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ARTICLE

Recruitment of Juvenile Atlantic Sturgeon in the Savannah River, Georgia

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Abstract
Atlantic Sturgeon *Acipenser oxyrinchus oxyrinchus* were once abundant along the Atlantic coast of North America from the Saint Lawrence River, Canada, to the St. Johns River, Florida. Severe overfishing, coupled with habitat losses during the 1900s, resulted in major population declines that eventually led to the subspecies' listing under the U.S. Endangered Species Act in 2012. Despite this listing, quantified recruitment data are largely lacking for most Atlantic Sturgeon populations, particularly those within the South Atlantic distinct population segment. The objective of this study was to quantify annual recruitment of Atlantic Sturgeon in the Savannah River, Georgia, by estimating annual abundance of age-1, river-resident juveniles. During the summers of 2013–2015, we used anchored gill nets and trammel nets to sample juvenile Atlantic Sturgeon throughout the Savannah River estuary. Ages of captured juveniles were determined by using length-frequency analysis, and abundance of each juvenile age-class was estimated with Huggins closed-capture models in RMark. We estimated the Savannah River to contain 528 age-1 juveniles in 2013, 589 in 2014, and 597 in 2015. The results from this study indicate that the Savannah River population is likely the second largest within the South Atlantic distinct population segment. Future studies are needed to determine the relative importance of the Savannah River as a natural source of recruitment for smaller, more imperiled populations in adjacent rivers. Consequently, we suggest that management efforts continue to prioritize the protection of both the population and the associated critical habitats within the Savannah River estuary.

Atlantic Sturgeon *Acipenser oxyrinchus oxyrinchus* are large, anadromous fish native to the Atlantic coast of North America, from the Saint Lawrence River, Quebec, to the St. Johns River, Florida (Vladykov and Greeley 1963). Adults often reside in shallow marine environments but migrate back to natal rivers where they spawn in freshwater habitats well above the freshwater–saltwater interface (Vladykov and Greeley 1963). During spawning events, demersal eggs are broadcast over hard bottom substrates in deep channels of the main stem or large tributaries (Scott and Crossman 1973). Upon hatching, the larvae begin a gradual but directed downstream migration toward nursery areas located within the estuarine habitats of their natal rivers (Bain 1997; Kynard and Horgan 2002). During their first 2 years, juveniles remain in these nursery areas, which may include both fresh and brackish channel habitats below the head of tide (Hatin et al. 2007). Upon reaching age 2, juveniles become increasingly tolerant of salinity, and at least some will begin their outmigration to nearshore marine waters where they will reside as subadults and nonspawning adults (Dovel and Berggren 1983; Bain 1997; Hatin et al. 2007). By age 5, most juveniles have likely completed their transition to salt water; however, as marine migratory juveniles (i.e., subadults), they are frequently encountered in estuaries of nonnatal rivers.

Atlantic Sturgeon have been subjected to a variety of anthropogenic factors that, when combined with their unique life history and diverse habitat requirements, have resulted in depleted populations across their range. Valued for both their meat and roe (caviar), Atlantic Sturgeon were commercially exploited throughout much of late 18th and 19th centuries

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(Smith 1985). Industrialization, damming, and dredging of spawning rivers within the same time period compounded population declines and severely hindered recovery of most populations (NMFS 1998, 2007). These declines continued until 1996 when all U.S. fisheries were closed by an emergency moratorium designed to establish 20 protected year-classes of females in each spawning stock and to increase numbers in current spawning stocks (ASMFC 1998). Even with these protections in place, many populations have shown little improvement during the past two decades, and in 2012, the subspecies was listed as federally endangered under the U.S. Endangered Species Act (ESA; NOAA 2012a, 2012b). Under this listing, five distinct population segments (DPSs) were designated within U.S. waters: Gulf of Maine, New York Bight, Chesapeake Bay, Carolina, and South Atlantic regions (ASSRT 2007). All populations were listed as endangered except for the Gulf of Maine DPS, which was listed as threatened (NOAA 2012a, 2012b).

Despite recommendations by the Atlantic Sturgeon Status Review Team (2007) to manage Atlantic Sturgeon rivers as individual subunits within each DPS, population assessments are still lacking in most rivers (NMFS 2007). Although Peterson et al. (2008) were able to estimate the annual run size of adults in the Altamaha River, similar assessments for other rivers have been confounded by the migratory nature and broad geographic range of adult fish. Consequently, several researchers have recently turned to assessment of annual age-1 recruitment as an alternative means of assessing the status of individual populations (Peterson et al. 2000; Schueller and Peterson 2010). Because juvenile Atlantic Sturgeon remain in their natal rivers through their second year of life (Dovel and Berggren 1983; Bain 1997; Hatin et al. 2007), juvenile cohorts can be estimated using traditional mark–recapture methods (Schueller and Peterson 2010). Consequently, studies of age-1 Atlantic Sturgeon can provide useful information about annual recruitment, frequency of successful spawning, and future population trends. Recent studies in the Hudson (Peterson et al. 2000) and Altamaha (Schueller and Peterson 2010) rivers, for example, have used this information to successfully quantify annual recruitment—a key metric of species recovery under the ESA listing.

Within the South Atlantic DPS, the Savannah River, Georgia, is known to contain an extant population of Atlantic Sturgeon; however, the status of that population is largely unknown. Despite nearly 20 years of protection under a federal ban on commercial fishing, the population has been subjected to many other anthropogenic disturbances, including dam construction, pollution, and habitat degradation. Impoundments on the Savannah River now block access to 90% of the historical spawning habitat within the river, and channel modifications within the harbor have degraded water quality within most, if not all, nursery habitats (NMFS 1998, 2011; Collins et al. 2000). The Savannah estuary is also home to one of the busiest ports on the Atlantic coast, and several lethal ship strikes of adult Atlantic Sturgeon have been reported in recent years (Georgia Department of Natural Resources, personal communication). Although adult mortality estimates resulting from ship strikes have not been directly quantified, Hightower et al. (2015) determined that mortality rates in southeastern populations were higher than expected and likely attributable to anthropogenic sources. Furthermore, the U.S. Army Corps of Engineers (USACE) has recently initiated a new multiyear dredging project that will ultimately deepen nearly 60 km of channel habitat within the lower Savannah estuary to accommodate larger container ships (USACE 2012). This dredging project, known as the Savannah Harbor Expansion Project (SHEP), is likely to further degrade habitats and water quality for juvenile Atlantic Sturgeon by removing foraging items and habitat and by increasing salinity and reducing dissolved oxygen (NMFS 2011).

To mitigate these potential negative effects that the SHEP may have on the native population of Atlantic Sturgeon, the USACE has planned to install oxygen injection systems throughout much of the presumed nursery habitat within the lower estuary (NMFS 2011; USACE 2012). Proposed mitigation also includes the construction of a fish bypass that will enable adult sturgeon to pass upstream from the New Savannah Bluff Lock and Dam located at river kilometer (rkm) 299 (NMFS 2011; USACE 2012). Although improved water quality and access to historical spawning habitats may help mitigate the potential degradation of juvenile habitat resulting from the dredging, the net effects of the SHEP are uncertain because the current status of the Atlantic Sturgeon population there is completely unknown. Consequently, the primary goal of this study was to assess the population using methods similar to those used in recent assessments of other Atlantic Sturgeon populations within the South Atlantic DPS. The specific objective of the study was to quantify annual recruitment and age-specific abundance of juvenile Atlantic Sturgeon in the Savannah River as a baseline assessment of the current population status. This baseline information will be valuable for future evaluation of population trends after the SHEP has been completed.

METHODS

Study site.—Flowing southeasterly from its headwaters in the southeastern Appalachian Mountains to the city of Savannah, Georgia, the Savannah River forms the east–west border separating the states of Georgia and South Carolina (Figure 1). The main stem flows approximately 484 km to the Atlantic Ocean and contains three large impoundments: Lake Hartwell, Lake Russell, and Clarks Hill Reservoir (USACE 2013). Near the coast, the river becomes braided into three main channels known as the Front, Middle, and Back rivers. The Savannah River is bordered on the north bank by the Savannah River National Wildlife Refuge in South Carolina

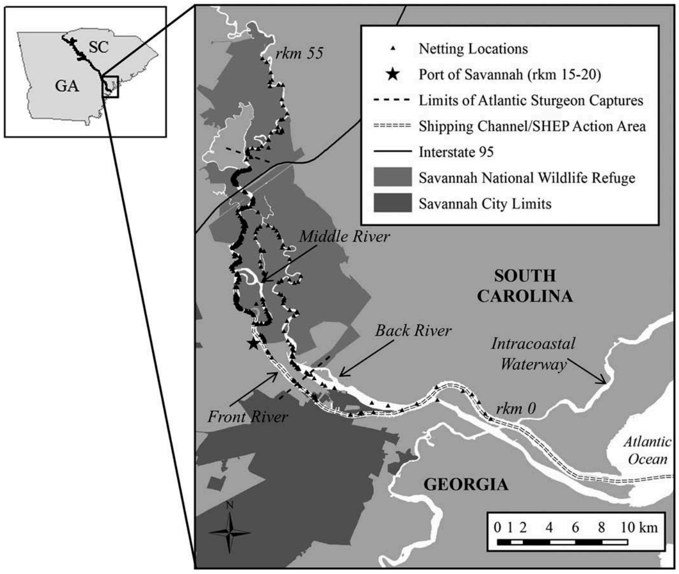

FIGURE 1. Study area for mark–recapture sampling of juvenile Atlantic Sturgeon in the Savannah River, Georgia, during the summers of 2013–2015. River kilometer (rkm) 0 was defined as the location where the Savannah River crosses the Intracoastal Waterway.

and on the south bank by the highly industrialized port city of Savannah. The port is designed to accommodate large container ships and is connected to the Atlantic Ocean by a 60-km channel that is maintained at a depth of approximately 13 m by regular dredging operations of the USACE. Once completed, the SHEP will deepen and maintain this channel to a depth of approximately 14.6 m (USACE 2012). This reach of the river is tidally influenced up to about rkm 69 with a tidal range of 1.5–3.0 m (Connor et al. 2007). The freshwater–saltwater interface is variable and not well defined, but in most years the river becomes noticeably brackish between rkm 33 and rkm 38 (Hall et al. 1991). Juvenile Atlantic Sturgeon reside below the head of tide in both fresh and brackish water habitats throughout the Savannah River estuary during summer months (Hall et al. 1991). Consequently, all sampling for this study occurred below the head of tide in the Front, Middle, and Back river channels, with most effort focused between rkm 0 and rkm 54.9 (Figure 1).

Fish sampling.—Juvenile Atlantic Sturgeon were sampled 4–5 d each week from May through July 2013–2015. All sturgeon were collected using anchored, monofilament gill nets and trammel nets fished perpendicular to the current in the main channel at depths from 2.1 to 19.7 m for 30–90 min during slack tides. All nets were 91.4 m long and 3.1 m deep. Gill nets consisted of a series of three randomly ordered 30.5-m panels constructed of 7.6-, 10.2-, or 15.3-cm monofilament mesh (stretch measure). Trammel nets were composed of an inner panel of 7.6-cm mesh and two outer panels of 30.5-cm mesh. Specific netting locations within the study area were selected based on sampling locations of previous studies (Hall et al. 1991; Collins et al. 2002) and preliminary sonar surveys that identified areas with adequate depth (>2 m) and clean (snag-free) bottom (Figure 1). As nets were retrieved, all sturgeon were removed and placed in a floating net-pen tethered to the research vessel. Captured sturgeon were measured to the nearest millimeter TL and inspected for tags. All unmarked sturgeon received a PIT tag injected into the musculature beneath the fourth dorsal scute. Pectoral fin ray sections were obtained from a random subsample of 70 juvenile Atlantic Sturgeon to verify age estimates from length-frequency histograms, as described by Schueller and Peterson (2010). All fish were then released at the capture site within 1 h of their initial capture.

Collection of environmental data.—Environmental data were collected at each netting location. Mean depth was recorded for each net, and surface and bottom water quality measurements—temperature (°C), dissolved oxygen (mg/L and % saturation), salinity (ppt), and conductivity (μS/cm)—were obtained by using a YSI Pro 2030 (YSI, Yellow Springs, Ohio). A one-tailed Wilcoxon rank-sum test was used to compare CPUE (number of juvenile Atlantic Sturgeon per net-hour) at sites with dissolved oxygen ≥5 mg/L to CPUE at sites with dissolved oxygen <5 mg/L. Environmental sampling was dispersed spatially and temporally throughout the study area for the purpose of providing ancillary data to facilitate future comparison of summer conditions in Atlantic Sturgeon nursery habitats after the SHEP is completed.

Age estimation.—Pectoral fin ray sections from juvenile Atlantic Sturgeon were allowed to air dry for at least 2 months before being sectioned with a Buehler IsoMet low-speed, diamond-blade saw (Buehler, Lake Bluff, Illinois), as described by Currier (1951). Sections were then mounted onto glass slides and viewed under a 20–60× light microscope. Age estimates of each fish were assigned based on the number of annuli present, as determined by two independent readers. Disagreements between readers were resolved by a third independent reader. Age estimates from fin ray sections were used to verify age assignments derived from the modal distribution illustrated on the juvenile length-frequency histograms (Figure 2; Peterson et al. 2000; Schueller and Peterson 2010).

Data analysis.—Huggins closed-capture models in RMark, a software package used with R 3.0.2, were used to estimate annual abundances of the juvenile cohorts of Atlantic Sturgeon (Huggins 1989; Cooch and White 2013; Laake 2013; R Core Team 2013). The Huggins closed-capture model assumed that the population was closed to births, deaths, emigration, and immigration, and that no tag loss occurred during the sampling period (May–July). The assumption of population closure was evaluated using Close Test, a statistical program that uses a χ^2 statistic to test the null hypothesis of a time-varying, closed-population model against the alternative Jolly–Seber open-population model (Stanley and Burnham 1999). At the conclusion of each sampling year, capture histories for individual fish were constructed based on weekly

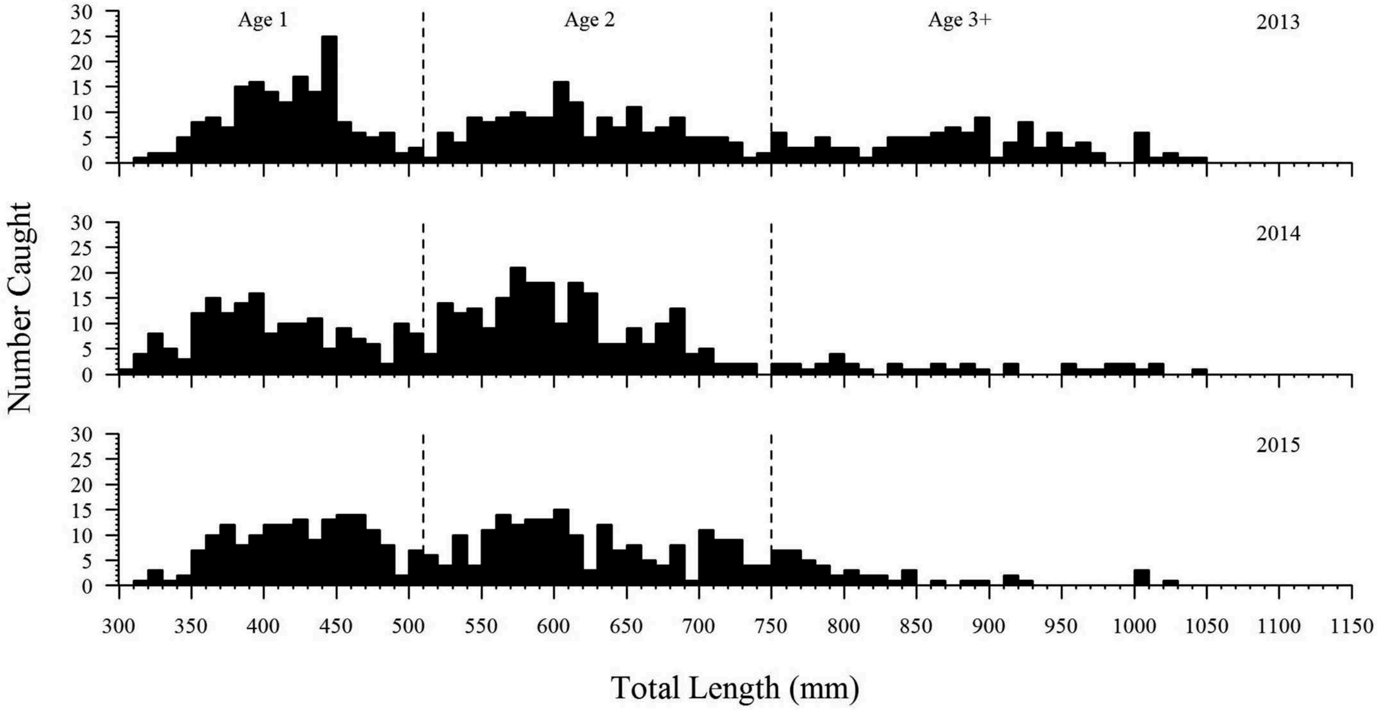

FIGURE 2. Length-frequency histograms and age assignments of juvenile Atlantic Sturgeon captured in the Savannah River, Georgia, during the summers of 2013–2015.

sampling periods as a statistical method to ensure that marked fish had ample time to randomly mix with unmarked fish before being recaptured in subsequent sampling periods (Conroy and Carroll 2009). Sampling periods used in each year were similar; sampling in 2013 was conducted during eight consecutive 1-week periods, and in 2014 and 2015, sampling was conducted over 10 consecutive 1-week periods. In all 3 years, captured juveniles were classified as either age 1, 2, or 3+ based on modal distributions of length-frequency histograms and subsequent age estimates from pectoral fin ray analyses (Schueller and Peterson 2010).

Once the age assignments had been completed for all juveniles, we evaluated a candidate set of models to obtain estimates of abundance for each year of the study. The most basic model, M_0, assumed constant capture probability. Several models tested the assumption of variable capture probability based on weekly sampling occasion (M_t), age-class (M_a), and additive (M_{t+a}) and interactive ($M_{t\times a}$) effects of sampling occasion and age-class. The relative likelihood of each model was evaluated using Akaike's information criterion (AIC; Akaike 1973), an information theoretic approach (Burnham and Anderson 2002) corrected for small sample size (AIC$_c$; Hurvich and Tsai 1989). Using this approach, we then assessed variation among models and subsequently selected the most plausible model for estimating the age-specific abundances of juveniles in each year.

RESULTS

A total of 761 individual nets (553 net-hours) were fished during the summers of 2013–2015 (Table 1). Mean weekly effort over the 3 years was 19.8 net-hours (27 individual net sets), although weekly effort varied from 3.8–43.1 net-hours (6–50 individual net sets). Nets were soaked for an average of 0.73 h per set, but individual soak times varied from 0.32 to 2.05 h. Water temperature in the study area varied from 21.3°C to 30.2°C, dissolved oxygen varied from 1.14 to 7.73 mg/L, and salinity varied from 0 to 19.7 ppt throughout the sampling period (Figure 3).

Over the three sampling years, a total of 1,550 juvenile Atlantic Sturgeon were sampled. Length-frequency analysis (Figure 2) and age estimation from fin ray sections (Figure 4) indicated that age-1 juveniles were 300–509 mm TL, age-2 juveniles were 510–749 mm TL, and age-3+ juveniles were 750–1,050 mm TL (Table 1). Readers agreed on age assignments for 86.7% of the fin ray sections observed, and the ability to assign an age-class to Atlantic Sturgeon of ages 1, 2, and 3 did not systematically change with age. All age-1 juveniles were captured between rkm 15.0 and rkm 39.9 in salinities less than 15 ppt. Of all juvenile Atlantic Sturgeon sampled, only one age-2 fish and three age-3+ fish were captured above rkm 40.0, and two age-2 fish were captured below rkm 14.9 in a total of 62 net sets (33.8 net-hours). The CPUE of juveniles varied both spatially and temporally;

TABLE 1. Annual sampling effort and catch results for age-1 (300–509 mm TL), age-2 (510–749 mm TL), and age-3+ (750–1,050 mm TL) juvenile Atlantic Sturgeon captured in the Savannah River, Georgia during the summers of 2013–2015.

			Age 1		Age 2		Age 3+	
Year	Sample period	Effort (net-hours)	Marked	Recaptured	Marked	Recaptured	Marked	Recaptured
2013	May 15–Jul 3	174.25	177	31	169	40	112	8
2014	May 12–Jul 18	225.59	176	28	233	39	38	6
2015	May 28–Jul 30	163.63	169	23	197	54	46	4

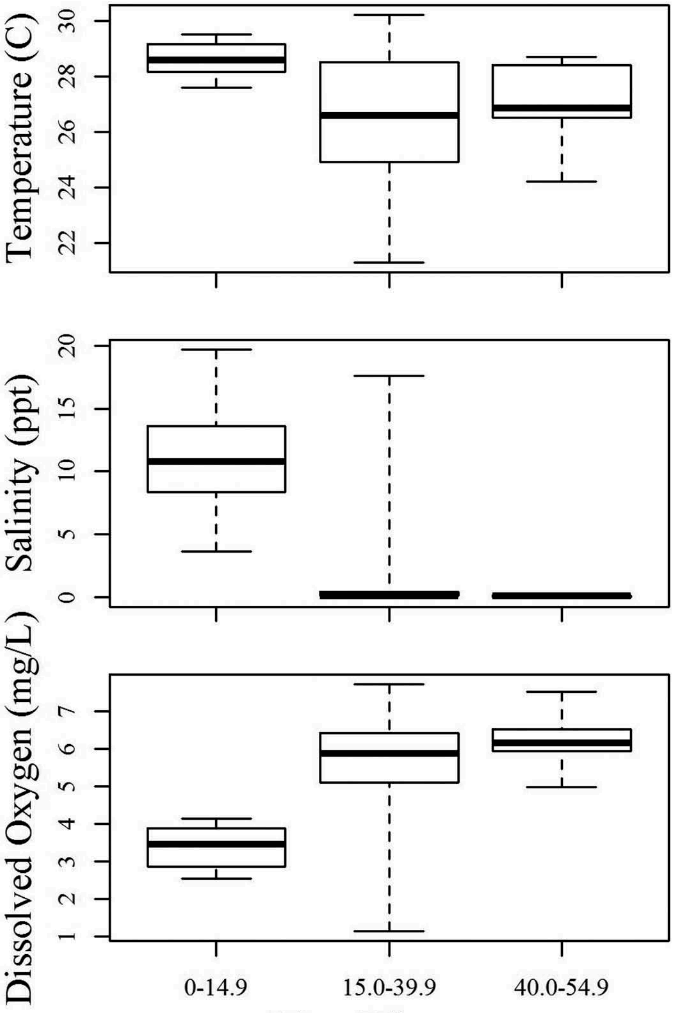

FIGURE 3. Box and whisker plots of the temperature (°C), salinity (ppt), and dissolved oxygen (mg/L) observed downstream from (river kilometer [rkm] 0–14.9), within (rkm 15.0–39.9), and upstream from (rkm 40.0–54.9) locations where juvenile Atlantic Sturgeon were captured in the Savannah River, Georgia, during the summers of 2013–2015. The horizontal line within the box indicates the median, the boundaries of the box indicate the 25th and 75th percentiles, and the whiskers indicate the highest and lowest values.

however, the highest mean catch rates (2.1–4.8 juvenile Atlantic Sturgeon/net-hour) were obtained between rkm 15.0 and rkm 34.9 (Table 2). Likewise, CPUE (mean ± SE) was higher (2.97 ± 0.14) at sites with dissolved oxygen ≥5 mg/L than at sites with dissolved oxygen <5 mg/L (1.80 ± 0.20) (Wilcox test: $P < 0.001$).

Different closed-capture models were appropriate for estimating recruitment during each year of the study. In 2013, AIC_c indicated that the time-and-age interactive model had the highest Akaike weight (w_i). Conversely, the time-only model had the highest w_i in 2014, and the time-and-age additive model had the highest w_i in 2015 (Table 3). Using each model in each respective year, we estimated age-1 Atlantic Sturgeon abundance (95% CI) to be 528 (402–726) in 2013, 589 (478–742) in 2014, and 597 (437–852) in 2015. Likewise, age-2 abundance was 389 (312–507) in 2013, 780 (637–973) in 2014, and 468 (382–594) in 2015, and age 3+ abundance was 686 (385–1,319) in 2013, 127 (95–179) in 2014, and 264 (124–657) in 2015 (Table 4). Results of Close Test (Stanley and Burnham 1999) indicated that estimates

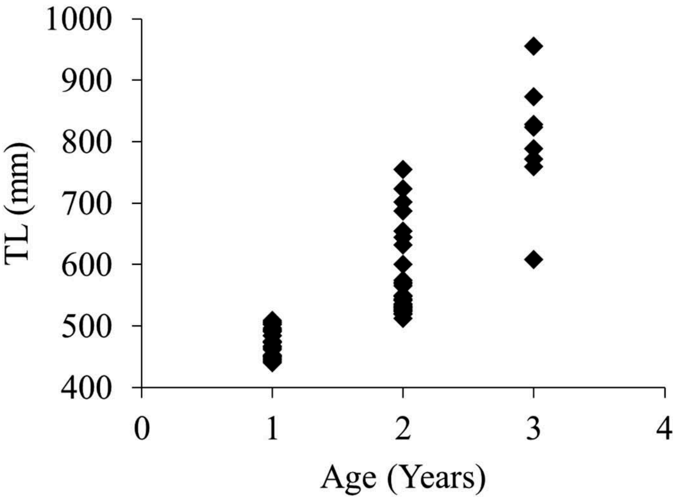

FIGURE 4. Total length at age of juvenile Atlantic Sturgeon (n = 70) captured in the Savannah River, Georgia.

TABLE 2. The CPUE (number of juvenile Atlantic Sturgeon per net-hour) by river kilometer in the Savannah River, Georgia, during the summers of 2013–2015. River kilometer 0 was defined as the location where the Savannah River crosses the Intracoastal Waterway. ND = no data; indicates strata that were not sampled in a given year.

	CPUE			
River kilometer	2013	2014	2015	Average
0–4.9	ND	0.00	ND	0.00
5.0–9.9	ND	0.30	0.00	0.24
10.0–14.9	ND	1.03	0.45	0.76
15.0–19.9	ND	4.29	1.30	3.09
20.0–24.9	1.68	1.99	2.90	2.14
25.0–29.9	5.55	4.03	4.65	4.75
30.0–34.9	2.28	1.62	3.24	2.30
35.0–39.9	0.93	0.21	1.01	0.77
40.0–44.9	ND	0.00	0.83	0.31
45.0–49.9	ND	0.00	0.00	0.00
50.0–54.9	ND	0.00	0.00	0.00
Average	3.26	2.46	3.10	2.89

from time-varying, closed-population models were similar to estimates from Jolly–Seber open-population models during all 3 years of the study (P = 0.43, 0.31, and 0.97, respectively).

TABLE 3. Huggins closed-capture models, AIC$_c$ values, Akaike weights (w_i), and number of parameters (K) used to describe variation in capture probability of juvenile Atlantic Sturgeon in the Savannah River, Georgia, during the summers of 2013–2015.

Capture probability	AIC$_c$	ΔAIC$_c$	w_i	K
	2013			
Time and age interactive	2,248.53	0.00	1.00	24
Time and age additive	2,292.08	43.55	0.00	10
Time	2,300.17	51.64	0.00	8
Age	2,534.18	285.65	0.00	3
Constant	2,542.13	293.60	0.00	1
	2014			
Time	2,681.87	0.00	0.88	10
Time and age additive	2,685.87	4.00	0.12	12
Time and age interactive	2,693.06	11.19	0.00	30
Constant	2,699.39	17.52	0.0	1
Age	2,703.37	21.50	0.00	3
	2015			
Time and age additive	2,520.67	0.00	0.87	12
Time	2,525.24	4.57	0.09	10
Time and age interactive	2,526.72	6.05	0.04	30
Age	2,566.62	45.95	0.00	3
Constant	2,571.18	50.51	0.00	1

TABLE 4. Age-specific abundance estimates for juvenile Atlantic Sturgeon in the Savannah River, Georgia, during the summers of 2013–2015. Estimates derived from Huggins closed-capture models in RMark.

Year	Age-class	Abundance estimate	95% CI
2013	1	528	402–726
	2	389	312–507
	3+	686	385–1,319
2014	1	589	478–742
	2	780	637–973
	3+	127	95–179
2015	1	597	437–852
	2	468	382–594
	3+	264	124–657

DISCUSSION

The lack of quantified assessment data for Atlantic Sturgeon populations has severely hampered ongoing efforts to assess population recovery since the subspecies' endangered listing in 2012. In recent years, however, mark–recapture estimates of age-1 abundance have been completed for several Atlantic Coast rivers, particularly within the South Atlantic DPS. Because the methods used in this study were similar, those previous recruitment estimates can be directly compared with the estimates obtained in this study. The Hudson River, New York, for example, is thought to contain one of the healthiest stocks of Atlantic Sturgeon in U.S. waters (NMFS 2007). In 1995, Peterson et al. (2000) estimated the age-1 cohort of that population at 4,314 individuals. Within the South Atlantic DPS, the Altamaha River, Georgia, is widely recognized as containing the healthiest population, with age-1 cohorts estimated at 333–1,318 individuals from 2004 to 2007 (Schueller and Peterson 2010). Although the cohort estimates obtained in this study (528–597) are considerably lower than those for the Hudson River, they do fall within the range of the more recent estimates obtained for the Altamaha River population, indicating that the Savannah River population is likely the second largest within the South Atlantic DPS.

The assumption of population closure was important to the reliability of the juvenile abundance estimates generated by the Huggins closed-capture models used in this study. Although this assumption cannot be proven per se, regular sampling occurred both above and below the known juvenile holding areas within the Savannah River, and in these reaches no age-1 juveniles and only six age-2+ juveniles were captured (Figure 1). These findings were also consistent with the results of Close Test (Stanley and Burnham 1999) as well as those of previous studies that have evaluated the closure assumption on other Georgia rivers (Schueller and Peterson 2010; Fritts et al. 2016).

The assumption of constant catchability was also evaluated and accounted for in the closed-capture models used to estimate juvenile abundances in this study. These analyses showed that the best-fitting model included temporal variation in capture probability during weekly sampling occasions to account for differences in effort and environmental conditions during each summer (Table 3). Given that ages of sturgeon, weekly sampling effort, and environmental conditions (e.g., water temperature, discharge, tidal stage) varied throughout the study, the models that included time and age provided plausible explanations for the observed variation in capture probability.

The presence of multiple, juvenile year-classes in the Savannah River, as shown by the length-frequency histograms (Figure 2) and age-1 recruitment estimates (Table 4), indicate that reproduction occurred consistently in the Savannah River during the past several years—one important indication of a healthy Atlantic Sturgeon population. Evidence of annual reproduction, as determined by the presence of age-1 juveniles, is also consistent with findings of Post et al. (2014) who documented putative spawning migrations in the Savannah River during 2011–2013. Although further corroborative evidence is needed, the abundance and distribution of juvenile age-classes within the Savannah River suggest that the population is likely recovering. Given that similar recent assessments documented several missing or weak year-classes (<100 individuals) in the Ogeechee, Satilla, and St. Marys rivers (Farrae et al. 2009; Fritts 2011; Fritts et al. 2016), the data from this study highlight the importance of the Savannah River population as one of the two best remaining within the South Atlantic DPS.

Because of its relative importance within the South Atlantic DPS, the Savannah River population of Atlantic Sturgeon should be carefully monitored in future years, as both natural and anthropogenic activities continue to alter habitats for the river-resident life stages. In all 3 years of this study, the highest mean CPUE of juveniles occurred between rkm 15.0 and rkm 34.9. Approximately 25% of this reach (rkm 15.0–19.9) will be directly impacted by SHEP dredging activities, and the indirect effects on water quality are likely to affect the quality of juvenile habitat throughout the entire reach (USACE 2012). Although the USACE has planned to install an extensive oxygen injection system to help mitigate these potential impacts, the net effects on juvenile Atlantic Sturgeon cannot be predicted. Consequently, future assessments of juvenile abundance within the Savannah estuary will be critical in monitoring long-term recruitment trends to ensure that proposed mitigation measures have achieved their desired effects.

The results of this study provide the first quantified assessment of Atlantic Sturgeon recruitment in the Savannah River. As a baseline for evaluating future population trends, these estimates should be used to evaluate the future effects of the SHEP—negative or positive—within the context of subspecies recovery. For example, harbor deepening is projected to increase salinity, reduce dissolved oxygen, and alter both flow and temperature regimes throughout the primary nursery habitat of Atlantic Sturgeon in the lower Savannah estuary (NMFS 2011). Because juvenile Atlantic Sturgeon are sensitive to all of these habitat variables (Secor and Gunderson 1998), the SHEP will likely have some negative effects on habitats of river-resident juveniles. Even within the context of this study, which was completed just prior to the initiation of the SHEP, dissolved oxygen levels below the 3 mg/L threshold were observed at several locations. This potential impact may be especially problematic given that CPUE of juveniles in this study was significantly lower at sites where dissolved oxygen was less than 5 mg/L. The proposed mitigation projects associated with SHEP, which include the installation of oxygen injection systems in the estuary and construction of a sturgeon fishway at the New Savannah Bluff Lock and Dam, may ameliorate at least some of the potential negative effects of dredging (NMFS 2011; USACE 2012). Regardless, the baseline recruitment estimates from this study should be used to objectively evaluate the net effects of the SHEP on the long-term recruitment trend of Atlantic Sturgeon within the Savannah River.

Recovery of Atlantic Sturgeon in all coastal rivers of the subspecies' range is an important objective for fisheries managers. Given the difficulties of evaluating adult populations (Schueller and Peterson 2010; Fritts et al. 2016), the use of multiyear studies to quantify age-1 recruitment is currently the best means of evaluating subspecies recovery within individual rivers. Future recruitment studies on the Savannah River and other populations throughout the range will be critical for successful management and recovery of Atlantic Sturgeon range-wide.

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