POPULATION DYNAMICS OF SHORTNOSE STURGEON, *ACIPENSER BREVIROSTRUM*, IN THE ALTAMAHA RIVER, GEORGIA

By

MICHAEL STANLEY BEDNARSKI

Under the Direction of Douglas L. Peterson

ABSTRACT

The endangered shortnose sturgeon, *Acipenser brevirostrum*, occurs in large tidal rivers along the Atlantic coast of North America, ranging from the St. John River, Canada, southward to the St. Johns River, Florida. Throughout their range, populations have declined in response to habitat degradation, overfishing, nutrient enrichment, and incidental harvest. Though the status of most populations is uncertain, available evidence suggests that populations south of the mid-Atlantic bight are in particularly poor condition; presently, only three appear to exceed 1,000 individuals. Unfortunately, long-term quantitative studies of southern populations are completely lacking, resulting in critical information gaps that hinder effective restoration. The objectives of this study were to assess recent trends in 1) abundance, 2) population structure, 3) recruitment, 4) habitat suitability and 5) apparent survival in the Altamaha River, Georgia, a large, relatively unaltered southern river system. I used anchored monofilament gill and trammel nets to sample shortnose from summer 2004-2010. Individual fish were measured, assigned to a specific life stage, PIT tagged, and released. I used the Huggins closed-capture model to estimate abundance for each life stage. Changes in size-structure were examined using a non-parametric multiple comparison procedure. Linear regression was used to identify the influences of high flow duration on age-1 recruitment. Correlation analysis was used to analyze the influences of summertime flow on temperature. I used a Cormack-Jolly-Seber model to assess the effects of drought on apparent survival. I captured 1737 unique shortnose (72 within-year and 153 among-year recaptures). Estimates of total abundance varied from 1206-5551. Population structure shifted from juvenile-dominated in 2004-2007 to adult dominated in 2008-2010. Age-1 recruitment ranged from 30-2976 and was strongly correlated with sustained high flow during the young-of-year period. Decreases in summer flow were negatively correlated with temperature. Drought appeared to negatively effect apparent juvenile survival. Our results indicate that the Altamaha River hosts the largest and healthiest southern population. However, given the population's accelerated life cycle, highly variable recruitment, and apparent sensitivity to variations in flow, we recommend that management focus on maintaining flows at levels likely to maximize long-term population persistence.

INDEX WORDS: shortnose sturgeon, endangered, population dynamics, mark-recapture, flow

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DEDICATION

I dedicate this dissertation to my family. They have provided invaluable support and have helped me to get through the trials and tribulations, the successes and failures, and the glamorous and not-so glamorous portions of completing this document. I am particularly indebted to my mother, Marsha Bednarski, who introduced me to the wonder of science, my father, Stanley Bednarski, who provided me with the technical experience necessary to repair and maintain mechanical equipment, and my sister, Sarah Bednarski, whose guidance has greatly aided me in the graduate experience. I would also like to thank my grandmother, Rose Hamernik, for her musings on life in New England. Her stories and anecdotes have provided me a welcome respite from the intensity of conducting summertime fieldwork in the swamps, marshes, and backwaters of southern Georgia.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Classification:

In 1818, LaSueur described the shortnose sturgeon as *Acipenser brevirostrum* based on a type specimen from the Delaware River, Delaware (Dadswell et al. 1984). Though other researchers have re-described and re-named the species, *Acipenser brevirostrum* is the currently accepted specific epithet. Shortnose are classified within kingdom Animalia, phylum Chordata, superclass Osteichthyes, class Actinopterygii, subclass Chondrosteii, order Acipenseriformes, family Acipenceridae (Dadswell et al. 1984).

Physical Characteristics:

Shortnose reach a maximum size of 1.22 m fork length (FL) and are the smallest North American species of *Acipenser* (Dadswell et al. 1984). Like other sturgeons, shortnose are poikilothermic, possess a physostomous swim bladder, and exhibit a pentagonal body shape characterized by five rows of large, ganoid scales. The shortnose's skeletal system is primarily cartilaginous; however, the skull, pelvic and pectoral girdle display extensive ossification (Vladykov and Greeley 1963). The head is typified by a blunt, flattened rostrum and four ventrally located sensory barbells. The mouth is relatively large and morphologically adapted for suctorial feeding. Shortnose possess paired pectoral fins, paired pelvic fins, single dorsal, anal and caudal fins and a heterocercal tail characterized by a relatively long upper lobe comprised of skeletal and muscular tissue and a lower lobe composed entirely of soft rays. Individuals display great diversity in color, varying from olive-brown to orange. The leading edges of the pectoral, pelvic, dorsal and anal fins are white on all individuals (Dadswell et al. 1984).

Distribution:

Shortnose occur in most large tidal rivers along the Atlantic coastline of North America, ranging from the St. John River, Canada, southward to the St. Johns River, Florida (Vladykov and Greeley 1963). In a 1998 recovery plan, the National Marine Fisheries Service (NMFS) segregated the species into 19 distinct population segments based on river of occurrence (NMFS 1998). At that time, limited information was available regarding the genetic character and metapopulation dynamics of each within-river population. Since then, genetic analyses have demonstrated that the species consists of several regionally specific metapopulations. Wirgin et al. (2010) identified 10 discrete population segments (DPS); two occurring in the Acadian biogeographic marine province, three in the Virginian Province, and five in the Carolinian Province.

Life History:

Like other sturgeons, shortnose exhibit a complex life cycle characterized by several discrete life history stages, each with unique habitat needs and physiological tolerances.

Shortnose demonstrate distinct egg, prolarval, larval, juvenile, and adult life stages (Buckley and Kynard 1981).

Eggs

Shortnose sturgeon eggs are adhesive and measure between 3.1 and 3.8 mm diameter (Dadswell et al. 1984). Hatching occurs after 13 days at 8 to 12° C and after 8 days at 18° C (Dadswell et al. 1984). In the laboratory, Buckley and Kynard (1981) note a hatching rate of only 19.3%.

Prolarvae

After hatching, shortnose begin their prolarval stage and measure 7-11 mm FL (Buckley and Kynard 1981, Dadswell 1980). Prolarvae exhibit a large yolk sac (31 and 37% TL), poorly developed eyes, and undeveloped pectoral and pelvic fins (Richmond and Kynard 1995). Prolarvae are photopositive for the first two days of life. After approximately seven days, prolarvae become photonegative and seek habitat with interstitial spaces of rocky substrates. Throughout the prolarval period, shortnose are incapable of directional swimming and move downstream through passive drifting (Richmond and Kynard 1995).

Larvae

At 9-12 days post-hatch, shortnose progress to the larval stage (Richmond and Kynard 1995, Buckley and Kynard 1981). As larvae, shortnose begin exogenous feeding and are capable of directional swimming (Richmond and Kynard 1995, Buckley and Kynard 1981). Larvae occupy deep, channel habitats where they forage on insect larvae and small crustaceans (Carlson and Simpson 1997, Dadswell 1984). As larvae, shortnose are primarily nocturnal (Richmond and Kynard 1995).

Juvenile

At approximately 20 mm FL, shortnose transition to the juvenile stage and resemble miniature adults (Dadswell et al. 1984). Juveniles actively migrate downstream to deep, channel habitats near the freshwater-saltwater interface of their natal estuary where they forage on mollusks, insect larvae and crustaceans (Dadswell et al. 1984).

Juvenile shortnose appear tolerant of a wide range of temperatures. In northern rivers, juvenile shortnose occur in systems where temperatures remain < 4° C for >4 months. Conversely, in southern systems, shortnose occur in systems where temperatures can be > 30° C for >3 months. Laboratory studies indicate an upper limit of safe tolerance for juveniles residing in freshwater of approx. 31.1° C (Ziegweid et al. 2008).

Throughout their range, juvenile shortnose rarely occur at salinities >10 ppt. Juvenile appear to be especially intolerant of saltwater and are rarely found at salinities > 4 ppt at temperatures >25° C, suggesting a temperature related physiological intolerance (Collins et al. 2000). Under high temperature conditions, juveniles often congregate near the freshwater saltwater-interface (Collins et al. 2000, Flournoy et al. 1992).

Juvenile shortnose require well-oxygenated habitats. Throughout their range, they are rarely found where dissolved oxygen levels are <3.5 mg/L. When exposed to prolonged hypoxia (<2.5 mg/L), juvenile shortnose experience mortality rates of between 20-80% (Jenkins et al. 1993).

Adult

Shortnose reach adulthood at 450-800 mm FL and, like other members of the genus, exhibit a high weight-specific fecundity (Dadswell et al. 1984). Depending on size, fecundity varies from 20,000-208,000 eggs. Age-at-maturity varies depending on sex and latitude. In southern systems, maturity occurs at either age 2-3 for males and age 3-5 for females. In northern rivers, maturity occurs at age 10-14 for males and age 14-20 for females (Dadswell et al. 1984). Spawning periodicity also varies with sex and latitude. In northern populations, shortnose sturgeon spawn at either 1-2 (male) or 3-5 (female) year intervals (Kieffer and Kynard 1996, Dovel et al. 1992, Dadswell 1979). Within southern populations, individuals of both sexes may spawn annually (Collins and Smith 1993).

Shortnose spawn in spring over hard bottom substrates at moderate depths (1.2-10.4 m) and current velocities (0.4-1.8 m/s) at temperatures of 9-18°C (P. Vinogradov in Kynard 1997, Kieffer and Kynard 1996). Depending on river system, shortnose exhibit one of two types of spawning migration. The first, a two-step migration, begins with a long (>50 km) late-fall migration towards spawning areas. Individuals then overwinter near the spawning area and subsequently migrate a short (<10 km) distance upstream to spawn when temperatures increase in the spring (Kieffer and Kynard 1993, O'Herron et al. 1993, Buckley and Kynard 1985). Two-step spawning migrations are typical of populations north of the Mid-Atlantic bight. In contrast, southerly populations do not overwinter near potential spawning habitat and instead perform a long, single-step migration (>200 km) during late winter and early spring (Rogers and Weber 1995, Hall et al. 1991).

When in non-spawning condition, shortnose occur primarily in the meso- and polyhaline portions of large tidal rivers (Dadswell et al. 1984, Holland and Yelverton 1973). While in these areas, adult shortnose forage on mollusks, insect larvae, and crustaceans when temperatures >7° C (Dadswell 1979). Populations restricted from saline waters exhibit slow growth, suggesting that estuarine areas contain better foraging opportunities and that adult shortnose instinctively seek out such areas (Dadswell et al. 1984, Taubert and Dadswell 1980). In northern areas, adult shortnose transition to overwintering areas when temperatures decrease in the fall. Overwintering sites are characterized as deep, lacustrine sections of large tidal rivers. In southern systems, adult shortnose migrate to discrete oversummering habitats when temperatures >25° C. Oversummering areas are characterized as the oligohaline portions of large tidal rivers in proximity to the freshwater-saltwater interface.

Current and Region-Specific Status:

Throughout their range, shortnose populations have been adversely affected by overfishing, dam construction, habitat loss, nutrient enrichment and chemical pollution (Collins et al. 2000, Kynard 1997, NMFS 1998). Currently, few populations are thought to contain >1,000 individuals; however, population estimates are lacking for most rivers. Several populations, notably those occurring south of the mid-Atlantic bight, appear extirpated or functionally extinct (NMFS 1998, Kynard 1997). All US populations are protected under state regulations and the United States Endangered Species Act. In Canada, populations are listed under the Canadian Species at Risk Act (NMFS 1998).

Acadian Province

The Acadian Province, which encompasses river systems from New Brunswick, Canada, southward to Cape Cod, Massachusetts, contains four systems that host shortnose; the St. John

River, Canada, the Penobscot and Kennebec Rivers, Maine, and the Merrimack River, Massachusetts (NMFS 1998). At least two DPSs occur within this region, one containing the St. John River, the other containing the Penobscot and Kennebec River populations (Wirgin et al. 2010). The genetic character of the Merrimack River is uncertain. Abundance varies by system, ranging from a low of <100 (Kieffer and Kynard 1996) in the Merrimack to a high of 18,000 in the St. John River (Dadswell 1979). The Kennebec and Penobscot River systems have been estimated to contain 7,222 (Squiers et al. 1982) and ~1,400 individuals, respectively (S.J. Fernandes 2008).

Shortnose populations within the Acadian Province demonstrate slow growth, high annual survival, and large maximum size. In the St. John River, individuals reach maturity between age-10 (males) and age-20 (females) (Dadswell 1979). Though juvenile growth is slow, shortnose in the St. John have a relatively low mortality rate (Z=0.12 to 0.15) and a lifespan of up to 67 years. The largest Acadian shortnose captured, a 1.22 m FL individual from the St. John River, represents the largest specimen on record (Dadswell et al. 1984, Dadswell 1979).

Although the historic status of shortnose within the Acadian Province is unclear,, populations within the St. John, Kennebec and Penobscot River appear relatively healthy based on recent abundance estimates. The Merrimack River population may be vulnerable to future decline because of its relatively low abundance. Several factors, such as incidental capture and future watershed development, threaten the future status of Acadian populations (NMFS 1998).

Virginian Province

The Virginian Province, which ranges from Cape Cod southward to the Outer Banks, North Carolina, contains four systems that host shortnose: the Connecticut River, Connecticut, the Hudson River, New York, the Delaware River, Delaware, and the Chesapeake Bay, Maryland and Virginia. Populations within the Connecticut and Hudson Rivers represent separate DPSs (Wirgin et al. 2010). The Delaware River and Chesapeake Bay populations comprise a single DPS.

The Virginian Province hosts several robust shortnose sturgeon populations. The Hudson River contains the largest known population, based on a 1995 estimate of 56,708 individuals (95% C.I. 50,862-64,072; Bain 2001 in Woodland and Secor 2007). The Delaware River hosts a large population, based on a 1984 estimate of 14,080 individuals (95% C.I. 10,079-20,378; Hastings et al. 1987). Abundance within the Connecticut River is significantly lower. In total, the Upper and Lower portions of the Connecticut River contain approximately 1300 individuals (Savoy and Shake in Kynard 1997, Taubert 1980). Current abundance within the Potomac, Susquehanna, and James Rivers is uncertain.

Maximum age and size within the Virginian Province are ~983 mm FL and 37 years, suggesting a shorter lifespan, lower survival rate, and smaller maximum size compared to Acadian populations (Woodland and Secor 2007, Dovel 1981 in Dadswell et al. 1984). Growth rate within the Virginian Province appears similar to the Acadian Province (Dadswell et al. 1984).

Although most Virginian populations appear relatively healthy, all watersheds within the region are highly impacted by anthropogenic activities. In nearly every system, dam construction, industrial pollution, and nutrient enrichment have caused habitat loss, migratory restrictions, disease, or impaired development (NMFS 1998). In the Delaware and Hudson River systems, direct mortality occurs because of harbor maintenance and powerplant operations. In all systems, incidental bycatch in commercial and recreational fisheries continue to cause unintended, direct mortality and illegal harvest (NMFS 1998).

Carolinian Province

The Carolinian Province, which ranges from the mid-Atlantic Bight in North Carolina southward through Florida, contains several river systems that host shortnose; the Cape Fear River, North Carolina, the Winyah Bay system, North and South Carolina, the Santee and Cooper Rivers, South Carolina, the Ashepoo, Combahee and Edisto Rivers, South Carolina, the Savannah River, South Carolina and Georgia, the Ogeechee, Altamaha, the Satilla and the St. Marys Rivers, Georgia (NMFS 1998). A damlocked population occurs in Lake Marion, South Carolina. Compared to their northerly counterparts, Carolinian populations exhibit a relatively high degree of mixing and may occur as multi-river metapopulations (Peterson and Farrae *in press*, Wirgin et al 2010). At least four DPSs exist within this province.

Abundance within Carolinian populations is significantly lower than that of Virginian and Acadian populations (Kynard 1997). Only the Pee Dee, Savannah, and Altamaha rivers appear to contain >1,000 individuals. Of these systems, the Altamaha River appears to be the largest and healthiest based on a 1988 estimate of 2,862 (95% C.I. 1,069-4,226; Rogers unpublished in NMFS 1998). No other populations appear to exceed 500 individuals. Populations in the Cape Fear, Satilla, and St. Marys Rivers may number <100 individuals (Rogers unpublished in Kynard 1997, Rogers and Weber 1995, Moser and Ross 1994).

Growth rates in the Carolinian Province significantly exceed those of both the Virginian and Acadian Provinces, suggesting an accelerated life cycle (Dadswell et al. 1984). Carolinian populations appear to exhibit relatively low survival, based on a maximum reported age of 25 years (Kynard 1997). The largest individual reported from the Carolinian Province measured approximately 1.19 m TL (Peterson and Farrae *in press*).

Collins et al. (2000) suggested that natural factors, such as high temperature, and anthropogenic factors, such as dam construction, flow alteration, and nutrient pollution, are responsible for low abundance within the Carolinian Province. Specifically, habitat and forage limitations may occur in warm, dry summers because of reduced freshwater inflow, which are thought to cause decreased habitat availability and hypoxic conditions (NMFS 1998). Because of their accelerated growth, low survival, and low abundance, southern shortnose populations may be acutely sensitive to stochastic events and may be particularly susceptible to decline and extirpation.

Justification:

Available evidence suggests that eight populations within the Carolinian province number below 1,000 individuals, the proposed minimum viable population size for vertebrate organisms (Thompson 1991). Without remediation, many of these populations may become extirpated in the near future. Before restoration of Carolinian populations can begin, however, researchers must gather critical information regarding the abundance and demographic rates of populations persisting in a functional, intact river system to determine measures likely to restore imperiled populations.

A unique research opportunity exists in the Altamaha River system. Unlike other southern systems, the Altamaha River is completely free-flowing throughout its course (ASSRT 2007). In this regard, the Altamaha is the least altered shortnose sturgeon river in the southeastern United States. Consequently, the goal of my research was to evaluate the critical linkages between ecology and habitat that ultimately govern the population dynamics of shortnose sturgeon within a southern river system. In accomplishing this goal, I analyzed data from a 7-yr mark-recapture study of the Altamaha River population. I was able to gather information regarding multi-year abundance trends, population structure, and factors affecting reproductive success in a quantified, statistically robust manner.

In chapter 2, I focus on assessing trends in shortnose abundance and population structure. In chapter 3, I concentrate on quantifying reproductive success and identifying interactions between environmental conditions and the survival of early life stages. In the fourth chapter, I quantify the effects of summer flow on habitat suitability and apparent survival of both juveniles and adults. In the concluding chapter, I summarize my findings and discuss the implications of my work for understanding regional differences in the population dynamics of shortnose as well as how the results of my study may be applied to the restoration of other southern populations.

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CHAPTER 2

ABUNDANCE AND SIZE STRUCTURE OF SHORTNOSE STURGEON, *ACIPENSER BREVIROSTRUM*, IN THE ALTAMAHA RIVER, GEORGIA[1]

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[1] Bednarski, M.S. and D.L. Peterson. To be submitted to *Transactions of the American Fisheries Society*

Abstract:

Endangered shortnose sturgeon, *Acipenser brevirostrum*, inhabit large tidal rivers along the Atlantic coastline of North America, ranging from the St. John River, Canada, southward to the St. Johns River, Florida. Currently, long-term assessments of abundance and age-structure of southern populations are completely lacking. To address this information gap, the objectives of our study were to assess recent changes in 1) abundance and 2) age-structure of shortnose sturgeon in the Altamaha River, Georgia. We sampled shortnose sturgeon during the summers of 2004-2010 using anchored entanglement gear. To estimate abundance, we used the Huggins closed-capture model in Program MARK. We assessed age-structure by using size-structure as a proxy and comparing the size of individuals captured each year of the study with a nonparametric multiple comparison procedure. In total, we captured 1737 shortnose sturgeon (72 recaptures). Total estimated abundance was variable, ranging from 1206 (95% C.I. 566 - 2759) in 2009 to 5551 (95% C.I. 2804 - 11304) in 2006. Our results indicated that although juvenile abundance varied by a factor of 50, adult abundance was relatively constant. However, rapid, significant shifts in size structure and a lack of an increase in adult abundance indicated rapid population turnover, which we attribute to a combination of mortality and permanent emigration. Though the Altamaha River population shares several characteristics with its northern counterparts, including variable juvenile and stable adult abundance, our results suggest that southern populations may be more susceptible to decline because of an accelerated life cycle.

Keywords: Shortnose sturgeon, population dynamics, size structure, population assessment, endangered

Introduction:

The shortnose sturgeon, *Acipenser brevirostrum*, inhabits most large tidal rivers along the Atlantic coastline of North America, ranging from the Saint John River, Canada, southward to the St. John River, Florida (Kynard 1997, Dadswell et al.1984, Vladykov and Greeley 1963). Compared to other sturgeons, shortnose are relatively small, reaching a maximum size of between 1.0-1.3 meters (Kynard 1997, Dadswell et al. 1984). Like other Acipenser species, shortnose exhibit a periodic life history, characterized by late age-at-maturity, long lifespan, high weight-specific fecundity, and protracted spawning periodicity (Kynard 1997, Dadswell et al. 1984, Dadswell 1979). Because the life cycle of shortnose is characterized by several discrete developmental stages, each with unique habitat needs and environmental tolerances, multiple interconnected habitats are required for the species to complete its life cycle (Richmond and Kynard 1995, Dadswell et al. 1984, Buckley and Kynard 1981). Throughout the species' range, habitat alteration caused by dam construction, nutrient enrichment, and sedimentation have adversely affected most populations (Collins et al. 2000). Currently, shortnose are classified as endangered with few extant populations containing more than 1,000 individuals (NMFS 1998, Kynard 1997).

Recent studies suggest that river systems north of the Mid-Atlantic Bight support the largest extant populations of shortnose (Kynard 1997, NMFS 1998), the largest of which occur in the Saint John River, Canada (Nhat = 18,000), and the Hudson River, New York (Nhat 61,057; Bain et al. 2007, Dadswell 1979). Two other northern river systems, the Kennebec River, Maine, and the Delaware River, Delaware, host populations exceeding 7,000 individuals (NMFS 1998, Squiers et al. 1982). In contrast, southern shortnose populations are typically much smaller. Within the southeastern United States, only the Altamaha River, Georgia, the Savannah River, Georgia and South Carolina, and the Pee Dee River, North Carolina, contain populations that exceed 1,000 individuals (Kynard 1997, Smith et al. 1995, Rogers and Weber 1994, Flournoy et al. 1992). Limited empirical information is available that links low abundances of shortnose in the southeastern United States with river and region specific factors; however, high summer temperature, low levels of dissolved oxygen, and incidental bycatch of adult shortnose in the American shad (*Alosa sapidissima*) fishery have been identified as potential impediments to recovery in many southern rivers (Collins et al. 2000, Kynard 1997).

Assessments of southern populations are needed to protect, and ultimately, restore existing populations. Although previous studies have provided valuable insights into the overall status of shortnose populations, long-term sequential assessments of total abundance and population structure are completely lacking (NMFS 1998). Because of their late age-at-maturity and protracted spawning periodicity, short-term population assessments are of limited utility for accurately assessing population trends. The lack of directed studies on viable shortnose populations inhabiting intact river systems has resulted in key information gaps that have hindered the assessment of populations occurring in impacted river systems.

Within the southern portion of their range, shortnose in the Altamaha River may provide the best remaining example of an undisturbed population. Although some development has occurred in the Altamaha watershed, the river has no impoundments downstream of the fall line, providing shortnose with unimpeded access to all known historic habitats with the system. In contrast to other southern river systems, essential estuarine habitats within the Altamaha do not suffer from summer hypoxia (<2.5 mg/L dissolved oxygen; Flournoy et al. 1992). In this regard, the Altamaha provides a unique opportunity to better understand the ecology and population dynamics of a relatively undisturbed shortnose population within a southern river system. The specific objectives of our study were to characterize the Altamaha River shortnose population by quantifying 1) annual abundance and 2) age-structure over a consecutive seven year period. By determining how both abundance and age-structure vary in the Altamaha River, our results may provide managers with new information regarding population dynamics of shortnose in the southern portion of their range.

Methods:

Study Site:

The Altamaha River system is formed by the confluence of the Ocmulgee and Oconee Rivers near Lumber City, Georgia, and flows approximately 212 km to its outlet to the Atlantic Ocean, approximately 1 km south of Darien, Georgia (Figure 2.1). The Altamaha River is one of the largest sources of freshwater on the Atlantic coast, with a mean yearly discharge of 380 m^3/s (USGS gauge 00022260). The Altamaha River is free flowing, with no man-made or natural barriers throughout its course.

Shortnose have access to a variety of habitats within the Altamaha River system. Hard bottom spawning habitat is abundant above rkm 80 on the Altamaha River and throughout the Oconee and Ocmulgee Rivers (Flournoy et al. 1992).. The lower 40 rkm of the Altamaha River are tidally influenced and represent the primary habitat of the species (Rogers and Weber 1994, Flournoy et al. 1992). During fall, winter, and spring, juveniles and adults may use the meso- and polyhaline portions of the estuary (Collins et al. 2000, Dadswell et al. 1984). During summer, shortnose appear to occur primarily in deep (>5m) main channel areas near the freshwater-saltwater interface of the Altamaha River estuary (Collins et al. 2000, Rogers and Weber 1995).

Sampling:

Sampling was conducted from late May to early August, 2004 to 2010. We allocated the majority of our sampling effort between rkm 10 and 35, which represents the general location of the fresh-saltwater interface within the Altamaha River Estuary (Figure 2.1). Within this reach, specific netting locations were selected where preliminary sonar surveys indicated relatively snag-free bottoms. At these sites, shortnose sampling was conducted 1-3 times per week using anchored monofilament gill and trammel nets deployed in the main channel for 30-45 min during slack tides. Total weekly effort varied between 3 and 16 sampling events. All nets were 91.4 m long and 3.1 m deep. Gill nets were constructed of three 30.5-m panels of 7.6, 10.2, or 15.3-cm monofilament mesh (stretch measure) sewn together in random order. Trammel nets were constructed of an inner panel of 7.6-cm mesh and two outer panels of 30.5-cm mesh. Nets were fished for 30-45 min, primarily during slack tides to maximize sampling efficiency (D. Peterson unpublished data).

As nets were retrieved, captured shortnose were removed and immediately placed in a floating net pen. Once all nets had been pulled, shortnose were measured (fork length; FL) and scanned for an existing PIT tag. If no tag was detected, we inserted one into the musculature beneath the fourth dorsal scute. All fish were released within 45 minutes of initial capture.

Data Analyses

We classified shortnose as either juveniles or adults based on fork length (FL), with any individual ≤ 499 mm FL assigned to the juvenile life stage and any individual ≥ 500 mm FL designated an adult (Figure 2.2; Kynard 1997, Dadswell et al. 1984). We then used the Huggins closed-capture model in Program MARK to estimate abundance of juveniles and adults (White and Burnham 1999, Huggins 1986). We sampled only during late spring and summer months, when shortnose are known to occur only in low salinity (<4.2 psu) areas near the freshwater-saltwater interface (Collins et al 2000, Flournoy et al. 1992). We assumed the population was closed and to ensure the assumption of closure was met, we regularly checked for shortnose occurrence upstream and downstream of the study area, allocating at least 10 sampling events/season in the 10 rkm immediately upstream and downstream of the study reach.

Population models were constructed using each sampling week as a unique capture period. During each year of the study, we considered the capture probability of juveniles and adults to be equal. To test the validity of this assumption, we modeled capture probability as either a linear or a quadratic function of individual length and used AICc (Burnham and Anderson 2002, Akaike 1973) to compare those model results to an alternative model where capture probability was held constant. Because weekly sampling effort was not equal, we modeled capture probability as varying among individual capture periods. The precision of each mark-recapture estimate was assessed by calculating 95% lognormal confidence interval within Program MARK as described by White and Burnham (1999). Inferences regarding abundance trends were based only on estimates that did not have overlapping confidence intervals. We quantified year-to-year variation in abundance by calculating the coefficient of variation (CV) of the point estimates for total, adult, and juvenile abundance (Woodland and Secor 2007, Rothschild and DiNardo 1987)

Traditional methods of aging fish, such as otolith extraction and fin-ray removal, may result in acute or delayed mortality, prohibiting their usage with an endangered species. Instead, we used size-structure, based on the length of each captured individual, as a non-invasive, indirect measure of the population’s age-structure. Multi-year trends in size-structure were assessed using a multiple comparison procedure relating FL to study year. We conducted two comparisons: one to examine total population size structure and one to examine changes in adult size structure. Based on the results of this examination, we performed a nonparametric analysis of length data using the multiple comparison procedure outlined by Ott and Longnecker (2010) to identify significant differences in mean length rank (α=0.05) among years.

To interpret the magnitude of year-to-year differences in size-structure, we calculated the 25%, 50%, and 75% quartiles of the length of both the total and the adult shortnose population. In the total population, decreases in the 25% quartile of length between years that were significantly different were interpreted as the entry of new juveniles to the population. Similarly, within the adult population, decreases in the 25% quartile between years that were significantly different were interpreted as the entry of juveniles to the adult population.

Results:

From 2004 and 2010, we set a total of 1,173 nets yielding a total catch of 1,737 shortnose (Table 2.1). Total annual effort varied from a min of 89.1 net-hours in 2004 to a max of 255.2 net-hours in 2010. Likewise, total catch varied annually, from a high of 412 individuals (15 recaptures) in 2004, to only 116 individuals (4 recaptures) in 2009. Annual catch of juveniles was highly variable, ranging from 6 individuals (0 recaptures) in 2009 to 265 individuals (10 recaptures) in 2004. Adult catch was less variable, ranging from 56 individuals (1 recapture) in 2006 to 211 individuals (14 recaptures) in 2010.

The results of our Huggins closed-capture models demonstrated that in four of seven years, models excluding a linear or quadratic relationship between length and capture probability had the greatest weight of evidence, suggesting a lack of size-selective bias during most years. For consistency, we based all subsequent inferences of abundance on only the yearly model that considered capture probability constant between juveniles and adults and that excluded an effect of length on capture probability. Our assessment of shortnose occurrence above and below the freshwater-saltwater interface resulted in the capture of zero shortnose, providing evidence that shortnose were not abundant above or below this section. As such, the requirement for population closure appears to have been met.

Total shortnose abundance was variable, ranging from a low of 1206 (95% C.I. 566 - 2759) in 2009 to a high of 5551 (95% C.I. 2804 - 11304) in 2005, with a total CV of 56.6% (Figure 2.3). Juvenile abundance varied from a low of 62 (95% C.I. 24 - 181) in 2009 to a high of 3467 (95% C.I. 1744 - 7095) in 2006 with a total CV of 88.9% (Figure 2.4). Adult abundance was comparatively constant, ranging from a low of 707 (95% C.I. 367 - 1421) in 2005 to a high of a 2122 in 2006 (95% C.I. 1,059 - 4,377) with a total CV of 32.0% (Figure 2.4).

Our non-parametric multiple comparison procedure of the total population indicated that the size-structure of the total population was significantly different during each year of the study (P <0.001). Annual 25% quartile size ranged from a low of 311 mm FL in 2004 to a high of 561 mm FL in 2009 (Figure 2.5). Decreases in 25% quartile size indicated the entry of juveniles to the population in 2004, 2006, and 2010. Within the adult population, five significantly different FL groups were present (Figure 2.6). The annual 25% quartile size of the adult population ranged from a low of 521 mm in 2007 to a high of 604 mm in 2010. Decreases in 25% quartile size indicated the entry of new individuals to the adult population in 2005 and 2006.

Discussion:

The results of this study provide the first sequential, multi-year assessment of abundance and size-structure of shortnose within a southern river system. Our highest estimate of total abundance, which reached a high of 5551 in 2006, was more than double that of the Pee-Dee (N=1000; citation) and the Savannah Rivers (N=1676; citation) and confirm that the Altamaha River shortnose population is the largest known population south of the Delaware River. Our study also showed that although the Altamaha population was characterized by stable adult abundance, even our highest abundance estimate was an order of magnitude lower than that of some northern populations, such as the St. John (N=18000; Dadswell 1979), Hudson (N=56708; Bain 2001 in Woodland and Secor 2007), and Delaware Rivers (N=14000; O'Herron et al. 1993). The results of our size-structure analysis, which indicated that the Altamaha population displayed rapid juvenile growth, early onset-of-maturity, and high levels of population turnover, may help explain why southern populations are typically smaller than those found in the northern half of the species' range.

Like other populations throughout the species range, the Altamaha shortnose population exhibited wide variation in annual recruitment. In this study, we observed about a 50 fold variation in annual juvenile abundance. Based on the rapid shifts in annual size structure we observed, it seems likely that strong year classes were produced in only three of the seven years of our study. Although confirmatory studies are needed for other southern populations, Woodland and Secor (2007) also observed variable year class strength in both the Hudson (CV=66.0%) and St. John Rivers (CV=44.0%) sns populations. Because shortnose are iteroparous, highly fecund, and long lived, their populations are well buffered against annual variation in recruitment caused by stochastic events such as drought, floods, etc. Hence, variable juvenile abundance is probably typical of healthy shortnose populations – in both northern and southern river systems.

Adult abundance was significantly less variable than juvenile abundance and was not significantly different during any year of the study. Interestingly, previous studies have documented similar patterns in other populations. A recent study of shortnose on the Ogeechee River (Peterson and Farrae 2011) documented a comparable level of population variability (CV=33.0%). Although Bain et al. (2007) did not provide a quantitative estimate of variability in annual adult abundance, their data showed that the adult shortnose abundance on the Hudson River was steady over the 4 yrs of their study.

Rapid and substantial shifts in adult size-structure have not been reported for other shortnose populations, yet we documented five significantly differing size-structure groups from 2004 -2010. Changes in adult size-structure in the Altamaha River population were clearly caused – at least in part - by the recruitment of juveniles to the adult population. Based on significant differences in size-structure and associated decreases in the 25% quartile of the adult population from 2005-2006 and again from 2006-2007, we inferred that juveniles present in 2004-2006 grew rapidly and recruited to the adult population in subsequent years. This observation was consistent with a previous study by Dadswell et al. (1984) who concluded that the mean age at maturity for the Altamaha populations was 2 to 4 years. In contrast, data from Dadswell (1979) showed that adult size-structure did not appear to change from 1974 to 1975 in the St. John River, Canada. Stable size-structures in northern systems are probably attributed to regional variations in growth and age-at-maturity; in contrast to the Altamaha population, shortnose in the Hudson and St. John Rivers reach maturity at 4-10 and 10-20 yrs, respectively (Dadswell et al. 1984). In short, slower growth and a delayed age-at-maturity in northern shortnose populations may dampen annual variations in adult size structure resulting from annual variations in recruitment.

The combination of rapid juvenile growth, and relatively early age-at-maturity observed here suggested that adult abundance in the Altamaha shortnose population would increase sharply in the latter years of our study, yet our data showed that the adult population was remarkably stable. Although the imprecision of our abundance estimates may have limited our ability to detect slight changes in adult abundance, the recruitment of >3,000 juveniles to an adult population of ~1500 should have been obvious. We attribute the stability to a relatively high rate of population turnover. Several mechanisms may foster rapid turnover. First, density dependent factors may have increased juvenile mortality as strong year classes approached adulthood. However, decreases in the 25% quartile of the adult population indicate that enough juveniles survived to shift the adult size structure. Because adult abundance did not increase, recruitment of juveniles must have been offset by an increase in adult mortality, emigration, or both.

Recent genetic evidence from Wirgin et al. (2010) indicates that shortnose in southern rivers exhibit a much higher degree of population mixing than previously thought. In fact, Peterson and Farrae (2011), who documented recurring movement of adult shortnose between the Altamaha and Ogeechee rivers, concluded that these systems may actually support a single metapopulation, with Altamaha emigrants functioning to supplement poor recruitment within the Ogeechee system. Although the causal mechanisms of shortnose emigration are unclear, previous studies by Kynard (1997) suggest that resource limitations within natal rivers may be an important factor. If correct, this hypothesis would suggest that the Altamaha population may have been at or near its carrying capacity during the years of our study.

Though the threshold for minimum viable population size is uncertain, there is little doubt that the probability of long-term persistence of a population is positively related to total abundance (Schaffer 1981). As such, abiotic constraints on habitat availability may be particularly important to the viability of shortnose populations in southern rivers like the Altamaha, where total abundance is < 6000 individuals. Moreover, because southern shortnose populations exhibit high rates of turnover and a reduced adult longevity, they may be particularly sensitive to any type of human disturbance that increases variability in annual recruitment. Reduced longevity of southern shortnose may limit the ability of southern populations to persist when human disturbances exacerbate or prolong the interval of recruitment failure. Undoubtedly, further studies are needed to quantify interactions among habitat availability, survival, environmental variation, recruitment success, and long-term viability of southern shortnose populations. Once these linkages are identified, managers will be better able to construct river-specific recovery plans that can help ensure the long-term persistence of shortnose in southern river systems.

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Table 2.1: Annual sampling effort and catch of juvenile (< 499 mm FL) and adult (>500 mm FL) shortnose sturgeon, *Acipenser brevirostrum*, in the Altamaha River, Georgia from 2004-2010.

			Juvenile		**Adult**	
Year	**Sample Period**	**Effort (net-hours)**	**Marked**	**Recaptured**	**Marked**	**Recaptured**
2004	May 30th to August 7th	89.1	265	10	147	5
2005	June 5th to August 13th	144.8	163	7	56	1
2006	June 4th to August 5th	104.0	182	6	112	1
2007	June 3rd to August 12th	123.6	88	3	89	2
2008	June 8th to August 9th	140.7	23	1	184	10
2009	May 31st to August 8th	160.1	6	1	110	3
2010	May 31st to August 1st	255.2	101	8	211	14

Figure 2.1: Map of Altamaha River (Estuarine section in inset). Black diamonds represent individual sampling locations. Solid line represents upstream incidence of shortnose sturgeon, *Acipenser brevirostrum*, capture between 2004-2010. Double line represents downstream incidence of shortnose sturgeon capture. Interstate 95 and Georgia State Route 17 supplied for spatial reference.

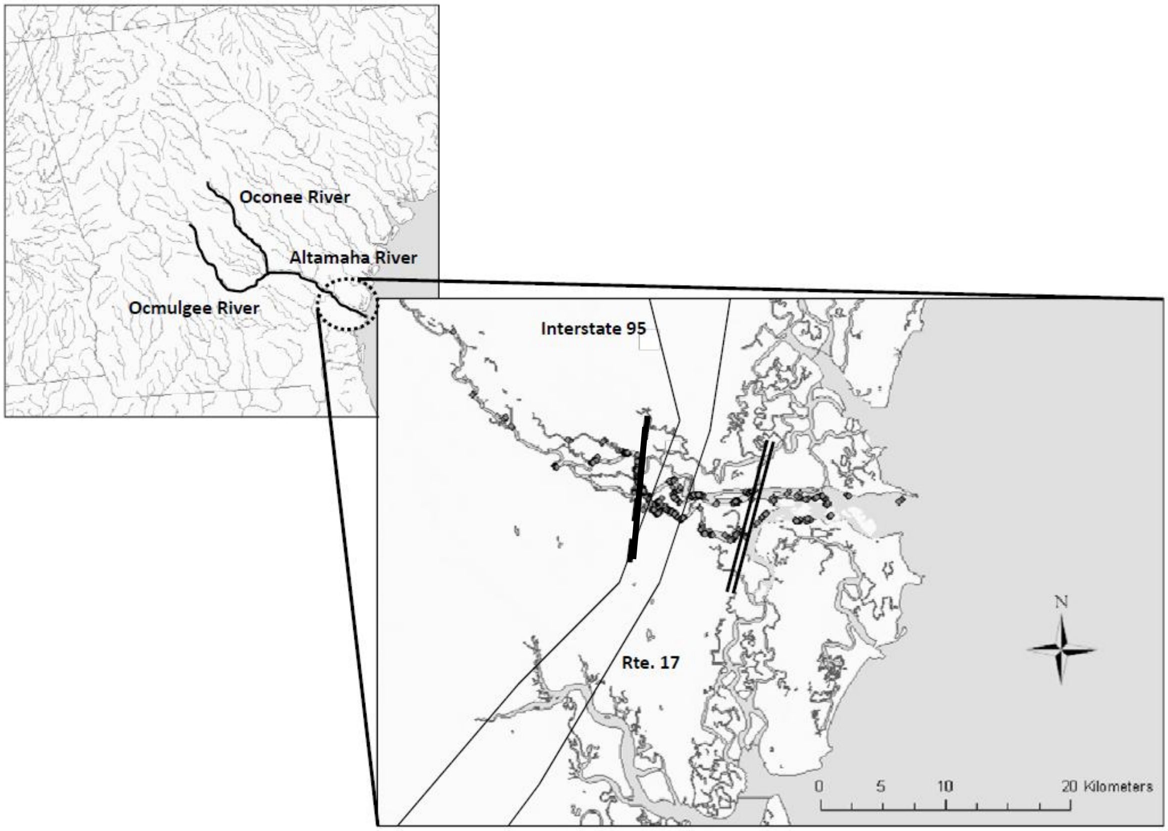


Figure 2.2: Relative proportion of shortnose sturgeon, *Acipenser brevirostrum*, contained within 10 mm size groups. Separation between between juvenile and adult individuals indicated by vertical line at 500 mm.

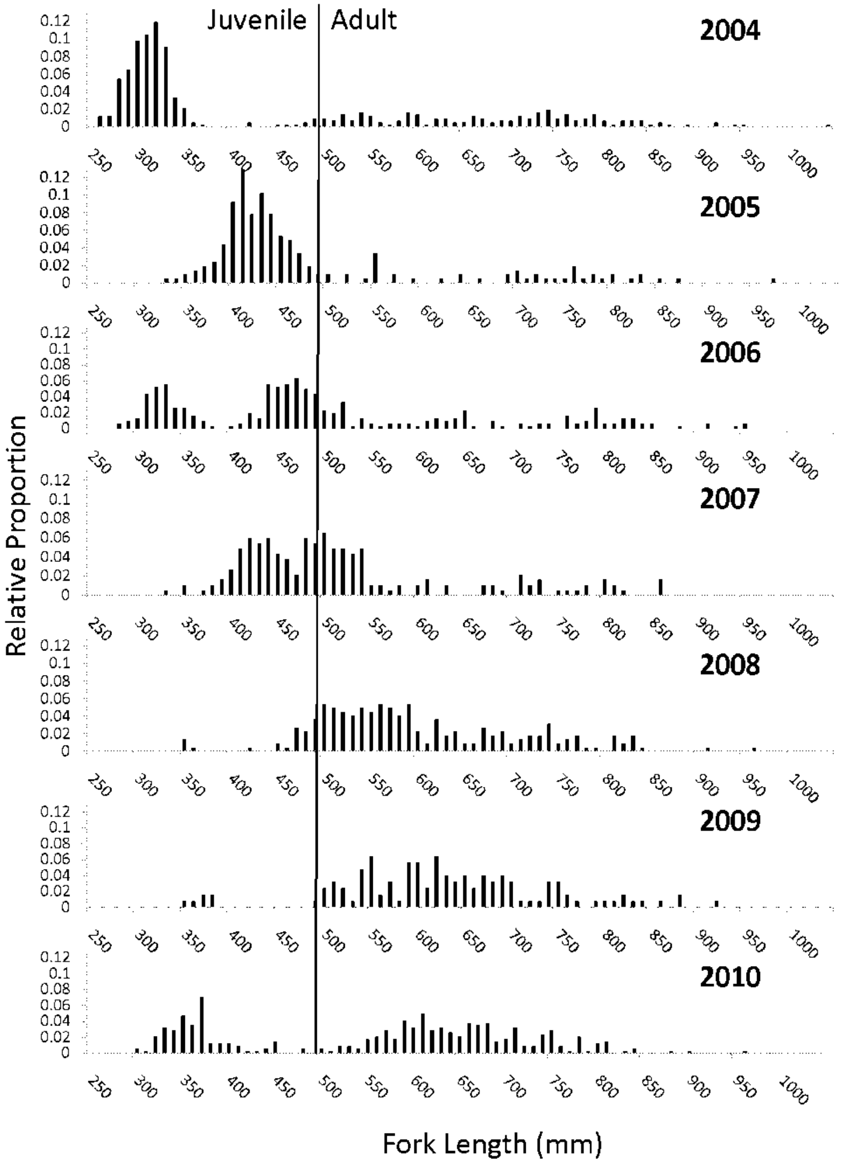


Figure 2.3: Total abundance, 2004-2010 of Altamaha River shortnose sturgeon, *Acipenser brevirostrum*. Error bars represent 95% lognormal confidence intervals.

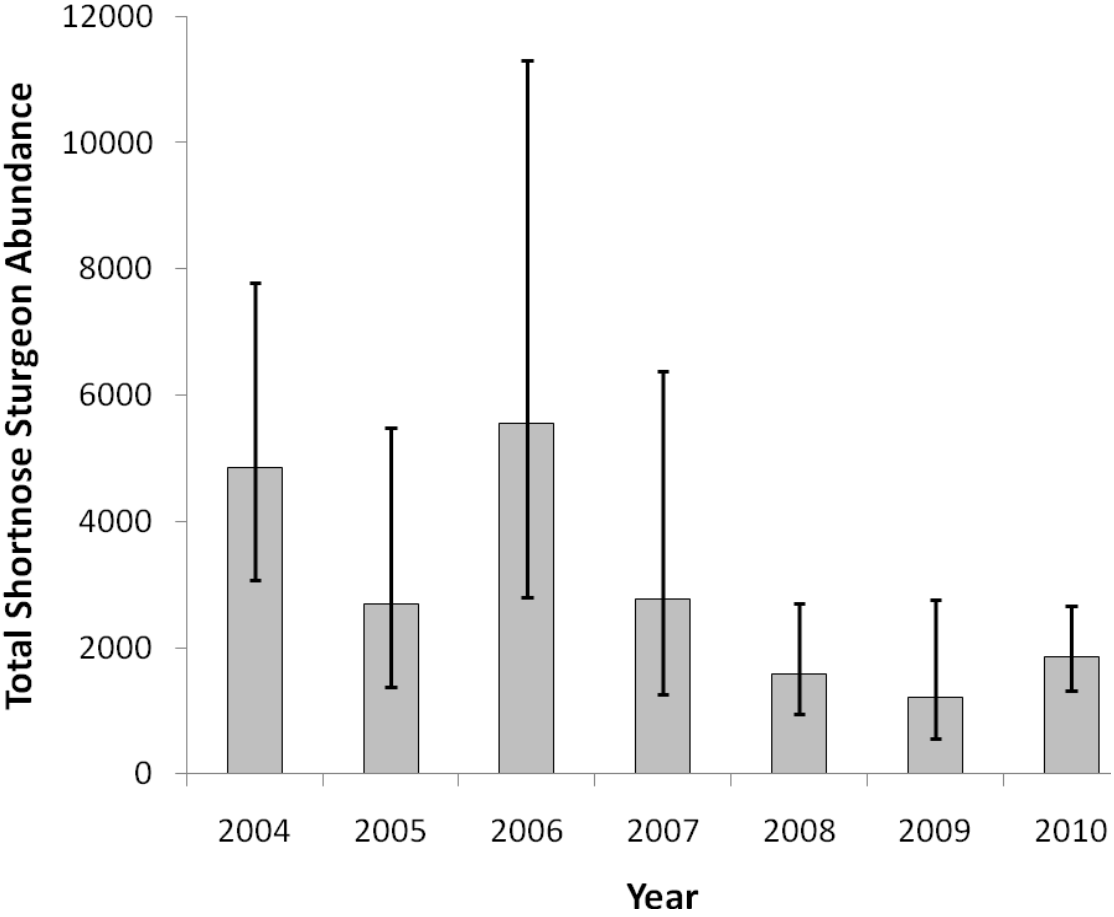


Figure 2.4: Abundance of juvenile and adult shortnose sturgeon, *Acipenser brevirostrum*, in the Altamaha River from 2004-2010. Error bars represent 95% lognormal confidence intervals.

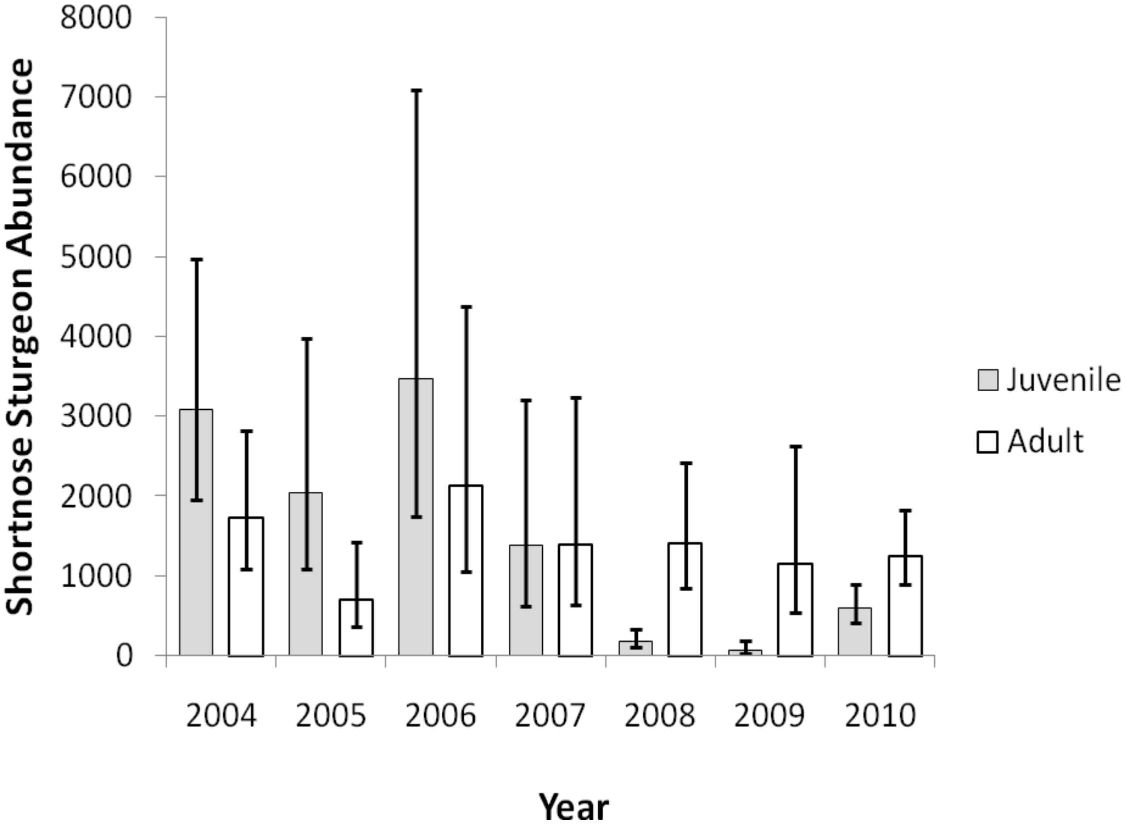


Figure 2.5: First, second and third quartile of fork length (FL) of shortnose sturgeon, *Acipenser brevirostrum*, in the Altamaha River, Georgia from 2004-2010. All years were significantly different (α=0.05) from each other, based on the non-parametric multiple comparison procedure of Longnecker and Ott (2010).

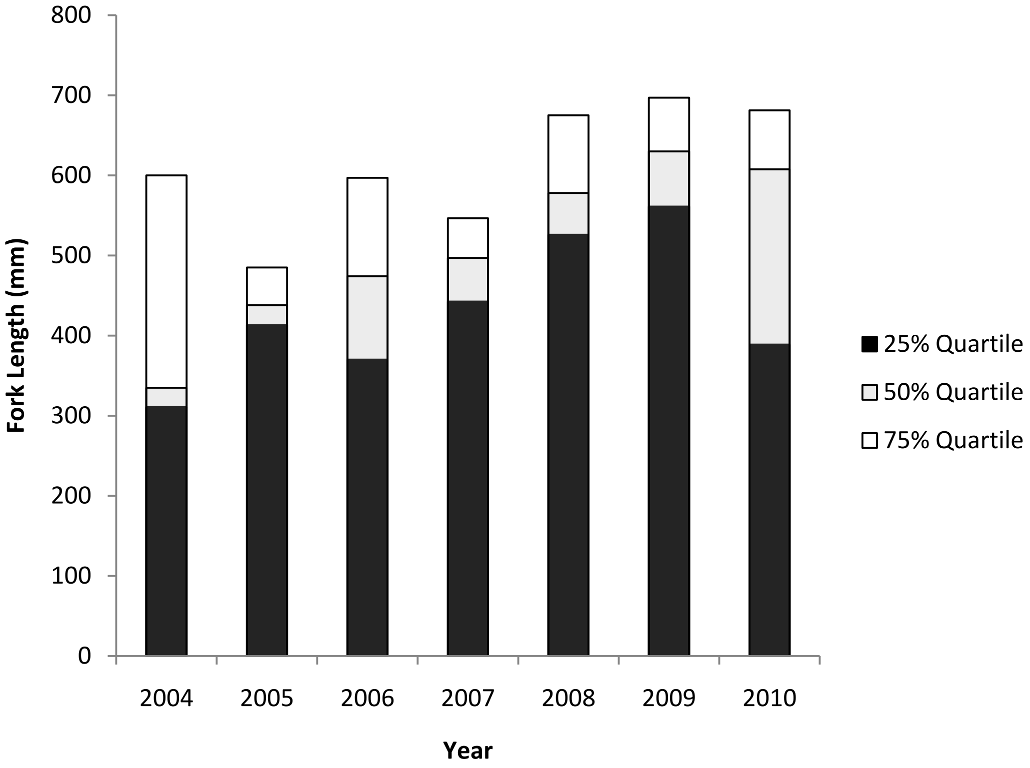
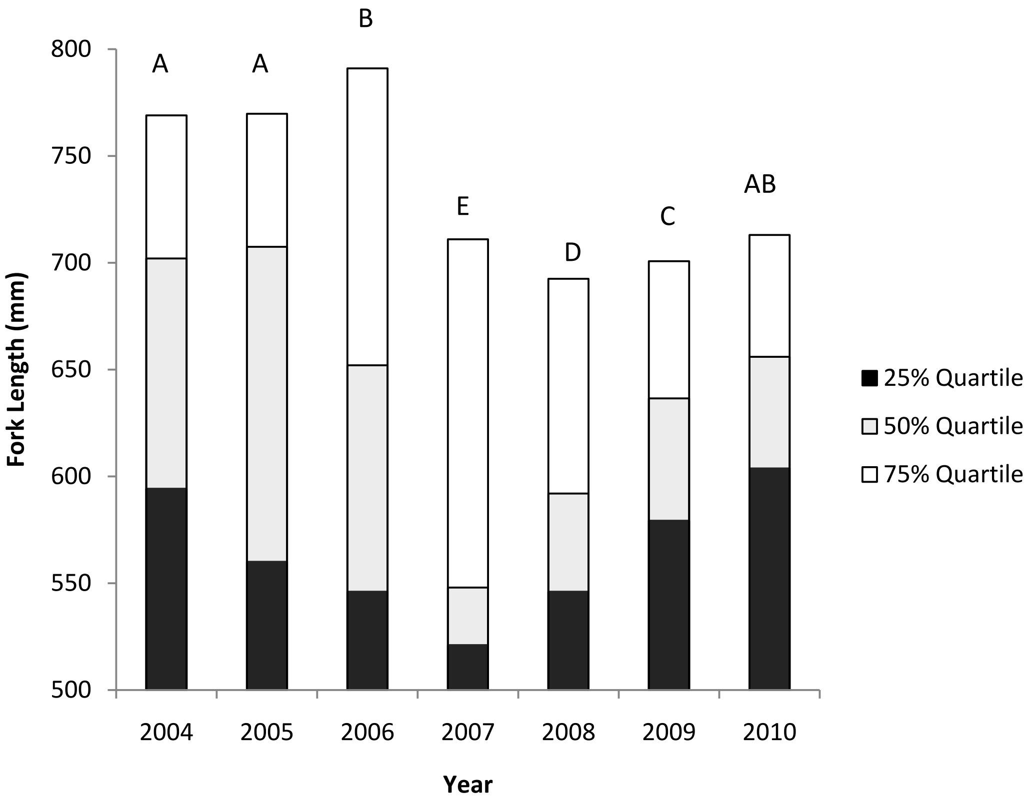


Figure 2.6: First, second and third quartile of fork length (FL) of adult shortnose sturgeon, *Acipenser brevirostrum*, in the Altamaha River, Georgia from 2004-2010. Letters above each year represent statistically significant groups (α=0.05) based on the non-parametric multiple comparison procedure of Longnecker and Ott (2010).



CHAPTER 3

INFLUENCES OF SEASONAL RIVER FLOW ON SHORTNOSE STURGEON, *ACIPENSER BREVIROSTRUM*, IN THE ALTAMAHA RIVER, GEORGIA[1]

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[1] Bednarski, M.S. and D.L. Peterson. To be submitted to *Environmental Biology of Fishes*

Abstract:

The shortnose sturgeon, *Acipenser brevirostrum,* is a long-lived endangered fish that inhabits most large tidal rivers along the Atlantic coastline of North America. Limited information exists regarding shortnose reproduction and the interactions between saltatory development, riverine condition, and subsequent recruitment to the population, particularly for populations south of the mid-Atlantic bight. To effectively conserve and restore shortnose sturgeon, further assessments are needed to determine the influences of environmental factors, such as flow, on juvenile recruitment. To address this information gap, the objectives of our study were to 1) characterize recent juvenile recruitment of shortnose within the Altamaha River, Georgia and 2) to determine the effects of flow on age-1 recruitment. We sampled shortnose using entanglement gear during the summer months in the Altamaha River. From 2004-2010, 1,737 individuals (72 recaptures) were captured and used length-frequency histograms to identify age-1 individuals. We used the Huggins closed-capture model to calculate estimates of age-1 abundance We then used age-1 population estimates as a measure of juvenile recruitment and compared these estimates to seasonal river flow. Age-1 abundance was variable (30-2,976 individuals) and positively correlated with prolonged high flow (>75th percentile) during the pre-spawn, spawn, and early young-of-year periods. Results suggest that high flow during the spawning period is required to establish a strong year-class within the Altamaha River. Our findings provide critical information for understanding the ecology and population dynamics of shortnose at the southern edge of their range.

Keywords: Recruitment, shortnose sturgeon, endangered, flow

Introduction:

The shortnose sturgeon, *Acipenser brevirostrum*, is a long-lived amphidromous species that inhabits most large tidal rivers along the Atlantic coastline of North America, ranging from the St. John River, Canada, southward to the St. John’s River in northern Florida (Kynard 1997, Dadswell et al. 1984, Vladykov and Greeley 1963). Like most other sturgeons, shortnose exhibit a complex life cycle characterized by a discrete egg, prolarval, larval, juvenile and adult life stage (Kynard 1997, Dadswell et al. 1984, Dadswell 1979). Throughout their range, shortnose populations have declined precipitously because of overfishing, dam construction, habitat loss, and industrial pollution (Collins et al. 2000, NMFS 1998). Of existing populations, those occurring in systems north of the mid-Atlantic Bight appear substantially larger than those in the southern portion of the range. Specifically, recent estimates suggest that the St. John River, Canada, the Kennebec/Androscoggin River, Maine, the Hudson River, New York, and the Delaware River, Delaware all contain populations >7,000 individuals. In contrast, no populations south of the Delaware River appears to contain >3,000 individuals (NMFS 1998, Kynard 1997).

In an effort to recover shortnose populations, the National Marine Fisheries Service (NMFS) authored a comprehensive recovery plan that focused on the assessment, conservation, and restoration of the species throughout its range (NMFS 1998). Before this plan can be implemented, studies are needed to identify and accurately quantify the factors that affect juvenile recruitment. Limited information exists regarding this demographic parameter, which because of the long life span, late age-at-maturity, and high fecundity, is critically important to determining status of individual shortnose populations (Gross et al. 2002). Recent work in the Hudson River, New York, by Woodland and Secor (2007) illustrates the importance of quantifying recruitment dynamics for this species. Over an 8-yr period from 1980-1998, these authors estimated a >300% increase in shortnose abundance resulting from an unusual period of persistently high juvenile recruitment.

In northern systems, shortnose recruitment appears positively correlated with prolonged periods of high discharge just prior to spawning, suggesting that spring flows may be a primary factor affecting reproductive success (Woodland and Secor 2007). Because of increasing groundwater withdrawal, persistent drought, and continued urban and agricultural development in the southeastern US, water resources are likely to become increasingly scarce in the future (USGS 2012, Marella and Berndt 2005). However, no studies have explored the linkages between juvenile recruitment, saltatory development, and flow in southern river systems. Several recent studies suggest that many southern shortnose populations may routinely suffer from prolonged periods of recruitment failure (Peterson and Farrae 2011, Smith 1995). Given the strong linkage between recruitment and population growth rate documented in northern systems, clinal differences in reproductive success may explain why southern populations are so much smaller. Unfortunately, the lack of shortnose recruitment assessments in southern systems precludes any direct comparison of recruitment dynamics in northern and southern populations This relationship between flow and shortnose recruitment must be understood to ensure that future watershed alterations do not adversely affect recovery of southern shortnose populations.

The largest and most viable southern shortnose population appears to occur in the Altamaha River, Georgia, a relatively unaltered southern river system. Recent research has shown that shortnose abundance in this system has recently exceeded 5,000 individuals because of strong year classes produced between 2004 and 2008 (Bednarski and Peterson – Chapter 2). Several researchers attribute the relatively high abundance of the shortnose in the Altamaha to the relatively undeveloped condition of its watershed. In contrast to most other Atlantic coast systems, the Altamaha River is undammed, providing anadromous fishes with complete access to all historic spawning habitats (Collins et al 2000). Moreover, because limestone shoal habitat is common above rkm 100 and represents known and suspected shortnose spawning areas within this system, spawning habitat does not appear to limit this population (DeVries and Peterson 2006, Collins et al. 2000). Accordingly, the Altamaha River provides a unique opportunity to assess shortnose recruitment in a relatively intact southern river system. The objectives of this study were to 1) characterize recent recruitment and 2) evaluate the specific influence of riverine flow on shortnose reproductive success and juvenile recruitment in the Altamaha River, Georgia.

Methods:

Study Site:

The Altamaha River is formed by the confluence of the Ocmulgee and Oconee Rivers near Lumber City, Georgia. From there, it flows approximately 212 rkm to its outlet to the Atlantic Ocean, located approximately 1 km south of Darien, Georgia (Figure 3.1). The Altamaha River's freshwater discharge averages just over 380 m^3/second per year, making it one of the largest sources of freshwater on the US Atlantic coast of the United States. In total, the Altamaha/Ocmulgee/Oconee River complex consists of 662 km (ASSRT 2007) of free flowing habitat and comprises the longest free flowing riverine system on the east coast of North America.

Sampling:

We sampled shortnose in seven consecutive summers from 2004 – 2010. Most samples were collected during May, June, July and August when shortnose are primarily found in the oligohaline portions of the Altamaha Estuary, just upstream of the freshwater-saltwater interface (Collins et al. 2000, Flournoy et al. 1992). Because this portion of the river contains abundant large woody debris, we selected individual sampling sites wherever clean bottom could be identified using basic sonar equipment. Shortnose were captured using anchored experimental monofilament gill and trammel nets. Each net was 91.4 meters long, 3.3 meters deep, and constructed of a 15.9 mm diameter foamcore floatline and a 124 g/m lead-core mudline. Experimental gill nets were constructed of one panel each of 7.6, 10.2, and 12.7 cm monofilament mesh (stretch measure). Trammel nets were constructed of two outer panels of 15.2-cm mesh and an inner panels of 7.6 cm mesh. Nets were typically soaked for 20-40 minutes primarily during slack tides maximize overall effectiveness (D. Peterson unpublished data).

Upon capture, each shortnose was placed into a floating net pen tethered alongside the research vessel. Each individual was then measured (fork length; FL) and scanned for a 125 kHz passive integrated transponder (PIT) tag. If a PIT tag was not detected, we inserted one into the musculature under the fourth dorsal scute. We returned all shortnose to the river at their capture site within 45 minutes of capture.

Data Analyses:

During each year of the study, we assigned each shortnose captured to a specific life stage – age-1, age-2+ juvenile, or adult based on annual length-frequency histograms as described by (DeVries and Frie 1996). We assigned all shortnose greater than 500 mm FL to the adult life history stage (Kynard 1997).

Annual abundance of each successive age-1 cohort was then estimated using the Huggins closed-capture model in Program MARK (White and Burnham 1999, Huggins 1989). We constructed separate estimation models for each year of the study. Because shortnose appear to become intolerant of salinities >4.2 ppt at temperatures above 27° C, we assumed that the population was closed to immigration and emigration during the entire summer sampling period (Collins et al. 2000). For all models, we varied capture probability between sampling events and assumed that capture and recapture probabilities were equal. To test for size-selective biases, we used Akaike's Information Criteria with the small sample size-adjustment (AICc; Hurvich and Tsai 1989, Akaike 1973) to compare a model that excluded an effect of individual FL on capture probability to two other models, one that incorporated a linear relationship between individual FL and capture probability and one that included a quadratic relationship between individual FL and capture probability. Based on this initial analysis, we subsequently considered capture probability equal among all sizes. To evaluate the relative precision of age-1 population estimates, we calculated 95% lognormal confidence intervals within Program MARK. We quantified annual variation in recruitment by calculating the coefficient of variation (CV) of the point estimates of age-1 abundance (Woodland and Secor 2007, Rothschild and DiNardo 1987).

We used linear regression to assess the effect of riverine flows during the young-of-year stage on recruitment to the age-1 stage (Neter et al. 1990). As our response variable, we used the point estimate of age-1 abundance for each year of the study. To identify potentially relevant biological predictor variables, we constructed a conceptual model of the species' spawning and developmental cycles specific to the southeastern United States, which allowed us to infer the specific saltatory developmental stages that appeared most sensitive to river flow (Figure 3.2). For each of these periods, we calculated the cumulative duration, in days, when flow exceeded the 75th percentile during each spawning and/or developmental period. The 75th percentiles for flow data were based on the period from 1 October 1970 to 16 August 2010 and determined using the Indicators of Hydrogic Alteration Version 7.1.0.10 Software (The Nature Conservancy, 2009). All flow data were obtained from the United States Geological Survey stream gage #0225000 located in Baxley, Georgia, just downstream of previously documented spawning habitats for shortnose (DeVries and Peterson 2006). Using these data, we constructed 29 linear regression models relating age-1 abundance to cumulative high flow duration (HFD) occurring during either one or two spawning and/or developmental periods. For each model we then calculated the variance inflation factor (VIF) of each predictor (Ott and Longnecker 2010). Any model including a predictor variable with a VIF > 5.0 was excluded from further evaluation because of probable multicollinearity. The relative weight of evidence for each specific model was evaluated using AICc as described by Burnham and Anderson (2002). Any model with >12.5% of the weight of the model with the greatest weight of evidence was included into the confidence set (Royall 1997). To assess the relative importance of each spawning and/or developmental period to the recruitment of age-1 shortnose, we then calculated the cumulative importance weight of each period based on its relative weight of evidence within the candidate set of models. The overall fit of each linear regression model was determined by calculating its coefficient of determination (Ott and Longnecker 2010).

Results:

From 2004-2010, we set a total of 1,173 individual nets and captured 1,737 unique shortnose (Table 3.2). Annual effort varied from 104 nets in 2004 to 344 nets in 2010. After constructing length-frequency histograms for each year of the study, we identified 437 individuals as age-1 juveniles (Figure 3.3). Annual catch of age-1 juveniles varied from a low of only 3 individuals in 2007 to a high of 253 individuals in 2004. The maximum size of age-1 individuals ranged from a minimum of 380 mm FL in 2004 to a maximum of 410 mm FL in 2010.

The results of our Huggins closed-capture model showed that in four of seven years, the model with the greatest weight of evidence excluded an effect of FL on capture probability, indicating that our assumption of constant capture probability for age-1, age-2+ juvenile, and adult individuals was appropriate. Hence, we were then able to estimate age-1 cohort size during years with few recaptures by applying information regarding capture probabilities of juvenile and adult individuals to that of age-1 individuals. For consistency among years, we based all subsequent inferences of annual age-1 cohort abundance on the model that considered capture probability constant among age-1, age 2+ juveniles, and adults.

Annual estimated age-1 abundance cohorts varied from a low of 30 (95% C.I. 13-85; figure 3.4) in 2008, to a high of 2976 (95% C.I. 1880-4810) with a CV of 151. Cohort abundance displayed a positive exponential relationship with the duration of high flow during the late pre-spawn, spawn, and early young-of-year periods (Figures 3.5-3.7). Because of apparent multicollinearity between HFD during the proposed late pre-spawn and early young-of-year periods (VIF=8.76), the model including both of these predictor variables was excluded from further consideration. All three models within the confidence set explained >89% of annual recruitment variation we observed (Table 3.3). The spawning/developmental period with the greatest importance weight was the early young-of-year period, with a weight of 0.524 (Figure 3.8).

Discussion:

Our results demonstrate that recent levels of shortnose recruitment in the Altamaha River are consistently lower than those documented in northern rivers. Further corroborative studies are needed, but existing data suggest that latitudinal differences in recruitment dynamics may explain why the major populations in the northern portion of the range are vastly larger than their southern counterparts. For example, age-1 abundance in the Altamaha peaked at 2,976 individuals during our study. In contrast, Woodland and Secor (2007) estimated that age-1 abundance in the Hudson River varied from 5,961 - 52,044 from 1980 and 1998. These authors showed that adult abundance also increased proportionately during this period. The most recent estimate of the Hudson population - 56,708 individuals - is an order of magnitude greater than that reported for the Altamaha River (Chapter 2). Given the relationship between age-1 recruitment and adult abundance, we suspect that differences in maximum recruitment rates and adult longevity are probably responsible for differences in population abundance documented for the major northern systems and that of southern populations.

Although recruitment variability appears common among many SNS populations, our observed CV, 151%, is the highest recorded. Previous studies of the St. John and the Hudson Rivers, estimated age-1 recruitment CVs of only 44% and 66%, respectively, values less than half of that obtained in this study. We suggest this relative high level of recruitment variability directly contributes to the relatively low abundance of southern shortnose populations. This assertion is supported by recent findings of Bednarski and Peterson, (Chapter 2) who documented significant shifts in adult shortnose age structure in the Altamaha population resulting from wide variations in annual recruitment. The results of this study suggest that the observed shifts in size structure were probably attributable to the maturation of the 2004 and 2006 age-1 cohorts. Furthermore, although our results confirm that the Altamaha population is the largest south of the Delaware, but also show that the spawning population is comprised primarily of only 2 year classes. In contrast, adult populations in northern rivers typically contain individuals from at least 25 discrete year classes. Future studies are needed to determine if recruitment variability documented in this study is typical of other southern river systems.

The results of our linear regression analyses identified high flow duration during the period immediately after the spawning period as the single most important factor affecting year-class strength of shortnose in the Altamaha River. Secondarily, our results indicated a high importance weight for both the pre-spawn and spawning periods. In fact, all models within our confidence set, each of which incorporated flow during one or two of these periods, explained >89 % of the total variation in annual recruitment we observed. Although the strong fit of our models may be attributed to the fact to having relatively few years of data, the precision of each of our parameter estimates suggests that it is unlikely that such a strong relationship between high flow duration and annual recruitment would result from random chance. Thus, we conclude that sustained periods of high flow before, during, and immediately after the spawning period are required to establish a strong year class of shortnose sturgeon in the Altamaha River. Because a similar relationship appears to occur within the Hudson River, it appears that shortnose populations, in both northern and southern systems, are dependent on prolonged periods of suitable flow during the spawning season.

Ultimately, our results provide quantified evidence that sustained high flows before, during, and after the spawning period are critical for the survival of age-0 shortnose in southern systems. Although further studies are needed to determine if recruitment in other southern populations is similarly affected, we hypothesize that spring flows may be equally important for shortnose in other southern rivers. Given the depressed status of many of these southern populations, we suggest that future restoration efforts focus on protection of natural flow regimes, particularly during and immediately after the spring spawning period. Furthermore, we suggest that future studies explore the linkages between flow and shortnose survival through the use of laboratory controlled micro- and mesocosm experiments designed to determine how different flow-related mechanisms influence shortnose recruitment.

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Figure 3.6. Relationship between age-1 shortnose sturgeon, *Acipenser brevirostrum*, abundance and the duration of high flow (>75th percentile, HFD) that occurred during the proposed early young-of-year period. Diamonds indicate age-1 abundance estimates determined from the Huggins closed-capture models.

Figure 3.7. Relationship between age-1 shortnose sturgeon, *Acipenser brevirostrum*, abundance and the duration of high flow (>75th percentile, HFD) that occurred during the proposed spawning and early young-of-year period. Dashed line represents the influence of early young-of-year HFD on age-1 abundance, solid line represents the influence of spawning HFD on age-1 abundance.

Figure 3.8: Relative importance weights of prolonged high (>75th percentile) flow during each proposed shortnose sturgeon, *Acipenser brevirostrum*, spawning/developmental period in the Altamaha River.

Table 3.1: Description and biological hypothesis of each shortnose sturgeon, *Acipenser brevirostrum*, spawning and/or developmental periods used to assess age-1 recruitment. Citations given were used to construct specific spawning/developmental periods.

Flow Period	**Inferred Spawning/Developmental Period**	**Citation**
October-November (prior to young-of-year)	Early Pre-Spawn: Prolonged high flow during the beginning of the pre-spawn period is necessary to cue adults to undertake a spawning migration	Woodland and Secor 2007
December-January (prior to young-of-year)	Late Pre-Spawn: Prolonged high flow immediately prior to the spawning period is necessary to cue adults to undertake a spawning migration	Buckland and Kynard 1985, Rogers and Weber 1995
February-March (young-of-year)	Spawning: Prolonged high flow during the spawning period is necessary to ensure egg, prolarval, and larval survival	Gilbert and Heidt 1979, Rogers and Weber 1995, Richmond and Kynard 1995
April-May (young-of-year)	Early Young-of-Year: Prolonged high flow during the larval and juvenile life stages is required to ensure survival and efficient downstream export	Richmond and Kynard 1995
June-Aug (young-of-year)	Summer Young-of-Year: Prolonged high flow during the juvenile life stage is required to ensure survival and the availability of suitable nursery habitat	Jenkins et al. 1993, Collins et al. 2000, Ziegweid et al. 2008
September-October (young-of-year)	Fall Young-of-Year: Prolonged high flow during the juvenile life stage is required to ensure survival and the availability of suitable nursery habitat	Ziegweid et al. 2008

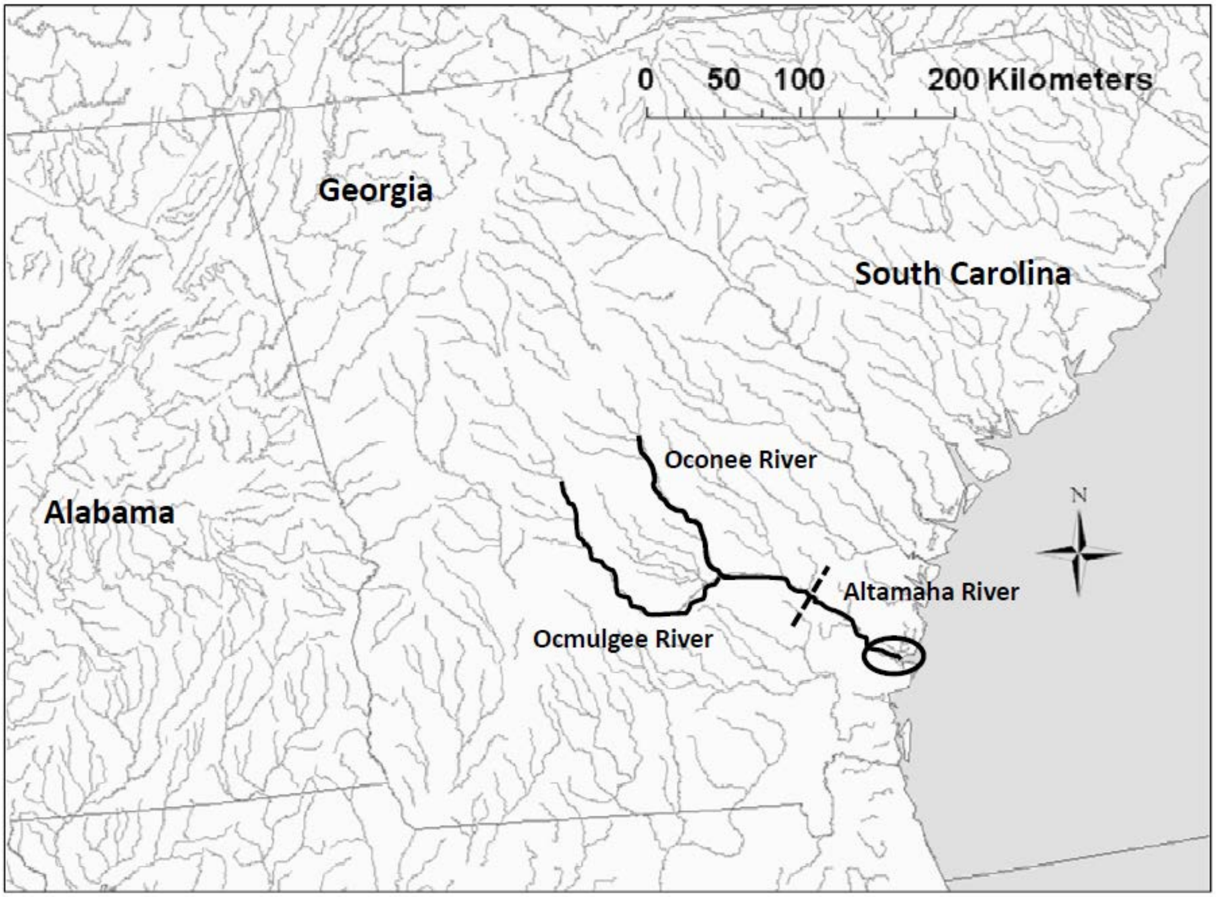
Table 3.2: Sampling period, sampling effort, and total annual age-1, juvenile, and adult shortnose sturgeon, *Acipenser brevirostrum*, catch in the Altamaha River between 2004-2010.

			Age-1		**Age-2+ Juvenile**		**Adult**	
Year	**Sample Period**	**Effort (net-hours)**	**Marked**	**Recaptured**	**Marked**	**Recaptured**	**Marked**	**Recaptured**
2004	May 30th to August 7th	89.1	253	10	12	0	147	5
2005	June 5th to August 13th	144.8	9	0	154	7	56	1
2006	June 4th to August 5th	104.0	77	3	105	3	112	1
2007	June 3rd to August 12th	123.6	3	0	85	3	89	2
2008	June 8th to August 9th	140.7	4	0	19	1	184	10
2009	May 31st to August 8th	160.1	5	1	1	0	110	3
2010	May 31st to August 1st	255.2	86	8	15	0	211	14

Table 3.3: Akaike's information criteria with the small sample adjustment (AICc), coefficient of determination (r^2), change in AICc (Δ AICc) and relative weight of the top ten models relating age-1 shortnose sturgeon abundance to high flow duration during proposed spawning/developmental periods. Models in bold represent those contained within the confidence set.

Predictor (s)	AICc	R^2	ΔAICc	Relative weight
Late Pre-Spawn Flow	**24.972**	**0.902**	**0.000**	**0.458**
Early Young-of-Year Flow	**25.483**	**0.894**	**0.511**	**0.355**
Spawning Period and Early Young-of-Year Flow	**26.992**	**0.982**	**2.020**	**0.167**
Summer Young-of-Year Flow	32.799	0.700	7.827	0.009
Spawning Period Flow	34.788	0.601	9.816	0.003
Late Pre-Spawn and Spawning Period Flow	35.653	0.939	10.680	0.002
Early Pre-Spawn Flow	35.491	0.559	10.518	0.002
Early and Summer Young-of-Year Flow	36.100	0.935	11.128	0.002
Early and Late Pre-Spawn Flow	38.803	0.904	13.830	0.000
Fall Young-of-Year Flow	41.221	0.000	16.249	0.000

Figure 3.1. Map of the Altamaha River system showing the Altamaha, Ocmulgee, and Oconee Rivers. The dashed line represents the downstream extent of shoal habitat. The oval represents our primary sampling area and the summertime habitat of shortnose sturgeon, *Acipenser brevirostrum.*



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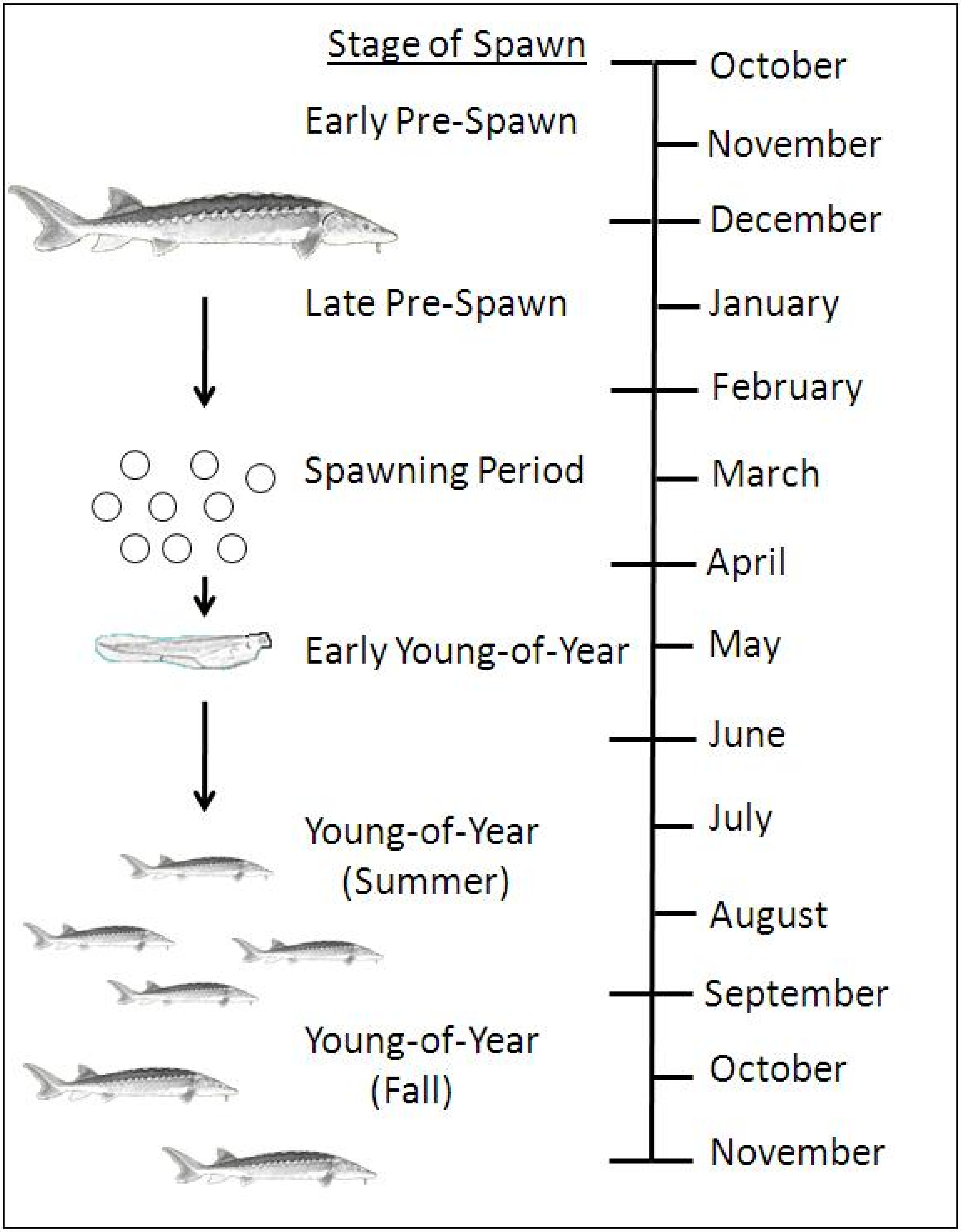
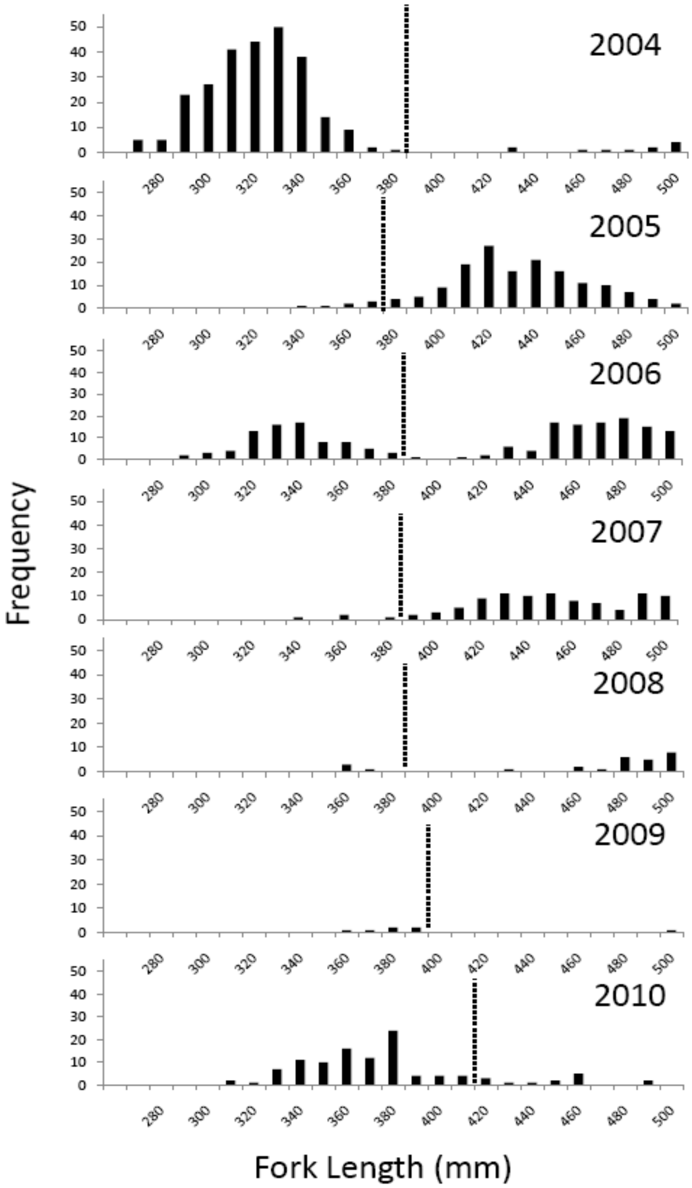


Figure 3.3. Length-frequency histograms of juvenile shortnose sturgeon, *Acipenser brevirostrum*, captured between 2004-2010 in the Altamaha River. The dashed line represents the partition between age-1 and age-2+ individuals. All individuals left of the dashed line were classified as age-1.



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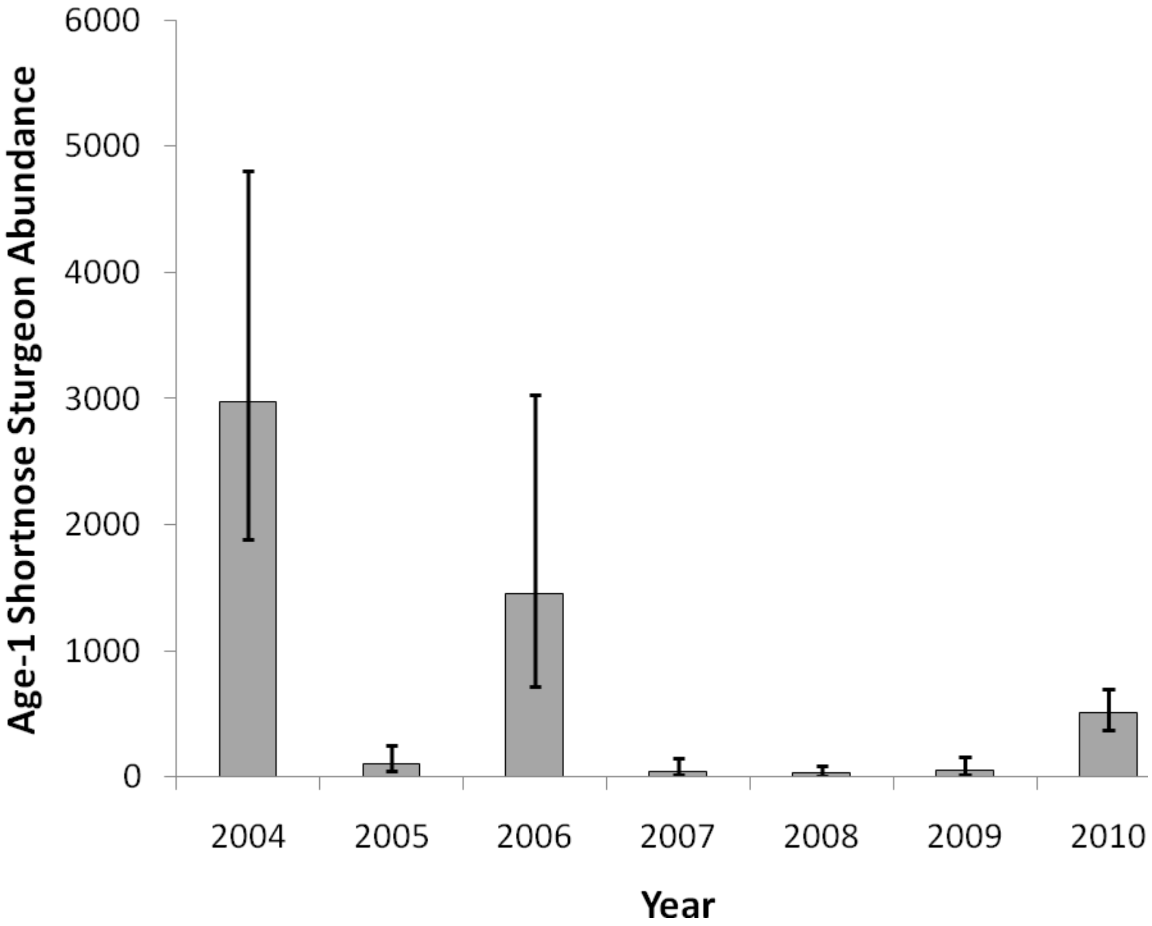


Figure 3.5. Relationship between age-1 shortnose sturgeon, *Acipenser brevirostrum,* abundance and the duration of high flow (>75th percentile, HFD) that occurred during the proposed late pre-spawn period. Diamonds indicate age-1 abundance estimates determined from the Huggins closed-capture models.

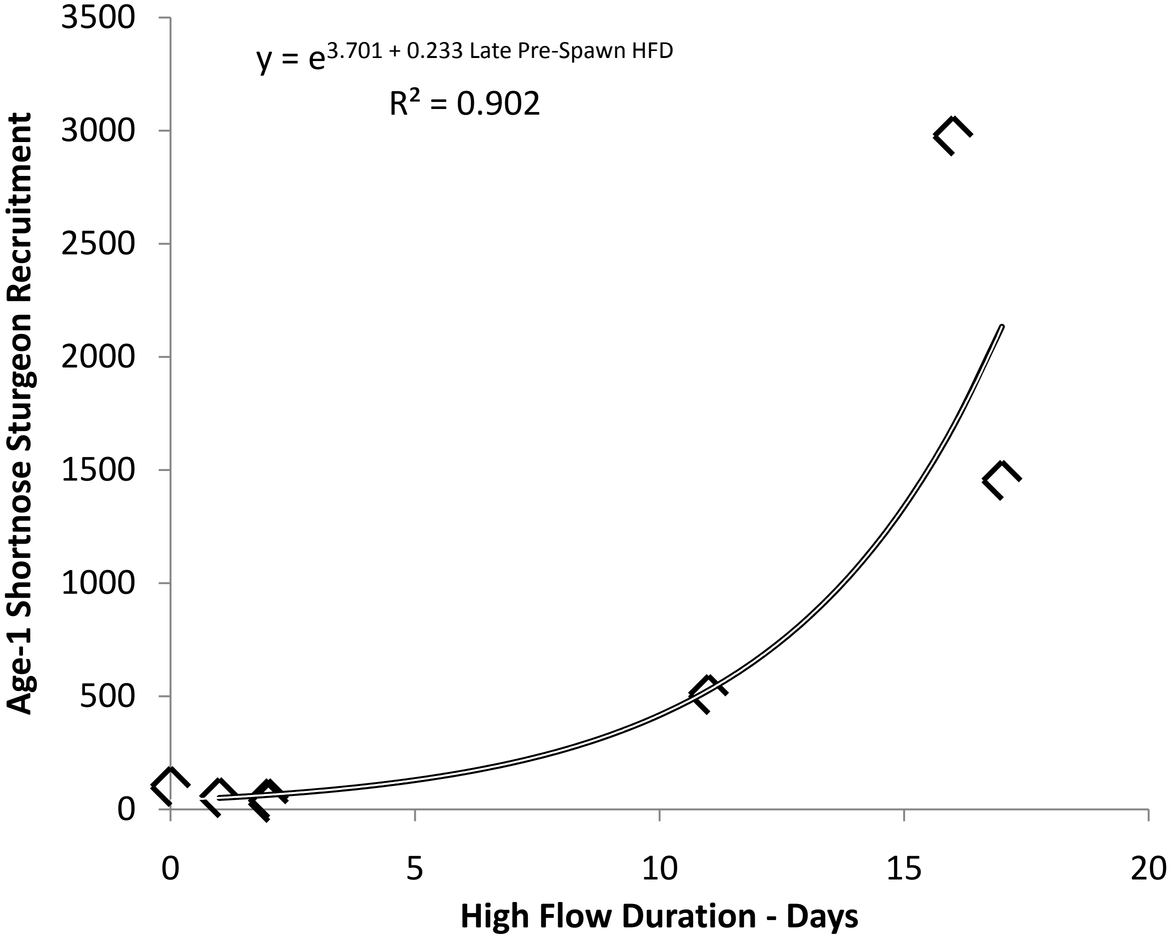


Figure 3.6. Relationship between age-1 shortnose sturgeon, *Acipenser brevirostrum,* abundance and the duration of high flow (>75th percentile, HFD) that occurred during the proposed early young-of-year period. Diamonds indicate age-1 abundance estimates determined from the Huggins closed-capture models.

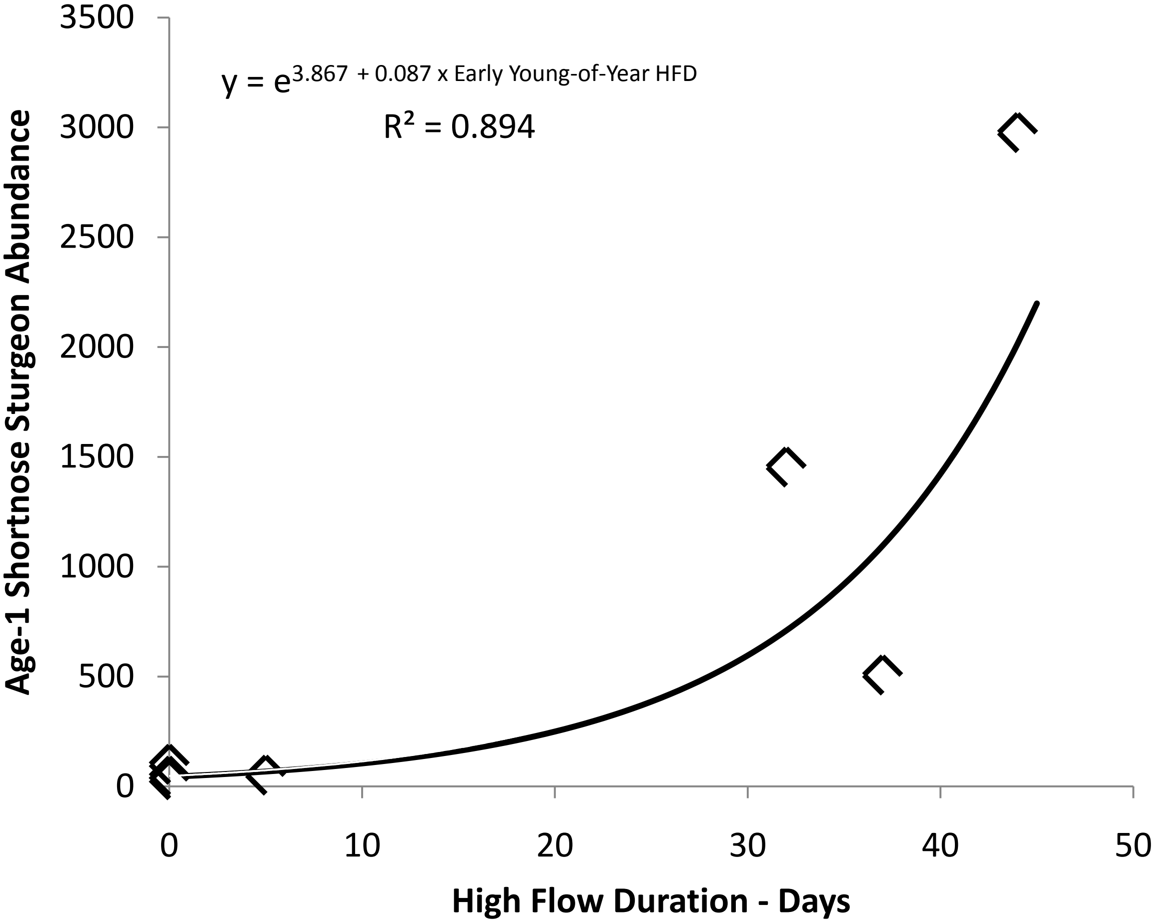
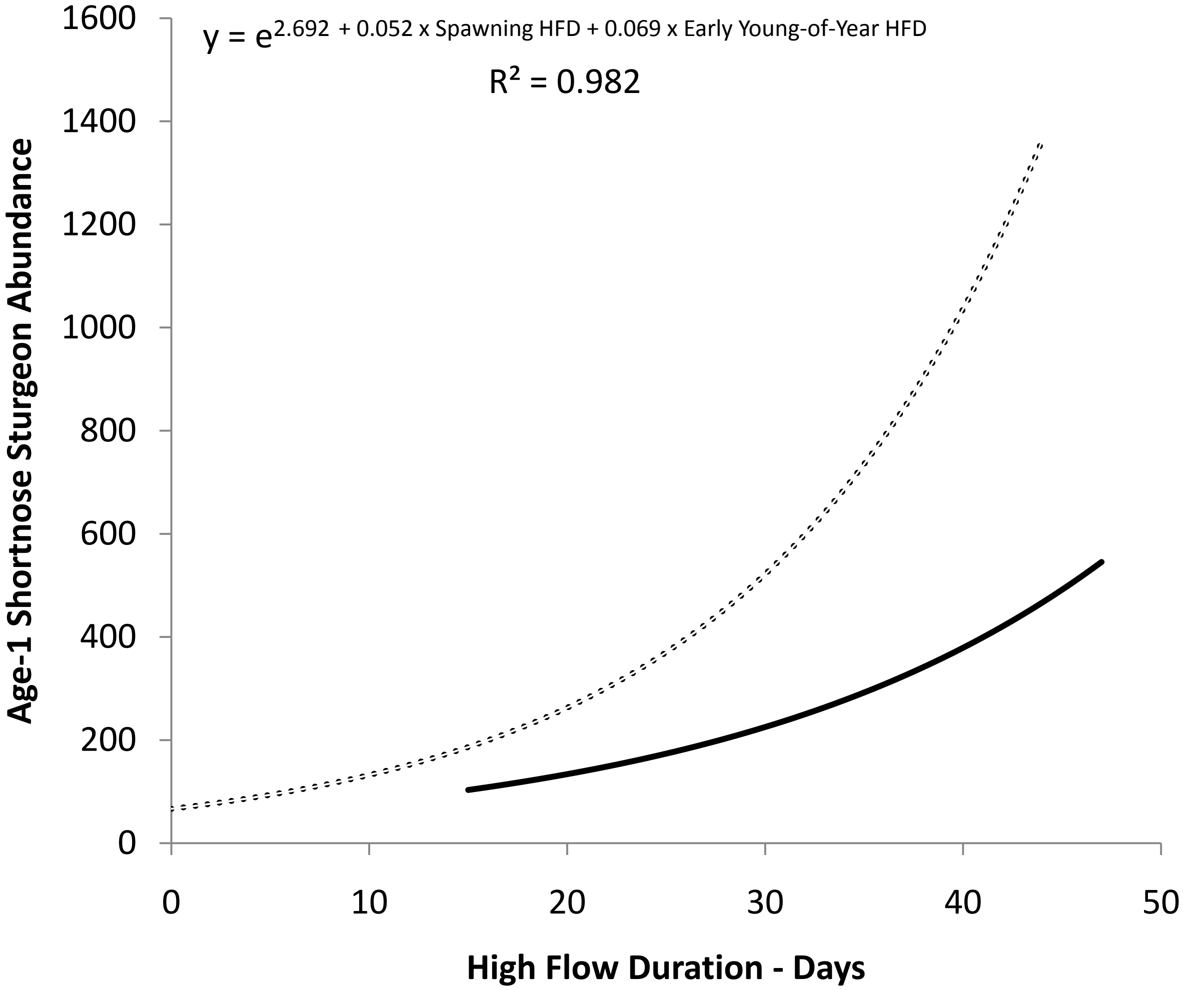


Figure 3.7. Relationship between age-1 shortnose sturgeon, *Acipenser brevirostrum*, abundance and the duration of high flow (>75th percentile, HFD) that occurred during the proposed spawning and early young-of-year period. Dashed line represents the influence of early young-of-year HFD on age-1 abundance, solid line represents the influence of spawning HFD on age-1 abundance.



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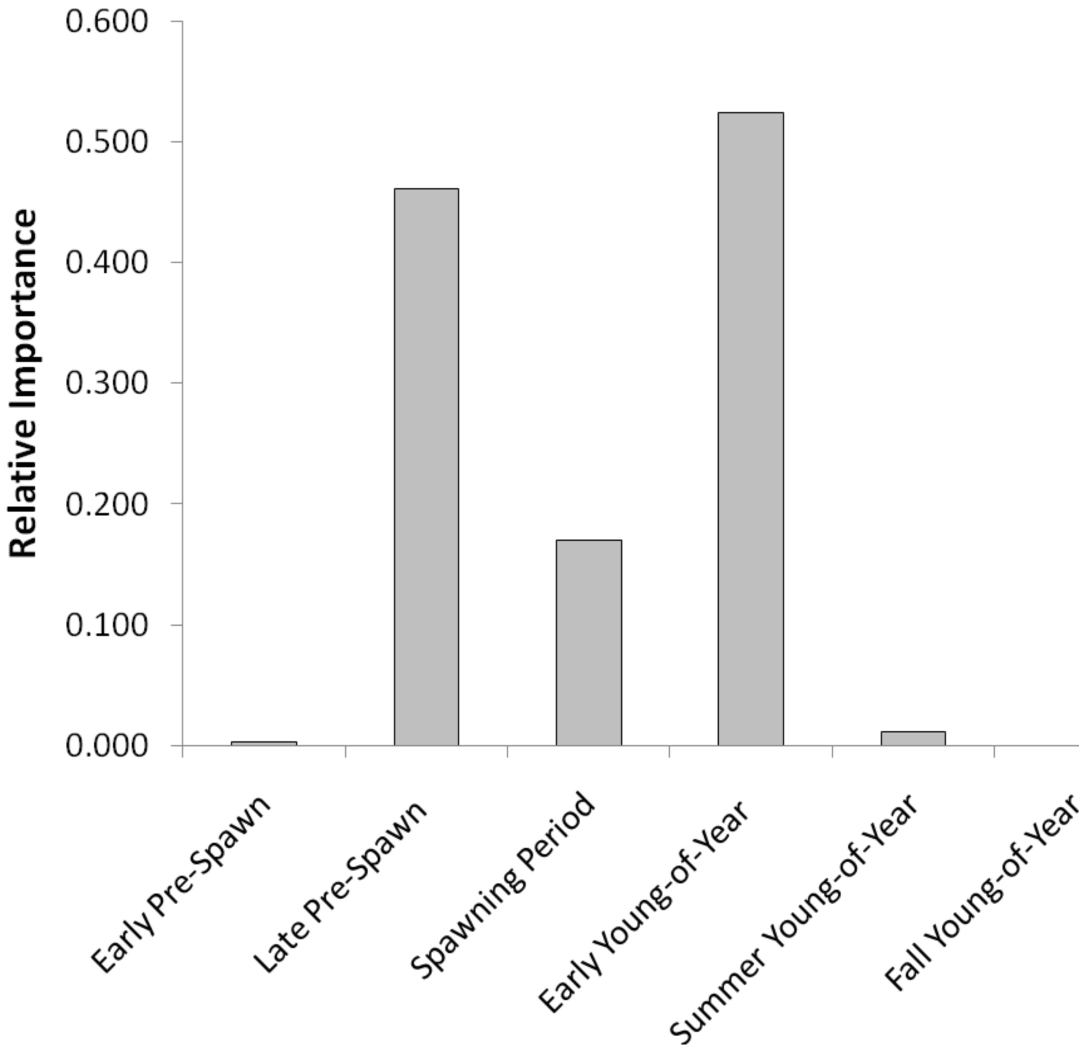

CHAPTER 4

EFFECTS OF SUMMER FLOW ON ESSENTIAL HABITATS AND APPARENT SURVIVAL OF SHORTNOSE STURGEON, *ACIPENSER BREVIROSTRUM*, IN THE ALTAMAHA RIVER, GEORGIA[1]

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[1] Bednarski, M.S. and D.L. Peterson. To be submitted to *Transactions of the American Fisheries Society*

Abstract:

The endangered shortnose sturgeon, *Acipenser brevirostrum*, inhabits most large tidal rivers along the Atlantic coastline of North America, ranging from the St. John River, Canada, southward to the St. Johns River, Florida. Currently, only three river systems south of the mid-Atlantic bight appear to support populations >1,000 individuals. Recent drought conditions in the southeastern United States appear to have exacerbated thermal and hypoxic stress in southern river systems, potentially resulting in acute mortality. Because drought conditions are expected to persist and water use is projected to increase in this region, managers require accurate, quantitative information regarding the linkages between flow, habitat suitability, and shortnose survival to construct effective recovery plans. To provide this information, the objectives of our study were to 1) determine the influences of flow on habitat suitability and 2) assess the impacts of drought on shortnose survival in the Altamaha River, Georgia. We first examined the relationship between flow and the duration of unsuitable temperature and dissolved oxygen. Then, to assess the impacts of drought on shortnose survival, we used a Cormack-Jolly-Seber mark-recapture model. The duration of unsuitable temperature was negatively correlated with decreased flow. Our Cormack-Jolly-Seber models indicated that juvenile survival was lower than that of adult survival, particularly during drought years. Given the observed relationship between flow, temperature, and apparent survival, we recommend that restoration and conservation plans focus on maintaining flow at levels likely to reduce thermal stress.

Key Words: essential habitat, drought, endangered, shortnose sturgeon

Introduction

Shortnose sturgeon, *Acipenser brevirostrum*, are found in most large tidal rivers along North America's Atlantic coastline, ranging from the St. John River, Canada, southward to the St. Johns River, Florida (Kynard 1997, Dadswell et al. 1984, Vladykov and Greeley 1963). Like other Acipenserids, shortnose exhibit a periodic life history typified by late age-at-maturity, high fecundity, high survival, and variable juvenile recruitment (Chapter 2, Woodland and Secor 2007, Dadswell et al. 1984). Shortnose sturgeon display a complex, amphidromous life cycle comprised of several discrete life stages, each with unique habitat requirements and physiological tolerances (Richmond and Kynard 1995, Dadswell et al. 1984, Buckley and Kynard 1981). Though these specific developmental and reproductive tactics foster rapid population growth under suitable conditions, the species' requirement for multiple, interconnected habitats has rendered it vulnerable to anthropogenic influences (Gross et al. 2002). Rangewide, populations have declined in response to habitat alteration, overfishing, and dam construction (Collins et al. 2000, NMFS 1998). Currently, shortnose are classified as endangered in the United States and as special concern in Canada (Kynard 1997, NMFS 1998).

Shortnose sturgeon populations occurring south of the Mid Atlantic Bight appear to be in particularly poor condition (NMFS 1998, Kynard 1997). Compared to their northerly counterparts, southern populations are typified by a shorter life span, lower abundance, and sporadic reproductive success (Chapter 2, Chapter 3). Currently, only three southern systems, the Pee-Dee River, North Carolina, the Savannah River, South Carolina and Georgia, and the Altamaha River, Georgia are thought to contain >1,000 shortnose (Chapter 2, Kynard 1997, Smith et al. 1992). In contrast, four northern river systems, the St. John River, Canada, the Kennebec/Androscoggin River, Maine, the Hudson River, New York, and the Delaware River, Delaware, all host populations >7,000 individuals (Kynard 1997). Though the specific factors contributing to low abundance in southern rivers are unclear, the combined effects of high summer temperatures (>30° C; citation), low dissolved oxygen (DO, <2.5 mg/L; Rogers and Weber 1995, Jenkins et al. 1993), incidental bycatch in American shad fisheries, and the presence of migratory barriers have been suggested as important by various authors (Collins et al. 2000, Kynard 1997).

Summer habitat suitability appears to be particularly important to the health of southern populations. During the summer months, shortnose congregate in the low salinity (<4.2 psu) portions of tidal estuaries near the freshwater-saltwater interface, where they remain until temperatures cool in the fall (Collins et al. 2000). While in these habitats, shortnose may be subject to temperatures up to 34° C and DO levels as low as 2.0 mg/L, resulting in physiological stress, and potentially, increased mortality (Ziegwied et al. 2008, Rogers and Weber 1995, Flournoy et al. 1992). Several researchers have postulated that these conditions are particularly harmful to juvenile shortnose; laboratory studies indicate that juveniles have an upper limit of safe temperature tolerance (ULST) of 31.1° C and a lower limit of oxygen tolerance of approximately 2.5 mg/L (Ziegweid et al. 2008, Jenkins et al. 1993). Prolonged periods of poor water quality have been documented during the summer months in several southern river systems. Specifically, the results of Smith et al. (1992) and Peterson and Farrae (2011) suggest that a lack of suitable summer habitat has resulted in chronic recruitment problems in the Savannah River, Georgia and South Carolina, and the Ogeechee River, Georgia. However, quantitative data relating environmental factors to the suitability of summertime habitat are completely lacking.

In recent years the southeastern United States has endured a severe drought that has resulted in prolonged periods of low river flow, low dissolved oxygen, and unusually high water temperatures during the summer months (USGS 2012, Seager et al. 2009). Although these conditions are probably not favorable for recovering depressed shortnose populations, they do provide a rare opportunity to quantify the impacts of low flow on summer habitat suitability, and subsequently, how these populations may respond to similar habitat alterations in the future. Given recent forecasts for increased demand for municipal water sources, quantitative information relating summer flows to the population dynamics of shortnose is currently a critical information gap necessary for developing an effective recovery plan for southeastern populations. Thus, the first objective of this study was to assess the impacts of reduced flow on temperature and DO within the Altamaha River estuary, the primary oversummering habitat of shortnose in the Altamaha River, Georgia from 2004-2009. The second objective of this study was to assess how drought conditions may have influenced apparent survival of juvenile and adult shortnose during the same period.

Methods

Study Site:

The Altamaha River system forms at the confluence of the Oconee and Ocmulgee Rivers near Lumber City, Georgia and flows approximately 210 km to its outlet at the Atlantic Ocean near Darien, Georgia (Figure 4.1). Annual mean discharge is 380 m^3/sec (USGS gauge 02226000), making the Altamaha one of the largest sources of freshwater on the southeastern coast of North America. In total, the Altamaha/Oconee/Ocmulgee River complex consists of approximately 662 rkm (ASSRT 2007) of free-flowing habitat. The lower 40 rkm of the Altamaha are tidally influenced and estuarine although the location of the fresh/saltwater interface varies depending on discharge (Sheldon and Alber 2005).

Sampling:

Seasonal variation in freshwater inflow was monitored by the USGS gage 02226000, located near Doctortown, Georgia, approximately 30 rkm upstream of the Altamaha Estuary. All water temperature data were obtained at 30 min intervals during June-September 2004-2009, from the Georgia Coastal Ecosystems Long Term Ecological Research Program (GCE-LTER) water quality monitoring station located at rkm 26 (Figure 4.1). Dissolved oxygen measurements were obtained near the substrate several times per week.

We used experimental gill nets and trammel nets to sample shortnose from May-August 2004-2010. We concentrated sampling effort within the low salinity (< 5ppt) portions of the Altamaha River estuary (rkm 15 to 30). Each net was 91.4 m long, 3.1 m deep, and constructed of monofilament webbing hung on a 15.9-mm foamcore floatline and a 124 g/m weighted lead line. Experimental nets consisted of one panel each of 7.6, 10.2, and 15.3 cm mesh (stretch measure) and trammel nets consisted of a 7.6 csm inner and two 30.5 csm outer panels. Nets were set mid channel, and soaked for 30-45 minutes primarily during slack . We concentrated sampling effort within the low salinity (<5 ppt) portions of the Altamaha River estuary (rkm 15 to 30). As nets were retrieved, sturgeon were removed and placed into a floating pen tethered to the side of the research vessel. Once all nets had been pulled, we scanned each fish for a PIT tag and recorded fork length (FL) to the nearest mm. If no PIT tag was present, we implanted one under the fourth dorsal scute before releasing the fish back to the river.

Statistical Analyses:

To characterize the influences of flow on habitat suitability, we performed a correlation analysis that related median yearly summer flow to either median yearly summer temperature or median yearly DO. Correlations were assessed by calculating the Pearson product-moment correlation coefficient (r) for each relationship (Rodgers and Nicewander 1988).

We quantified variation in annual apparent survival relative to variations in median summer flow through the Cormack-Jolly-Seber model in Program MARK (White and Burnham 1999). We varied apparent survival between years when median summer flow exceeded and did not exceed the 30Q2 flow threshold (106.7 cms), a widely used indicator of the onset of drought (USGS 2012). To account for variations in survival related to life-stage, we varied the apparent survival probability of all individuals identified as age-1 between their age-1 to age-2 and all other transitions. Because shortnose begin to mature at age-2 in the Altamaha River, all age transitions after age-2 were assumed to cumulatively represent “adult survival” (Dadswell et al. 1984). Age-1 shortnose were identified using length-frequency histogram analysis (Chapter 3). We designated each individual contained within the first mode of a given year as age-1, and all others age-2+. To assess a potential interactive effect between life stage and drought, we varied apparent survival between drought and non-drought years only for the age-1 to age-2 transition. In each model, we considered capture probability variable among years and constant between juveniles and adults (Chapter 2 and 3).

We then constructed six candidate Cormack-Jolly-Seber survival models that either included or excluded effects of age, drought, or an interaction between age and drought. We assessed the support for a specific model by determining its AICc and relative weight within

Program MARK. Any model containing >12.5% of the weight of evidence of the model with the greatest weight of evidence was incorporated into the confidence set (Royall 1997). The importance weight of each factor was determined based on the cumulative relative weight of all models that contained a specific factor. Differences in apparent survival based on each factor were based on the point estimate of each apparent survival parameter in each candidate model contained within the confidence set.

Results:

During our study, median yearly summer flow ranged from 60.7 cms during 2008 to 437.5 cms during 2005 (Table 4.1). Temperature ranged from 22.7° C in September 2004 to 33.1 °C in August 2007. Complete daily temperature data were available for all years except 2006; within 2006, no data were available for 1-2 June. Median summer temperature varied from 28.1 in 2005 to 30.1 in 2006 (Table 4.1). Dissolved oxygen varied from 3.3 mg/L during July 2008 to a high of 6.8 mg/L during July 2009.

During our study, we deployed 1173 nets and captured 1582 unique shortnose (Table 4.2). Of these, 436 were initially captured as age-1 and 1146 were initially captured as age-2+. Yearly capture of age-1 individuals ranged from 3 in 2007 to 253 in 2004. Total annual age-2+ catches were similarly variable, ranging from 92 in 2009 to 194 in 2005. Yearly recaptures ranged from 16 in 2005 to 38 in 2010.

Median yearly summer flow was negatively correlated with median yearly summer temperature ($r = -0.93$; Figure 4.2). Median yearly summer flow did not appear to be correlated with median yearly DO ($r = 0.07$; Figure 4.3).

Median summer flow was below the 30Q2 threshold during 2006-2009, indicating drought. All six of our CJS models relating apparent survival to life stage and drought were incorporated into our confidence set. Of the factors, life stage had the highest important weight (0.45). The interaction between drought and life stage had the next highest importance weight (0.28). Drought along had the lowest importance weight (0.25) of all variables examined. All models including life stage suggested that juvenile apparent survival was lower than adult apparent survival, with an effect size of between -0.21 and -0.37 (Table 4.3). The model including an interaction between life stage and drought indicated a decrease in apparent juvenile survival of 0.35. All models including an effect of drought indicated a decrease in apparent survival, with an effect size of between -0.05 and -0.22.

Discussion:

The results of this study suggest that annual variations in freshwater input may be a critical factor influencing the suitability of summer shortnose habitat in the Altamaha River. Although we did not note a correlation between median yearly summer flow and median yearly summer DO, we did detect a strong negative correlation between median yearly summer flow and the median yearly temperature. This finding suggests that future reductions in flow – regardless of cause – may increase both the frequency and magnitude of thermally stressful events for shortnose sturgeon in the Altamaha River. In fact, thermal stress already appears to occur within the Altamaha River; in all but one year of our study, maximum temperature exceeded the species' ULST, suggesting that further increases are likely to further exacerbate thermal stress for the population.

Although studies exploring the influences of environmental variation on habitat suitability are not uncommon, our results provide the first quantitative assessment of the linkages between life stage, flow, and apparent survival for shortnose. Our top CJS model indicated that apparent survival increased following the transition to adulthood, suggesting that within the Altamaha, juveniles must progress through a period of reduced survival before reaching maturity. This finding contrasts sharply with hypotheses posed for northern systems, which suggests that shortnose survival is constant after the juvenile stage (Gross et al. 2002). Three models in our confidence set, collectively comprising 53% of the weight of evidence, indicated that reduced apparent survival was associated with the presence of drought. In two of these models, these decreases were restricted to juvenile individuals, suggesting that drought may disproportionately affect juveniles. The relationship between drought and apparent juvenile survival, coupled with the correlation between flow and temperature, provide evidence that thermal stress may result in reduced recruitment to the adult population. This inference provides additional support for the theories of Collins et al. (2000), who postulate that low juvenile abundance documented in many southern rivers may result from prolonged periods of unsuitable water temperatures during the summer months.

Because of their relatively r-selected life history, southern shortnose may be especially well adapted to counter reductions in juvenile survival that result from poor summer habitat conditions that are common during severe drought. Specifically, southern shortnose exhibit rapid growth and a much earlier age-at-maturity than their northern counterparts. By examining the apparent survival rates obtained in this study, the effect of these demographic differences on adult recruitment rate can be quantified. In this study, for example, our results demonstrate that under ideal conditions, 54-75% of age-1 individuals recruited to age-2 (onset of maturity).

These calculations suggest that under ideal conditions, southern populations may exhibit relatively rapid population growth, compared to other *Acipenser* species. Further, even during drought conditions, 37% of juvenile shortnose in the Altamaha reach adulthood, a rate of juvenile to adult recruitment similar to that of more northerly populations. We conclude that southern populations have an inherently high biotic potential, and accordingly, are readily capable of rapidly rebounding from stochastic events that temporarily reduce juvenile survival.

Further studies are needed to better understand how the interactions of biotic and abiotic variables affect the supply of summer habitat for shortnose sturgeon in southern rivers, but the results of our study suggest that protection of conditions within these estuarine habitats should be prioritized in any future recovery plans for the species. Although drought conditions are difficult to forecast, our data show that the supply of fresh water inputs may be a critical factor for maintaining the Altamaha population. In river systems influenced by upstream impoundments, managers should work to ensure that water releases are sufficient to preserve the integrity of summer habitat. Additional water releases may represent one option for mitigating the effects of drought, by reducing the duration of potential stressors, such as high temperature, during the summer months.

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Table 4.1: Summary statistics for flow, temperature, and dissolved oxygen observed in the Altamaha River Estuary from 2004-2010. Daily flow recorded from USGS gauge #02226660 in Doctortown, Georgia. Daily temperature recorded from Georgia Coastal Ecosystem Long-Term Ecological Research Program’s water quality monitoring station located in Darien, Georgia. Dissolved oxygen readings based on point readings taken during concurrent shortnose sturgeon, *Acipenser brevirostrum*, sampling.

	Flow (cms)			**Temperature (°C)**			**Dissolved Oxygen (mg/L)**		
Year	**Minimum**	**Median**	**Maximum**	**Minimum**	**Median**	**Maximum**	**Minimum**	**Median**	**Maximum**
2004	81.4	145.3	1462.6	22.7	29.2	31.2	3.9	5.0	6.8
2005	108.6	437.5	1092.1	24.9	28.1	29.7	4.5	5.0	5.7
2006	59.1	75.2	136.0	26.7	30.1	32.4	3.9	4.6	5.7
2007	62.6	81.1	211.1	27.4	29.5	33.1	3.7	5.3	6.5
2008	47.6	60.7	119.4	28.6	29.8	31.5	3.3	4.9	6.4
2009	59.4	88.8	683.4	24.9	29.4	32.6	3.9	5.1	6.8

Table 4.2: Yearly capture and subsequent recapture of age-1 and age-2+ shortnose sturgeon, *Acipenser brevirostrum*, in the Altamaha River, Georgia from 2004-2010.

Age 1	Initially	Recaptured					
Year	Marked	2005	2006	2007	2008	2009	2010
2004	253	11	6	5	3	2	4
2005	8	.	0	0	0	0	0
2006	77	.	.	2	1	1	0
2007	3	.	.	.	0	0	0
2008	4	.	.	.	.	0	0
2009	5	.	.	.	.	.	2
2010	86	.	.	.	.	.	.

Age 2+	Initially	Recaptured					
Year	Marked	2005	2006	2007	2008	2009	2010
2004	159	5	6	2	3	1	5
2005	194	.	15	3	8	3	6
2006	190	.	.	6	9	4	5
2007	156	.	.	.	11	3	4
2008	167	.	.	.	.	5	6
2009	92	.	.	.	.	.	6
2010	188	.	.	.	.	.	.

Table 4.3: Candidate Cormack-Jolly-Seber models and parameters relating annual apparent shortnose sturgeon, *Acipenser brevirostrum*, survival in the Altamaha River to life stage and the presence of drought conditions. All models were incorporated into the confidence set. Parameters not estimated within a specific model indicated by NE. Numbers within parentheses represent 95% confidence intervals.

				Drought Effect		**No Drought Effect**	
Model	**ΔAICc**	**Weight**	**Parameters**	**Juvenile**	**Adult**	**Juvenile**	**Adult**
Phi{Age}p{t}	0	0.28	8	NE	NE	0.54 (0.35-0.73)	0.75 (0.64-0.84)
Phi{Drought x Age}p{t}	0.06	0.28	8	0.37 (0.13-0.71)	NE	0.72 (0.63-0.79)	0.72 (0.63-0.79)
Phi{.}p{t}	0.76	0.19	7	NE	NE	0.72 (0.63-0.80)	0.72 (0.63-0.80)
Phi{Drought + Age}p{t}	1.04	0.17	9	0.37 (0.13-0.71)	NE	0.59 (0.35-0.80)	0.74 (0.63-0.83)
Phi{Drought}p{t}	2.65	0.08	8	0.70 (0.53-0.83)	0.70 (0.53-0.83)	0.75 (0.55-0.88)	0.75 (0.55-0.88)

Figure 4.1: Map of the Altamaha River system. The circle represents the known summer habitat of shortnose sturgeon, *Acipenser brevirostrum*, within this system. The triangle represents the Georgia Coastal Ecosystems Long-Term Ecological Research Program's water quality monitoring station. The square indicates USGS flow gauge #02226660.

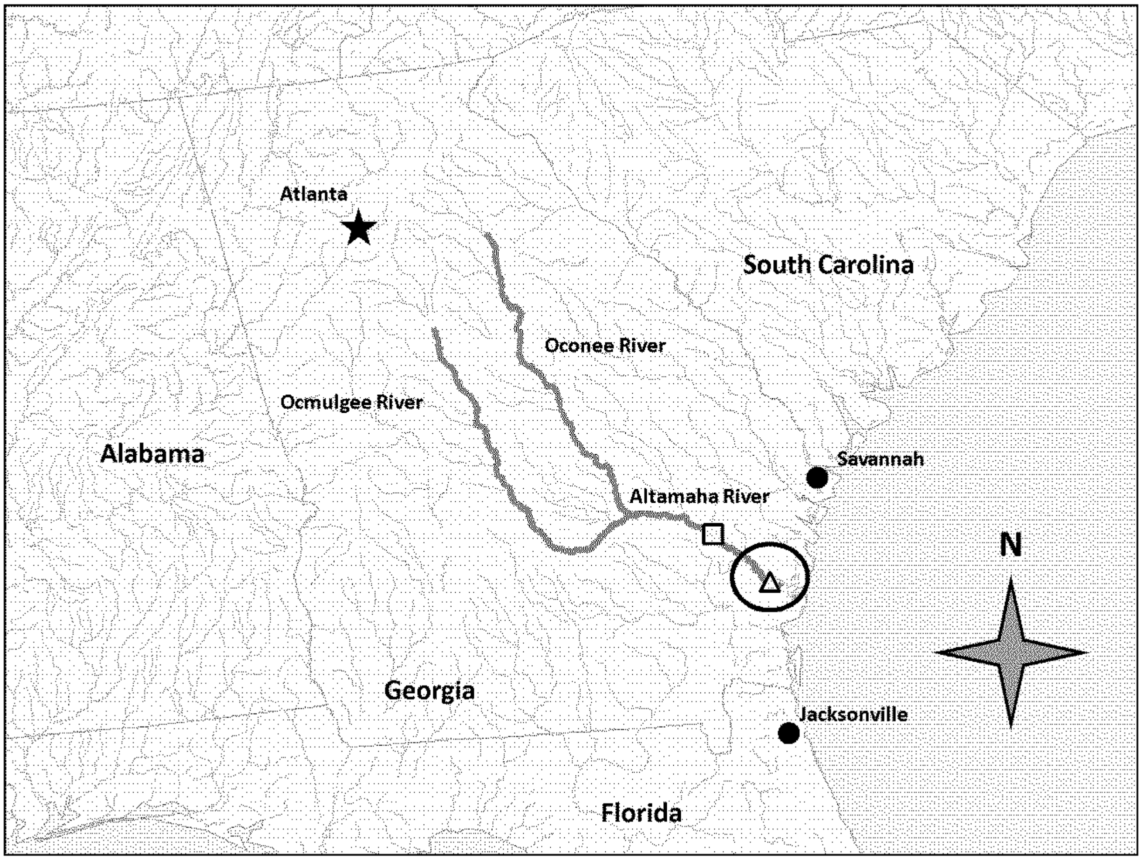


Figure 4.2: Correlation between median yearly summer flow and median yearly summer temperature, in the estuary of the Altamaha River, Georgia. Temperature based on continuous data recorded at the Georgia Long-Term Ecological Research Program's water quality monitoring station near Darien, Georgia. Flow based on daily average readings recorded at USGS gauge #02226000.

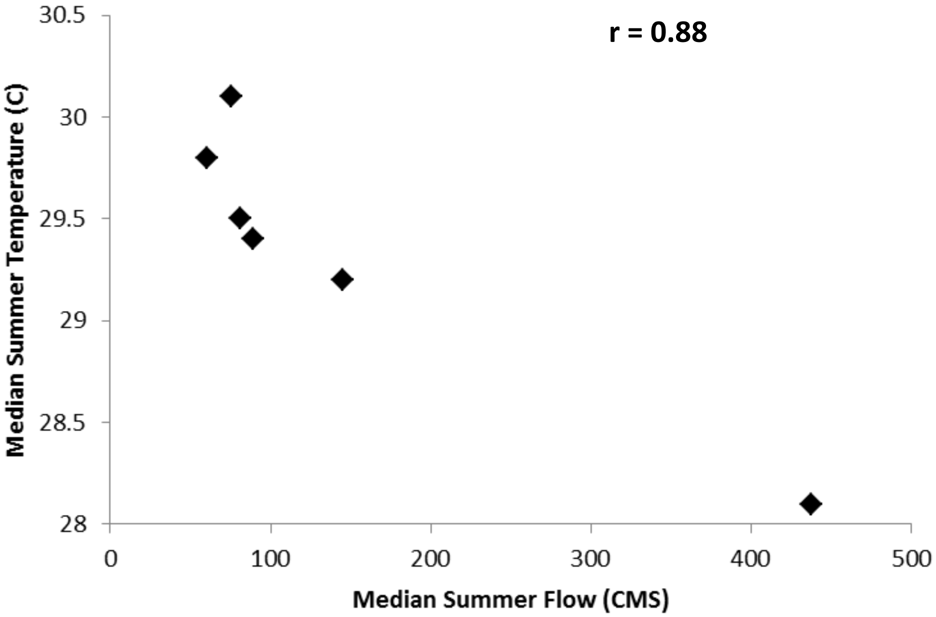
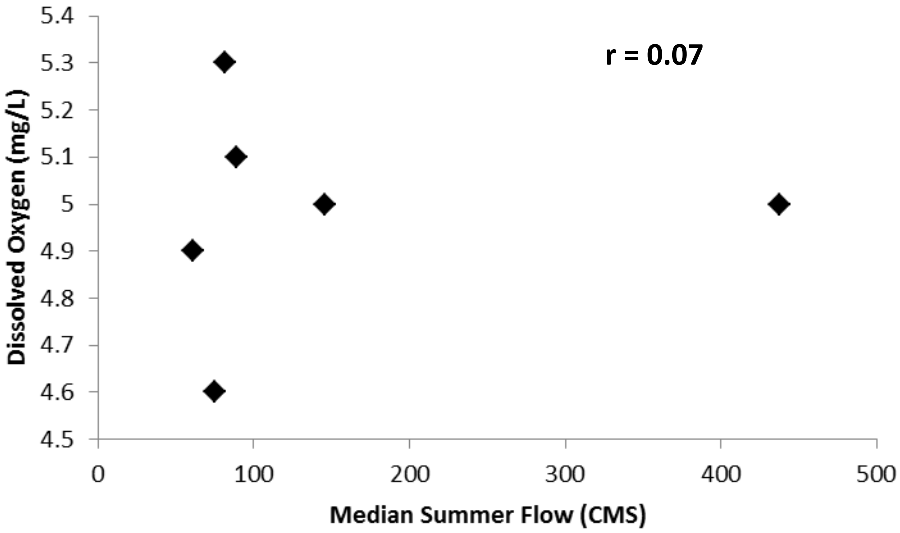


Figure 4.3: Correlation between median yearly summer dissolved oxygen and median yearly summer flow in the Altamaha River estuary. Dissolved oxygen based on data recorded during concurrent shortnose sturgeon, *Acipenser brevirostrum*, sampling. Flow based on daily average readings recorded at USGS gauge #02226000.



CHAPTER 5

CONCLUSIONS AND MANAGEMENT IMPLICATIONS

The observed characteristics of the Altamaha shortnose sturgeon population, which included low annual survival, highly variable annual recruitment, and a potential interaction between drought conditions and juvenile survival, have not been documented in northern populations. Because shortnose rely on a long-life span to buffer against variable recruitment, reduced survival in southern rivers probably diminishes the effectiveness of this basic life history strategy common to all *Acipenser* species. Recruitment appears to be more variable in southern populations, so annual abundance may also become less stable, ultimately making southern shortnose more vulnerable to stochastic events such as drought, disease etc. Comparatively low juvenile survival in the Altamaha suggest that southern shortnose must survive a prolonged critical period during their first summer that does not occur in northern rivers. Based on the findings from all research chapters (2-4), I suggest that these clinal variations in life history and habitat may provide an explanation for the relatively low abundances documented for southern populations.

The aforementioned characteristics of the Altamaha shortnose population appear to be cause for concern, yet decreased survival and highly variable recruitment may be a natural characteristic of southern populations. In the Altamaha River, temperatures rarely fall below 10°

C, but they typically exceed the ULST for several weeks each summer. In contrast, northern populations, like those inhabiting the Hudson and Saint John Rivers, are not subjected to the water temperatures above the ULST. Because poikilothermic organisms, such as shortnose, typically display lower annual survival in warmer climates, my findings regarding lower annual survival in Altamaha are not surprising (Munch and Salinas 2009). Also, natural differences in flow regime during the spawning period appear to contribute to trends in recruitment variability.

When taken in concert with the findings of previous research, the results of my work suggest that recruitment variability in shortnose sturgeon appears to increase with decreasing latitude. I hypothesize that because flow is inherently more stable in northern rivers, so is recruitment (Dettinger and Diaz 2000). The Altamaha River appears to contain the largest and healthiest population of southern shortnose. Our highest estimate of total abundance, 5,551 individuals, is the largest documented for any southern population. Even our lowest abundance of 1,206, is greater than all but one annual point estimate for the Savannah River population (NMFS 1998). I attribute the abundance of the Altamaha population to the comparatively high frequency of reproductive success. In three of seven years, we identified age-1 cohorts of >500 individuals. Comparable studies are lacking, but previous research indicates that populations in other southern systems, such as the Ogeechee and Savannah rivers, frequently exhibit recruitment failure (Smith et al. 1992, NMFS 1998). The unique traits of the Altamaha River system, which include unimpeded access to 662 rkm of deep channel and shoal habitats, probably contribute to relatively high rates of annual recruitment. We hypothesize that because of habitat availability and consistent annual recruitment, the Altamaha River population is representative of one occurring in a restored or naturally functioning system.

Despite the Altamaha's apparent health, several factors appear that may endanger its future status. In chapter three, we identified a strong positive relationship between recruitment success and high flow duration during the spring and early summer months. In chapter four, I quantified differences in juvenile survival in response to the duration of summer temperature extremes, which ultimately were correlated with summer flows. My results suggest that until juvenile shortnose reach age-2, they may be particularly sensitive to reduced summer flows and potentially, high temperature. . As such, any anthropogenic or natural factors that reduce summer flows, regardless of cause, are likely to adversely affect this population. Because drought conditions are expected to persist in the near future and water withdrawals are expected to increase, careful habitat protection and population monitoring will be critical to ensuring the long term viability of the Altamaha shortnose. (USGS 2012, Seager et al. 2009). I recommend that when deciding how to allocate water resources within the Altamaha Basin, managers carefully consider the potential impacts on shortnose recruitment and juvenile survival.

Future studies of other southern populations of shortnose are needed to develop effective restoration plans throughout the southern portion of its range. Our methodologies, which included a long-term mark-recapture study, allowed us to assess abundance, population structure, recruitment, and survival in a direct manner. By completing similar studies on other southern rivers, managers can compare results, and potentially garner important information about how to proceed with river-specific restoration plans. If, for example, a population appears to be depressed, differences in recruitment and survival should be quantified. If recruitment levels are found to be low, we first suggest that managers explore the effects of recent flow patterns. Subsequently, if recent flows were abnormally low, managers should then determine if flow reductions were caused by water diversions or drought. In this scenario, future water management represents a viable option for helping maintain or restore shortnose populations in southern rivers.

In the absence of long-term assessment, we recommend that managers use caution when interpreting results from short-term (<3 yrs) studies. Prior to this study, no assessment of a southern shortnose population had exceeded three consecutive years. In each previous study, managers suggested that a population characterized by a juvenile dominated structure was "healthy" and, conversely, that populations characterized by an adult-dominated structure was "imperiled" (Smith et al. 1992, NMFS 1998). During the course of our 7-yr study, we detected both adult and juvenile dominated population structures, resulting from widely varying levels of annual recruitment. Hence, I suggest that inferences regarding population status based solely on short-term assessments of size-structure are probably invalid for southern populations. Without long-term assessments, evaluation of population status is not likely possible, precluding the development of an appropriate management plans. Ultimately, the implication of my work is that direct, long-term assessment is currently the best available option for accurately assessing southern shortnose populations.

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