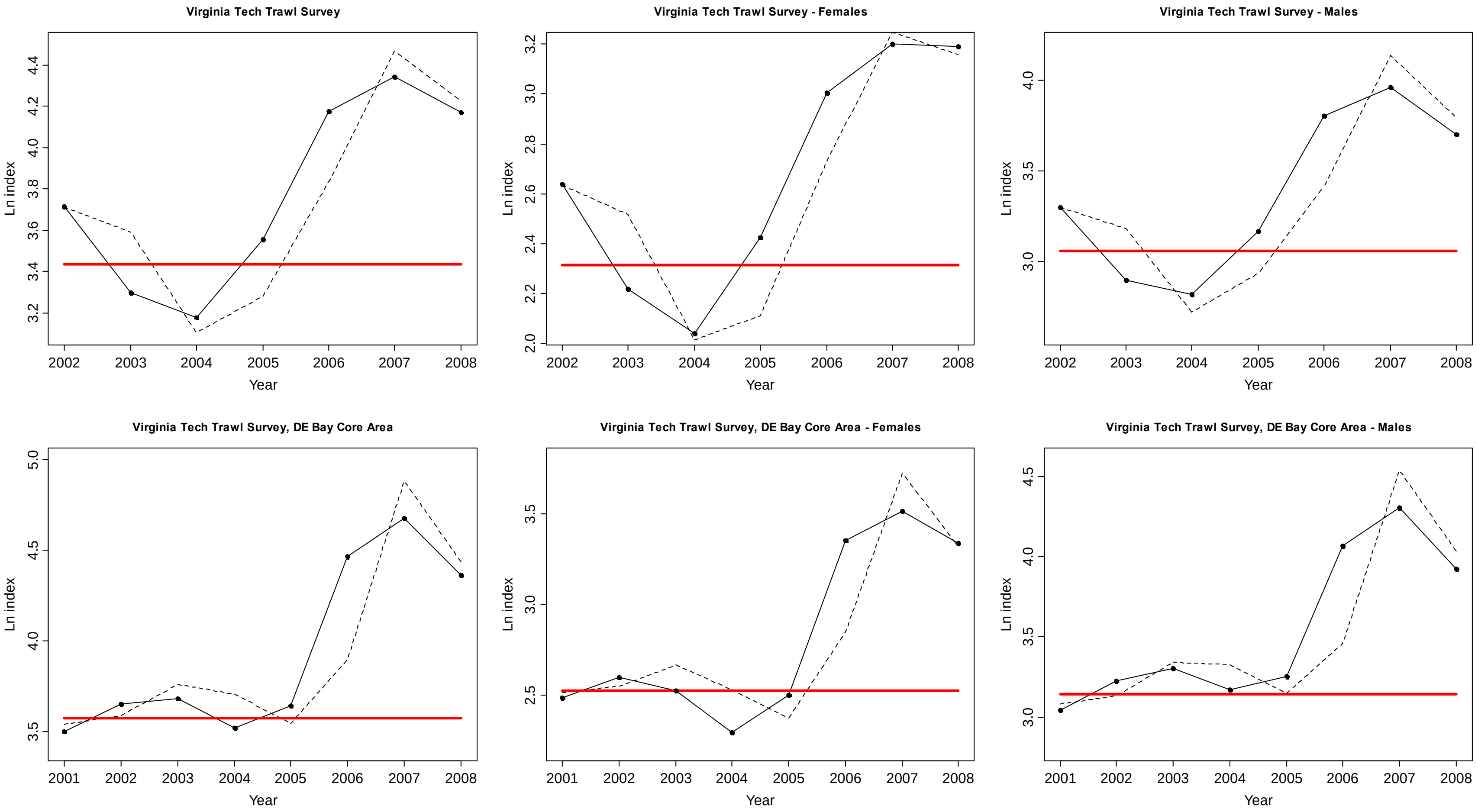


Figure 12. Virginia Tech horseshoe crab trawl survey ARIMA models. The solid line represents the observed indices and the dashed line represents the fitted indices. The red horizontal line represents the q25 reference point (1998 reference point is not given because the Virginia Tech Trawl survey began in 2001).

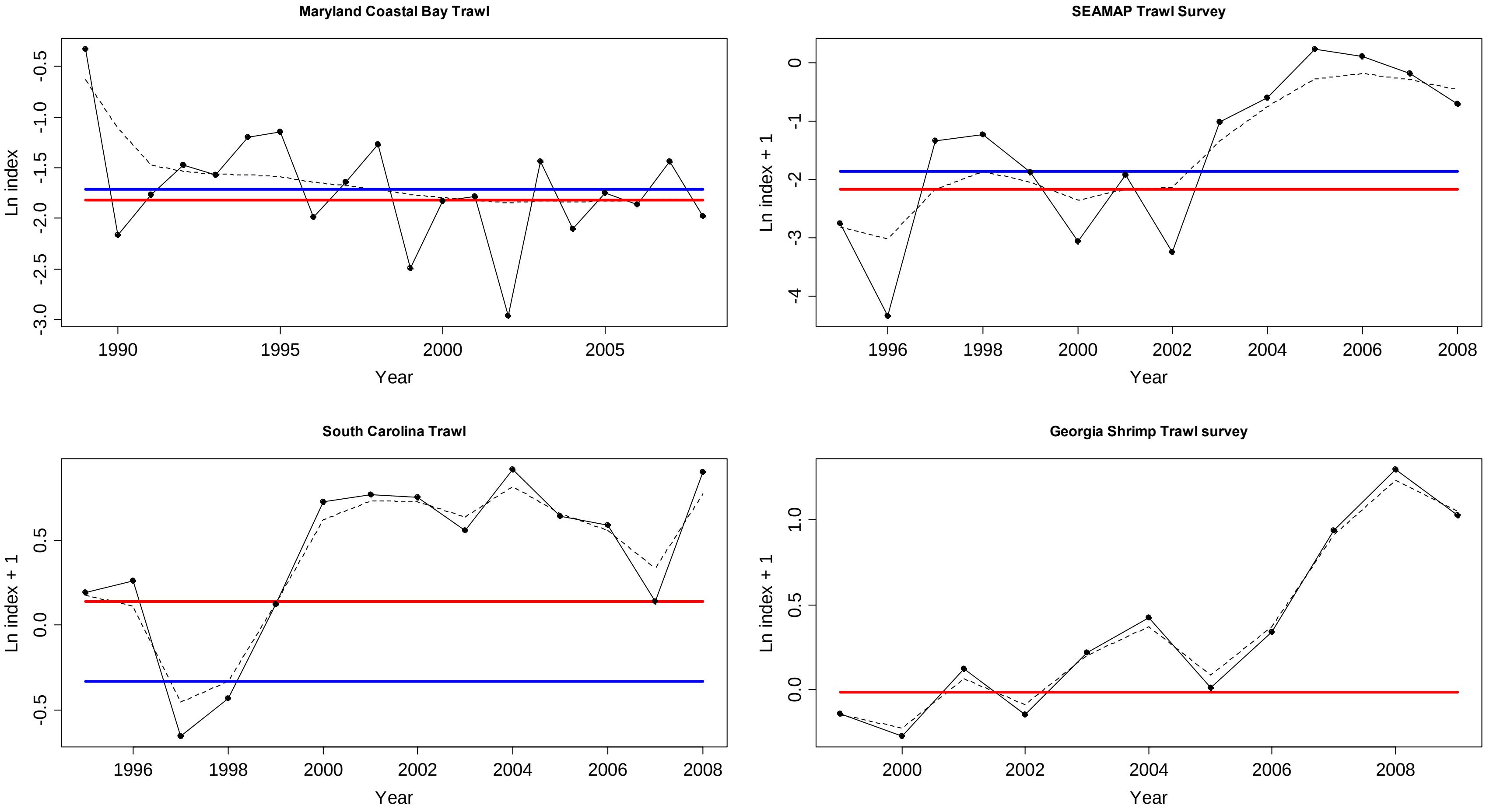


Figure 13. Maryland and southeastern horseshoe crab ARIMA models. The solid line represents the observed indices and the dashed line represents the fitted indices. The red horizontal line represents the q25 reference point and the horizontal blue line represents the 1998 reference point.

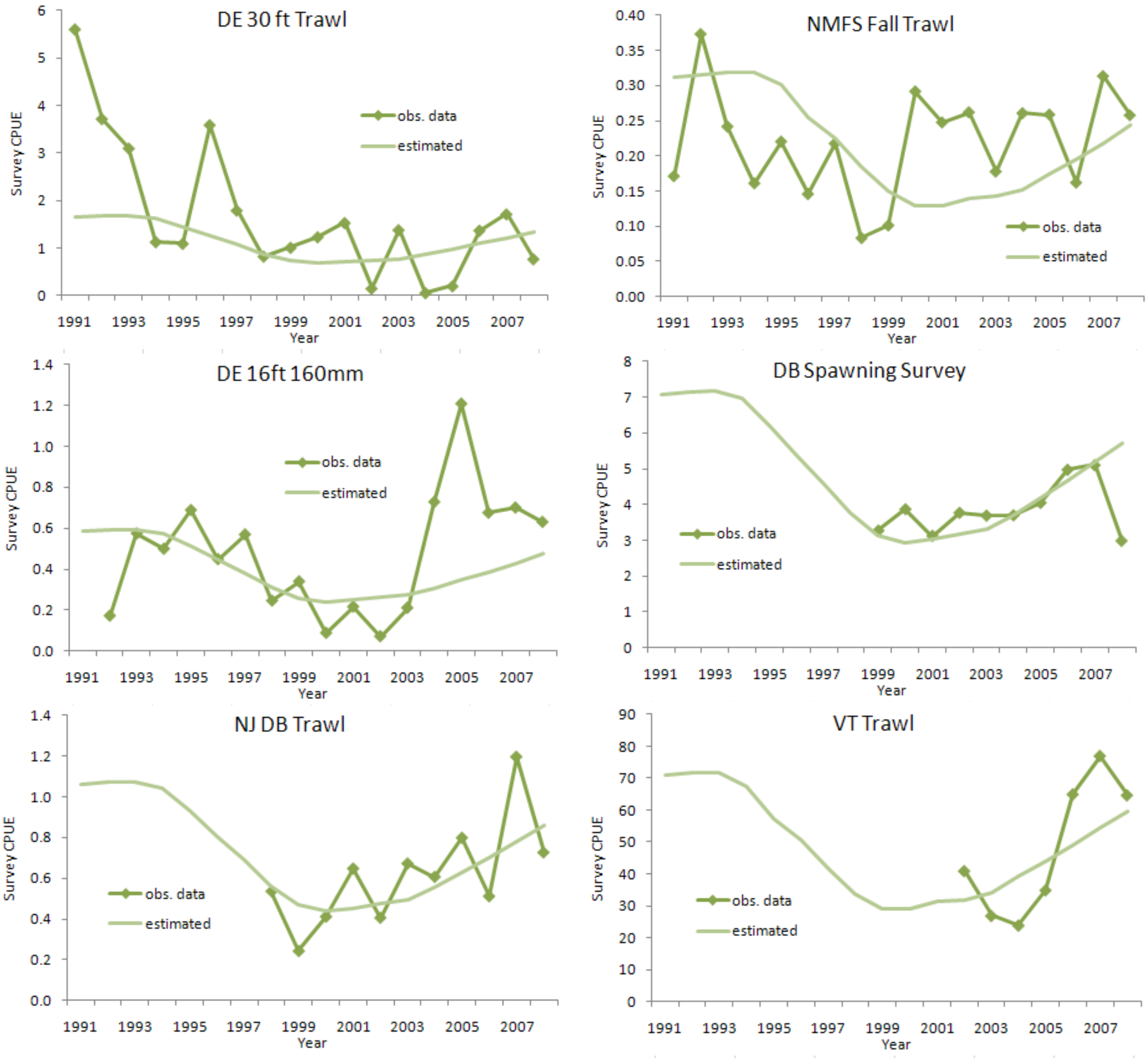


Figure 14. Observed survey data and the survey values estimated by the surplus production model for both sexes of horseshoe crab combined.

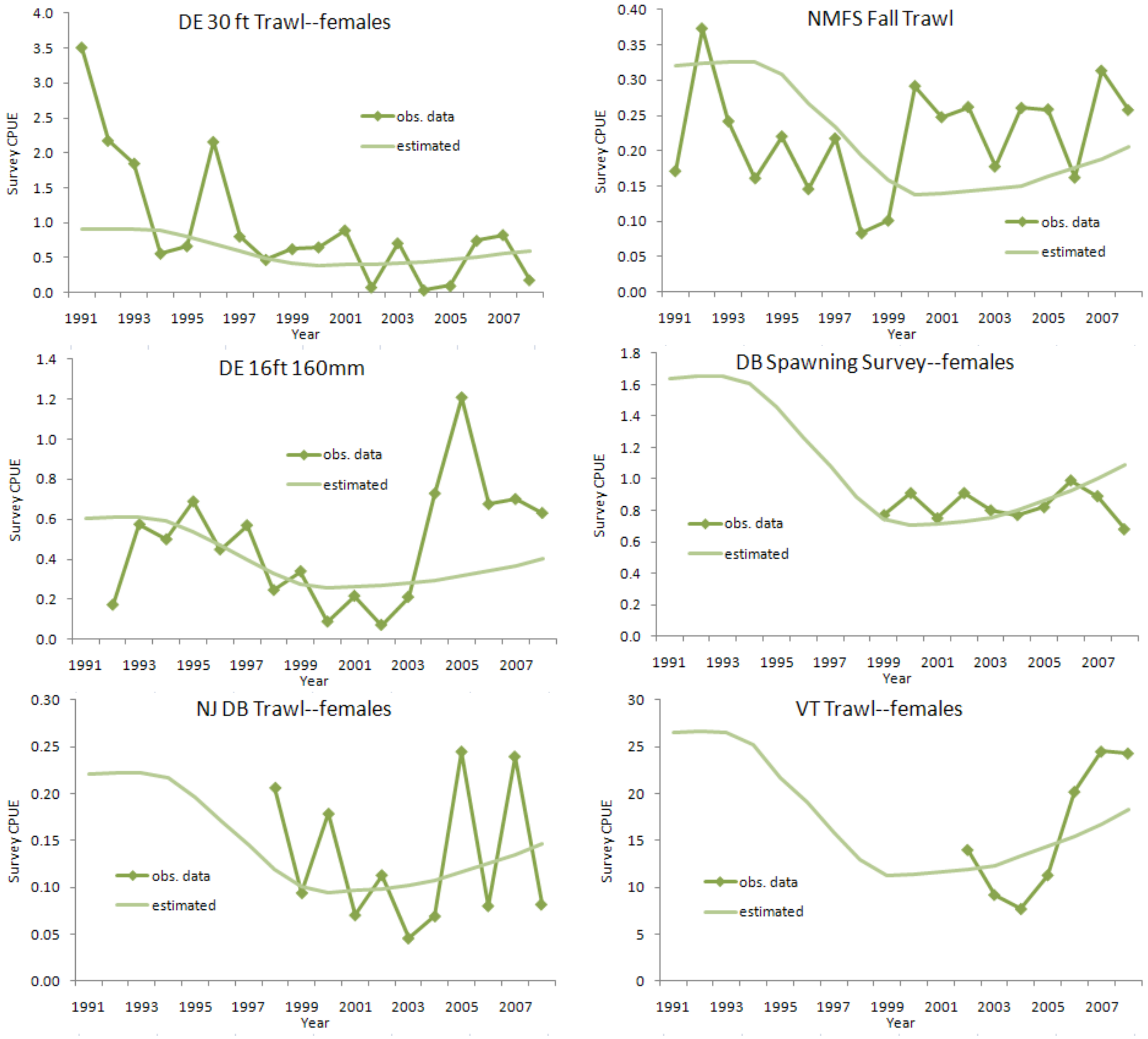


Figure 15. Observed survey data and the survey values estimated by the surplus production model for female horseshoe crabs.

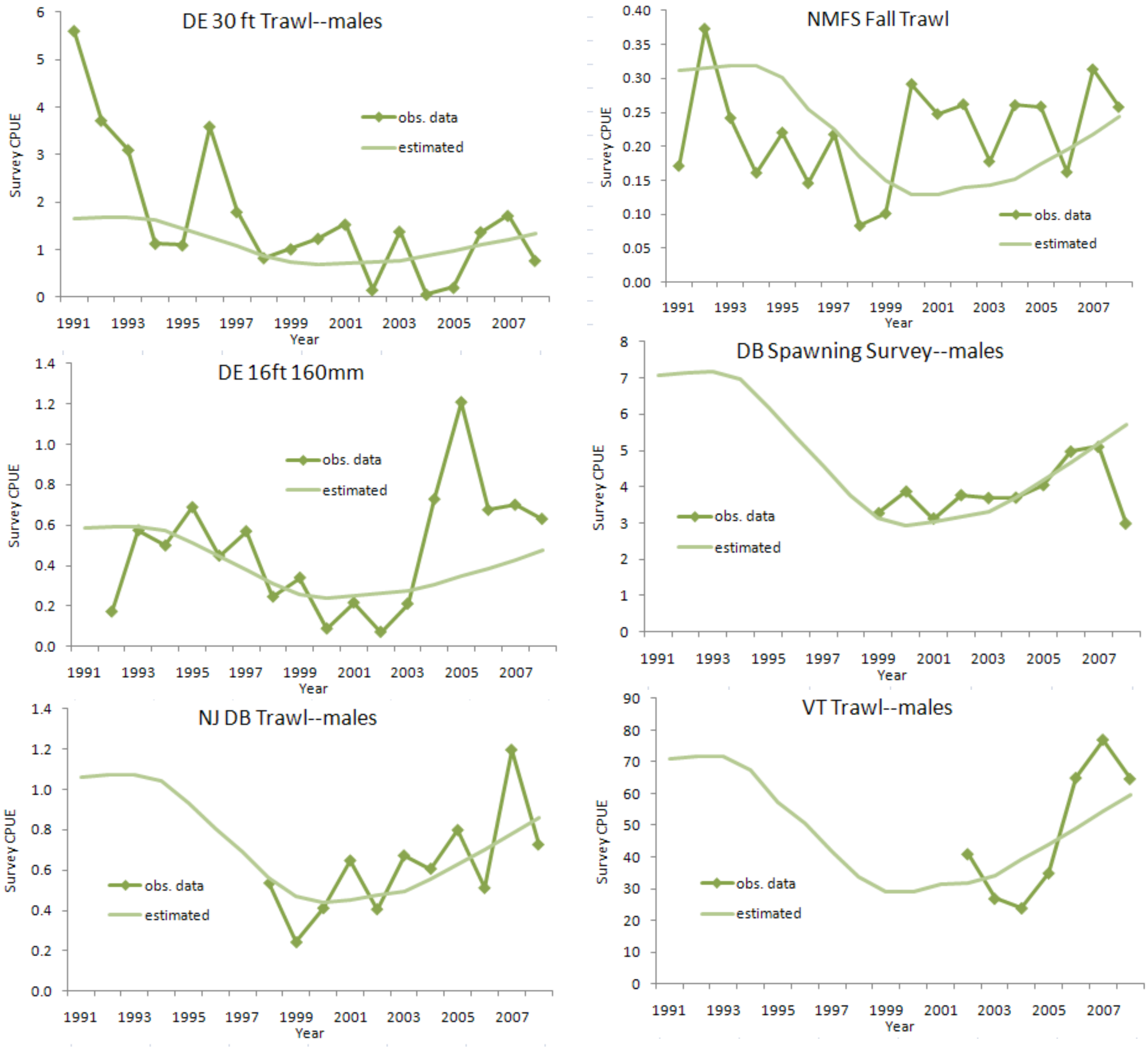


Figure 16. Observed survey data and the survey values estimated by the surplus production model for male horseshoe crabs.

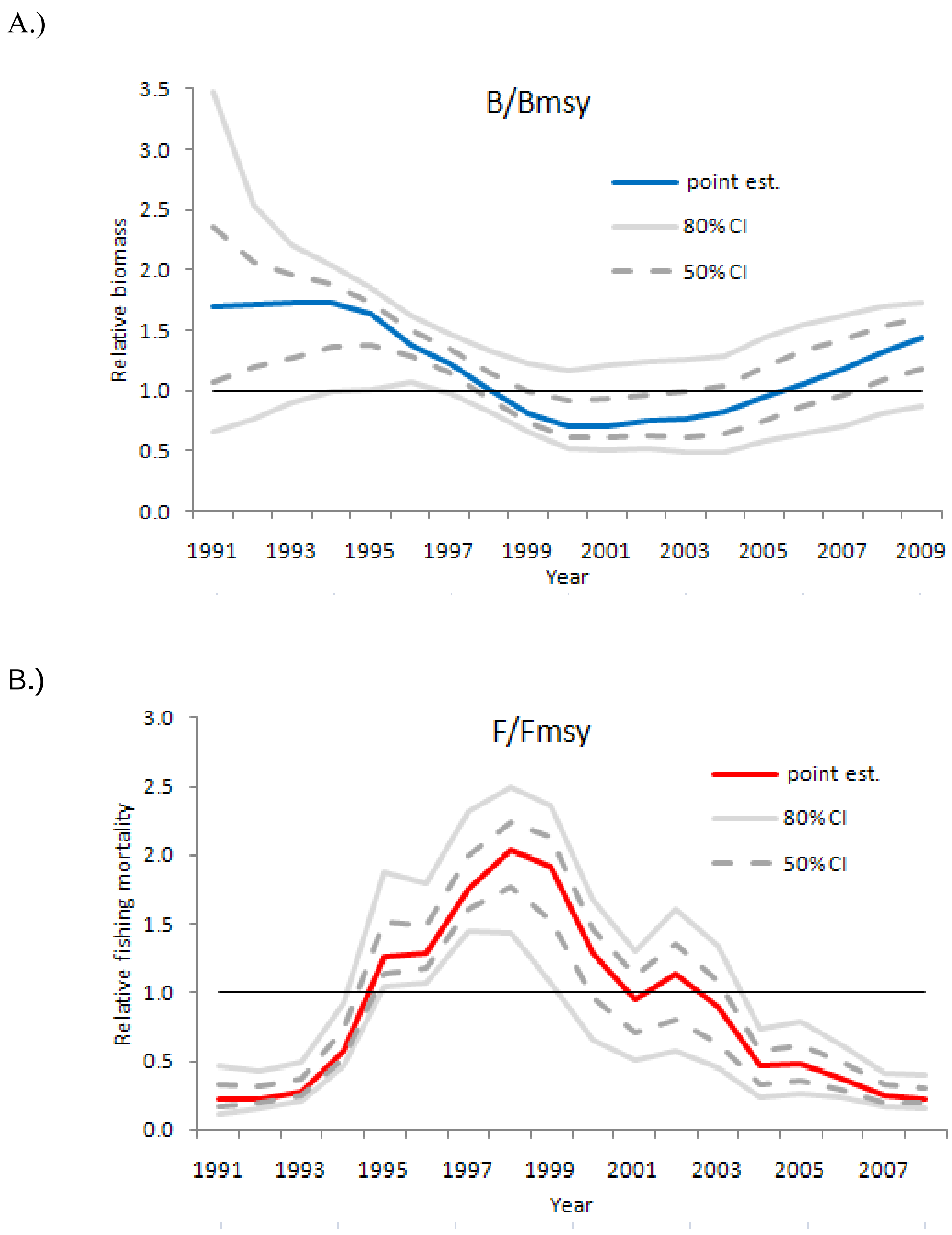
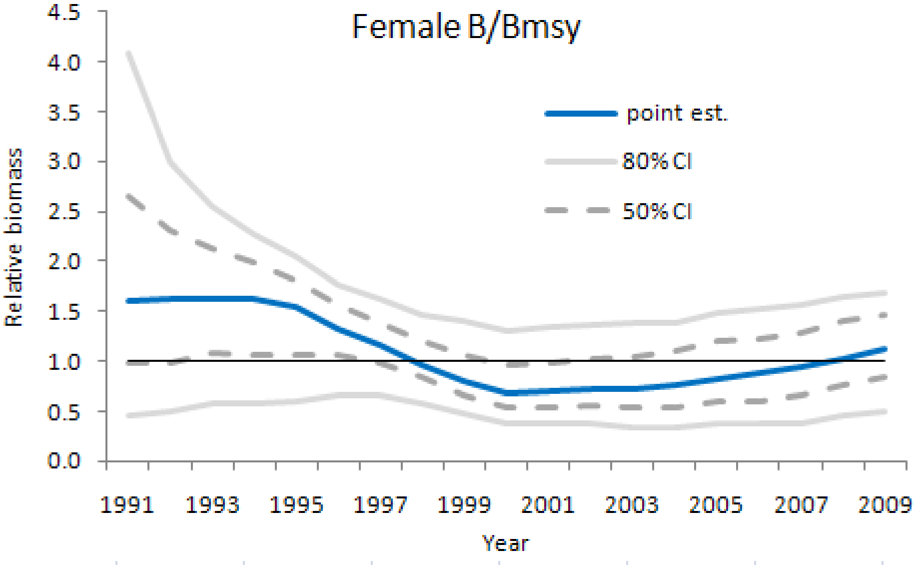


Figure 17. Relative biomass (B/B$_{MSY}$) and relative fishing mortality (F/F$_{MSY}$) with 50% and 80% bias-corrected confidence intervals for both sexes of horseshoe crab combined as estimated by the surplus production model.

A.)



B.)

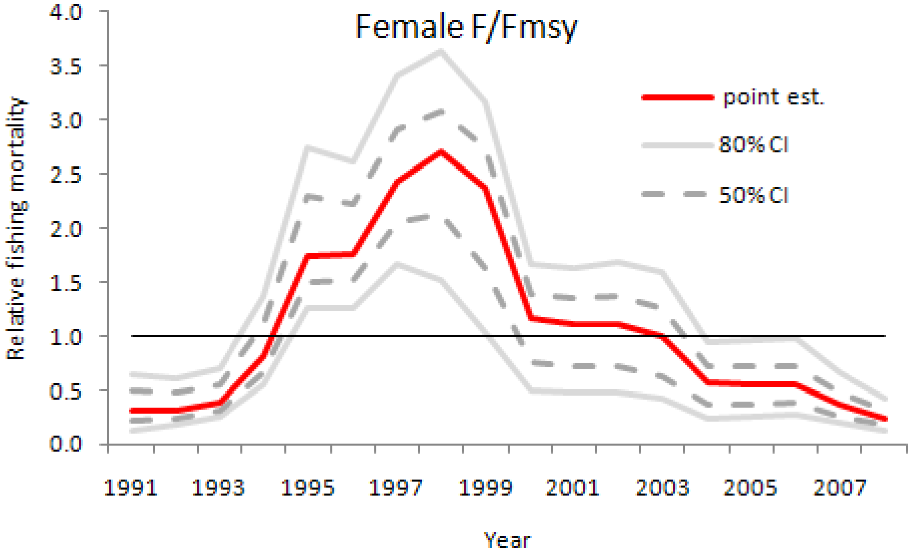
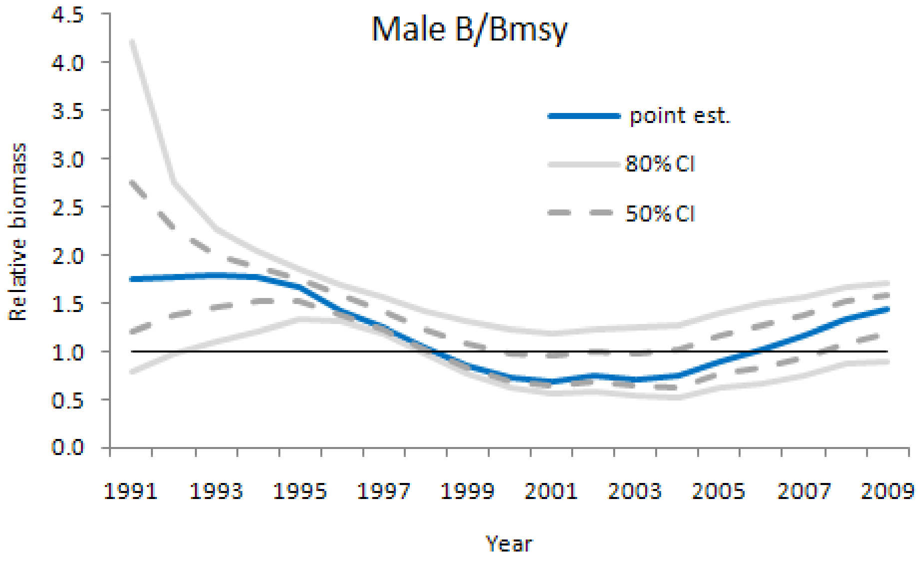


Figure 18. Relative biomass (B/B_{MSY}) and relative fishing mortality (F/F_{MSY}) with 50% and 80% bias-corrected confidence intervals for female horseshoe crabs as estimated by the surplus production model.

A.)



B.)

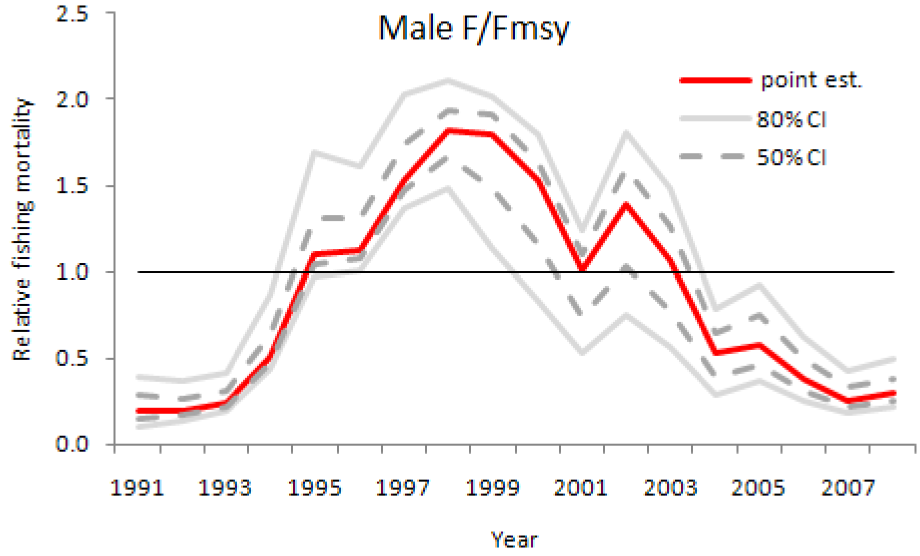


Figure 19. Relative biomass (B/B$_{MSY}$) and relative fishing mortality (F/F$_{MSY}$) with 50% and 80% bias-corrected confidence intervals for male horseshoe crabs as estimated by the surplus production model.

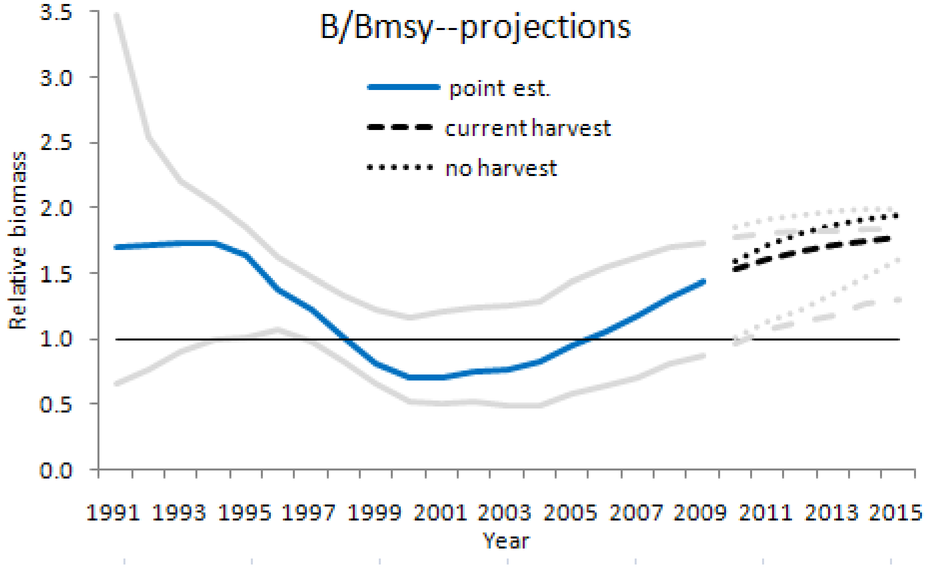


Figure 20. Relative biomass and 80% bias-corrected confidence intervals for both sexes of horseshoe crab combined, with harvest projected for 6 years at the 2008 harvest level of 334,000 horseshoe crabs (dashed lines) or no harvest (dotted lines), as estimated by the surplus production model.

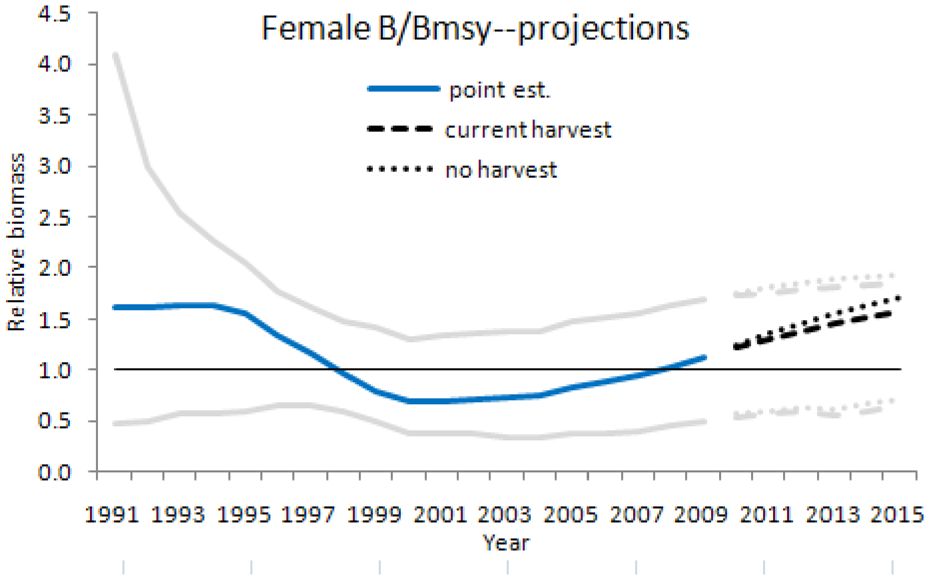


Figure 21. Relative biomass and 80% bias-corrected confidence intervals for female horseshoe crabs, with harvest projected for 6 years at the 2008 harvest level of 94,000 female horseshoe crabs (dashed lines) or no harvest (dotted lines) , as estimated by the surplus production model.

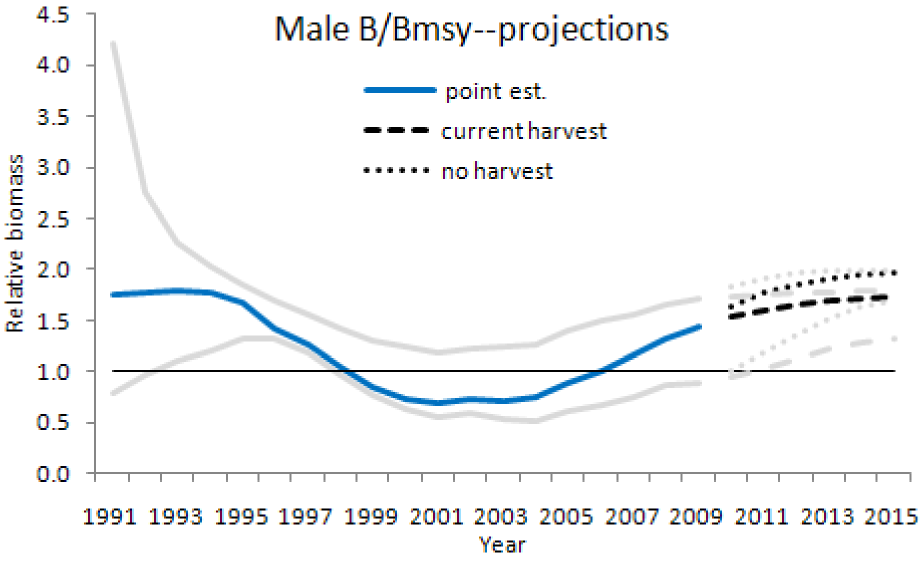


Figure 22. Relative biomass and 80% bias-corrected confidence intervals for male horseshoe crabs, with harvest projected for 6 years at the 2008 harvest level of 240,000 male horseshoe crabs (dashed lines) or no harvest (dotted lines) , as estimated by the surplus production model.

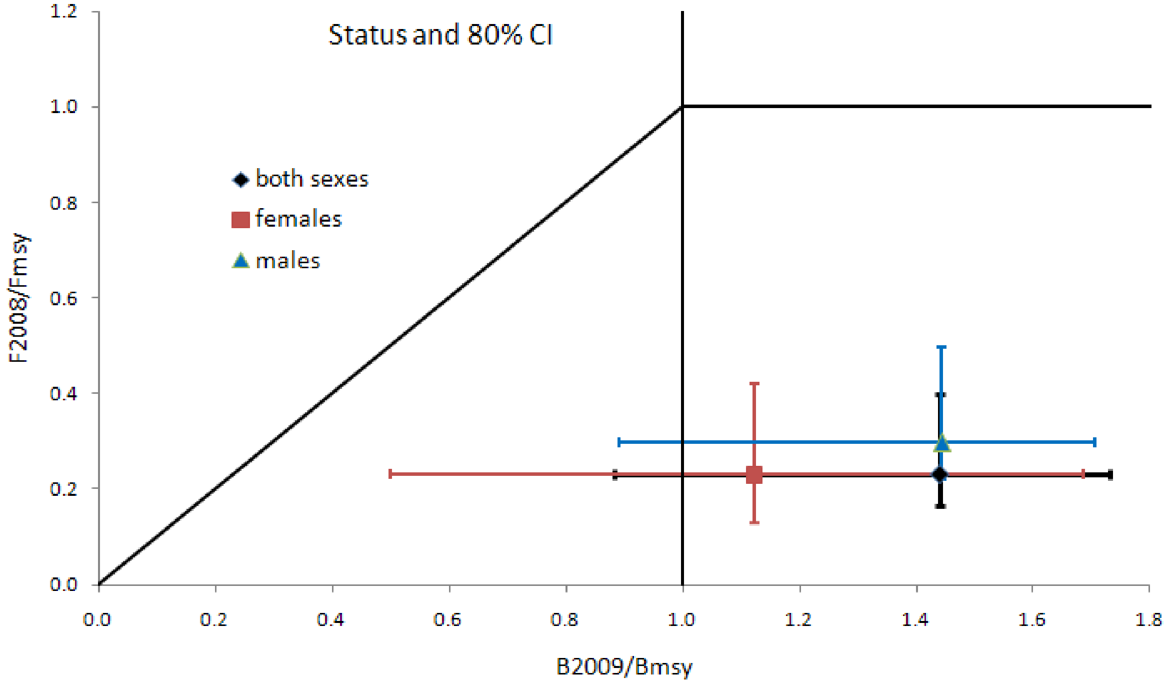


Figure 23. Relative biomass and relative fishing mortality (and 80% bias-corrected confidence intervals) for Delaware Bay horseshoe crabs, as estimated by surplus production models.

APPENDICES

Appendix A: List of Stock Assessment Subcommittee Members
Appendix B: Details of Fishery-Independent Surveys
Appendix C: Catch Survey Analysis Description and Results

Appendix A
List of Horseshoe Crab Stock Assessment Subcommittee Members

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Appendix B
Details of Fishery-Independent Surveys Used in Trend Analysis and ARIMA by Region

Southeast Region

Delaware Bay Region

New York Region

New England Region

Southeast Region

South Carolina Trawl Survey Methodology

Years Sampled: 1995- present

Gear Type: Trawl (20’ head rope with 3/8” tickler chain, ½” bar mesh)

- 50’ research vessel at 2.5 knots for 15 minutes/tow

Spatial Coverage: Charleston Harbor area (Estuary code=1) south through North and South Edisto River (Est code=2), St. Helena Sound (Est code=3), Port Royal Sound (Est code=4), and Calibogue Sound (Est code=5);

Temporal Coverage: Biweekly-Monthly for Charleston Harbor; March, April, June, October, and December for other areas. Some months not sampled every year.

Sample Design: Fixed stations

Sample Frequency and Number: Approximately 200 per year

Information Collected: Sex, prosomal width, weight (since August 1998), temperature, salinity

Changes in Sample Design: Starting in 2002, SC went from two trawls on one vessel to one trawl on a different vessel using the same rig. SC attempted to do side-by-side survey comparisons but did not catch enough HSCs to produce a conversion factor. CPUE has been doubled from 2002 on.

Georgia DNR Shrimp Assessment Survey

Years sampled**:** 1976 - present (horseshoe crab data since December 1998)

Gear type**:** Flat 40ft shrimp net with 1 7/8" stretched mesh throughout with no liner, with tickler chain.

- Tow duration 15 minutes
- Tow speed 2 - 2.5 knots
- Average tow distance is about 1064 m currently using GADNR R/V Anna (60-ft)

Spatial coverage**:** 6 sound systems, with 2 offshore (out to 3 mi), 2 sound, and 2 creek/river stations in each system for a total of 36 fixed stations

Temporal coverage**:** monthly

Sample design**:** fixed stations

Sample frequency**:** 36 stations/month

Information collected**:** Since 1999: prosomal width (mm), weight (pounds), sex (M/F/Unk), total weight caught (lbs), total number caught, number measured; tow location, date, time, duration, tow direction (relative to channel; coded), tide stage (coded), tide height (ft), lunar phase (coded), wind direction (degrees), wind speed (coded), air temperature (C), surface water temperature (C), surface salinity (ppt), depth (ft)

SEAMAP Trawl Survey Methodology

Years Sampled: 1995 - present

Gear Type**:** The R/V Lady Lisa, a 75-ft (23-m) wooden-hulled, double-rigged, St. Augustine shrimp trawler owned and operated by the South Carolina Department of Natural Resources (SCDNR), was used to tow paired 75-ft (22.9-m) mongoose-type Falcon trawl nets (manufactured by Beaufort Marine Supply; Beaufort, S.C.) without TED's at a speed of approximately 2.5 knots. (Tow speed can be calculated from tow distance/tow duration). The body of the trawl was constructed of #15 twine with 1.875-in (47.6-mm) stretch mesh. The cod end of the net was constructed of #30 twine with 1.625-in (41.3-mm) stretch mesh and was protected by chafing gear of #84 twine with 4-in (10-cm) stretch "scallop" mesh. A 300 ft (91.4-m) three-lead bridle was 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 1-ft chain drop-back was used to attach the 89-ft foot-rope to the trawl door. A 0.25-in (0.6-cm) tickler chain, which was 3.0-ft (0.9-m) shorter than the combined length of the foot-rope and drop-back, was connected to the door alongside the foot-rope. Trawls were towed for twenty minutes, excluding wire-out and haul-back time, exclusively during daylight hours (1 hour after sunrise to 1 hour before sunset).

Spatial Coverage**:** Samples were taken by trawl from the coastal zone of the South Atlantic Bight (SAB) between Cape Hatteras, North Carolina, and Cape Canaveral, Florida. Each station is towed for approximately 0.8 nautical miles. For depth-zone coverage, see Sample Design.

Temporal Coverage**:** Multi-legged cruises were conducted in spring (early April - mid-May), summer (mid-July – early August), and fall (October - mid-November). Trawls were towed for twenty minutes, excluding wire-out and haul-back time, exclusively during daylight hours (1 hour after sunrise to 1 hour before sunset).

Sample Design**:** The coastal zone of the South Atlantic Bight between Cape Hatteras, North Carolina, and Cape Canaveral, Florida was divided into twenty-four shallow water strata. Additional latitudinal strata were sampled in deeper waters with station depths ranging from 10 to 19 m.

1995-2000

A total of 78 stations were sampled each season within twenty-four inner strata and the number of station towed within each stratum was constant from year to year. Fixed stations were randomly selected from a pool of trawlable stations within each stratum. Initially, the number of stations in each stratum was proportionally allocated according to the total surface area of the stratum. Inner or shallow strata were delineated by the 4 m depth contour inshore and the 10 m depth contour offshore. Additional stations were sampled in deeper strata with station depths ranging from 10 to 19 m. Twenty-seven stations located within ten outer strata in the southern half of the SAB were sampled only in spring to collect data on spawning of white shrimp.

Sixteen stations in the seven outer strata off North Carolina were sampled in fall to gather data on the reproductive condition of brown shrimp. No stations in the outer strata were sampled in summer.

2001-present

Fixed stations were randomly selected from a pool of stations within each stratum. The number of stations sampled in each stratum was determined annually by optimal allocation. A total of 102 stations were sampled each season within twenty-four shallow water strata, representing an increase from 78 stations previously sampled in those strata by the trawl survey (1990-2000). Strata were delineated by the 4 m depth contour inshore and the 10 m depth contour offshore. In previous years, stations were also sampled in deeper strata with station depths ranging from 10 to 19 m. Those strata were abandoned in 2001 in order to intensify sampling in the shallower depth-zone.

Sample Frequency and Number**:** Each stratum is sampled seasonally. See Sample Design.

Information Collected**:** Prosoma width in mm, prosoma length (or total length in early collections) in mm, individual weight (g), and sex are recorded for each horseshoe collected. Although the measurement of prosoma width has been consistent, the techniques used to measure prosoma length have varied. Where information is blank, the individual was discarded before measurements were taken and only presence in trawl is recorded.

Hydrographic data collected at each station included surface and bottom temperature and salinity measurements taken with a Seabird SBE-19 CTD profiler, sampling depth, and an estimate of wave height. Additionally, atmospheric data on air temperature, barometric pressure, precipitation, and wind speed and direction were also noted at each station.

Changes in Sample Design**:** See Sample Design.

Florida Seahorse Key (Gulf) Spawning Survey
(Dr. H. Jane Brockmann, University of Florida)

Years sampled**:** 1992 to 2009 (except 1998, 1999, 2001-2003)

Gear type**:** Visual sighting

Spatial coverage**:** University of Florida Marine Laboratory at Seahorse Key (SHK), a 2-km long by 0.5-km wide (at its widest point) island 5.6 km from Cedar Key (29^{o} 5' 47" N, 83 ^{o} 3' 55" W**;** Fig. 1) in the Big Bend region of Florida's west coast.

Temporal coverage**:** Five to 7 tidal cycles during late Feb or early March to May. Tidal cycle defined as 2 day before to 5 days after spring tide. Spawning was observed on the two daily high tides.

Sample design**:** Beach was divided into 9 or 10 fixed seqments (100 m in length)

Sample frequency**:** All beach segments were observed on the two daily high tides during the tidal cycle in late Feb or March to May

Information collected**:** Counts of spawning males and females. Spawning behavior, such as paired or unpaired status.

Delaware Bay Region

North Carolina Pamlico Sound/Neuse River Gillnet

Years sampled: 1999 - present

Gear type: Floating gill nets are used to sample shallow strata while sink nets are fished in deeper strata. Each net gang consists of 30-yard segments of 3, 3.5, 4, 4.5, 5, 5.5, 6, and 6.5 inch stretched mesh, for a total of 240 yards of nets combined.

Spatial coverage: Neuse River, Palmico River, and Pungo River

Temporal coverage: Sampling occurs each year from February 15th to December 14th

Sample design: Nets are deployed parallel or perpendicular to the shore based on the strata and common fishing techniques for the area. Gear is typically deployed within an one hour of sunset and fished the next morning to keep soak times within 12 hours.

Sample frequency and number: The catch from the gang of nets comprises a single sample. Each of the sampling areas within each region is sampled twice a month. Within a month, 32 core samples were completed (8 areas x twice a month x 2 samples) for F-70 and the same number completed in the PNWGNS river systems. For the southern area (New and Cape Fear rivers) 12 samples are completed, comprised of 8 from New River (2 areas-upper and lower x twice a month x 2 samples-shallow and deep) and 4 from Cape Fear (1 area x twice a month x 2 shallow samples)

Information collected: Numbers of horseshoe crabs, lengths, weights, sex, and CPUE

Changes in sample design: From 1999 to 2002 sampling was conducted year round; see Temporal Coverage for current sampling.

NMFS/NEFSC Spring & Autumn Trawl Surveys

Years sampled: Spring: 1968 – present
Autumn: 1963 – present

Gear type: #36 Yankee Bottom Trawl

- 100 ft. footrope/ 60 ft. headrope
- 5 in. strech mesh wings and body
- 4.5 in. stretch mesh codend
- 0.5 in. mesh liner
- 97 ft. fishing line ("traveler")
- Sweep: 80 ft. - wing end sections 22.5 ft of 4 in. rubber cookies; 9.5 ft sections (2) and center 16 foot section with 16 in. diameter by 5 in. wide hard rubber rollers separated by two rubber spacers 5 in. diameter by 7 in. wide.
- 30 ft. leglines (upper legs 5/8 in wire / lower legs ½ in. chain); 9.5 ft. backstraps of ½ in. Trawlex
- 550 kg. BMV oval doors 1963 – 1984; 450 kg. polyvalent doors 1985 - present
- 30-minute tows (24h basis)
- 3.5 knots (randomized direction)
- FRV Albatross IV or FRV Delaware II

Spatial coverage: Cape Hatteras – Canadian waters (5 to 200 Fathoms)

Temporal coverage: Spring: generally March and April
Autumn: generally September and October

Sample design: Random stratified (depth)

Sample frequency and number: Approx. 300 annually

Information collected: Count, sex, prosomal width available some years, wave height, lat/lon, salinity, depth, temperature, weather.

Changes in sample design: BMV oval doors 1963 – 1984; Polyvalent doors 1985 - present

Virginia Tech Mid-Atlantic Benthic Trawl

Years sampled: 1999 - present

Gear type: 16.8 meter chartered commercial fishing vessel fitted with a two-seam flounder trawl of 18.3m headrope, 24.4m footrope, and Texas Sweep of 13mm link chain and a tickler chain. Net body is 6 inch stretched mesh and bag mesh is 5.5 inch stretched.

Spatial coverage: Atlantic City, NJ, to eastern shore area of Virginia from shore to 12 nautical miles out

Temporal coverage: From late September to mid October

Sample design: Survey area is stratified by distance from shore (0-3nm, 3-12nm) and bottom topography (trough, non-trough), following the results of the 2001 pilot study. Random stations sampled within each strata.

Sample frequency and number: Between 40 and 50 stations with one 15 minute bottom time tow per station

Information collected: number of crabs, prosomal width, sex, maturity, CPUE

Changes in sample design: None

New Jersey Ocean Trawl Survey Methodology

Years sampled: 1989 – present

Gear type: Three-in-one trawl (all tapers are three to one). The forward netting is 12 cm stretch mesh, rear netting is 8 cm, and liner is 6.4 mm bar mesh. The headrope is 25 m long and the footrope is 30.5 m long. The trawl bridle is 20 fathoms long, the top leg consisting of 0.5-inch wire rope and the bottom leg comprised of 0.75-inch wire rope covered with 2 3/8 inch diameter rubber cookies. A 10 fathom groundwire, also made of 0.75 inch wire rope with 2 3/8 inch diameter rubber cookies extends between the bridle and trawl doors. The trawl doors are wood with steel shoes, 8 ft x 4 ft 2 in, and weigh approximately 1000 lbs each. The net is towed for 20 minutes.

Spatial coverage: New Jersey waters from Ambrose Channel south to Cape Henlopen Channel. At depths between 5.5 m (3 fathom isobath) and 27.4 m (15 fathom isobath). This area is divided into 15 sampling strata.

Temporal coverage: Sampling is conducted in January, April, June, August, and October. The January and June surveys were excluded due to the unavailability of horseshoe crabs to the survey due to overwintering and spawning behavior.

Sample design: Stratified random design. Latitudinal boundaries of strata are identical to those used by NMFS Northwest Atlantic groundfish survey. Exceptions occurred at the extreme northern and southern strata, which were truncated to include only waters adjacent to NJ. Longitudinal boundaries consist of the 5, 10, and 15 fathom isobaths. Where these bottom contours were irregular the boundaries were smoothed, which results in the longitudinal boundaries being similar but not identical to NMFS.

Sample frequency and number: 40 stations are sampled during each monthly survey.

Information collected: The total weight of each species is measured, and lengths of all individuals or a subsample (depending on catch size) are measured. The following physical information is collect at each site; salinity, dissolved oxygen, and surface and bottom water temperatures.

Changes in sample design: None

New Jersey Surf Clam Inventory

Years sampled: 1998 - present

Gear type: hydraulic clam dredge with 6’ knife

Spatial coverage: Shark River to Cape May, NJ, shore to 3 nm

Temporal coverage: June - August

Sample design: stratified random with optimal allocation based on variance of target species from previous five years

Sample frequency and number: 320-330 stations annually

Information collected: Numbers of horseshoe crabs, prosomal widths, sex, and CPUE

Changes in sample design: None

New Jersey Delaware Bay Trawl

Years sampled: 1998 - present

Gear type: 16’ finfish trawl with ¼” codend liner

Spatial coverage: NJ portion of Delaware Bay, Cohansey River to The Villas, Cape May

Temporal coverage: April through October

Sample design: fixed stations

Sample frequency and number: 11 stations sampled monthly

Information collected: Numbers of horseshoe crabs, prosomal widths, sex, and CPUE

Changes in sample design: None

Maryland Coastal Bays Trawl Survey

Years sampled: 1972 – present (consistent sampling intensity since 1988)

Gear type: Bottom trawl

- 17–foot headrope / 22-foot footrope
- 1.25-inch stretch mesh in wings and body 1 1/2
- 0.5-inch stretch mesh liner inserted in cod end
- footrope with 3/16-inch galvanized chain tied tight to footrope (no excluders or chaffing gear used)
- 12-inch x 24-inch plyboard doors with iron shoes
- 6-minute tows
- 3 – 3.5 knots
- 23-foot Sea Hawk fiberglass 'V'-hull vessel powered by twin 70 hp outboards
- 'A'-frame stern trawling rig

Spatial coverage: Throughout MD's Coastal Bays

Temporal coverage: April through October

Sample design: Fixed

Sample frequency and number: 20 stations per month

Information collected: Count, sex (where possible), prosomal width, tide stage, wave height, latitude/longitude, salinity, depth, temperature, dissolved oxygen, weather.

Changes in sample design: Variable sampling intensity (temporal, spatial, effort) prior to 1988.

Delaware 16” (Juvenile and YOY) Trawl Survey

Years sampled: 1992 – present (YOY & <160mm); 1998 – present (>160mm)

Gear type: Bottom trawl
- 17–foot headrope / 21-foot footrope
- 1.5-inch stretch mesh in wings and body
- 0.5-inch stretch mesh liner inserted in cod end
- footrope with 1/8-inch galvanized chain hung loop-style (no excluders or chaffing gear used)
- 12-inch x 24-inch plyboard doors with iron shoes
- 10-minute tows (against tide)
- 2.5 – 3 knots
- 23-foot aluminum ‘V’-hull w/ ‘A’-frame stern trawling rig

Spatial coverage: Western Delaware Bay and Delaware (Index stations from about C&D Canal – Fowler’s Beach)

Temporal coverage: April through October (YOY Index months August – October)

Sample design: Fixed

Sample frequency and number: 40 stations per month (indices use 34 stations)

Information collected: Count, sex (where possible), , CPUE, prosomal width, tide stage, wave height, latitude/longitude, salinity, depth, temperature, dissolved oxygen, weather.

Comments: Juvenile (<160mm) relative abundance based on all months and stations; YOY relative abundance based on August through October data (when YOY recruit to the survey gear); Adult (> 160mm) based on all months. Six stations sampled in the DE River excluded from all indices as no horseshoe crabs have been collected at these stations.

Delaware 30-Foot Trawl Survey

Years sampled: 1990 – present

Gear type: Bottom trawl

- 30.5–foot headrope / 39.5-foot footrope
- 3-inch stretch mesh in wings and body
- 2-inch stretch mesh cod end
- footrope with ¼-inch galvanized chain hung loop-style (no excluders or chaffing gear used)
- 40-foot leglines
- 54-inch x 28-inch wooden doors with iron shoes and weights
- 20-minute tows (against tide)
- 2.5 – 3 knots
- 65-foot wooden displacement-hulled vessel w/ eastern-rigged trawling system (side trawler)

Spatial coverage: Western Delaware Bay (Woodland Beach – Brown Shoal areas)

Temporal coverage: March through December (Index months April – July)

Sample design: Fixed

Sample frequency and number: 9 stations per month

Information collected: Count, sex, CPUE, prosomal width, weight, tide stage, wave height, latitude/longitude, salinity, depth, temperature, dissolved oxygen, weather.

Changes in sample design: August 2002 survey switched to 62-foot deep-'V' semi-displacement hull vessel with an 'A'-frame stern-rigged trawling rig. Some tow comparisons made with previous vessel, but not yet analyzed. Tows are made at depths greater than would be expected for hull displacement, engine noise, or prop wash to interfere with catches, particularly since HSCs are a slow-moving bottom dwelling organism. Retrieval speeds similar to previous survey.

Comments: Index includes both juvenile and adult horseshoe crabs

Delaware Bay Spawning Survey

Years sampled: 1990 - present

Gear type:

- 1990 to 1998: Counting within 50 m transects.
- 1999 to present: Counting within 1 sq m quadrats

Spatial coverage: Baywide from the mouth of the bay upriver to Woodland Beach on the Delaware side to Sea Breeze on the New Jersey side.

Temporal coverage:

- 1990 to 1998: Weekend day nearest to the new or full moon at the end of May.
- 1999 to present: Sampling occurs within 5 days of the new and full moons of May and June, i.e., surveys occur 2 days prior, the day of, and 2 days after the new and full moons.

Sample design:

- 1990 to 1998: informal sampling design
- 1999 to present: Multi-stage, stratified design. Strata are state (DE and NJ) and lunar period (5 day periods centered on the new and full moons in May and June). Selected beaches are subsampled by systematically placed 1 sq m quadrats.

Sample frequency and number:

- 1990 to 1998: each beach was sampled no more than a couple times during May and June.
- 1999 to present: Each beach is sampled at least 12 times during May and June.

Information collected: Counts of males and females.

Changes in sample design: Sampling design changed profoundly in 1999. Peak counts can be calculated from the redesigned survey, however, the index of spawning activity can not be calculated for years prior to 1999 because of insufficient sampling frequency and number. See Smith et al. (2002b) for more information.

New York Region

NYSDEC Peconic Bay Small Mesh Trawl Survey

Years sampled: 1987- present

Gear type: 4.8 meter semi-balloon shrimp trawl, the body has 3.8 cm mesh, the codend has 3.2 cm mesh, and the codend liner has 1.3 cm mesh. The footrope is 0.95 cm rope 6.4 m long, with legs extended 0.9m and wire rope thimbles spliced at each end, 0.6 cm chain hung in loop style on the footrope. The net was towed for 10 minutes at approximately 2.5 knots. The vessel used was a 10.7 meter lobster style workboat

Spatial coverage**:** Peconic Bay

Temporal coverage: May through October

Sample design: Random survey based on a block grid design. The survey area was divided into 77 sampling blocks with each block measuring 1' latitude and 1' longitude.

Sample frequency and number: 16 stations were randomly chosen each week to sample

Information collected: All finfish species identified and counted. Several macro-invertebrates were also recorded including horseshoe crabs (by number). Environmental information (surface and bottom temperature, salinity, dissolved oxygen, and secchi disc readings) were recorded at each station.

Changes in sample design: From 1987 to 1990 the net was set by hand and retrieved using a hydraulic lobster pot hauler. From 1991 to the present the net was set and retrieved using hydraulic trawl winches and an A-frame. Net haul back speed should not affect HSC GM.

NYSDEC Western Long Island Beach Seine Survey

Years sampled: 1984 - present, consistent methodology starting in 1987

Gear type**:** 200 ft x 10 ft beach seine with ¼ inch square mesh in the wings, and 3/16 inch square mesh in the bunt. From 1984 – 1998 a 500 ft x 12 ft seine with stretch mesh in the wings, and stretch mesh in the bag was used for one sampling round generally in the spring. The seine is set by boat in a "U" shape along the beach and pulled in by hand.

Spatial coverage: Little Neck (LNB) and Manhasset Bay (MAN) on the north shore of Long Island (WLIS), and Jamaica Bay (JAM) on the south shore. Other bays have been sampled on a shorter time frame.

Temporal coverage: May through October. Pre-2000 sampling was conducted 2 times per month during May and June, once a month July through October; 2000 – 2002 2 times per month from May through October.

Sample design: Fixed site survey. Generally 5 – 10 seine sites are sampled in each Bay on each sampling trip.

Sample frequency and number: Generally 5 – 10 seine sites are sampled in each Bay on each sampling trip.

Information collected **:** All finfish species identified and counted, starting in 1987 invertebrates consistently counted. Since 1998 HSC have been counted, measured, and sex has been identified. Environmental information (air and water temperature, salinity, dissolved oxygen, tide stage, wind speed and direction, and wave height) has been recorded at each station. Bottom type, vegetation type, and percent cover have been recorded qualitatively since 1988.

Changes in sample design: Macro invertebrates not counted reliably until 1987, 500 ft seine discontinued in 1997 – this should not effect the HSC GM since the catch is standardized to the 200 ft seine, sampling frequency increased from one to two trips a month from July to October from 2000 to the present – this will not effect the HSC GM since index is based on only May and June catches.

CTDEP Long Island Sound Trawl Survey

Years sampled: 1984 – present

Gear type: 14 m high-rise otter trawl, 102 mm mesh in wings and belly, 76 mm mesh in the tailpiece and 51 mm mesh codend. Footrope is 14 m long with 13mm combination wire rope. Sweep is a combination type, 9.5 mm chain in belly and 7.9 mm chain in wing. Ground wires are 18.2 m, 6 x 7 wire, 9.5 mm diameter. Bottom legs are 27.4 m, rubber disc type, 38 mm diameter. Net was towed for 30 minutes at 3.5 knots. The vessel used was the 15.2 m aluminum R/V Dempsey.

Spatial coverage: Connecticut and New York waters of Long Island Sound from 5 to 46 m in depth.

Temporal coverage: Spring (April, May, June) and fall (Sept., Oct.)

Sample design: Stratified-random design. Sampling area is divided into 1x2 nautical mile sites with each site assigned to one of 12 strata defined by depth interval (0-9.0 m, 9.1-18.2 m, 18.3-27.3 m, or 27.4^{+} m) and bottom type (mud, sand, or transitional).

Sample frequency and number: 40 samples per month for a total of 200 sites annually.

Information collected: Catch is sorted by species. Finfish, lobsters and squid are counted and weighed in aggregate by species. Selected finfish, lobsters, and squid are measured. Starting in 1992 all species are weighed in aggregate by species. Horseshoe crab counts, weights, sex are sampled and CPUE are available.

Changes in sample design: Macro invertebrates (excluding lobsters) were not weighted until 1992, so the HSC time series starts in 1992. The total HSC sample at each station is weighed; individual crabs are counted in each tow starting in 2002.

New England Region

New Hampshire Spawning Survey

Years sampled: 2001 - present

Gear type: Sighting along 300 foot stretches of beach

Spatial coverage: Five survey locations around Great Bay

Temporal coverage: Annually May through September

Sample design: Count horseshoe crabs at each location during the new and full moons. Each survey is time as closely as possible to the high tide at each site.

Sample frequency and number: At each location, surveys during the new and full moons from May through September

Information collected: Number of crabs; spawning activity; subsample for sex, prosomal width, and weight; climatological parameters and water conditions

Changes in sample design: None

Massachusetts Inshore Bottom Trawl Survey

Years sampled: 1978 – present (Spring and Autumn)

Gear type: ¾ North Atlantic Type Two Seam "Whiting" Trawl

- 51 ft. footrope/ 39 ft. headrope
- 0.5 in. stretch mesh liner
- Sweep: Chain sweep (3.5 inch diameter rubber cookies)
- 60 ft. leglines
- Wooden doors (40 in. x 72 in. / 325lb.)
- 20-minute tows (24h basis)
- 2.5 knots (randomized direction)
- F/V Frances Elizabeth (55 ft stern trawler) 1978–82; R/V Gloria Michelle (65 ft stern trawler) 1983 – 2002

Spatial coverage: MA Bay to Merrimac River, Cape Cod Bay, waters south and east of Cape Cod and Nantucket, Nantucket Sound and Buzzards Bay/Vineyard Sound.

Temporal coverage: Spring and Autumn

Sample design: Stratified (depth) random

Sample frequency and number: Approx. 94 annually

Information collected: Count, weight, sex, prosomal width available some years, wave height, lat/lon, salinity, depth, temperature, weather.

Changes in sample design: Vessel changed in 1982 – gear performance trials showed identical average fishing height and wingspread

URI/GSO Trawl Survey Methodology

Years Sampled**:** 1959-present

Gear Type**:** Trawl (34' head rope, 48.6' foot rope; 2.5" belly, 2" cod)
- -53' vessel at 2.0 knots for 30 minutes/tow

Spatial Coverage**:** Fox Island and Whale Rock stations in lower west passage of Narragansett Bay

Temporal Coverage**:** Two stations sampled weekly for 12 months

Sample Design**:** Fixed

Sample Frequency and Number**:** Approximately 100 tows per year

Information Collected**:** Number/tow for the entire time series, weight/tow beginning 1994. No prosomal width available.

Changes in Sample Design**:** None

Marine Research Inc (RI) Trawl Survey Methodology

Years Sampled**:** 1973-1974, 1988-present

Gear Type**:** Trawl (25’ head rope, 36’ foot rope; 4.8” belly, 1.5” cod end)
-38’ vessel at 2.5 knots for 15 minutes/tow

Spatial Coverage**:** Mt. Hope Bay, RI

Temporal Coverage**:** April-October

Sample Design**:** Fixed

Sample Frequency and Number**:** Approximately 60 - 70 tows per 6 month sampling period.

Information Collected**:** Number / tow only

Changes in Sample Design**:** None

Marine Research Inc. (RI) Power Plant Impingement

Years sampled: 1992 - present

Gear type: Traveling screens at 3 water intake units equipped with 9.5mm square mesh panels; 38mm mesh at Units 1 and 2 and 25mm at Unit 3 from May to October to reduce horseshoe crab impingement

Spatial coverage: 3 water intakes of the Brayton Point Station in the Mount Hope Bay

Temporal coverage: year round

Sample design: Screens are connected to an in-line collection tank. During sampling, water is diverted for a fixed period of time (typically 8 hours) to the collection tank, where fish are collected and processed.

Sample frequency and number: Sampling is performed 3 times per week (except during February 1997 to December 2003 when sampling was performed daily)

Information collected: number of horseshoe crabs

Changes in sample design: Sampling frequency increased from February 1997 and December 2003

RI DEM Marine Fisheries Trawl

Years sampled: 1979 – present (Horseshoe crabs began to be measured in 1998)

Gear type: Trawl net (see attached for net dimensions)

Spatial coverage: Narragansett Bay, RI Sound, Block Island Sound

Temporal coverage: Survey runs all year

Sample design: The survey is split in to 2 components, a random stratified "seasonal" component, and a fixed station monthly component

Sample frequency and number: There are approximately 84 random stratified stations done per year (42 in the spring and 42 in the fall) and approximately 150 fixed stations done per year (about 13 per month)

Information collected: Number of horseshoe crabs, prosomal widths, total weight, sex, and CPUE

Changes in sample design: The vessel was changed in 2005

Stout Survey Methodology

Years Sampled**:** 1975-2002

Gear Type**:** Visual count

Spatial Coverage**:** Pt. Judith Pond, RI; South Shore Rhode Island Coastal Pond

Temporal Coverage**:** Standard transect surveyed annually during spawning season.

Sample Design**:** Fixed

Sample Frequency and Number**:** 1 survey annually

Information Collected**:** Number of crabs observed within standard transect

Changes in Sample Design**:** None

Appendix C: Exploration of the catch-survey model for describing horseshoe crab population dynamics (by Rich Wong, DE Div. of Fish & Wildlife)

Model Background and Configuration

The catch-survey population model simulates stock dynamics through time using only two stages: pre-recruits and fully recruited crabs (Collie and Sissenwine 1983). Minimum data requirements for the model include: 1) annual indices of relative abundance (in numbers) for each size stage; 2) relative selectivities of size stages to the survey gear; 3) annual total harvest in numbers; and 4) an estimate of instantaneous natural mortality rate. The catch-survey model is based on the first order difference equation:

$$N_{0,y+1} = (N_{0,y} + R_{0,y} - C_y)\, e^{-M} \quad (1)$$

which relates the fully-recruited stock size at the beginning of the year ($N_{0,y+1}$), to the fully-recruited stock size at the beginning of the previous year ($N_{0,y}$), plus recruitment in the previous year ($R_{0,y}$), minus the catch (C_y), all discounted by natural mortality, M.

Given an October to September model year (due to the timing of the survey indices), the current model difference equation is as follows:

$$N_{0,y+1} = [(N_{0y} + R_{0y})\, e^{-0.50M} - C_y)]\, e^{-0.50M} \qquad (2)$$

with the midpoint of harvest occurring at a point 50% into the survey year.

Survey indices of abundance are related to absolute stock sizes by

$$n'_{y'} = q_n N_{0y} e^{\eta t} \qquad (3)$$

and

$$r'_{y'} = q_r R_{0y} e^{\delta t} \qquad (4)$$

where r'_y and n'_y are the observed research indices of recruit and fully-recruited crabs, q is the catchability coefficient of the research survey gear, and $e^{\eta t}$ and $e^{\delta t}$ are lognormally distributed random variables, which represent survey measurement errors for the recruits and fully-recruited indices. These observation error quantities represent the difference between the observed survey indices of recruits and fully-recruited animals and the expected indices predicted within the nonlinear least squares (NLLS) framework by the DeLury difference equation. Another source of error, called process error, arises from the DeLury equation itself, which is the difference between calculated indices of fully-recruited animals and the expected value of the fully-recruited indices again predicted within the NLLS framework from the catch-survey model.

Substituting the above equations including the lognormally distributed process error ($e^{\varepsilon t}$) yields the following model difference equation:

$$n_y = [(n_{y-1} + r_{y-1} / s_r)\, e^{-0.50M} - q_n C_{y-1}]\, e^{-0.50M}\, e^{\varepsilon t} \qquad (5)$$

where

$$s_r = q_r / q_n \qquad (6)$$

is the relative selectivity of recruits to the fully-recruited crabs.

Thus, the above equation is a statistically estimable function with $2Y$ parameters to be estimated; n_y for all years Y, r_y for all years except the last year, and q_n. Estimates of these parameters (θ) are obtained by minimizing the least squares objective function (S):

$$S(\hat{\theta}) = \lambda_\varepsilon \sum_{y=2}^{Y} \varepsilon_y^2 + \sum_{y=1}^{Y} \eta_y^2 + \lambda_\delta \sum_{y=1}^{Y-1} \delta_y^2 \qquad (7)$$

where λ_ε and λ_δ are relative weights for the process error and recruit measurement error, respectively (relative to the measurement error for indices of the fully-recruited size). Conser (1995) describes an approach to weighting process and measurement errors within the least squares objective framework that is implemented in this analysis to evaluate model sensitivity. At this early stage of model development, I chose to weight the process error three-fold relative to the observation error components.

Given estimates of n_y, r_y, and q_n from the nonlinear least squares minimization and the value of relative selectivity, s_r, population abundances for pre-recruit and fully-recruited crabs are

$N_y = n_y / q$

and

$R_y = r_y / s_r\, q$.

Fishing mortality rate

Annual instantaneous fishing mortality rate (F) was calculated from instantaneous total mortality rate (Z), exploitation rate (μ), and annual percent mortality (A), derived from model estimates of annual stock size. Total mortality (Z) is expressed as the log survival ratio:

$$Z_{R+N,y} = \log_e\left[\frac{N_{0y} + R_{0y}}{N_{0,y+1}}\right] \qquad (8)$$

A range of annual exploitation rates, μ, was calculated using the input catch in numbers divided by exploitable stock size. Three estimates of exploitable stock size were calculated, providing theoretical upper and lower bounds of exploitable abundance to account for the unknown amount of recruitment into the fishery occurring within the year due to growth of pre-recruits (Kahn and Helser 2005). Given this unknown level of within-year recruitment, upper and lower bounds around an estimate of exploitable stock size were created for calculating exploitation rates and fishing mortality rates.

The best approximation of annual exploitable stock size, based on the method detailed by Collie and Kruse (1998) was assumed to be R + N, decremented by natural mortality over the time period until the harvest occurs

$$\mu_a = \left(\frac{harvest}{(R+N) * e^{(-M(T_C - T_S))}}\right),$$

where R and N are the absolute abundances of pre-recruits and post-recruits, M =instantaneous natural mortality rate, T_c = time when the harvest occurs, T_s = time when the survey occurs.

Maximum annual stock size was assumed to be R + N. Using a maximum estimate of annual stock size yields a lower bound of exploitation rate,

$$\mu_{\mathrm{b}} = \left(\frac{harvest}{(R+N)} \right).$$

Minimum exploitable stock size was defined as the annual catch plus all post-recruits surviving to the next survey year. Using a minimum estimate of annual stock abundance in the following equation,

$$\mu_{\mathrm{c}} = \left(\frac{harvest}{(catch + N_{t+1})} \right)$$

results in an upper bound of exploitation rate.

Fishing mortality is calculated by solving the catch equation for F,
$F = \mu Z/A$,
where μ and Z are as defined and A is the total annual mortality as a percent,
$A_t = (1 - N_{t+1}/(R_t + N_t)) = (1 - e^{(-Z)})$.

Data Inputs

Pre-recruit and full-recruit indices were based on densities of primiparous and multiparous female horseshoe crabs observed in the VA Tech Benthic Trawl Survey (Hata and Hallerman 2009) (Table 1). I assume that 1) all primiparous animals will recruit into the multiparous stage within the model time step; 2) harvest only occurs on multiparous horseshoe crabs. Natural mortality was set equal to M=0.15. This is the instantaneous mortality rate whereby 5% of a population remains after 20 years of longevity (under no fishing mortality). T_C (time point where 50% of the harvest occurs) was input as 0.5.

Table 1. Model inputs.

	Survey density		**Harvest**		
Year	**r**	**n**	**C**	**M**	**Tc**
2001	124	793	325,602	0.149787	0.5
2002	167	868	285,087		
2003	17	949	177,117		
2004	129	633	171,377		
2005	122	849	174,806		
2006	338	1810	116,870		
2007	380	2375	72,192		
2008	470	1635			

Harvest

Harvest was relegated to multiparous female horseshoe crabs of Delaware Bay origin only (Table 2). Delaware and New Jersey harvests were assumed to be 100% DE Bay origination. Ocean harvests from NY, MD, and VA were assumed to be of DE Bay origin

(Michels pers. comm.). State and year-specific sex ratios were used to quantify the female portion of harvest where needed (Michels pers. comm.). Since the trawl survey occurs in September-October, the survey year (t) corresponds to the harvest year (t+1) in the model inputs (Table 1). Therefore, there is a three month lag (Oct-Dec) between the timing of the survey and the harvest. If there is considerable DE Bay origin harvest in Oct-Dec, then it would be useful to reallocate those landings into the proper model time step in future modeling.

Table 2. Delaware Bay origin female harvest.

	VA	**MD**	**NY**	**NJ**	**DE**	**TOTAL**
2000	213,157	78,527	3,667	95,248	95,078	485,677
2001	26,171	83,797	6,778	68,240	135,317	320,303
2002	11,849	101,537	15,284	79,313	117,618	325,602
2003	52,965	72,605	7,594	29,422	122,502	285,087
2004	42,246	64,765	14,189	12,844	43,074	177,117
2005	36,341	61,053	3,529	21,125	49,329	171,377
2006	53,369	89,891	3,867	1,416	26,264	174,806
2007	11102	101349	4420	0	0	116870
2008	421	66258	5513	0	0	72192

Results

Initially, the raw indices were inadequate for this modeling exercise, working under the assumption that both primiparous and multiparous animals are equally susceptible to the survey gear. The year to year raw index values simply could not be described by the model difference equation (5). In three out of seven years the raw multiparous index was greater than the combined primiparous + multiparous indices of the previous year (Table 3). This is outside the realm of reality given the confines of the model equation.

Table 3. Raw index values at time t and t+1.

t	R t + N t	N t+1	Difference
2001	916.6	868.3	48.3
2002	1035.4	948.6	86.8
2003	965.5	632.7	332.8
2004	761.2	848.6	-87.4
2005	970.4	1810.2	-839.8
2006	2147.7	2375.2	-227.5
2007	2754.8	1635.4	1119.4
2008	2105.2	0	2105.2

Ultimately, the model needed the survey selectivity of primiparous animals to be much lower relative to the multiparous stage. Therefore, I allowed the model to freely estimate the selectivity of the primiparous stage relative to the multiparous stage. In this case, $s_r = 0.356$, or roughly 3X less susceptible to the gear than multiparous animals. The model fits to the observed indices were excellent with no biases in residual patterns (Figures 1-2). The fit of model-calculated multiparous abundance to the observed multiparous index was also good (Figure 3). One note of caution, the largest disagreement in fit occurs in the terminal year multiparous estimate (Figures 2, 3). The catchability coefficient was q=0.000368, resulting in stock sizes between 2.7 and 9.6 million females (Table 4). Fishing mortality rates declined from F=0.13 to 0.01 from model year 2001 to 2007 (Table 5).

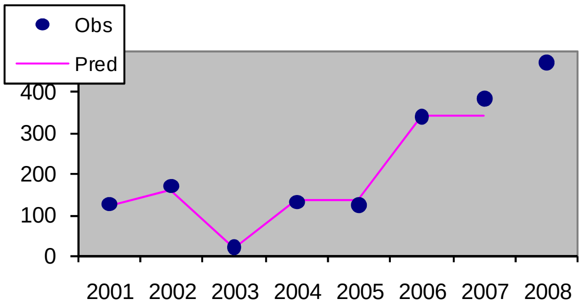

Figure 1. Observed and predicted primiparous indices.

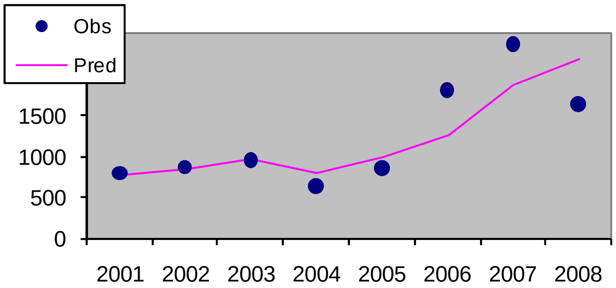

Figure 2. Observed and predicted multiparous indices.

Figure 3. Observed and calculated multiparous indices.

Table 4. Model estimated stock sizes.

	Primiparous	Multiparous	Total
2001	9.30E+05	2.08E+06	3.01E+06
2002	1.22E+06	2.26E+06	3.47E+06
2003	1.28E+05	2.61E+06	2.74E+06
2004	1.03E+06	2.12E+06	3.15E+06
2005	1.04E+06	2.67E+06	3.71E+06
2006	2.61E+06	3.43E+06	6.04E+06

2007	2.62E+06	5.14E+06	7.76E+06
2008	3.59E+06	5.99E+06	9.57E+06
Mean	1.37E+06	2.90E+06	4.27E+06
Median	1.04E+06	2.61E+06	3.47E+06

Table 5. Model estimated mortality and exploitation rates. Z=instantaneous total mortality rate; A=annual mortality rate; μ =exploitation rate; F=fishing mortality rate.

	Z	A	μ (Collie-Kruse 1998)	μ (upper)	μ (lower)	F (C-K)	F (u)	F (l)
2001	0.29	0.25	0.12	0.13	0.11	0.13	0.15	0.12
2002	0.28	0.25	0.09	0.10	0.08	0.10	0.11	0.09
2003	0.26	0.23	0.07	0.08	0.06	0.08	0.09	0.07
2004	0.16	0.15	0.06	0.06	0.05	0.06	0.07	0.06
2005	0.08	0.07	0.05	0.05	0.05	0.05	0.05	0.05
2006	0.16	0.15	0.02	0.02	0.02	0.02	0.02	0.02
2007	0.26	0.23	0.01	0.01	0.01	0.01	0.01	0.01
					mean	0.07	0.07	0.06
					median	0.06	0.07	0.06

Discussion

The CSA model is very promising for describing horseshoe crab stock dynamics, in part because there are no underlying assumptions about stock productivity built into the model equation. The model merely balances numbers of individuals from one stage to the ensuing stage given known natural mortality across one year, while scaling these numbers to known harvest. In our specific case, after allowing the model to estimate primiparous selectivity, the fits to observed data were unusually good. I also observed very good model stability in all parameters across different starting values.

Given the short time series and the need to estimate selectivity, I hesitate to place great confidence in the estimate of q. The parameter q is highly sensitive to the value of primiparous selectivity (s_r). Therefore, all model outputs are very strongly hinged on the accuracy of the estimated selectivity. Any further progress related to this modeling approach requires an external investigation of primiparous versus multiparous selectivity in the trawl survey.

Weighting of error components can also significantly affect the estimation of q. I experimented with various weights on process error, ultimately settling on 3X for my base model. I do not have much justification, other than I felt that there was much uncertainty in the observed data due to the short time series and given the omnipresent issue with primiparous selectivity. In essence, overweighting process error gives more emphasis to fitting the model equation. Without exerting greater weight on process error residuals, the observed indices are essentially exactly fit by the predicted indices. Even with the 3 factor on process error residuals, the fit to observed indices was still extremely tight. Ultimately, q increases as process error weighting increases, resulting in declining estimates of absolute abundance.

The estimate of primiparous selectivity was very stable, but it was based solely on minimizing the NLLS and not on any biological, ecological, or mensuration information. I explored this issue briefly by examining what the theoretical ratio of multiparous to primiparous females in an equilibrium population would be under 1) our implicit constant natural mortality rate M=0.15, 2) age 9 to 10 stage transition (all age 9 females=primiparous, all age 10+ females=multiparous), and 3) F=0.1 at ages>9 (Table 6). Under these fixed scenarios, the ratio is 3.2 to 1 multiparous: primiparous. Under F=0, the ratio is about 4.8. In the VA Tech survey, the observed ratio is about 5.7 (Table 7). The model estimates of stock size reveal a ratio of about 2, indicating that much more primiparous animals are required for best model fit (hence the 0.35 primiparous selectivity).

Table 6. Age structure of equilibrium population given assumptions about M, F, and age at first capture.

M -0.150
F 0.10
t_c 9

age	**n**
0	100
1	86.08917
2	74.11344
3	63.80365
4	54.92803
5	47.28708
6	40.70905
7	35.04608
8	30.17088
9	25.97386
10	20.23278
11	15.76067
12	12.27704
13	9.563409
14	7.44958
15	5.802977
16	4.520327
17	3.521186
18	2.742887
19	2.136619

Table 7. Observed and theoretical multiparous to primiparous ratios.

Data source	Multiparous:Primiparous Ratio
VT Survey	5.7:1
Life table F=0	4.8:1
Life table F=0.1	3.2:1
CSA Model	2:1

Examining multi:primi ratios can shed light on the selectivity issue. First, are the multi:primi ratios from the equilibrium population in Table 6 realistic? The assumed natural mortality rate will strongly affect these multi:primi ratios. Is M greater than the assumed 0.15 for adults due to spawning or earlier than expected senescence (i.e. exaggerated max age)? Is M higher during the stage transition? Is fishing mortality higher than suspected, or is there significant unseen harvest? These conditions would cause the ratio to be lower (closer to the 2:1 ratio seen in the model). As a reference, the multi:primi ratio from the stage structured model by Sweka et al. (2007) was between 2:1 and 3:1 (Sweka, pers. comm.).

Why is the multi:primi ratio in the VT survey then so much higher than the ratios from the equilibrium population and model outputs? Assuming the equilibrium population ratio is realistic, then primiparous females must be less susceptible to the VT survey gear than multiparous females. Do movement or migration patterns explain this differential selectivity? Are there differential habitat preferences (depth, substrate, salinity, etc.)? Are there behavioral differences that would allow primiparous females to evade the gear more effectively (e.g. burying or swimming)? Are primiparous females much smaller than multiparous females? Are primiparous females mistakenly identified as multiparous? These issues hopefully can be discussed in order to determine what the realistic range of selectivities should be for this modeling approach (Table 7). Selectivity is the primary issue for moving forward with this model.

Summary

Although model fits to observed indices were surprisingly good, there is a great deal of uncertainty in model outputs caused by the need to estimate primiparous selectivity. Given further investigation of the selectivity issue, the CSA model holds excellent promise for future horseshoe crab stock assessments.

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