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Recruitment of juvenile Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*) in the Savannah, Ogeechee, and Satilla Rivers in Georgia

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Abstract—The Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*) is a anadromous fish found along the east coast of North America and is listed under the Endangered Species Act of the United States. Decades of overfishing and habitat degradation have caused range-wide population declines, and the population status of this species in many rivers is unclear. Quantifying annual recruitment is one way to assess the status of sturgeon populations, but such assessments are few. The objective of this study was to quantify recruitment of juvenile Atlantic sturgeon in the Savannah, Ogeechee, and Satilla Rivers in Georgia. Because we used identical methods in 3 rivers simultaneously, we were able to directly compare recruitment among these populations with that of other populations observed in contemporaneous studies in other rivers. We conducted mark-recapture sampling during 2014–2017 and used Huggins closed population models to estimate annual recruitment. Because there are no historical data for comparison, we evaluated the 3 populations in terms of recruit abundance, variation, and consistency. The Savannah River annually had relatively large numbers of recruits (639–937 individuals). Fewer recruits were produced in the Ogeechee (27–57 individuals) and Satilla (51–134 individuals) Rivers; recruitment occurred in only some years in those rivers. Populations that produce few recruits or do not have regular recruitment may be experiencing bottlenecks preventing recovery.

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The Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*) inhabits the rivers and coastal waters of eastern North America from the St. Lawrence River in Canada to the St. Johns River in Florida. Five distinct population segments (DPSs) of this species have been listed as threatened or endangered under the Endangered Species Act of the United States since 2012 (Federal Register, 2012), and in the United States, these DPSs, based on geographic, genetic, and ecological factors, are independently managed (ASSRT, 2007). For each DPS, genetically distinct spawning populations have been found in one or more rivers (Wirgin et al., 2000; Grunwald et al., 2008). Although this species has now been protected from harvest for over 2 decades, no information indicates that any populations of this species are recovering. The species continues to face other threats, including restriction of spawning habitat due to impoundments in some rivers (ASSRT, 2007), bycatch (Collins et al., 1996), ship strikes (Brown and Murphy, 2010), and dredging (Smith and Clugston, 1997; Winger et al., 2000). Spawning populations of Atlantic sturgeon are currently present in fewer than 30 rivers (Hilton et al., 2016).

Atlantic sturgeon are anadromous: adults generally inhabit marine waters but return to their natal rivers to spawn (Vladykov and Greeley, 1963; Scott and Crossman, 1973). Upon hatching, larvae begin a gradual downstream migration, eventually settling in the upper estuary as river-resident juveniles (RRJs). During their first ~2 years of life, RRJs remain in the freshwater and brackish habitat below the head of tide in their natal river (Bain, 1997). Between the ages of 2 and 4, individuals begin to migrate to coastal marine habitats and enter the life stage of marine-migratory juveniles (Bain, 1997; Fox and Peterson, 2019). Marine-migratory juveniles reside in nearshore waters until they mature, although they may return to natal or non-natal estuarine or riverine habitats for prolonged periods during this life stage (Dovel and Berggren, 1983; Bain, 1997).

The highly migratory life history of the Atlantic sturgeon makes it difficult to quantify abundance. Adults and marine-migratory juveniles are highly dispersed in marine waters, and not all adults in a population return to their natal river to spawn every year. River-resident juveniles, however, remain in their natal river until at least age 2 (Fox and Peterson, 2019), and their abundance can be estimated by using mark-recapture methods. In several recent studies, such as those in the Delaware River (Hale et al., 2016), the Savannah River (Bahr and Peterson, 2016), and the Altamaha River, also located in Georgia (Schueller and Peterson, 2010; Baker et al., 2023), abundance of the age-1 cohort has been estimated to quantify annual recruitment in those systems. Although the National Marine Fisheries Service has identified recruitment estimates as a key research need to aid species recovery (ASSRT, 2007), assessments are currently lacking for many other populations in other rivers.

The South Atlantic DPS extends from South Carolina to Florida and comprises populations in 8 rivers at the southern part of the range of this species (ASSRT, 2007). The population in the Altamaha River has been identified as one of the most robust in both the South Atlantic DPS and the entire range (ASSRT, 2007; Schueller and Peterson, 2010). Baker et al. (2023) estimated that the Altamaha River had up to 3839 age-1 recruits per year during 2008–2020 and reported that recruitment was highly variable in this river. The Savannah River appears to host a smaller but still robust population—Bahr and Peterson (2016) reported annual recruitment estimates of up to 597 fish for the period 2013–2015. Recruitment of populations of Atlantic sturgeon in the nearby Ogeechee and Satilla Rivers has not been assessed since the species was listed. The objective of this study was to quantify the contemporaneous annual recruitment of juvenile Atlantic sturgeon in the Savannah, Ogeechee, and Satilla Rivers. The expectation was that these concurrent quantitative data would close a data gap identified by the National Marine Fisheries Service and allow direct comparison of the annual recruitment of Atlantic sturgeon throughout the state of Georgia and among the populations that make up much of the South Atlantic DPS.

Materials and methods

Study sites

This study was conducted in the estuaries of 3 coastal rivers in Georgia (Fig. 1). The Savannah River delineates the border between Georgia and South Carolina and is one of the most anthropogenically altered rivers within the range of the Atlantic sturgeon (Pearlstine et al.[1]). It originates in the southeastern Appalachian Mountains and is impounded by 3 dams as it flows 484 km to the Atlantic Ocean. The Ogeechee River flows unimpounded for 390 km from the Piedmont province of Georgia to the Atlantic Ocean; its mouth lies approximately 28 km south of the mouth of the Savannah River. Because of its tannic, nutrient-poor water, the Ogeechee River is classified as a blackwater river, although its pH is closer to neutral than other blackwater systems (Meyer et al., 1997). During the summer months, low flows and hypoxic conditions are common throughout the Ogeechee River estuary (ASSRT, 2007; Farrae et al., 2014). The blackwater Satilla River lies approximately 100 km south of the Ogeechee River and is situated entirely within the coastal plain of Georgia. This 320-km river is unimpounded, but hypoxic conditions have been widespread in the tidally influenced areas of the river during summer months (Fritts, 2011).

Sampling of Atlantic sturgeon

Sampling was conducted below the head of tide in each river system. Data collection in the Savannah River occurred in 2016 and 2017, and sampling in the Ogeechee and Satilla Rivers took place during 2014–2017. In all rivers, netting was conducted on weekdays (weather and tides permitting) between May and August. Atlantic sturgeon were captured with anchored monofilament gill and trammel nets designed to capture juveniles; all nets were 91.4 m long and 3.1 m deep. Gill nets comprised 3 randomly ordered panels of equal length and made of 7.6-, 10.2-, and 15.3-cm (stretch measure) mesh. Trammel nets comprised a 7.6-cm mesh inner panel enclosed by two 30.5-cm mesh outer panels. Nets were deployed within the main channels of the rivers for periods of 30–90 min around slack tides; a typical sample included the catch of 2 gill nets and 1 trammel net. Some of the sampling locations were sites used in previous studies (e.g., Schueller and Peterson, 2010; Farrae et al., 2014; Bahr and Peterson, 2016), and other locations were new sites with similar characteristics (e.g., deeper areas with limited woody debris).

Each captured Atlantic sturgeon was measured to the nearest millimeter in total length (TL) and fork length (FL) and inspected for tags. If no tag was present, a passive integrated transponder tag was injected under the fourth dorsal scute. For a subset of juveniles, we also collected a section (~0.5–1 cm) of the left pectoral-fin spine from near the base of the spine by using a scalpel, wire cutter, or small hacksaw. For fish caught in the Savannah and Ogeechee Rivers, spine samples were collected from the

[1] Pearlstine, L. R., R. Bartleson, W. Kitchens, and P. Latham. 1989. Lower Savannah River hydrological characterization. Univ. Fla., Fla. Coop. Fish Wildl. Res. Unit, Tech. Rep. 35, 139 p. [Available from Fla. Coop. Fish Wildl. Res. Unit, Dep. Wildl. Ecol. Conserv., Univ. Fla., Bldg. 106, 2295 Mowry Rd., P.O. Box 110485, Gainesville, FL 32611-0485.]

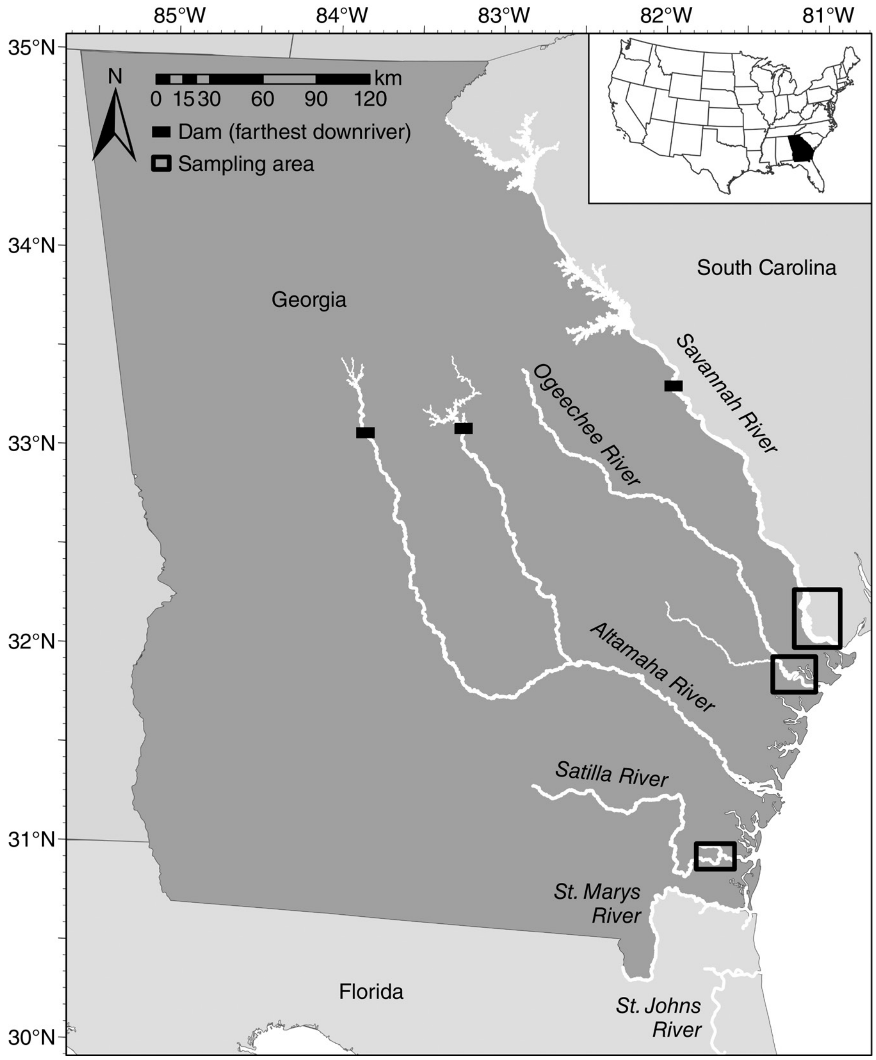

Figure 1

Map showing the locations of areas where Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*) were sampled in rivers of Georgia between May and August during 2014–2017. Sampling with gill and trammel nets occurred in the estuaries of the Savannah, Ogeechee, and Satilla Rivers.

first 5 fish captured in each preselected size bin: <299 mm TL, 50-mm intervals from 300 to 700 mm TL, and 100-mm intervals from 700 to 1000 mm TL.

Age determination

We constructed a length–frequency histogram of the entire catch for each sampling year in each river. The modal distribution of juveniles depicted in each length–frequency histogram was used to assign ages to fish on the basis of length (Schueller and Peterson, 2010; Bahr and Peterson, 2016). We examined pectoral-fin spines and counted alternating light and dark rings (Baremore and Rosati, 2014) to validate the age assignments of a subset of individuals caught in the Savannah and Ogeechee Rivers; we did not use fin spines to evaluate age assignments for fish from the Satilla River in this study. Samples of pectoral-fin spines were air dried for at least 2 months and then sectioned with a low-speed saw. The sections were mounted to glass microscope slides and photographed at 1.6× magnification with a digital camera attached to a dissecting microscope. Three (and occasionally 4) independent readers aged each fin-spine section by counting annuli. Readers were trained by someone with numerous years of experience in aging hard structures in fish. Disagreements were settled by group consensus. If readers could not agree, that sample was removed from the analysis.

Recruitment estimation

For each river and year, we divided the sampling period into weekly sampling occasions and constructed capture histories for each individual fish. We then used Huggins models that estimate capture probabilities for closed populations (Huggins, 1989) in the package RMark (vers. 2.2.7; Laake[2]) in statistical software R (vers. 4.2.1; R Core Team, 2022) to estimate the abundance of age-1 juveniles in each year of the study for each river (Schueller and Peterson, 2010; Bahr and Peterson, 2016). The assumptions for our models were that 1) the population was closed to births, deaths, emigration, and immigration during the sampling period, 2) the probability of recapture did not change after initial capture, 3) individuals could randomly disperse in between capture events, 4) individuals were correctly identified, and 5) no tag loss occurred during the sampling period (Conroy and Carroll, 2009). Results from a concurrent telemetry study in the Ogeechee, Altamaha, and Satilla Rivers (Fox and Peterson, 2019) indicate that age-1 individuals typically remained within the study sites and did not leave their natal rivers during the summer sampling periods, supporting the assumption of closure. Additionally, occasional sampling upriver and downriver from the study sites did not result in the capture of any Atlantic sturgeon. Within each year, the weekly sampling periods presumably allowed adequate time for random mixing of marked and unmarked fish between each successive week of sampling.

We developed a suite of candidate models to obtain estimates of juvenile abundance. In the most basic model, a constant capture probability is assumed, and in other models variable capture probability is assumed, by age (as assigned by length–frequency analysis), by weekly sampling occasion, and by additive and interactive combinations of these covariates. The relative likelihood of each model was then assessed by using Akaike information criterion (AIC) (Akaike, 1973; Hurvich and Tsai, 1989) with an adjustment for small sample size (AICc) (Burnham and Anderson, 2002). The most plausible model from the candidate set was selected for estimating abundance in each study year.

To compare populations, we calculated the percentage of study years in each river for which we were able to estimate recruitment and the percentage of years in which we observed age-1 sturgeon. We calculated the mean annual recruitment in each population, as well as the standard deviation (SD) and coefficient of variation (CV) of recruitment, for all years of the study period. In these calculations, recruitment was considered to be zero if an estimate could not be obtained because of no observations of age-1 sturgeon. In cases where recruitment could not be estimated because of a lack of recaptured age-1 fish, recruitment was considered *not available* and the population in that river and year was omitted from calculations of mean annual recruitment and the associated SD and CV.

This study was conducted under National Marine Fisheries Service permits 16482 and 17861 and approved by the University of Georgia Institutional Animal Care and Use Committee.

Results

Sampling of Atlantic sturgeon

During this study, we set 1972 nets, for a total of 1366 h of sampling effort (Table 1). We captured 1336 Atlantic sturgeon with FLs of 182–1945 mm (Fig. 2). Across all rivers and all years, 280 fish were recaptured. In the Savannah River, annual catch varied from 350 to 497 individuals (mean: 423.2 individuals [SD 104.9]), and we marked 847 fish. In the Ogeechee River, we marked 270 Atlantic sturgeon, and annual catch varied from 18 to 105 fish (mean: 71.5 individuals [SD 38.7]). In the Satilla River, we marked

[2] Laake, J. 2013. RMark: an R interface for analysis of capture-recapture data with MARK. Alaska Fish. Sci. Cent., AFSC Processed Rep. 2013-01, 25 p. [Available from website.]

Table 1

Effort and catch during sampling of Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*) in 3 coastal rivers of Georgia, the Savannah, Ogeechee, and Satilla Rivers, from May through August in 2014–2017. Effort is given as hours of net soak time; identical nets were used across all 3 rivers. Catch is given as the number of unique Atlantic sturgeon (ATS) and unique age-1 river-resident juveniles (RRJs) that were captured. NA=not applicable because sampling was conducted by Bahr and Peterson (2016).

	Savannah River			Ogeechee River			Satilla River		
Year	Effort (h)	ATS catch	RRJ catch	Effort (h)	ATS catch	RRJ catch	Effort (h)	ATS catch	RRJ catch
2014	NA	NA	NA	137	69	0	93	34	1
2015	NA	NA	NA	175	105	38	153	69	43
2016	253	497	310	156	94	21	168	84	8
2017	188	350	160	14	18	15	29	16	0

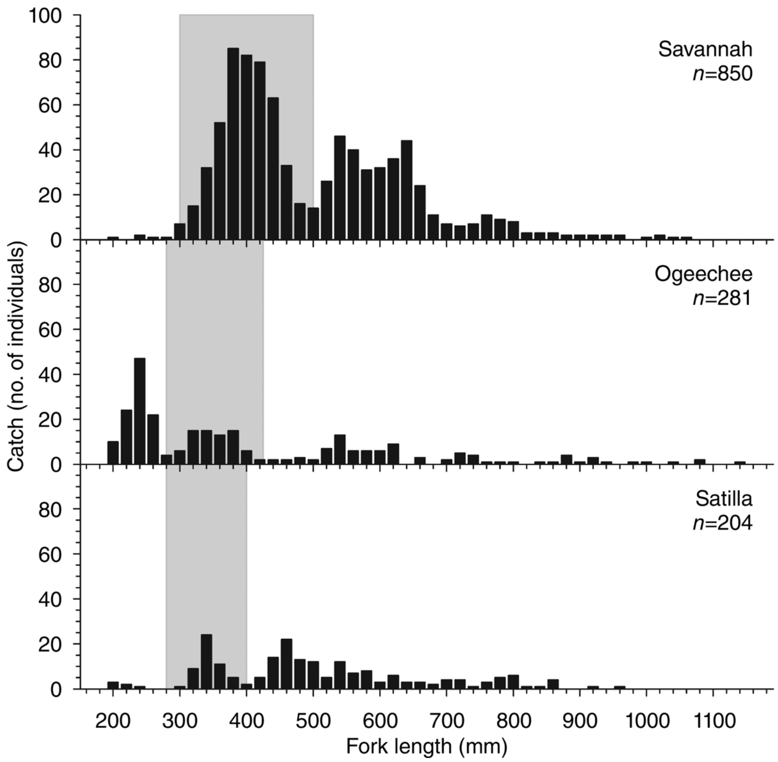

Figure 2

Length–frequency histograms for catch of juvenile Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*) in the Savannah, Ogeechee, and Satilla Rivers in Georgia. Data are from sampling in the Savannah River from May through August in 2016 and 2017 and in the Ogeechee and Satilla Rivers from May through August in 2014–2017. Data include only the initial capture of each individual (number of samples [*n*] is provided on the graph for each river). Histograms are truncated to remove individuals over 1200 mm in fork length. The gray-shaded areas indicate the size ranges for age-1 Atlantic sturgeon.

196 individuals, and annual catch was 16–84 individuals (mean: 50.8 individuals [SD 31.2]).

Age determination

Across all rivers, we classified 596 fish as age-1 (Table 1). In the Savannah River, age-1 RRJs were 300–500 mm FL. In the Ogeechee and Satilla Rivers, age-1 RRJs were 280–420 mm FL and 280–400 mm FL, respectively. In the Savannah River, we captured age-1 fish in both 2016 and 2017. In the Ogeechee River, we captured at least 1 age-1 fish in each year during 2015–2017, but none were caught in 2014. In the Satilla River, we captured at least 1 age-1 fish in each year during 2014–2016, but none were caught in 2017. We evaluated the ages of 99 juveniles (<725 mm FL) captured from the Savannah and Ogeechee Rivers in 2015 and 2016. In all cases, initial reader-assigned ages were within 1 year of each other. Overall, readers reached a consensus on the ages of 94% of specimens, and the remaining 6% were removed from additional analysis. Our assigned ages (Fig. 3) largely aligned with the results of the length–frequency analysis. For instance, fin spines were collected from 15 fish captured in the Ogeechee River, and all 15 fish were classified as age 1 on the basis of both our length–frequency analysis and fin-spine analysis.

Recruitment estimation

Results from comparisons of AICc values indicate that the best Huggins closed capture model for estimating recruitment varied among rivers and years of this study (Suppl. Table). The *time* covariate was featured in the best model for 6 of the 7 combinations of year and river for which an estimate could be calculated. The *age* covariate was also featured in several of the best models as part of either an additive or interactive effect. We successfully estimated recruitment for most years in all 3 rivers (Table 2). Estimates of annual recruitment of age-1 Atlantic sturgeon in the Savannah River varied from a low of 639 individuals in 2017 to a high of 973 individuals in 2016 (Table 2). In the Ogeechee River, estimates of annual recruitment varied from a low of 27 individuals in 2016 to a high of 57 individuals in 2017; recruitment could not be estimated for 2014. In the Satilla River, estimates of annual recruitment varied from a low of 51 individuals in 2016 to a high of 134 individuals in 2015; recruitment could not be estimated for 2014 or 2017.

Discussion

The results of this study provide recruitment estimates for 3 populations of Atlantic sturgeon in the southernmost DPS within the range of this species. The best Huggins closed capture models we used to estimate recruit abundance in each year were similar to the best models used in other studies. For example, the best models used by Bahr and Peterson (2016) for estimating recruitment in all years featured *time* or a combination of *time* and *age* as covariates. We were able to compare our results to estimates from some prior studies conducted in each river.

For the Savannah River, Bahr and Peterson (2016) used Huggins closed capture models to estimate that the abundance of age-1 recruits in 2013–2015 was 528–597 fish per year. Our estimates for the 2 subsequent years indicate greater numbers of age-1 Atlantic sturgeon (973 fish in 2016 and 639 fish in 2017). Abundance of age-1 recruits may be increasing in the Savannah River, but more data are needed to confirm this trend. For the Ogeechee River,

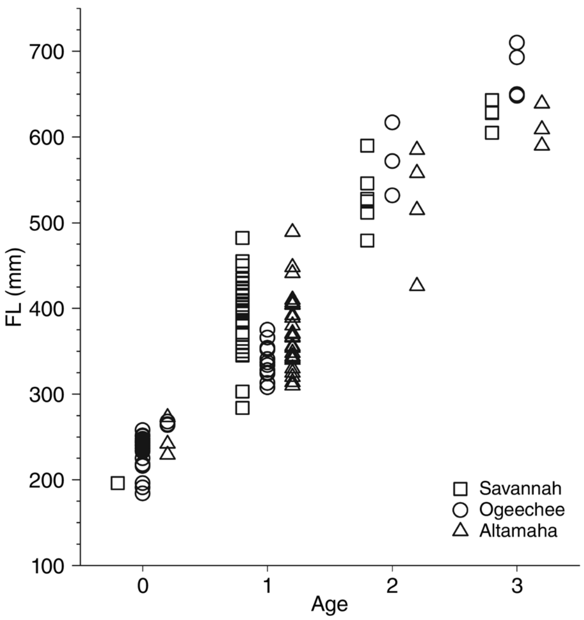

Figure 3

Lengths at age for juvenile Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*) caught in 3 rivers of Georgia from 2015 through 2016. Fork lengths (FLs) and ages are from analysis of pectoral-fin spines of fish caught in the Savannah and Ogeechee Rivers for this study. Data for fish caught in the Altamaha River, based on spines collected and analyzed concurrently to those in this study by using identical methods, are included for comparison. From fish sampled in the Savannah River, we collected 20 spines in both 2015 and 2016 and successfully aged 38 spines (95%). We collected 26 spines in 2015 and 33 spines in 2016 from fish captured in the Ogeechee River; 55 spines (95%) were successfully aged.

Farrae et al. (2009) used Huggins closed capture models to estimate that 450 juvenile (age-1–3) Atlantic sturgeon were present during the summer of 2007. By multiplying Farrae et al.'s (2009) total juvenile abundance estimate by their reported percentage of age-1 fish (24%), we calculated that there were 142 age-1 fish present in the Ogeechee River in 2007. This value is almost triple the number of recruits that we estimated more than a decade later. In the Satilla River in 2008–2010, Fritts et al. (2016) captured only a handful of age-0–1 Atlantic sturgeon, and they were unable to estimate age-1 abundances. Similarly, we could estimate recruitment in the Satilla River for only 2 of the 4 years of this study.

We observed substantial variation among rivers in the lengths of age-1 Atlantic sturgeon. Little is known about the growth of juvenile sturgeon, especially in southern river systems, and future studies are needed to address these differences in lengths. The Ogeechee and Satilla Rivers are both blackwater systems with low dissolved oxygen (Zheng et al., 2004; Farrae et al., 2014), a condition that may explain why age-1 fish in these rivers were more similar in length than they were to age-1 fish in the Savannah or Altamaha Rivers (Fig. 3; senior author, unpubl. data; Baker et al., 2023). Our results highlight the need for river-specific information on length at age, especially when classifying age-1 juveniles for estimation of recruitment.

In some rivers, Atlantic sturgeon have been reported to spawn in both the spring and the fall (e.g., the James River; Balazik and Musick, 2015). The Savannah River may (Vine et al., 2019) or may not (White et al., 2021) feature such dual spawning. In this study, our recruitment estimates represent total annual recruitment of age-1 fish and do not distinguish between RRJs that potentially spawned in the spring or fall. The presence of juveniles produced in 2 chronologically distinct

Table 2

Estimates of the abundance (recruitment) of the age-1 cohorts of Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*) in the Savannah, Ogeechee, and Satilla Rivers in Georgia during the summers of 2014–2017. Estimates and 95% confidence intervals (CIs) were derived from Huggins models that estimate capture probabilities for closed populations in RMark. An asterisk (*) indicates a result from Bahr and Peterson (2016). NA=not available because no or too few age-1 recruits were captured or recaptured.

	Savannah River		Ogeechee River		Satilla River	
Year	No. of individuals	95% CI	No. of individuals	95% CI	No. of individuals	95% CI
2014	589*	478–742	NA	NA	NA	NA
2015	597*	437–852	55	45–78	134	81–265
2016	973	786–1233	27	23–39	51	23–133
2017	639	449–953	57	25–193	NA	NA

spawning runs is one possible explanation for why, through length–frequency analysis, we found a larger upper size limit for age-1 fish in the Savannah River than for such fish in the other rivers in this study (i.e., the fall and spring modes in Figure 2 could have blurred together). However, the shape of the length–frequency distribution and upper size limit for age-1 Atlantic sturgeon in the Savannah River is the same as those for such fish in the Altamaha River (Baker et al., 2023), where spawning occurs in only the fall. Therefore, the larger size of some age-1 juveniles in the Savannah River, compared with the size of juveniles in the Ogeechee and Satilla Rivers, could instead be attributed to river conditions that enable faster growth.

Overlapping fall and spring cohorts, or simply variation in growth rates among individuals, may explain why results from our analysis of pectoral-fin spines did not align completely with results from our length–frequency analysis, particularly for fish over 500 mm FL. Results from genetic analysis in other studies indicate that dual spawning also occurs in the Ogeechee River (White et al., 2021; Wirgin et al. 2023). In that system, we observed a mode of juveniles with lengths below our age-1 size bracket (Fig. 2). We classified fish in that smaller size bracket as age 0—they were not part of the same annual cohort as the age-1 fish we quantified. Instead, these smaller fish may have been from a spring spawning run that occurred after the fall run.

Within a population, increased abundance of recruits over time could be an indicator of recovery. However, the number of recruits alone may not provide enough information to assess population growth. For instance, the abundance of recruits might be limited by the carrying capacity of the nursery habitat. Additionally, fecundity of female Atlantic sturgeon varies from 0.4 million to 2 million eggs (Van Eenennaam et al., 1996). Recruit abundance does not necessarily reflect the number of spawning adults. Therefore, without the context of historical recruitment data, we cannot state that the population in the Satilla River is any further from recovery than the population in the Savannah River simply because it produces fewer fish each year. A small, coastal plain river like the Satilla River may have never hosted as large a population of Atlantic sturgeon, or as many age-1 recruits per year, as the much larger Savannah River.

When it comes to assessing recruitment in a population of sturgeon (in the absence of historical data), we suggest that there are 3 important recruitment metrics that should be considered: 1) the abundance of age-1 fish (i.e., annual recruitment), 2) the variation in annual recruitment, and 3) the consistency of successful recruitment across multiple years. Because we assessed populations in the Savannah, Ogeechee, and Satilla Rivers concurrently and used the same methods, we can directly compare values for these metrics among these rivers. We can also compare recruitment in these river systems to that of other populations in the southernmost portion of the range of this species, thanks to concurrent studies in which identical methods were used in all other rivers of Georgia and Florida in which Atlantic sturgeon occur (Fig. 1).

Abundance of recruits

As a population recovers, an increase in the number of juveniles surviving to maturity should cause an increase in the number of recruits each year in that population. Atlantic sturgeon are intermittent spawners, returning to their natal rivers to spawn every 1–2 years (Hagar et al., 2020; Breece et al., 2021). Comparing recruitment year to year would not necessarily be informative because not every adult spawns every year. However, over a period of ~5 years, every mature adult in a population should have the chance to spawn, and the maximum cumulative effective population size (N_e) (Waldman et al., 2019) occurred in <5 years of sampling in the Savannah, Ogeechee, and Altamaha Rivers during our study. Because sturgeon spawn intermittently, a single annual calculation of N_e likely underestimates the total number of breeding adults. Waldman et al. (2019) calculated the cumulative N_e for several sequential years, with the juvenile input data for each year consisting of that year's recruits plus all recruits from all previous years. When these results were plotted, the resulting curve had a peak or asymptote, which Waldman et al. (2019) called the *maximum* N_e—an estimate of N_e for the whole population that includes adults that spawn only intermittently. In a recovering population of Atlantic sturgeon, the general trend should be an increase in annual recruitment over time, reflecting the increased number of spawners. Increased recruitment, in turn, should result in faster population recovery, as has been reported, for example, for modeled populations of white sturgeon (*Acipenser transmontanus*) in Idaho (Paragamian and Hansen, 2008).

The Altamaha River likely hosts the most robust population of Atlantic sturgeon within the South Atlantic DPS (ASSRT, 2007), and in 2014–2017, the river had more age-1 recruits per year than any other river in Georgia. For the period 2004–2020, annual recruitment in the Altamaha River varied from 163 to 3839 age-1 recruits per year (Fig. 4; Schueller and Peterson, 2010; Baker et al., 2023). During just the 3 years of 2014–2017 (the period of this study), the mean estimate of recruitment from Baker et al. (2023) was 1173.8 individuals, far greater than the mean number of recruits we observed in any river in this study (Table 3). The St. Marys River, in Georgia, and the St. Johns River also host populations of the South Atlantic DPS; they are located south of the rivers we examined in this study. During 2014–2017, Fox et al. (2018a) were unable to capture enough age-1 fish in the St. Marys River to calculate any recruitment estimates. In 2014–2015, Fox et al. (2018b) observed no age-1 Atlantic sturgeon in the St. Johns River.

Variation in recruitment

In the Altamaha River, Baker et al. (2023) observed annual recruitment that varied from a few hundred to several

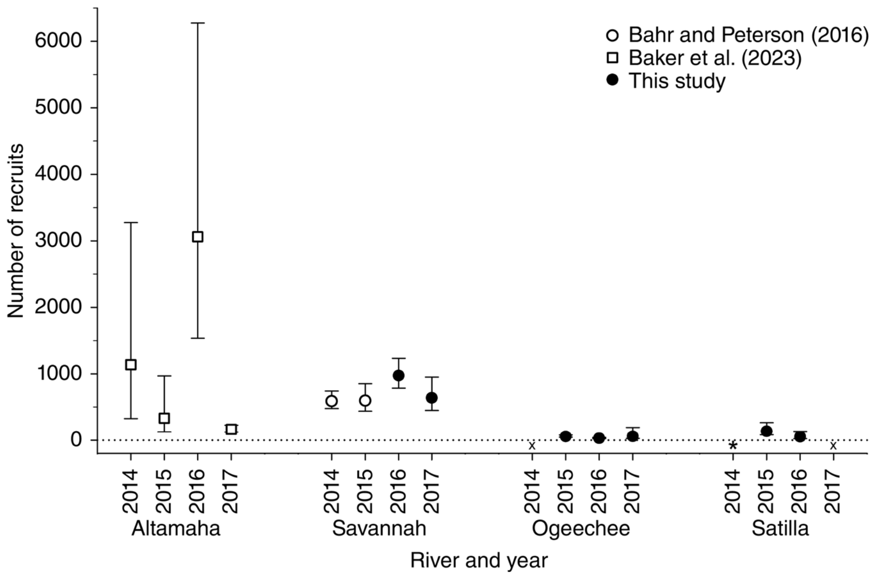

Figure 4

Estimates of recruitment of Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*) to age 1 for 4 rivers in Georgia. Estimates provided for comparison are from this study and from previously published works, Bahr and Peterson (2016) and Baker et al. (2023). Error bars indicate 95% confidence intervals. The horizonal dotted line indicates the *y*-axis value of 0. An asterisk (*) indicates that too few age-1 recruits were captured or recaptured to calculate an estimate. A letter × indicates that no age-1 recruits were captured; therefore, no estimate could be calculated.

Table 3

Comparison of the recruitment of Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*) in rivers of Georgia and Florida. Values for recruitment metrics were synthesized for each river by using data only from 2014 through 2017, including results from previously published literature. The metrics presented are the number of years during 2014–2017 in which sampling for juvenile Atlantic sturgeon occurred, the mean of all existing estimates of age-1 juvenile abundance (if available), the standard deviation (SD) and coefficient of variation (CV) of all available recruitment estimates, the percentage of sampled years in which age-1 fish were observed, and the percentage of sampled years for which a recruitment estimate could be calculated. NA=not available because of a lack of recaptured age-1 fish.

		Age-1 cohort size (no. of individuals)			Percentage of years sampled		
River	No. of years sampled	Mean	SD	CV	with age-1 fish detected	with recruitment estimate	Source
Savannah	4	699.5	183.6	0.26	100	100	This study; Bahr and Peterson (2016)
Ogeechee	4	34.8	26.9	0.77	75	75	This study
Altamaha	4	1173.8	1328.1	1.13	100	100	Baker et al. (2023)
Satilla	4	61.7	67.6	1.10	75	50	This study
St. Marys	4	NA	NA	NA	25	0	Fox et al. (2018a)
St. Johns	2	0.0	0.0	0.00	0	0	Fox et al. (2018b)

thousand age-1 fish per year (Fig. 4); for 2014–2017, the SD of mean annual recruitment from that study was 1328.1, and the CV was 1.13 (Table 3). During the same time period in the Savannah River in our study, the SD of the mean annual recruitment was 183.6, and the CV was 0.26. In our study, the Ogeechee River had an SD of mean annual recruitment of 26.9 and a CV of 0.77, and the Satilla River had an SD of mean annual recruitment of 67.6 and a CV of 1.10.

Atlantic sturgeon are periodic spawning strategists. As such, variations in recruitment among years are expected—recruitment should be high under appropriate environmental conditions and low otherwise (Winemiller, 2005). Therefore, multiple consecutive years of estimates of the recruitment of Atlantic sturgeon should be considered, to ensure that the estimate for any given year is not an outlier. Interestingly, for the period 2014–2017, the greatest number of recruits was estimated for 2016 in both the Altamaha and Savannah Rivers, indicating that the environmental conditions of both rivers were particularly suitable when that cohort was spawned. The Altamaha River features a single spawning run in the fall (Ingram and Peterson, 2016), meaning that the age-1 RRJs in 2016 would have spawned in the fall of 2014. Because there may be dual spawning in the Savannah River, the age-1 RRJs that we quantified in 2016 could have been produced either in the fall of 2014 or in the spring of 2015. A lower abundance of adult spawners also results in decreased variability in recruitment (DeAngelis et al., 1990), which may explain why, in our study, the (presumably) smaller populations in the Ogeechee and Satilla Rivers did not have a similar increase in recruits in 2016.

Unlike the Altamaha River, the Savannah River is dammed below the fall line, although sturgeon can still access 92% of their historic habitat (ASSRT, 2007). Dams change natural flow regimes in rivers by increasing minimum flows and decreasing maximum flows (Magilligan and Nislow, 2005). For Gulf sturgeon (*Acipenser oxyrinchus desotoi*), decreased river discharge resulted in decreased availability of spawning habitat (Flowers et al., 2009), which could result in decreased recruitment. Although spawning habitat can be extensive in many rivers (e.g., the Altamaha River; Ingram and Peterson, 2016; senior author, unpubl. data), the amount and extent of spawning habitat has not yet been identified in the Ogeechee River or Satilla River. These relatively small rivers are largely or wholly confined to the coastal plain and may not have substantial reaches of hard-bottom habitat.

In the Savannah River, spawning occurs only below the lowest impoundment, in just a fraction of the historic spawning habitat. In systems with limited spawning habitat, discharge-related fluctuations in availability could have relatively large effects on recruitment. Because the dams of the Savannah River reduce variability in flow, and because the habitat has been heavily channelized, sturgeon there may no longer experience the occasional optimal environmental conditions that would allow the production of a much larger juvenile cohort in some years. Although relatively high recruitment occurred in 2016 in the Savannah River, anthropogenic alterations to the habitat in that river may have prevented recruitment from being even better that year, with levels more comparable with that in the Altamaha River.

Both the Ogeechee and Satilla Rivers had relatively high CVs of recruitment compared with that in the Savannah River; however, these systems had far fewer recruits on average each year. Comparing populations solely on the basis of variation in recruitment is not a useful exercise. When the number of annual recruits is very low, annual increases or decreases of just a few fish result in large changes to the CV of recruitment, and this metric may be less useful for comparing systems. For example, recruitment in the Ogeechee River more than doubled from 2016 to 2017, but the actual increase in number of recruits was just 30 individuals. However, with such a limited data set, we cannot determine which of those years featured “normal” recruitment in that river. By looking at both the mean number of recruits and how the number of recruits varies, it may be possible to gain insight into relative population health and the environmental constraints a population may be experiencing.

Consistency of recruitment

Although recruitment in a population of Atlantic sturgeon may be variable, a healthy or recovering fish population should produce measurable recruitment every year. The catch of no age-1 recruits in some years could be attributed to environmental conditions that prevented a spawn or inhibited survival of young juveniles, to a lack of adult spawners that year, or to other bottlenecks.

Age-1 fish were observed every year during 2004–2020 in the Altamaha River (Schueller and Peterson, 2010; Baker et al., 2023). In the Savannah River during 2014–2017, age-1 recruits were also observed every year (Table 3; Bahr and Peterson, 2016). In the Ogeechee River, we observed recruitment in 75% of study years, although estimates of the abundance of age-1 fish were in the tens of individuals, compared with the hundreds of recruits in the Savannah River or the thousands of recruits in the Altamaha River. The fact that recruitment is so consistent in the Ogeechee River could indicate that the population there has recovered to this river’s (naturally small) carrying capacity, but such a recovery is unlikely given that 2 separate spawning runs are producing so few juveniles. The lack of recruitment in 25% of study years indicates that an intermittent impediment to successful spawning could be slowing or preventing recovery. In the future, relative contributions of the fall and spring spawning runs to total annual recruitment may provide additional information about the conditions that promote successful recruitment in the Ogeechee River.

The Satilla, St. Marys, and St. Johns Rivers are the southernmost rivers in the historic range of the Atlantic sturgeon, and we have observed inconsistent—or no—annual recruitment of the populations in all 3 rivers, despite our multiyear monitoring. The Satilla River had age-1 cohorts similar in size to or larger than those in the Ogeechee River, but age-1 fish were observed in only 2 years of the 4-year study period. Again, this low level or lack of recruitment indicates a bottleneck, although further research is needed to determine whether this issue can be attributed to a lack of spawners, to environmental conditions, or to other factors. In the St. Marys River, surveys for juvenile sturgeon occurred in 2008–2010 (Fritts, 2011), in 2013–2019 (Fox et al., 2018a; senior author, unpubl. data), and in 2021–2022 (senior author, unpubl. data), but age-1 fish have been observed in only 2 years, in 2014 and 2019.

Conclusions

Annual recruitment of age-1 Atlantic Sturgeon varied substantially among populations in 3 rivers of Georgia, the Savannah, Ogeechee, and Satilla Rivers. Because we lack historical data on recruitment, we compared characteristics of recruitment in the populations examined in our study to the characteristics of the robust population in the Altamaha River. In addition to producing larger numbers of recruits, healthier populations appear to have had consistent recruitment every year, even if the number of annual recruits was variable. Our results indicate that the population in the Savannah River is relatively healthy in comparison to the other populations that make up the South Atlantic DPS, but the populations in other rivers, especially those populations in the southernmost rivers, had only low numbers of age-1 fish per year, and they may not have had successful recruitment every year.

Resumen

El esturión del Atlántico (*Acipenser oxyrinchus oxyrinchus*) es un pez anádromo que se encuentra a lo largo de la costa este de Norteamérica y está incluido en la Ley de Especies Amenazadas de Estados Unidos. Décadas de sobrepesca y degradación del hábitat han provocado descensos de la población en toda su área de distribución, y el estado de la población de esta especie en muchos ríos no está claro. Cuantificar el reclutamiento anual es una forma de evaluar el estado de las poblaciones de esturión, pero dichas evaluaciones son escasas. El objetivo de este estudio fue cuantificar el reclutamiento de juveniles del esturión del Atlántico en los ríos Savannah, Ogeechee y Satilla en Georgia. Dado que utilizamos métodos idénticos en 3 ríos simultáneamente, pudimos comparar directamente el reclutamiento entre estas poblaciones con el observado en otras poblaciones en estudios contemporáneos en otros ríos. Realizamos muestreos de marcado y recaptura durante 2014–2017 y utilizamos modelos de población cerrada de Huggins para estimar el reclutamiento anual. Dado que no existen datos históricos para comparar, evaluamos las 3 poblaciones en términos de abundancia de reclutas, variación y consistencia. El río Savannah tuvo anualmente un número relativamente grande de reclutas (639–937 individuos). Se produjeron menos reclutas en los ríos Ogeechee (27–57 individuos) y Satilla (51–134 individuos); el reclutamiento sólo se produjo en algunos años en esos ríos. Las poblaciones que producen pocos reclutas o no tienen un reclutamiento regular, pueden estar experimentando cuellos de botella que impiden su recuperación.

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