RECRUITMENT OF ATLANTIC STURGEON AND SHORTNOSE STURGEON WITHIN THE SAVANNAH RIVER, GEORGIA AND SOUTH CAROLINA

by

ALEXANDER JEFFREY CUMMINS

(Under the Direction of Douglas L. Peterson)

ABSTRACT

The endangered Atlantic (*Acipenser oxyrinchus oxyrinchus*) and Shortnose Sturgeons (*A. brevirostrum*) were once abundant within major rivers along North America's Atlantic coast from the St. John River, Canada and the St. Johns River, Florida. Anthropogenic factors such as over-harvest and habitat degradation have contributed to severe declines in populations of both species throughout their ranges. Despite both species being listed as endangered, significant gaps in scientific literature, particularly population demographics are still present. The objectives of this study are to quantify annual recruitment of juvenile Atlantic and Shortnose Sturgeons in the Savannah River, and to determine environmental drivers of recruitment. The results of this study provide baseline abundance data that will be critical in evaluating long-term population trends and for assessing the effects of dredging in the Savannah River. This study provides key information regarding long-term management of endangered Atlantic and Shortnose Sturgeon throughout the southern reaches of their range.

INDEX WORDS: Atlantic Sturgeon, Shortnose Sturgeon, recruitment, population dynamics, environmental drivers

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DEDICATION

I would like to dedicate this thesis to Katherine and Mosley Brinson, my parents, Jeff and Betsy Cummins, and everyone else who has constantly supported and encouraged me during my time working on this thesis. You have all helped me get to where I am today, as well as greatly contributing to the completion of this thesis and my sanity over the past few years.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Sturgeons are a unique family of fishes found throughout the Northern Hemisphere (Bemis and Kynard 1997). As members of the order Acipenseriformes, sturgeons are characterized by a heterocercal tail and five rows of bony scutes along their lateral and dorsal surfaces (Birstein 1993). A total of 27 sturgeon species can be found across the continents of North America, Europe, and Asia; nine species are native to North America (Birstein 1993; Bemis and Kynard 1997). Over-exploitation, habitat loss, and pollution have resulted in many sturgeon species becoming threatened or endangered (Birstein 1993; Boreman 1997).

Two sympatric species, the Atlantic Sturgeon (*A. oxyrinchus oxyrinchus*) and Shortnose Sturgeon (*Acipenser brevirostrum*) are found along the Atlantic coast of North America. Both species are benthic invertivores that inhabit major coastal river systems from New Brunswick, Canada, to northern Florida (Vladykov and Greeley 1963). Atlantic Sturgeon are capable of growing to lengths of 2.7 m while Shortnose Sturgeon can exceed 1.3 m (Scott and Crossman 1973). Both species can reach ages of 60 years (Murawski and Pacheco 1977). Maximum size and age at maturity vary latitudinally in both species, and several distinct genetic populations have been identified (Grunwald et al. 2008; Wirgin et al. 2010).

As an anadromous species, Atlantic sturgeon spend most of their adult lives in marine environments, returning only periodically to their natal rivers to spawn (Smith 1985; Vladykov and Greeley 1963). Spawning periodicity is typically 1-5 years and 3-5 years for males and females, respectively (Smith 1985). In southern populations, male

Atlantic Sturgeon mature at 8-9 years and females at 10-12 years (Smith 1985; Schuller 2010); however, age at maturity in northern latitudes is typically 20 years or more (Scott and Crossman 1973). In northern populations, spawning takes place between May and July (Smith 1985; Bain 1997); in southern populations adults begin their spawning migrations during the spring and summer with spawning occurring from September - December (Ingram and Peterson 2016). Typical spawning habitat is usually found in the upper reaches of large rivers with substrates consisting of hard gravel, rubble, or clay-stone and flows of about 1 m/s (Smith and Clugston 1997). During spawning, the sticky demersal eggs are broadcast across the substrate where they incubate for 4-7 days (Murawski and Pacheco 1977; Smith 1985; Vladykov and Greeley 1963). Shortly after hatching, the larvae begin to migrate to downstream nursery areas near the fresh-saltwater interface (Smith and Clugston 1997). Throughout their first 2 years within the estuary, river-resident juveniles become increasingly tolerant of salinity, though outmigration does not typically occur until the fish reach age 2-4 (Bain 1997; Fox and Peterson 2018). Once reaching the marine environment, marine migratory juveniles (aka subadults) grow rapidly until they mature and return to their natal river to spawn (Bain 1997).

Unlike the anadromous Atlantic Sturgeon, Shortnose Sturgeon are amphidromous. Adults spend a majority of their time near the freshwater-saltwater interface of their natal rivers, migrating to marine environments only for brief periods of foraging during the late fall and winter months (Buckley and Kynard 1985). Hall *et al*. (1991) found that adult Shortnose Sturgeon typically occupy depths of 6-10 m and salinities less than 6 ppt within the estuary of their natal river. Like Atlantic Sturgeon, Shortnose Sturgeon also periodically migrate upriver to spawn. Spawning periodicity is 2-3 years for females and 1-2 years for males. In southern populations, males mature between ages 2–5 and females mature between ages 6-7 (Dadswell et al. 1984). In contrast, northern populations may require 10-13 years to reach maturity. In southern rivers, spawning migrations typically occur from January to March, as water temperatures reach 8-12 °C (Ingram 2014). Preferred spawning habitats are characterized by woody debris, gravel or hard clay substrates and flows of about 1 m/s at depths of 6-9 m (Dadswell *et al*. 1984; Hall *et al*. 1991). Like the Atlantic Sturgeon, Shortnose Sturgeon eggs are also adhesive and demersal. After fertilization, the eggs incubate for 7-13 days, depending on water temperature (Buckley and Kynard 1981). Once they hatch, the larvae migrate downstream towards the freshwater-saltwater interface where both juvenile and adult cohorts reside together (Kynard and Horgan 2002).

Throughout the 20th century, the combined effects of overfishing and habitat destruction have diminished all major populations of both Atlantic Sturgeon and Shortnose Sturgeon. Hydropower development and dam construction throughout this period have been identified as major causes of sturgeon population declines (Williot et al. 2002). Restoration efforts for both species have also been complicated by their complex life histories, degraded habitats, and incidental bycatch in commercial fisheries (Collins *et al*. 2000; Smith and Clugston 1997; ASSRT 2007). In 1967, Shortnose Sturgeon were listed as endangered under the Endangered Species Preservation Act (Miller 1972). Commercial exploitation of Atlantic Sturgeon, however, continued until 1996 when an emergency moratorium on all US commercial fisheries was implemented by the National Marine Fisheries Service (ASMFC 1998). Although the fishery has remained closed, populations in many rivers have shown minimal improvement, and in 2012 Atlantic Sturgeon were also listed as endangered under the US Endangered Species Act (NOAA 2012). In prelude to this listing, the Atlantic Sturgeon Status Review Team (2007) evaluated all extant populations based on physical, genetic, and physiological factors and conservation status. Using microsatellite genetic analyses, the team found five separate distinct population segments (DPS) within the US: the Gulf of Maine, New York Bight, Chesapeake Bay, Carolina, and South Atlantic. All five DPS were listed as "endangered," except for the Gulf of Maine DPS which was listed as "threatened" (NOAA 2012). Unlike Atlantic Sturgeon, Shortnose Sturgeon are currently managed as a single continuous population without DPS designations, although NMFS (1998) has recommended that they be managed within 19 distinct DPSs to prevent loss of genetic diversity. A better understanding of recovery and population dynamics for both species is critical for future management and conservation (NMFS 1998; ASSRT 2007).

Assessments of Atlantic Sturgeon and Shortnose Sturgeon populations are also an important part of evaluating the species' status and recovery (NMFS 1998). Although abundance estimates have been completed for several populations of both species along the Atlantic coast, estimates for rivers in the South Atlantic DPS are largely lacking (NMFS 1998, ASSRT 2007). For northern populations of Shortnose Sturgeon, Dadswell (1979) estimated that the Saint John River, New Brunswick, contained 18,000 total individuals and Bain *et al*. (2007) estimated the Hudson River, New York, population at 61,057 fish. Comparable estimates for southern populations are rare, but one notable exception was a 7-year population study by Peterson and Bednarski (2013) on the Altamaha River, Georgia. Unfortunately, similar total population estimates for Atlantic

Sturgeon are difficult because of their complex migratory life history. Several recent studies, however, have focused on assessing annual recruitment in Atlantic Sturgeon as an alternative to attempting broader estimates of an entire population (Schueller and Peterson 2010; Bahr and Peterson 2016b). Because Atlantic Sturgeon juveniles remain in their natal rivers until age-2, annual assessments of age-1 cohorts can provide at least one quantifiable measure of population trends (Dovel and Berggren 1983; Peterson *et al*. 2000). For example, within the South Atlantic DPS, Schueller and Peterson (2010) estimated between 333 and1,318 age-1 juveniles over a 4-year period in the Altamaha River, Georgia. Similar assessments of Shortnose Sturgeon recruitment can also be used to assess recovery (Woodland and Secor 2007), particularly if those studies can be conducted over several consecutive years. The long-term monitoring of age-1 cohorts for both species allows researchers and managers to quantify and assess recovery within a particular river system. Similar assessments in other rivers both within and among DPS would provide equally valuable information regarding the current status of other populations.

Within the South Atlantic DPS, the Savannah River contains extant populations of both sturgeon species (Hall *et al*. 1991, Bahr and Peterson 2016); however, information regarding the status of these populations is limited (NMFS 2007; NMFS 2010). As home to one of the busiest ports in the United States, the Savannah River is also one of the most altered river systems within the range of either species (Pearlstine *et al*. 1989). In 2015, the U.S. Army Corps of Engineers (USACE) initiated the Savannah Harbor Expansion Project (SHEP), a 5-year port expansion project that will ultimately deepen 60 river kilometers (rkm) of the lower estuary by nearly 1.5 m (USACE 2012). Although the project's effects on local sturgeon populations are unclear, the environmental impact assessments for SHEP indicate that salinities will likely increase and dissolved oxygen levels will likely decrease throughout the entire estuary (NMFS 2011). The USACE is currently installing oxygen injection systems throughout the lower estuary and planning a sturgeon bypass at the New Savannah Bluff Lock and Dam (NSBLD) near Augusta, Georgia to alleviate possible negative effects (USACE 2012).

Developing an understanding of sturgeon population status before habitat alteration occurs will be critical to assessing the impacts that SHEP will have on both Atlantic Sturgeon and Shortnose Sturgeon within the Savannah River. Bahr and Peterson (2016) completed initial 3-year baseline population estimates for both species just prior to the implementation of SHEP. Mitigation work began in the lower Savannah River in 2015 and river dredging will begin during 2018 and continue through at least 2021. The goal of this study was to improve the understanding of sturgeon population dynamics within the Savannah River to help inform future management decision. The specific objectives of the project were to 1) quantify annual recruitment of Atlantic Sturgeon and Shortnose Sturgeon in 2016 and 2017; and 2) determine if a relationship exists between annual recruitment and temperature or river flow of both species.The results of the project will provide important new baseline population data for both species through the early phases of SHEP, and will extend the population assessments from Bahr and Peterson (2016). The resulting 5-year pre-SHEP baseline will provide a robust set of population data for future evaluation of population trends of both species once the SHEP project has been completed.

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CHAPTER 2

ATLANTIC STURGEON RECRUITMENT WITHIN THE SAVANNAH RIVER, GEORGIA

[1]Cummins, A. J., and D. L. Peterson. To be submitted to *Transactions of the American Fisheries Society*.

Abstract:

The Atlantic Sturgeon *Acipenser oxyrinchus oxyrinchus* was once abundant within all major river systems along North America's Atlantic coast. Habitat degradation from anthropogenic factors such as over-harvest, pollution, and dam construction has contributed to severe declines in populations range-wide. Despite being listed as endangered species, significant gaps in scientific literature, specifically species demographics are still present. The objectives of this study are to quantify annual recruitment (age-1 cohort) of juvenile Atlantic Sturgeon in the Savannah River, as well as determine environmental drivers of recruitment. During 2016-2017, anchored monofilament gill and trammel nets were used to sample juvenile Atlantic Sturgeon throughout the Savannah River estuary. Huggins closed-capture models were used to estimate recruitment in RMark, resulting is an age-1 estimate of 991 in 2016, and 622 in 2017. Because previous abundance data has been collected within the Savannah River, the results of this study allow for a 5-year long-term data set which is critical in evaluating trends, as well as effects of early stages of SHEP dredging within the river system. This study provides key information for long-term management of Atlantic Sturgeon throughout the southern reaches of their range.

Introduction

The Atlantic Sturgeon (*Acipenser oxyrinchus oxyrinchus*) is a long-lived, anadromous fish native to the Atlantic coast of North America. Historically, spawning populations occurred in most large river systems from the St. Lawrence River, New Brunswick, Canada, and the St. Johns River, Florida (Vladykov and Greeley 1963). Adults commonly reside in marine and coastal waters but will periodically return to their natal rivers to spawn (Vladykov and Greeley 1963; Caron et al. 2002). During spawning, adhesive eggs are broadcast over hard-bottom substrates such as gravel and cobble (Scott and Crossman 1973; Smith and Clugston 1997). After hatching, the free swimming embryos quickly seek cover within interstitial spaces of rocky substrates as they begin a gradual migration downstream to estuarine nursery habitats (Kynard and Horgan 2002). Juveniles remain in the lower estuary, typically below the head of tide, for at least two years (Hatin et al. 2007) before outmigrating to marine environments (Dovel and Berggren 1983; Bain 1997; Hatin et al. 2007).

Throughout the 20th century, Atlantic Sturgeon populations suffered major declines resulting from many different anthropogenic factors including commercial fishing and widespread habitat degradation (Smith 1985). Although commercial exploitation was banned in 1996, a century of damming, dredging, and discharging industrial effluents into spawning rivers has seriously reduced suitable spawning and nursery habitats throughout the range (NMFS 1998; ASSRT 2007). Despite the ban on further harvest, populations in many rivers showed little improvement and in 2012 the species was listed as endangered under the US Endangered Species Act (NOAA). In prelude to this listing, the Atlantic Sturgeon Status Review Team (2007) evaluated all extant populations based on physical, genetic, and physiological factors and conservation status. Using modern microsatellite genetic analyses, the team found that five separate distinct population segments (DPS) should be designated within United States including: the Gulf of Maine, New York Bight, Chesapeake Bay, Carolina, and South Atlantic DPS. Populations in all five DPS were listed as "endangered" except for those in the Gulf of Maine DPS where they were listed as "threatened" (NOAA 2012).

An understanding of population dynamics within individual rivers is vital for future recovery of Atlantic Sturgeon (NMFS 1998; ASSRT 2007). Unfortunately, the complex migratory life history of the species makes quantified population assessments difficult. Consequently, these assessments are almost completely lacking for most populations. Although non spawning adults are difficult to count because of their migratory behavior, young juveniles remain in nursery habitats within their natal rivers until at least age-2 (Bain 1997; Fox and Peterson 2018). Consequently, assessments of age-1 cohorts provide a critically important measure of annual recruitment that can provide managers with at least one quantifiable metric of population trend (Dovel and Berggren 1983; Peterson et al. 2000). When multiple recruitment assessments can be collected over time, they can provide a quantified and objective measure of population recovery.

The Savannah River contains one of the largest remaining populations of Atlantic Sturgeon within the South Atlantic DPS (Bahr and Peterson 2016). Like many other nearby populations, it too was subjected to historical overfishing. It has also suffered from the effects of damming and dredging of sturgeon habitats throughout its entire reach and although recent evidence suggests the population may be in the early stages of recovery (Bahr and Peterson 2016), the status of the population remains unclear because of new and ongoing habitat threats, and because recent long term population data are not currently available (NMFS 2011). Because the Savannah River is home to one of the of the busiest ports in the United States, it also has become one of the most altered river systems within the Atlantic Sturgeon's range (Pearlstine et al. 1989). In 2015, the U.S. Army Corps of Engineers initiated a new 5-year port expansion project (the Savannah Harbor Expansion Project, aka: SHEP) - that will ultimately deepen 60 river kilometers of the lower estuary by nearly 1.5 meters (USACE 2012). Although the potential effects on sturgeon are unclear, the environmental impact assessments of SHEP predict that salinities in the estuary will likely increase, while dissolved oxygen levels decrease (NMFS 2011). To mitigate the potential negative effects on Atlantic Sturgeon and other estuarine fishes, the USACE is currently installing oxygen injection systems throughout the lower estuary as well as a new fish passage infrastructure for sturgeon at the New Savannah Bluff Lock and Dam (NSBLD) near Augusta, Georgia (USACE 2012).

Developing an understanding of Atlantic Sturgeon population status before habitat alteration occurs is critical to assessing the potential impacts of SHEP once the project has been completed. Consequently, the primary objective (1) of this study was to quantify annual recruitment (age-1 cohort size) of Atlantic Sturgeon in the Savannah River in 2016 and 2017 and then, (2) to combine recruitment data from this study with those from Bahr and Peterson (2016) to provide a continuous 5-year assessment of annual recruitment for the population to evaluate environmental influences on annual recruitment of the Savannah River population.

Methods

Study Site

The Savannah River originates in the southeastern Appalachian Mountains of Georgia, South Carolina, and North Carolina. The mainstem flows approximately 484 km to the Atlantic Ocean, and forms the entire border between the states of Georgia and South Carolina (Figure 2.1). The basin drains over 27,000 km^2, covering the blue ridge, piedmont, and coastal plain ecoregions of Georgia and South Carolina. (USACE 2013). Near its mouth, the river is bordered to the north by the Savannah River National Wildlife Refuge and to the south by the highly industrialized port city of Savannah. Under typical conditions, tidal influence within the river extends to river kilometer (rkm) 83, and although the saltwater interface is variable, the river typically becomes noticeably brackish between rkm 33–38 (Hall *et al*. 1991). The US Army Corps of Engineers maintains the lowest 60 km of the Savannah River as a shipping channel for large container ships using the Port of Savannah; the channel is currently dredged to a minimum depth of 12.8 m. Juvenile Atlantic Sturgeon reside below the head-of-tide within the brackish habitats throughout the Savannah estuary, including portions of the shipping channel, middle river, and back river reaches (Collins *et al*. 2000; Bahr and Peterson 2016).

Capture and Tagging

Atlantic sturgeon were sampled using gill and trammel nets deployed 3-5 d/wk mostly between rkm 30-50 from mid-May to mid-July, in 2016 and 2017. Nets were 3.1-m deep by 91.4-m long and were constructed of monofilament webbing. Gill nets consisted of three randomly ordered mesh sizes of 7.6 cm, 10.2 cm, and 15.3 cm (stretch) randomly ordered in 30.5-m panels. Trammel nets consisted of three layered panels including an inner panel of 7.6-cm mesh, and two outer panels of 30.5-cm mesh. Nets with similar configurations have been well documented as an effective sampling gear for capture of juvenile Atlantic Sturgeon in other Georgia rivers (Schueller and Peterson 2010; Bahr and Peterson 2016). Nets were typically anchored on the river bottom perpendicular to the current at mid channel, and soaked for 30-60 minutes during slack tides. Specific netting locations were based on successful sturgeon captures in previous studies (Hall *et al* . 1991; Collins *et al* . 2000, Bahr and Peterson 2016), and on preliminary sonar surveys that identified areas of clean bottom (Figure 2.1). Water temperature (^oC), dissolved oxygen (mg/l and % saturation), and salinity (ppt) were also recorded at each netting site. As nets were retrieved, captured sturgeon were immediately removed from nets and placed into a floating net pen tethered to the research vessel. Once all nets had been retrieved, each captured individual was measured (TL), inspected for external tags, and scanned with a portable passive integrated transponder (PIT) tag detector. If no PIT tag was present, one was inserted subcutaneously under the 4^{th} dorsal scute. A 1-cm section of the pectoral fin ray was then removed from a random sample of juveniles for subsequent age estimation. All sturgeons were released at their original capture sites within one hour of capture.

Data Analysis

At the conclusion of each sampling season, the length measurements of all captured juveniles were used to construct a length-frequency histogram (LFH) of the entire catch for that sampling year. The age distribution of juveniles depicted in the LFH were then verified from the pectoral fin ray samples as described by Schueller and Peterson (2010). The verified juvenile age distribution on the LFH was then used to assign a nominal age to each juvenile within that annual catch. To estimate abundance, I first used the mark-recapture data to construct capture histories for each individual fish. These capture histories were then used with Huggins closed-capture models in RMark (in R 3.3.2) to estimate abundance of age-1 juveniles in each year of the study (Huggins 1989; Schueller and Peterson 2010; Cooch and White 2013; Bahr and Peterson 2016). The model assumed that the population was closed to births, deaths, emigration, and immigration, and that no tag loss occurred during the sampling period (Conroy and Carroll 2009). Nets were deployed both upstream and downstream of known summer holding areas to help ensure the assumption of closure within our mark-recapture sampling area. Within each year, the sampling period was divided into 11-12 weekly sampling occasions to help ensure adequate time for random mixing of marked and unmarked fish between each successive week of sampling (Conroy and Carroll 2009). Population models incorporating variation in capture probability throughout sampling periods were also incorporated in the abundance estimation. The most basic model assumed a constant capture probability (M_0), while other models assumed variable capture probability by age class (M_a), weekly sampling occasion (M_t), and additive (M_{t+a}) and interactive (M_{t*a}) combinations of these factors. The relative likelihood of each model was then assessed using Akaike's information criterion (AIC) (Akaike 1973; Hurvich and Tsai 1989). The most plausible model was subsequently selected for estimating abundance in each study year.

To assess the potential correlation of riverine flow and temperature on the recruitment of age-1 Atlantic Sturgeon, we used a 5-year set of recruitment data, spanning 2013-2017, including the 2 years of estimates from this study and the 3 previous years of similarly conducted estimates from Bahr and Peterson (2016). We then obtained flow data for the same corresponding 5-year recruitment period from the USGS stream gage 02197000 located at the New Savannah Bluff Lock and Dam. Linear regression models were used to evaluate the seasonal relationships of flow and temperature during different 1-month and 2-month periods of the year using our annual point estimates of age-1 abundance as the response variable. The intervals of flow and temperature data were also characterized by the corresponding developmental periods of Atlantic Sturgeon (e.g. early pre-spawn, late pre-spawn, spawning, etc.) to better illustrate the potential biological significance of each respective period based on similar analyses by Bednarski (2012), Smith et al. (2015), and Ingram and Peterson (2016). To quantify high flow events, we calculated the cumulative number of days when flows exceeded the 75th percentile ("high flow duration", or HFD) within each period. The median flows used to identify the 75^{th} percentiles were based on mean flows from 1 October 1883 to 12 November 2017 and were determined using the United States Geological Survey (USGS) WaterWatch Hydrograph builder website (http://waterwatch.usgs.gov/). To examine the relationship between temperature and recruitment, we first calculated the cumulative number of days in each period when water temperature exceeded 28° C ("high-temperature duration" or HTD). Temperature data were acquired from the USGS stream gage 021989773 in Savannah, Georgia. Using HFD and HTD as the independent variables, 18 linear regression models were then constructed to relate age-1 abundance to each variable during each period. The variance inflation factor (VIF) was calculated for each predictor in each model as described by Ott and Longnecker (2010). Any model that included a predictor variable with a VIF > 5.0 was excluded from further evaluation because of possible multicollinearity. The relative weight of evidence for each specific model was evaluated using an information theoretic approach (AIC) as described by Burnham and Anderson (2002). Models with >12.5% of the weight of the model with the greatest weight of evidence were included into the confidence set (Royall 1997). Finally, the overall fit of each linear regression model was determined by calculating its coefficient of determination (Ott and Longnecker 2010).

Results

During the summers of 2016 and 2017, a total of 625 individual nets were fished for a total of 437 net-hours (Table 2.2) yielding a total catch of 835 unique Atlantic Sturgeon. Length-frequency histograms were constructed for each year, and ages of individual fish were verified by examining pectoral fin ray sections from a subsample of the catch (Figure 2.2). The total catch of unique age-1 juveniles was 303 in 2016, and 150 in 2017. Total lengths of these juveniles varied from 300 - 540 mm. All age-1 juveniles were captured between rkm 18-39, where salinities varied from 0-14.7 ppt. Over the two summers of sampling, water temperatures and dissolved oxygen concentrations in this reach varied from 20.9-30.3 C and 1.26-8.46 mg/l respectively. The Huggins closed-capture model indicated that in both years of the study the time- and age-interactive model held the highest Akaike weight (Table 2.3). The resulting age-1 abundance estimates were 991 (95% CI; 791-1273) in 2016 and 622 (95% CI; 434-938) in 2017.

High flow duration and high temperature duration were calculated for individual months and for two-month spawning and developmental periods of Atlantic Sturgeon (Table 2.3). Flow data revealed that January had the highest average flow of 14,358.6 cubic feet per second (CFS) and October (spawning period) had the lowest average CFS at 4,655.2. HFD corresponded with the highest monthly mean CFS, but the month with the lowest HFD was March. The mean for the 75th percentile was 10,479.0 CFS across all years of the study. Mean monthly temperature varied from a high of 28.3 in July to a low of 10.3 in January. HTD was observed from June through October.

Linear regression analyses showed that annual recruitment from 2013-2017 was much more strongly related to HFD than to HTD (Table 2.4). Several models from both HFD and HTD analyses were removed because of multicollinearity among months within spawning and developmental periods and hence, were subsequently excluded from further analyses. Interestingly, the regression analyses also revealed a positive exponential relationship between HFD and recruitment during May and June (early pre-spawn; Figure 2.3). Models included within the confidence set explained nearly 98% of the variation in annual recruitment over the 5-year period included in the analyses (Table 2.5). Similarly, there was a positive relationship between HTD and recruitment during September (spawning period) and the spawning period. The models included within our confidence set explained ~72% of the variation in annual recruitment. (Table 2.6).

Discussion

Although a lack of historical data have impeded recent efforts to assess the recovery status of many Atlantic Sturgeon populations, the results of this study, combined with those of Bahr and Peterson (2016) provide a robust five-year data set of annual recruitment for the Savannah River population (Table 2.4). From 2013 to 2017, age-1 cohort estimates varied from 528-991 individuals annually. These relatively consistent estimates of annual recruitment suggest that the currently population is stable and likely is recovering; although the rate of recovery is difficult to evaluate without additional demographic data. Regardless, the regular presence of age-1 cohorts over the past five years is clearly indicative of a population that is consistently producing viable offspring. Because the methods in this study are similar to those of previous recruitment studies of other Atlantic Sturgeon populations, the annual recruitment estimates obtained from this study are directly comparable. In the Altamaha River, which is considered the largest contributor of Atlantic Sturgeon in the South Atlantic DPS, Schueller and Peterson (2010) estimated annual recruitment from 2004-2007 to vary from 333-1,318 (ASSRT 2007). The results of this study suggest that the Savannah River population is also a major contributor to total species abundance within the South Atlantic DPS. Recent assessments of annual recruitment in other Georgia populations have documented inconsistent, or infrequent recruitment in the Ogeechee (Farrae et al. 2009), Satilla (Fritts et al. 2016), and St. Mary's rivers (Fox and Peterson, in press), highlighting the importance of the Savannah River population within the South Atlantic DPS.

From 2013-2017 we found that annual recruitment was related to both flow (HFD) and temperature (HTD). Model selection suggested that HFD from May through June (early pre-spawning period), was the best predictor of annual recruitment. Although few previous studies have attempted to determine if a relationship exists between Atlantic Sturgeon recruitment and flow or temperature, Flowers et al. (2009) found that flow has significant influences on Gulf Sturgeon (*Acipenser oxyrinchus desotoi*) spawning and recruitment in the Apalachicola River, Florida. Although causal mechanisms for the relationship with late spring flows is unclear, Ingram and Peterson (2017) found that at least 25% of adult spawners in the Altamaha River began their spawning migrations in April and May (Ingram and Peterson 2016), even though these fish did not spawn until the ensuing fall. The relationship between annual recruitment and HTD during late summer was also significant, explaining 72% of annual recruitment variation, but less strong than that for HFD, which explained 98% of recruitment variation. Still, previous studies by Secor and Gunderson (1998) show that high water temperatures can affect year-class strength of Atlantic Sturgeon. Given that our results were limited to only five years of recruitment data, however, we suggest that additional recruitment assessments are needed to more confidently assess the complex relationships between environmental variables and annual recruitment in Atlantic Sturgeon.

The combined results of this study suggest that the Savannah River currently supports a robust population of Atlantic Sturgeon, but extensive channel modifications currently underway as part of the ongoing Savannah Harbor Expansion Program (SHEP) are expected to alter important juvenile habitats in the lower estuary (Figure 2.4). Although the potential impacts on Atlantic Sturgeon are uncertain, expected habitat changes include altered flow and temperature regimes, increased salinity, and decreased dissolved oxygen throughout the lower Savannah estuary (NMFS 2011). In light of previous studies examining environmental tolerances of juvenile Atlantic Sturgeon (Secor and Gunderson 1998), the expected habitat changes resulting from SHEP could have negative consequences for the Savannah River population. However, proposed mitigation measures of the project, including dissolved oxygen injectors, may help alleviate or at least minimize any potential negative effects to Atlantic Sturgeon, as well as other estuarine biota (NMFS 2011; USACE 2012). Regardless, the 5-year recruitment data from this study and Bahr and Peterson (2016) should provide a solid recruitment baseline for the population, from which future recruitment trends can be evaluated.

Acknowledgements

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Tables and Figures

Table 2.1. Annual sampling effort and catch results for age-1 (<540 mm TL) and total captures of Atlantic Sturgeon in the Savannah River during 2016 and 2017

Year	Sampling Period	Effort (net- hour)	Total Captures	Age-1	
				Marked	Recaptured
2016	May-13 – August 2	253.0	584	303	55
2017	May 8 – July 27	187.7	409	150	23

Table 2.2. Huggins closed-capture models, AIC_c values, change in AIC (ΔAICc), Akaike weights (W), and number of parameters (K) used to describe the variation of Atlantic Sturgeon capture probability in the Savannah River during 2016 and 2017.

Year	**Capture Probability**	**AICc**	**ΔAICc**	**W**	**K**
2016	Time and Age Interaction	2,992.11	0.00	1.00	39
	Time	3,007.73	14.62	0.00	13
	Time and Age Additive	3,009.92	16.81	0.00	15
	Constant	3,204.14	211.03	0.00	1
	Age	3,206.33	213.22	0.00	3
2017	Time and Age Additive	2,143.19	0.00	0.93	15
	Time	2,148.45	5.25	0.07	13
	Time and Age Interaction	2,162.09	18.89	0.00	39
	Constant	2,296.55	153.35	0.00	1
	Age	2,301.73	158.56	0.00	3

Table 2.3. Recruitment year breakdown by month and associated spawning and developmental periods of Atlantic Sturgeon used to assess the relationship of age-1 recruitment and high river flow and temperature. High flow duration (HFD) was calculated as the number of days within a period that river flow in cubic feet per second (CFS) was above the 75th percentile. High temperature duration (HTD) was determined as the number of days within a period that exceeded 30.

Spawning/developmental period	Month	Mean CFS	Total HFD	Mean Temp	Total HTD
Early Pre-Spawn	May	4,747.3	2	23.8	0
	June	5,292.2	8	27.4	58
Late Pre-Spawn	July	9,054.5	32	28.3	119
	August	6,686.5	31	28.0	108
Spawning	September	5,069.4	18	26.6	24
	October	4,655.2	6	22.7	1
Early Young-of-year	November	7,441.2	29	16.7	0
	December	8,165.8	33	14.9	0
Winter Young-of-year	January	14,358.6	61	10.3	0
	Febuary	7,959.9	16	11.9	0
Spring Young-of-year	March	6,977.1	1	15.7	0
	April	6,700.6	14	19.9	0

2.4. Age-1 abundance (recruitment) estimates for the Savannah River from 2013-2017. Estimates from 2013-2015 are from Bahr and Peterson (2016).

Year	**Age-1 abundance**	**95% CI**
2013	528	402 – 726
2014	589	478 – 742
2015	597	437 – 852
2016	991	791 – 1273
2017	622	434 – 938

Table 2.5. Akaike's information criteria, change in AIC (ΔAIC), relative weight (W), and coefficient of determination (r2) of the top five models relating Atlantic Sturgeon recruitment (2013-2017) to high-flow duration during spawning and/or developmental periods in the Savannah River. Models in bold represent those contained within the confidence set.

Predictor	AIC	ΔAIC	W	R^2
May	**54.50**	**0.00**	**0.57**	**0.965**
Early Pre-spawn	**55.10**	**0.61**	**0.42**	**0.973**
March	70.35	15.85	0.00	0.171
January	70.90	16.40	0.00	0.075
December	71.00	16.51	0.00	0.052

Table 2.6. Akaike's information criteria, change in AIC (ΔAIC), relative weight (W), and coefficient of determination (r2) of the top five models relating Atlantic Sturgeon recruitment (2013-2017) to high-temperature duration during spawning or developmental periods in the Savannah River, Georgia. Models in bold represent those contained within the confidence set.

Predictor(s)	AIC	ΔAIC	W	R^2
September	**64.92**	**0.00**	**0.63**	**0.720**
Spawning	**66.79**	**1.87**	**0.25**	**0.727**
October	70.35	5.43	0.04	0.171
August	71.22	6.22	0.03	0.030
July	71.29	6.37	0.03	0.014

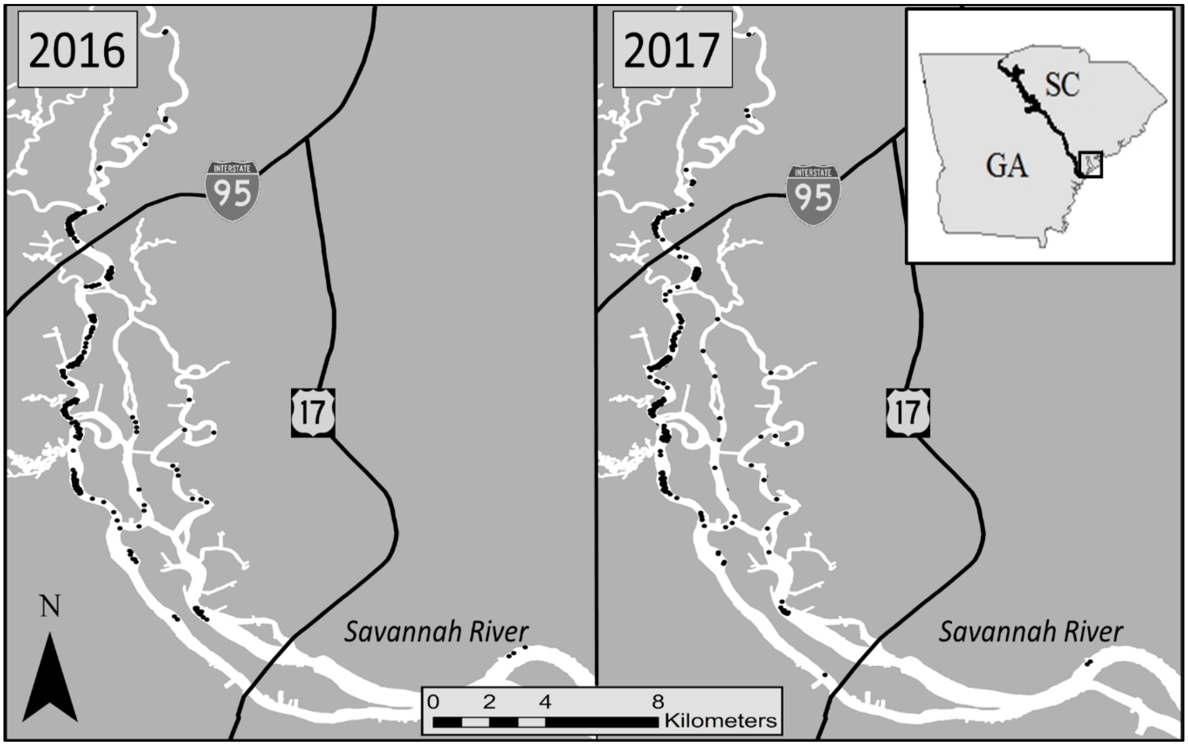

Figure 2.1. Study area and netting locations (●) for mark-recapture sampling of Atlantic Sturgeon in the Savannah River, during 2016 and 2017.

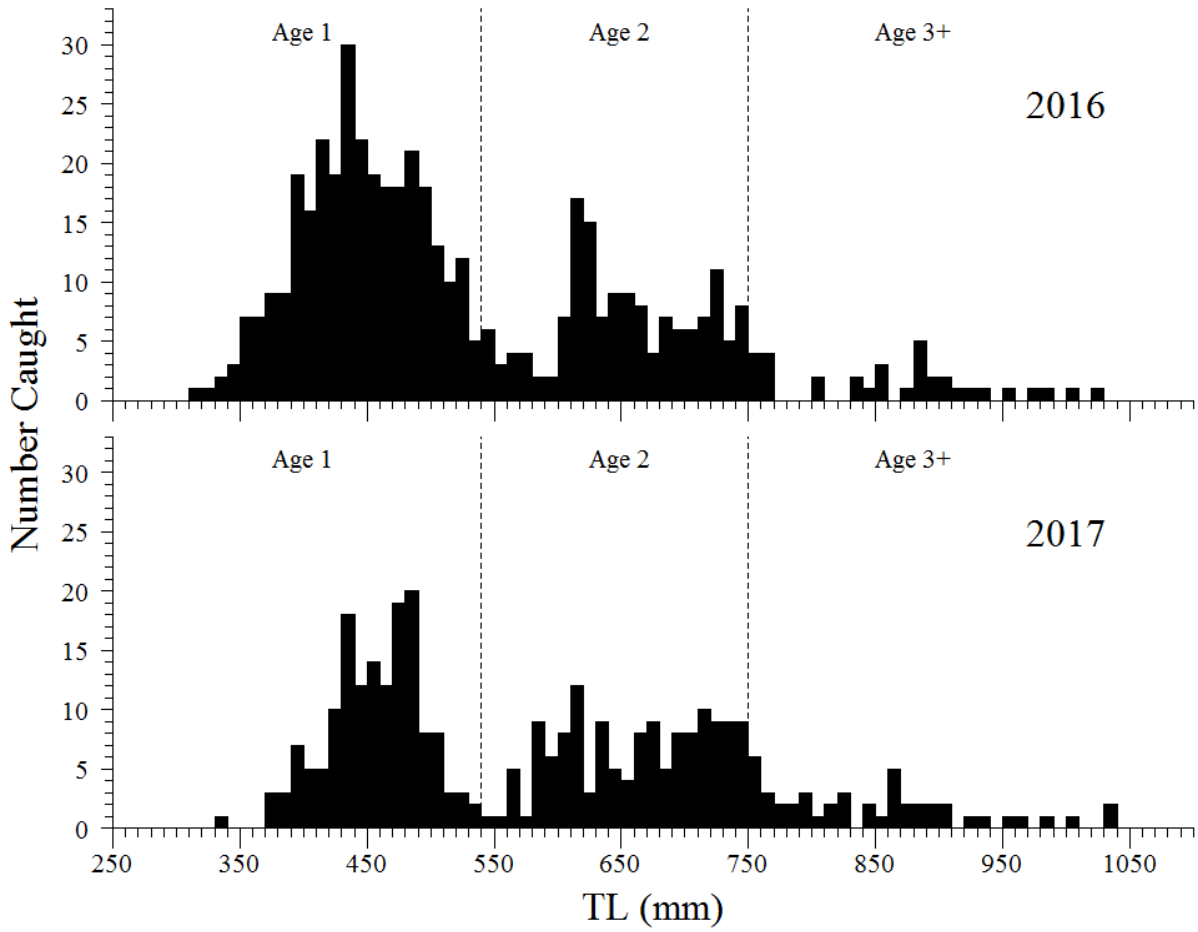

Figure 2.2**.** Length-frequency histograms and age assignments of Atlantic Sturgeon in the Savannah River for 2016 and 2017.

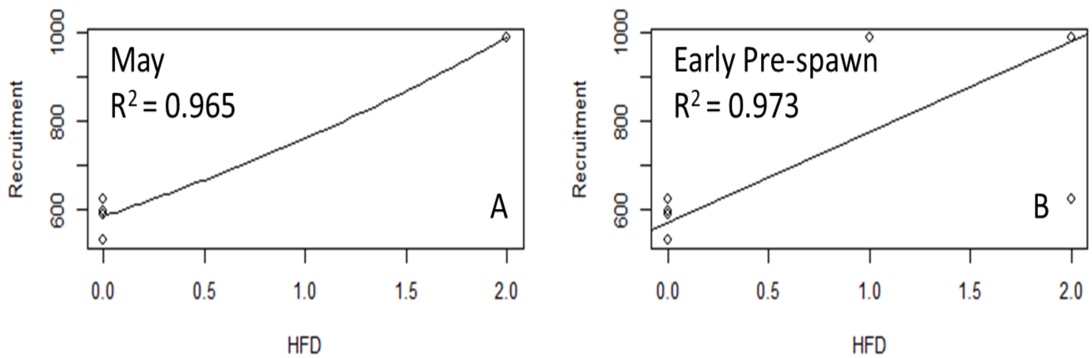

Figure 2.3. Relationship between age-1 Atlantic Sturgeon abundance and the duration of high flow (>75th percentile, HFD) that occurred during the May (A); and May-June (B) early pre-spawn periods. Circles indicate age-1 abundance estimates determined from the Huggins closed-capture mark-recapture models.

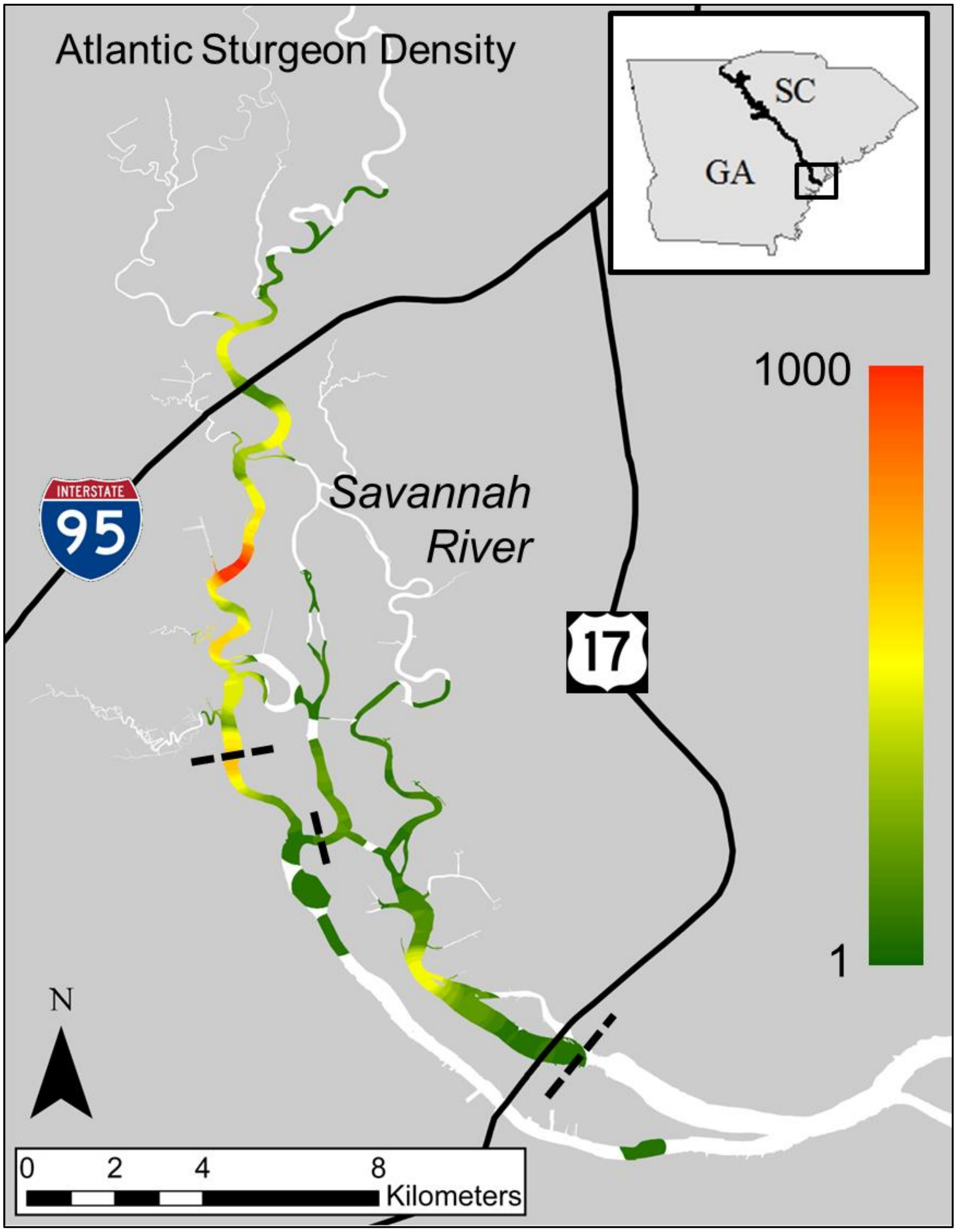

Figure 2.4. Summer Atlantic Sturgeon captures between 2013-2017 within the Savannah River, Georgia. Scale represents number of captured individuals within a 750m radius. High captures (yellow and red) represent summer holding locations for juvenile Atlantic Sturgeon. Locations downstream of the dashed lines (---) will be dredged as part of the Savannah Harbor Expansion Project.

CHAPTER 3

SHORTNOSE STURGEON RECRUITMENT WITHIN THE SAVANNAH RIVER, GEORGIA

[1]Cummins, A. J., and D. L. Peterson. To be submitted to *Transactions of the American Fisheries Society*.

Abstract:

The Shortnose Sturgeon *Acipenser brevirostrum* was once abundant within major river systems along North America's Atlantic coast. Habitat degradation from anthropogenic factors such as over-harvest, pollution, and dam construction has contributed to severe declines in populations range-wide. Despite being listed as endangered species, significant gaps in scientific literature, specifically species demographics are still present. The objectives of this study are to quantify annual recruitment (age-1 cohort) of juvenile Shortnose in the Savannah River, as well as determine environmental drivers of recruitment. During 2016-2017, anchored monofilament gill and trammel nets were used to sample juvenile Shortnose Sturgeon throughout the Savannah River estuary. Huggins closed-capture models were used to estimate recruitment in RMark, resulting is an age-1 estimate of 105 in 2016, and 523 in 2017. Because previous abundance data has been collected within the Savannah River, the results of this study allow for a 5-year long-term data set which is critical in evaluating trends, as well as effects of early stages of SHEP dredging within the river system. This study provides key information for long-term management of Shortnose Sturgeon throughout the southern reaches of their range.

Introduction

The Shortnose Sturgeon (*Acipenser brevirostrum*) is an endangered, benthic fish that occurs in large rivers along the Atlantic coast of North America. Historically, populations occurred from the Saint John River, New Brunswick, Canada, to the St. Johns River, Florida (Vladykov and Greeley 1963). Like other sturgeon species, Shortnose Sturgeon are long-lived and exhibit protracted spawning periods. In southern portions of its range, the species has a life span of 10-25 years and can reach a max length of 1-m FL (Vladykov and Greeley 1963; Dadswell et al. 1984).

Shortnose Sturgeon is an amphidromous species that is well adapted to a benthic existence in the large coastal rivers where they reside (Buckley and Kynard 1985). During February and March, when river temperatures are 9-12 °C, adults move upriver to suitable spawning habitat (Dadswell et al. 1984). During spawning events, adhesive eggs are broadcast over hard-bottom substrates such as gravel and cobble (Buckley and Kynard 1981). Upon hatching, larval Shortnose Sturgeon begin a gradual migration downstream to nursery habitats they will inhabit as juveniles (Kynard and Horgan 2002; Dadswell et al. 1984). Once mature, adults reside near the fresh-saltwater interface at salinities of 0-6 ppt, but occasionally move into marine waters where they actively forage on benthic marine invertebrates (Hall et al. 1991; Buckley and Kynard 1985).

Throughout the 19th and 20th centuries, Shortnose Sturgeon populations suffered major declines due to a variety of anthropogenic factors. Historically, they were subjected to unregulated commercial harvested for both their meat and roe (caviar) (Dadswell 1979; Kynard 1997). In addition to overharvest, the species suffered from water pollution and dam construction that limited access to spawning sites and modified natural hydrologic flow and temperature regimes (NMFS 1998, Cooke and Leach 2004). Severe population declines throughout the species' range resulted in its federal listed as "endangered" in 1967 (Miller 1972). In 1998, the National Marine Fisheries Service (NMFS) developed a recovery plan that recommended that the species be managed as 19 distinct population segments (DPSs) to account for reproductive isolation among populations. However, this plan was never implemented and historical population data from which to gauge recovery are largely lacking. Consequently, modern assessments of Shortnose Sturgeon population dynamics within individual rivers is critical for evaluation of species recovery and future management (NMFS 1998). Although Northern populations (e.g. the Hudson River) have been well-studied (NMFS 1998) since the federal listing, quantified population data are limited for many southern populations, particularly those in Georgia.

Within the South Atlantic Bight, recent studies of Shortnose Sturgeon by Peterson and Bednarski (2012) and Bahr and Peterson (2016) have estimated total numbers of juveniles in the Altamaha and Savannah rivers in Georgia. Findings from these studies indicate that the Altamaha and Savannah Rivers are likely the two most robust populations of remaining within the South Atlantic Bight. These authors also showed that annual assessments of age-1 juvenile cohorts (annual recruitment) provide valuable information regarding the current status and trends of southern populations.

In addition to supporting a robust population of Shortnose Sturgeon, the Savannah River is also home to one of the of the busiest shipping ports in the United States and as such, has become one of the most altered river systems within the Shortnose Sturgeon's range (Pearlstine et al. 1989). Beginning in 2015, the U.S. Army Corps of Engineers (USACE) initiated the Savannah Harbor Expansion Project (SHEP) – a multi year project that will ultimately deepen 60 river kilometers of the lower estuary by nearly 1.5 meters

(USACE 2012). The effects that this dredging will have on Shortnose Sturgeon are unclear, but environmental impact assessments for SHEP have predicted that salinities will increase and dissolved oxygen levels will decrease throughout the estuarine habitat used by both juvenile and adult life stages (NMFS 2011). To mitigate possible negative effects of these habitat changes, the USACE is currently installing oxygen injection systems throughout the lower estuary and planning a specially designed sturgeon bypass at the New Savannah Bluff Lock and Dam (NSBLD) near Augusta, Georgia (USACE 2012).

Developing an understanding of Shortnose Sturgeon population status in the Savannah River prior to the habitat alterations associated with SHEP will be critical to assessing any potential population impacts from the project. The primary objective of this study was to quantify annual recruitment (age-1 abundance) of Shortnose Sturgeon in the Savannah River in 2016 and 2017. These recruitment estimates will supplement and extend the initial population assessment of Bahr and Peterson (2016) that was conducted from 2013-2015. The secondary objective of this study was to use the combined 5-year data set from both studies to quantify the effects of key environmental variables on annual recruitment of Shortnose Sturgeon in the Savannah River population.

Methods

Study Site

The Savannah River forms the border between Georgia and South Carolina. It flows approximately 484 km from its headwaters in the lower Appalachian Mountains to the Atlantic Ocean, and the watershed drains over 27 thousand square kilometers

(USACE 2013; Figure 3.1). The NSBLD is the lowermost dam on the river mainstem and prevents Shortnose Sturgeon from accessing up to 90% of their historic spawning habitat (NMFS 2011). Located within the lower estuary, the port of Savannah is connected to the Atlantic Ocean by a 60-km channel currently maintained to a minimum depth of 12.8 m by regular dredging by the USACE. Under typical conditions, the river becomes noticeably brackish between river kilometer (rkm) 33–38 and tidal influence extends upstream approximately 83 rkm from the Atlantic Ocean (Hall et al. 1991). Both Juvenile and adult Shortnose Sturgeon reside below the head of tide within the brackish habitats of the Savannah estuary (Hall et al. 1991; Collins et al. 2002; Bahr and Peterson 2016).

Capture and Tagging

Shortnose Sturgeon sampling in this project was similar to that by Bahr and Peterson (2016). Shortnose Sturgeon sampling was conducted 3-5 days per week between rkm 30-50 from May-July in both 2016 and 2017. All Shortnose Sturgeon were captured using anchored monofilament gill and trammel nets deployed perpendicular to flow in the main channel and soaked for 30-60 min during slack tides. Water temperature (^{o}C), dissolved oxygen (mg/l and % saturation), and salinity (ppt), were also recorded at each netting site on each sampling occasion. Sampling locations were based on successful sampling locations identified in previous studies (Hall *et al*. 1991; Collins *et al* . 2002, Bahr and Peterson 2016). Additional sampling sites were also located by preliminary sonar surveys that indicated nearby areas of snag-free river bottom (Figure 3.1). As nets were retrieved, captured sturgeon were immediately removed from the nets and placed into a floating net pen that was tethered to the research vessel. After all the nets has been retrieved, each captured fish was removed from the net pen and measured (FL). Captured

Shortnose Sturgeon were inspected for external tags and scanned with a portable passive integrated transponder (PIT) tag detector. If no PIT tag was detected, a tag was inserted under the 4th dorsal scute. Once tagged, all captured individuals were released (typically within one hr of capture) at their original capture sites.

Data Analysis

To estimate abundance, mark-recapture data were used to construct individual capture histories for each Shortnose Sturgeon in the catch. Captured juveniles were classified as age-1 or age-2+ based on fork length (FL) and their corresponding modal distributions apparent within length-frequency histograms for each study year (Bednarski and Peterson 2013; Bahr and Peterson 2016). Subsequently, each age-1 juvenile was also assigned to a nominal year class to identify the specific year when each was spawned. Using the individual capture histories, I then constructed Huggins closed-capture models in RMark to estimate abundance of age-1 juveniles (i.e. annual recruitment) in each of the two study years (Huggins 1989; Cooch and White 2013). A key assumption of this model was that the population was closed to births, deaths, emigration, and immigration (Conroy and Carroll 2009). To help ensure that the population closure assumption was met, nets were deployed both upstream and downstream of known holding areas to confirm closure of our mark-recapture sampling area. Additionally, sampling duration for each annual recruitment estimate was limited to an 8-10 week period in May, June and July and was divided into weekly sampling occasions to ensure adequate time for random mixing of marked and unmarked fish between each successive sampling occasion (Conroy and Carroll 2009; Bahr and Peterson 2016). Models incorporating variation in capture probability throughout sampling periods were used for abundance estimates. The simplest model assumed a constant capture probability, while other models assumed variable capture probability by weekly sampling occasion and age of fish capture (M_a), as well as additive and interactive combinations of both. Models were evaluated using Akaike's information criterion (AIC; Akaike 1973) corrected for small sample size to determine relative likelihood (Hurvich and Tsai 1989). AIC comparison allowed for assessment of model variation and selection of the most accurate model for estimating annual age-1 abundance.

To assess the possible relationship between river flow or temperature on young-of-year Shortnose Sturgeon, linear regressions were used with a 5-year recruitment data set consisting of 2 years from this study and 3 previous years from Bahr and Peterson (2016). Annual point estimates of age-1 abundance were used as the response variable. The predictor variables were temperature and flow, which have both been identified as being potentially important for annual year-class strength in Shortnose Sturgeon (Woodland and Secor 2007; Ziegeweid et al. 2008; Bednarski 2012) To identify biologically relevant time periods for these predictor variables, we ran models based on both monthly and two-month periods. These periods allowed me to infer the specific spawning and developmental stages that appeared most sensitive to river flow and temperature based on previously documented life cycle processes of Shortnose Sturgeon in southern river systems (Bednarski 2012). To determine the relation of flow and annual recruitment, I first calculated the cumulative duration, in days, when flow exceeded the 75th percentile ("high flow duration", or HFD) within each period. The 75th percentiles for flow data were determined from the period from 1 October 1883 to 12 November

2017 and were obtained from the United States Geological Survey (USGS) WaterWatch Hydrograph builder website. (http://waterwatch.usgs.gov/). Flow data corresponding to each of the 5 years of recruitment data (2013-2017) were obtained from the USGS stream gage 02197000 located at NSBLD near Augusta, Georgia. To determine the relation of temperature and recruitment, if first calculated the cumulative number of days, when temperature exceeded the 75th percentile ("high temperature duration", or HTD) in each period. Temperature data were acquired from the USGS stream gage 021989773 in Savannah, Georgia. Eighteen linear regression models were constructed using HFD and HTD as the independent variable for each period. The variance inflation factor (VIF) for each predictor was calculated and we excluded any model featuring a predictor variable with a VIF > 5.0, due to possible multicollinearity as described by Ott and Longnecker (2010). The relative weight of evidence for each model was then evaluated using ΔAIC as described by Burnham and Anderson (2002). Models with >12.5% of the weight of the model with the greatest weight of evidence were included into the confidence set (Royall 1997). The overall fit of each linear regression model was determined by calculating its coefficient of determination (r^2) (Ott and Longnecker 2010).

Results

During the summers of 2016 and 2017, a total of 625 nets (437 net-h) were deployed resulting in a total catch of 446 individual Shortnose Sturgeon (Table 3.1). Across both years of the study, nets were soaked for an average of 0.63 net-hr (range of 0.13-2.0). Length-frequency analysis identified 90 individuals as age-1 juveniles (Figure 3.2), with all individuals >400 mm FL considered to be age-2+ . The annual catch of age-

1 juveniles varied from 11 individuals in 2016 to 79 in 2017 (Table 3.1), with a total of 5 recaptures across both years of the study. All age-1 individuals were captured between rkm 24-36, although extensive sampling was conducted both above and below this reach. Salinity in the reach were age-1 fish were captured varied from 0 to 14.7 ppt, while water temperature varied from 20.9 to 30.3, and dissolved oxygen varied from 1.26 to 8.46 mg/L. The results of our Huggins closed-capture AICc model selection indicated that in 2016 the time-only model had the highest Akaike weight (W_i), while in 2017 the time*age interactive model had the greatest W_i (Table 3.2). These models estimated the age-1 abundance of Shortnose Sturgeon (with 95% confidence limit) as 105 (52-229) in 2016 and 523 (254-1193) in 2017.

High flow duration and high temperature duration were compiled for individual months and two-month periods, and then related to the specific spawning and developmental periods of Shortnose Sturgeon in southern rivers (Table 3.3). These analyses showed that over the course of the study, January (the late pre-spawn period) had the highest average flow of 14,358.6 cubic feet per second (CFS) and October (early pre-spawn period) had the lowest average CFS of 4,655.2. January had the highest HFD during the study, but the month with the lowest HFD was March (spawning period). The mean 75th percentile of HFD was 10,479.0 CFS across all years of the study. The mean monthly temperature varied from a high of 28.8 ^{o}C in July to a low of 11.3 ^{o}C in January. HTD was observed from June through October.

The results of the linear regression analyses identified a positive exponential relationship between recruitment from 2013 to 2017 and HFD within the Savannah River (Table 3.4; Figure 3.3). The total number of HTD had no relationship with recruitment (Table 3.5). Several models from both HFD and HTD analyses were removed because of multicollinearity between months within spawning and developmental periods. The models included within our confidence set suggested that high flow during December, February, March, and May (late pre-spawn, spawning, and early young-of-year) had the greatest relationship with annual recruitment (Table 3.6). Each model explained at least 82% of the variation in annual recruitment documented from 2013 through 2017.

Discussion

The results of this study, combined with those from Bahr and Peterson (2017), provide a robust 5-year data set of Shortnose Sturgeon recruitment in the Savannah River (Table 3.4). Age-1 cohort estimates from 2013 to 2017 varied from 81-523, and at least some recruitment was documented in each year of the study. Over a 7-year period, Bednarski and Peterson (2013) found similar annual recruitment rates in the Altamaha River. The Shortnose population is currently thought to be the largest anywhere south of the Delaware River. Although our Savannah River recruitment estimates were generally lower than those for the Altamaha, our estimates were within the ranges reported for that population (Peterson and Bednarski 2013), suggesting that the Savannah River population is similarly robust.

Linear regression analyses indicated that flows - not high temperatures, had a strong relationship with annual recruitment of Shortnose Sturgeon in the Savannah River, at least during the 5 years of our study. An evaluation of spawning habitat within the Savannah River identified temperatures at time of spawning and early development, instead of high summer temperatures, to be most critical in Shortnose Sturgeon recruitment (USACE 2010). The strong relationship between recruitment and HFD was illustrated by the best-fitting models that included high-flows during February and March (spawning), as well as in December (late pre-spawn) and May (early young-of-year). Although our data set only compared 5 years of recruitment and flow data, our results are similar to those of Bednarski (2012) who conducted a similar analyses of Shortnose Sturgeon recruitment in the Altamaha River. Similar findings have also been reported within the Hudson River (Woodland and Secor 2007), suggesting that the effects of high-flows during and immediately before and after spawning may be a key environmental variable affecting Shortonse Sturgeon recruitment throughout the species range. Future studies are needed however, to future corroborate and quantify this relationship on both regional and population levels.

The Savannah River currently supports a robust population of Shortnose Sturgeon – probably the second largest within the US South Atlantic region; however, the river is currently undergoing major habitat changes from estuarine dredging associated with SHEP. In fact, dredging activities are expected to occur within close proximity to summer holding areas of Shortnose Sturgeon identified in this study (Figure 3.4~~3~~) and by Collins (2002). This dredging is also expected to dramatically alter water quality throughout Shortnose Sturgeon nursery habitat located well upstream of the areas where dredging will occur (NMFS 2011). Although the effects that these habitat changes will have on Shortnose Sturgeon are not yet clear, previous studies on the environmental tolerances of the species suggest that several of the predicted changes in water quality could be detrimental to the population. For example, Campbell and Goodman (2004) found that decreased DO levels (2.2-3.1 mg/L) and increased temperatures (22-30 ^{o}C) lead to increased mortality in young-of-year Shortnose Sturgeon. In this study DO levels <2 mg/l were documented on several occasions within the lower Savannah estuary.

Consequently, we suggest that any subsequent reduction in summer DO levels related to SHEP dredging could be problematic for the Shortnose Sturgeon population. Planned mitigation projects, including installation of oxygen injections systems in this reach of the river may help alleviate at least some of these effects, however, future population assessments will be critical in evaluating the effectiveness of proposed mitigation measures associated with the SHEP project (NMFS 2011, USACE 2012).

The cumulative results of this study and previous studies by Bahr and Peterson (2016) indicate that the Savannah River currently supports one of the most robust populations of Shortnose Sturgeon within the southern portion of the species range. Unfortunately, this population may be at risk from habitat alterations associated with the SHEP, as the project is expected to alter several habitat variables that are important for Shortnose Sturgeon, including flow regime. Although the effects of the predicted habitat changes are uncertain, the results of this study found that flow regime has a strong relationship with annual recruitment within the Savannah River populations. Consequently, we suggest that future populations assessments are needed after SHEP has been completed to identify any potential change in annual recruitment as compared to the baseline recruitment estimates provide in this study.

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Tables and Figures

Table 3.1. Annual sampling effort and catch results Shortnose Sturgeon in the Savannah River, 2016-2017. Age-1 sturgeon are <540 mm total length.

Year	Sampling Period	Effort (net- hours)	Age-1 Marked	Age-1 Recaptured	Total Captures
2016	May 13 – August 2	253.0	11	0	225
2017	May 8 – July 27	187.7	79	5	221

Table 3.2. Huggins closed-capture models for estimating Shortnose Sturgeon capture probability in the Savannah River. For each year, model AIC_c values, change in AIC (ΔAICc), Akaike weights (W), and number of parameters (K) are provided.

Year	Capture Probability	AICc	ΔAICc	W	K
2016	Time	1,170.46	0.00	0.85	12
	Time and age additive	1,173.96	3.50	0.15	14
	Time and age interaction	1,193.43	22.97	0.00	36
	Constant	1,225.95	55.49	0.00	1
	Age	1,229.42	58.96	0.00	3
2017	Time and age interaction	1,195.82	0.00	0.89	39
	Time	1,200.63	4.81	0.08	13
	Time and age additive	1,202.93	7.11	0.02	15
	Constant	1,272.77	76.95	0.00	1
	Age	1,275.04	79.22	0.00	3

Table 3.3. Recruitment year breakdown by month and associated spawning and developmental periods of Shortnose Sturgeon used to assess influences on age-1 recruitment by high river-flow and temperature. High flow duration (HFD) was calculated as the number of days within a period that river flow in cubic feet per second (CFS) was above the 75th percentile. High temperature duration (HTD) was determined as the number of days within a period that exceeded 30.

Spawning/developmental period	**Month**	**Mean CFS**	**Total HFD**	**Mean Temp**	**Total HTD**
Early Pre-Spawn	October	4,655.2	7	22.7	0
	November	7,441.2	29	16.7	0
Late Pre-Spawn	December	8,165.8	33	14.3	0
	January	14,358.6	61	11.3	0
Spawning	February	7,959.9	16	11.9	0
	March	6,977.1	1	15.7	0
Early Young-of-year	April	6,700.6	14	19.9	0
	May	5,164.1	7	23.8	0
Summer Young-of-year	June	5,391.6	8	28.8	45
	July	9,121.1	32	28.6	119
Fall Young-of-year	August	6,793.1	31	28.0	107
	September	5,245.5	19	26.8	24

3.4. Shortnose Sturgeon age-1 abundance estimates (recruitment) and 95% confidence intervals for the Savannah River from 2013-2017.

Year	Age-1 abundance	95% CI
2013	81*	27 – 264
2014	270*	162 – 468
2015	245*	104 – 691
2016	105	52 – 229
2017	523	254 – 1193

*from Bahr and Peterson (2016)

Table 3.5. The top 5 models relating Shortnose Sturgeon recruitment in the Savannah River (2013-2017) to the number of high-temperature days during spawning year months or developmental periods. Akaike's information criteria, change in AIC (ΔAIC), relative weight (W), and coefficient of determination (r2) of the top five models relating Shortnose Sturgeon recruitment (2013-2017) to high-temperature duration during spawning year months or developmental periods in the Savannah River, Georgia. Models in bold represent those contained within the confidence set.

Predictor(s)	AIC	ΔAIC	W	R^2
September	**70.23**	**0.00**	**0.24**	**0.108**
June	**70.61**	**0.39**	**0.20**	**0.036**
August	**70.73**	**0.51**	**0.19**	**0.013**
July	**70.78**	**0.56**	**0.19**	**0.003**
Summer Young-of-year	72.04	1.81	0.10	0.141

Table 3.6. The top 5 models relating Shortnose Sturgeon recruitment in the Savannah River (2013-2017) to the number of high-flow days during spawning year months or developmental periods. Each model's Akaike's information criteria (AIC), change in AIC (ΔAIC), relative weight (W), and coefficient of determination (r^2) are provided. Models in bold represent those contained within the confidence set.

Predictor(s)	AIC	ΔAIC	W	R^2
May	**61.95**	**0.00**	**0.20**	**0.829**
February	**62.02**	**0.08**	**0.19**	**0.827**
December	**62.18**	**0.23**	**0.18**	**0.874**
Spawning	**62.42**	**0.47**	**0.16**	**0.821**
November	63.28	1.33	0.10	0.777

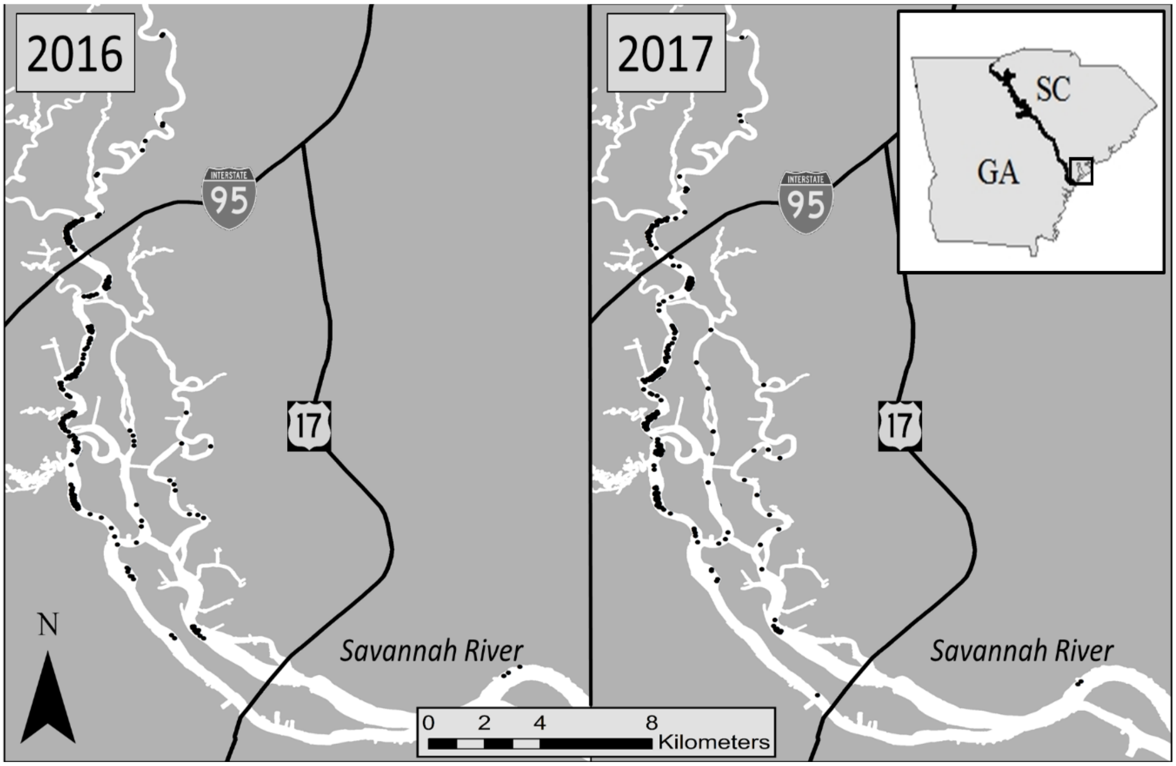

Figure 3.1. Study area and netting locations (●) for mark-recapture sampling of Shortnose Sturgeon in the Savannah River, during 2016 and 2017.

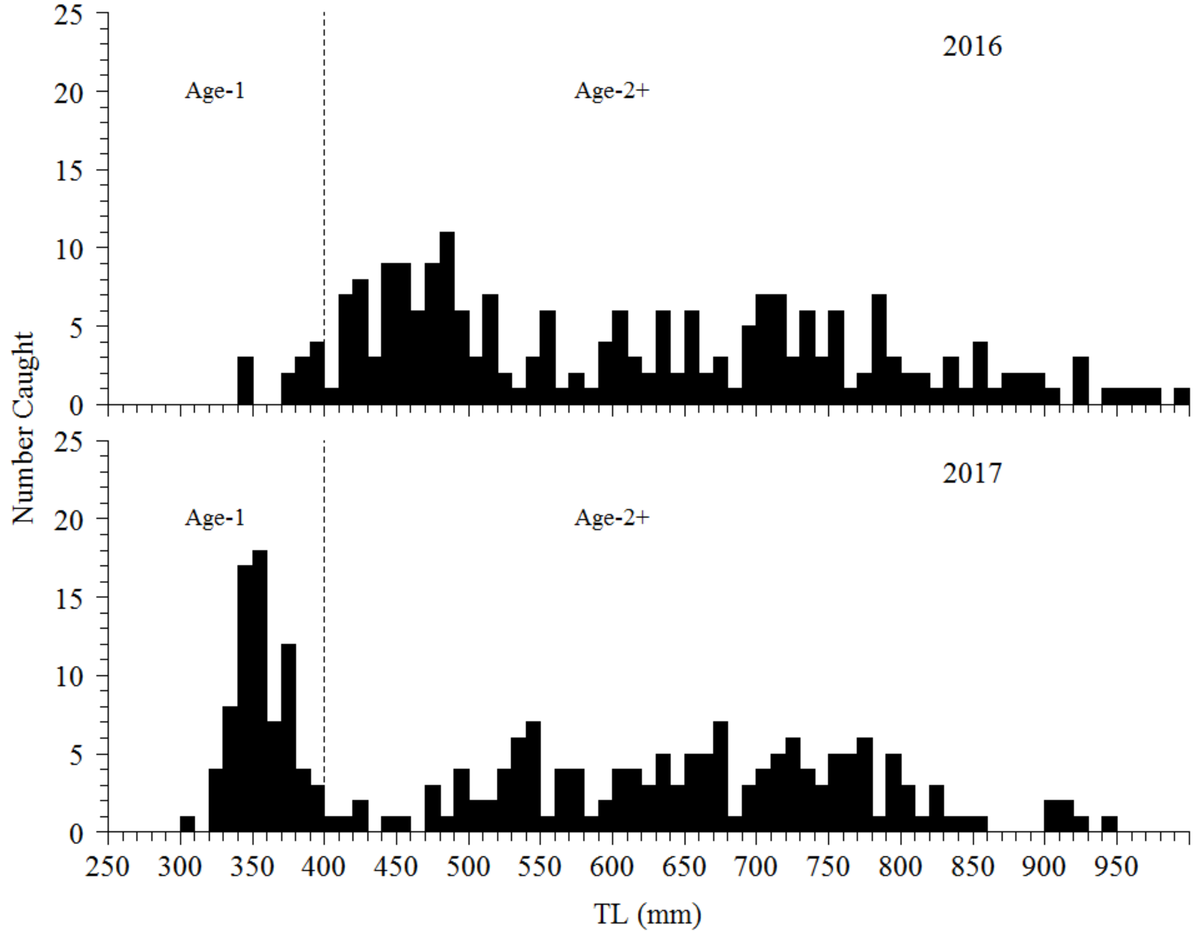

Figure 3.2**.** Length-frequency histograms and age assignments for Shortnose Sturgeon captured in the Savannah River, GA, in 2016 and 2017.

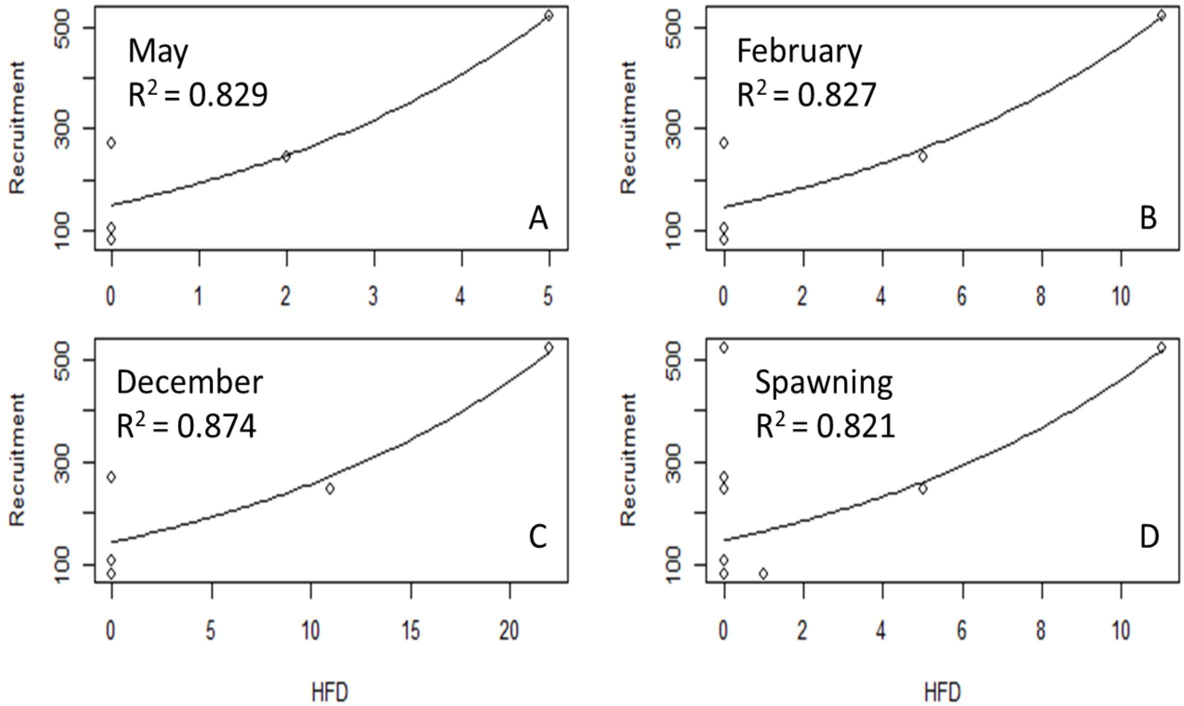

Figure 3.3. Relationship between age-1 Shortnose Sturgeon abundance and the duration of high flow (>75th percentile, HFD) that occurred during the May (A), February (B), December (C), and February-March (D) spawning periods. Circles indicate age-1 abundance estimates determined from the Huggins closed-capture models.

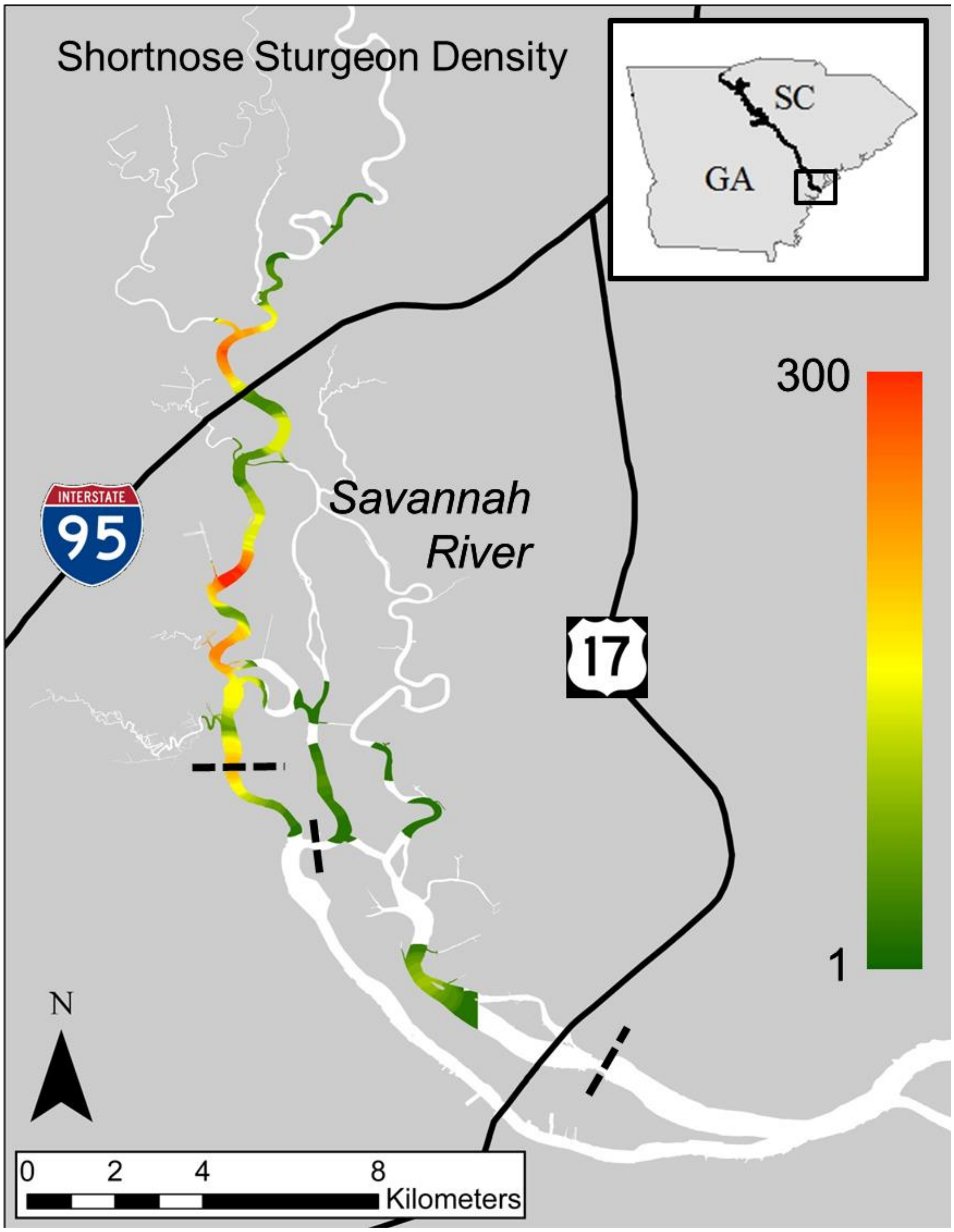

Figure 3.4. Density of summer Shortnose Sturgeon captures between 2013-2017 within the Savannah River, Georgia. Density is number of captured individuals within a 750m radius. High densities (yellow and red) represent summer holding locations for juvenile Shortnose Sturgeon. Locations downstream of the dashed lines (---) will be dredged as part of the Savannah Harbor Expansion Project.

CHAPTER 4

CONCLUSIONS

Quantified assessments of Atlantic Sturgeon and Shortnose Sturgeon recruitment have been identified as a key research need for evaluating the recovery of these endangered species (NMFS 1998; ASSRT 2007). The Savannah River likely hosts the second largest populations of both species in the South Atlantic US (Bahr and Peterson 2016a; Bahr and Peterson 2016b). Data from 2013-2017 indicate that these populations are stable and likely recovering. However, habitat changes resulting from with the Savannah Harbor Expansion Project (SHEP) will likely degrade important summer habitats for juveniles of both species (SHEP; USACE 2012). Although the proposed mitigation measures of SHEP may alleviate some of the anticipated negative effects of the project, the net effects on sturgeon populations are uncertain.

Because historic population data for both sturgeon species is largely lacking for the Savannah River, the 5-years of recruitment assessments provided by this study and from Bahr and Peterson (2016a; 2016b) will provide managers with important long-term baseline data on both populations from which future population trends may be evaluated. The results of this also provide new information regarding the seasonal effects of flow and temperature on annual recruitment of both Atlantic Sturgeon and Shortnose Sturgeon populations within the Savannah River system. For future assessments of the impacts of SHEP, researchers will need to distinguish natural variation in annual recruitment from actual recruitment trends caused by anthropogenic impacts. Our 5-year recruitment data set allowed us to identify and quantify patterns in how annual recruitment responds to extremes in both temperature and flow. The result of our modeling analyses suggests that high flow during spawning months has a strong relationship with annual recruitment in both species, providing further corroboration of similar results for the Shortnose Sturgeon population of the Altamaha River, GA (Shueller and Peterson 2010; Bednarski 2013). These analyses also showed that high temperatures had a limited correlation with Atlantic Sturgeon recruitment, but not Shortnose Sturgeon recruitment within the Savannah River. The population data provided in this study, as well as the analyses of how high temperatures and flows interact with annual recruitment, will provide future researchers with a quantified baseline for both populations that will help identify and quantify potential population trends after the SHEP has been completed.

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