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ARTICLE

# Age and Growth of Juvenile Atlantic Sturgeon in the Lower Hudson River

**Thomas Kehler,* John A. Sweka, and Jerre Mohler**
*U.S. Fish and Wildlife Service, Northeast Fishery Center, Post Office Box 75, Lamar, Pennsylvania 16848, USA*

**Amanda Higgs**
*Cornell University, New York State Department of Environmental Conservation, 21 South Putt Corners Road, New Paltz, New York 12561, USA*

**Gregg Kenney**
*New York State Department of Environmental Conservation, Division of Marine Resources, 21 South Putt Corners Road, New Paltz, New York 12561, USA*

***Abstract***
**The precipitous decline of Atlantic Sturgeon *Acipenser oxyrinchus oxyrinchus* coupled with their recent listing under the U.S. Endangered Species Act necessitates investigations into their population dynamics. Our objectives were to (1) estimate age of juvenile Atlantic Sturgeon by using pectoral spine sections; (2) determine annual growth periodicity in hatchery-reared and recaptured wild Atlantic Sturgeon to validate our aging method; (3) determine growth rates for recaptured juveniles; and (4) back-calculate lengths from ages estimated by using pectoral spine sections from captured juveniles. Fish were captured via gillnetting in Newburgh and Haverstraw bays, Hudson River, during fall 2003, spring and fall 2004, and spring and fall 2005. Two readers agreed upon 91% ($n$ = 474) of ages estimated for juvenile Atlantic Sturgeon, establishing a coefficient of variation of 1.7%. Eight year-classes (ages 1–8) were represented, with age-4 fish making up the largest age-class (39%; $n$ = 203) and age-1 fish being the least represented (<1%; $n$ = 4). Multi-annual oxytetracycline injections in four cohorts of hatchery-reared Atlantic Sturgeon ($n$ = 34) demonstrated a two-part zone for each year of growth, as did four recaptured juveniles that were at liberty for a least 1 year, which exhibited mean growth rates of 0.3 mm/d and 2.4 g/d. We back-calculated median FLs from annulus positioning in ages 2–8 by using dorsal and ventral lobes of pectoral spine sections and compared the results to actual reported lengths. Dorsal and ventral lobes underestimated the median FLs of all age-classes except ages 3 and 7, for which lengths were overestimated. We found statistical differences between dorsal- and ventral-derived median FLs, suggesting that both regions must be evaluated. Our overall goal is to provide researchers with a baseline of age and growth data for future work on juvenile Atlantic Sturgeon.**

The Atlantic Sturgeon *Acipenser oxyrinchus oxyrinchus* is one of the largest anadromous fish endemic to the Atlantic coast of the United States and Canada, with a range extending from the Saint Lawrence River, Canada, to the St. Johns River, Florida (Smith 1985). The largest Atlantic Sturgeon on record was harvested from New Brunswick, Canada, in 1924, having a length of 4.4 m and weighing 365 kg (Dadswell 2006). The oldest Atlantic Sturgeon documented at harvest was a 64-year-old individual captured in 2010 from the Minas Basin, a subbasin of the Bay of Fundy, Canada (Hilton et al. 2016).

*Corresponding author: thomas_kehler@fws.gov
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Evidence of early human exploitation of Atlantic Sturgeon along the northeast Atlantic coast can be traced as far back as 2190 B.C. (Smith and Clugston 1997). Although the harvest of these fish was evident prior to 1850, it was not prominent. In the mid-1850s, important changes influenced the Atlantic Sturgeon fishery. With improvements to caviar preparation and preservation and established sturgeon markets, the demand for Atlantic Sturgeon increased dramatically (Secor 2002). The harvest of Atlantic Sturgeon occurred within all major rivers along the eastern seaboard and coincided with the spawning migration (Smith 1985). A peak harvest of 3,200 metric tons was taken in 1888. Juvenile Atlantic Sturgeon (<1 m in length) that were incidentally captured in small-mesh gill nets were quickly destroyed to avoid unnecessary net damage. Fishermen, who primarily harvested sturgeon for caviar, targeted only large females but often killed and discarded the males. As a result of the heavy exploitation, the fishery collapsed by 1901 (Secor 2002).

Even though overharvest is believed to be the single greatest cause of the Atlantic Sturgeon's decline, other anthropogenic factors have impaired the recovery of this once-abundant species. Construction of dams has prevented Atlantic Sturgeon from reaching historic spawning areas. Water quality degradation and dredging have negatively affected critical spawning and nursery areas (Smith and Clugston 1997). Between 1880 and 1901, an estimated 234,000 female Atlantic Sturgeon resided along the eastern coast of the United States, and 6,000 of these fish lived in the Hudson River, New York (Secor 2002), likely representing the greatest spawning stock in the river (Kahnle et al. 2007). A temporary increase in harvest occurred from the mid-1980s to 1996, with most catches coming from the New York Bight, the mouth of the Hudson River (Dunton et al. 2015). Despite this temporarily increased harvest, the fishery remained depressed compared to levels observed at the turn of the 20th century. In 1998, the Atlantic States Marine Fisheries Commission (ASMFC) imposed a 40-year moratorium on the possession and harvest of Atlantic Sturgeon. Key moratorium objectives included protecting mature adults and initiating research to locate individual stocks, with a special emphasis on juvenile assessment every 5 years, thereby securing future spawning populations (ASMFC 1998).

Currently, federal protection under the U.S. Endangered Species Act is in effect for five distinct population segments of Atlantic Sturgeon along the Atlantic seaboard (USOFR 2012). The Atlantic Sturgeon of the Hudson River are part of the New York Bight Distinct Population Segment (Dunton et al. 2016). Given the long history of data collection from the Atlantic Sturgeon fishery in the Hudson River, it has one of the only two adult spawning population estimates along the East Coast, at roughly 850 adults (ASSRT 2007; Kahnle et al. 2007). Since juvenile presence reflects successful adult spawning, the ASMFC places a high priority on juvenile Atlantic Sturgeon assessments in the Hudson River, and a benchmark stock assessment to evaluate stock status (the last stock assessment was in 1998) is scheduled for 2017 (ASMFC 2017).

To understand the dynamics of fish populations, knowledge of growth and age structure is essential for the management of a species (e.g., population assessments or life history models; Van Den Avyle and Hayward 1999). The process of age determination for sturgeon has been documented by using clavicles, cleithra, scutes (Brennan and Cailliet 1989), otoliths, and leading pectoral fin spines (hereafter, "pectoral spines"; Stevenson and Secor 1999). Pectoral spines and scutes are preferred for estimating the ages of sturgeon because the fish do not need to be sacrificed (Beamish 1981). The use of transverse sections of pectoral spines to determine age in sturgeon has been documented as far back as 1916 (Cuerrier 1951). Moreover, the determination of annual growth using calcified structures (e.g., pectoral spines) for aging requires validation (DeVries and Frie 1996). One such way of documenting growth periodicity is through the use of mark–recapture techniques in which the targeted species is collected, a fluorochromic marking agent is administered to the fish, and the fish is then released to allow recapture at another time. After recapture, a calcified structure is removed and analyzed to determine the correlation between growth and time between captures (Campana 2001).

Fluorochromic agents, such as oxytetracycline (OTC), are commonly used to validate growth periodicity through the examination of calcified structures (Beamish and McFarlane 1983). When injected, OTC permanently binds in calcified tissues, which emit a visual indicator when exposed to an ultraviolet light source (Nielson 1992). Rien and Beamesderfer (1994) reported the presence of yellow marked areas in the pectoral spines of White Sturgeon *Acipenser transmontanus* after OTC injection. Stevenson and Secor (1999) performed the only growth periodicity study using OTC as a marking agent on Atlantic Sturgeon. However, they examined a pectoral spine from only one fish at 1 year after OTC injection. Therefore, a study using greater numbers of Atlantic Sturgeon belonging to different age-classes could greatly substantiate the findings reported by Stevenson and Secor (1999).

The purpose of this study was to provide pertinent age and growth information for enhancing the current understanding of Atlantic Sturgeon population dynamics in the Hudson River. Our objectives were to (1) describe the age composition of captured juvenile Atlantic Sturgeon by examining pectoral spine sections; (2) conduct a growth periodicity study with multiple year-classes of hatchery-reared Atlantic Sturgeon by using OTC as a marking agent and compare with results from recaptured fish; (3) determine growth rates from recaptured juveniles; and (4) determine back-calculated lengths at age of juveniles based on examination of pectoral spines and compare the back-calculated lengths with actual length measurements.

## METHODS

*Study location.—* Juvenile Atlantic Sturgeon were captured within the Newburgh Bay and Haverstraw Bay–Tappan Zee reaches of the Hudson River during a total of five spring and fall sampling periods from October 2003 through November 2005 (Figure 1). Spring sampling occurred in March and April, and fall sampling occurred in October and November.

*In-field collection.—* Juvenile Atlantic Sturgeon were captured by using anchored monofilament gill nets measuring 61 m in length and 2.4 m in depth. One "net set" consisted of three gill nets (with 76-, 102-, and 127-mm stretched-mesh panels) placed parallel to each other, with approximately 60 m of space between nets. Tidal stages did not influence the timing of net sets. Net sets were only deployed during daytime hours outside of the designated river navigation channel, and nets were allowed to soak for a minimum of 2 h. Net locations were spatially stratified and randomly selected by substrate and depth (Sweka et al. 2007). Each captured juvenile Atlantic Sturgeon was measured for FL and TL, weighed, and visually and electronically inspected for any identification tags or marks. All unmarked juveniles were injected with a PIT tag and fitted with a Carlin tag. Each PIT tag was injected into the fish's muscle tissue approximately 1.5 cm below the dorsal fin; the Carlin tag was secured at the base of the dorsal fin. A 5–10-mm segment of leading pectoral spine from the left pectoral fin was removed for age determination. Stevenson and Secor (1999) concluded that examining pectoral spines from juvenile Atlantic Sturgeon was an unbiased method of age determination. Collins and Smith (1996) evaluated the growth and survival of wild Atlantic Sturgeon after the removal of a pectoral spine and found no long-term detrimental effects. To prevent severe bleeding (reported by Rossiter et al. 1995 for Lake Sturgeon *Acipenser fulvescens*), the removed section of pectoral spine was least 5 mm from the point of articulation.

*Pectoral spine processing and aging.—* Excess skin and secondary fin rays were removed from each pectoral spine while maintaining a distinction between the dorsal and ventral lobes of each spine. Since the dorsal and ventral lobes were distinguishable due to skin coloration—black on the dorsal side and white on the ventral side—we marked each dorsal lobe with a permanent marker after all skin was removed. Spine segments were embedded in Epo-fix, an embedding resin and hardener, and were sectioned using a Buehler Isomet low-speed saw fitted with two diamond-tipped saw blades. A plastic shim separated the blades, producing multiple sections with each cut. Six to eight spine sections were cut from each segment, ranging from 0.19 to 0.45 mm in thickness, and were permanently mounted on microscope slides in the order of sectioning (i.e., proximal to distal from each pectoral fin). Because the diamond-tipped saw blades produced smooth cuts, no further processing was warranted for mounted spine sections.

Age determination protocols were selected from published guidelines for Atlantic Sturgeon and other sturgeon species (Cuerrier 1951; Dovel and Berggren 1983; Wilson 1987; Rien and Beamesderfer 1994; Stevenson and Secor 1999; Farr and Jones 2014) and were refined to provide a standardized aging technique using the following select definitions:

1. *Annulus*: considered a two-part zone containing an opaque band and a translucent band corresponding with 1 year of growth and must be distinct and represented throughout at least one lobe of the pectoral spine.
2. *Central star*: a star- or tree-shaped translucent zone surrounding the center of ossification and the principal blood vessel, which are located at the basal area of each spine section. This structure represents the first completed year of life.
3. *False annulus*: an annulus is considered false when growth zones do not maintain distinction throughout adjacent annuli and at least one lobe region.
4. *Age determination*: counting the number of annuli present within a spine section, starting with the first annulus closest to the principal blood vessel and ending at the apex of a lobe.

Our aging technique started at the central star, which counted as year 1, and proceeded toward the apex of each lobe region while the annuli that were present within ventral and/or dorsal areas of the spine section were counted. Two experienced readers independently viewed pectoral spine sections with a monitor-equipped Zeiss STEMI SR dissecting microscope. Four pectoral spine sections from each captured Atlantic Sturgeon were selected for age determination to be conducted by both readers. Readers assessed all four pectoral spine sections independently and provided an age for each section. The median of these four ages represented the final age from a given reader; the final age was recorded and compared for precision. When the readers did not agree upon an age for a particular fish, both readers re-examined the pectoral spine sections independently so that a consensus could be reached. The measure of precision reported for this study only included the initially estimated ages. Box plots were constructed to graphically describe median FL-at-age data for juvenile Atlantic Sturgeon, and age agreement between readers was reported in percentiles and within an age–bias graph. Estimated aging precision between readers for each

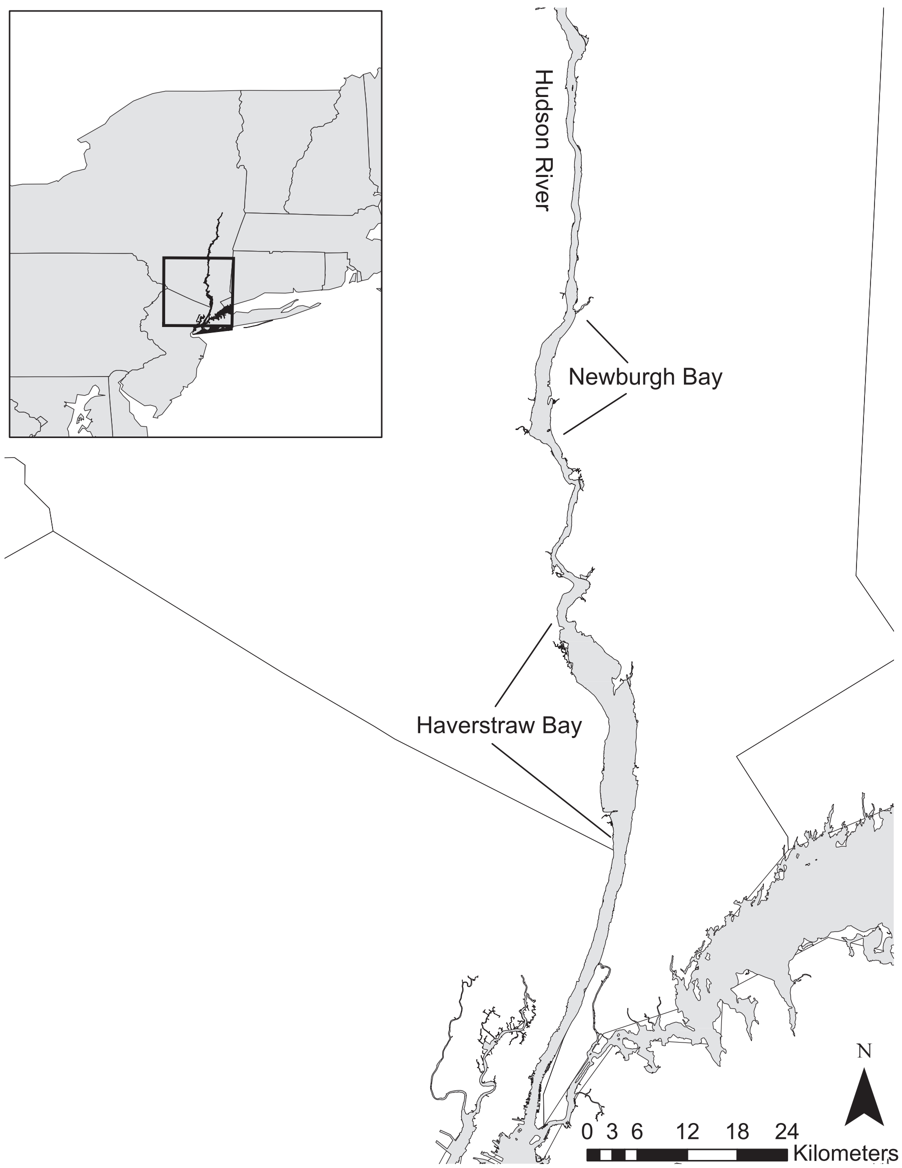


FIGURE 1. Sampling locations for juvenile Atlantic Sturgeon in the lower Hudson River from October 2003 to November 2005.

fish was reported using the coefficient of variation (CV), which was then averaged across all fish to produce an overall mean (Chang 1982; Campana et al. 1995):

$$\mathrm{CV}_j = 100 \times \frac{\sqrt{\sum_{i=1}^{R} \frac{(X_{ij} - X_j)^2}{R-1}}}{X_j},$$

where $\mathrm{CV}_j$ is the coefficient of variation for the $j$th fish; $X_{ij}$ is the $i$th age for the $j$th fish; $X_j$ is the mean age of the $j$th fish; and $R$ is the number of times each fish was aged. An overall CV was reported by averaging all CV values between readers.

*Age interpretation from growth increments.—* Annual growth periodicity from OTC-injected, hatchery-reared Atlantic Sturgeon and from individually recaptured wild juveniles were used to validate our aging method.

In April 2003, 51 hatchery-reared Atlantic Sturgeon from four different year-classes located at the U.S. Fish and Wildlife Service (USFWS) Northeast Fishery Center (Lamar, Pennsylvania) were used to determine annual growth deposition in pectoral spines. All hatchery fish were previously PIT-tagged for identification. Ten individuals from each year-class were anesthetized with tricaine methanesulfonate, were measured for length and weight, and received an intramuscular injection of OTC at a dosage of 50 mg/kg of body weight to establish an initial time period mark within each fish. The other 11 fish, serving as controls, were measured for length and weight but received no injection. During April 2004, all fish were anesthetized, their length and weight measurements were recorded, and a small (5–10-mm) segment of spine was removed from the left pectoral fin, no closer than 5 mm from the point of articulation. Previously injected fish received another OTC injection at the same dosage as the previous year. Control fish were handled in an identical manner except that they received no OTC injection. All collected spines were processed as previously described. In April 2005, all fish were treated exactly as in April 2004 except that a small segment of spine was removed from the right pectoral fin of each individual. Mortalities were recorded throughout the study. Three examiners independently viewed all slides by using a Zeiss AXIOSKOP 2 compound microscope equipped with epi-fluorescence capability to evaluate OTC presence and annual growth patterns. Spine sections were photographed by using a Fuji FinePix S1 Pro digital camera.

To validate annual growth periodicity from recaptured wild Atlantic Sturgeon, a right pectoral spine segment was removed from each fish (i.e., since a left pectoral spine segment was removed at initial capture). Collected spines were processed as previously described. Two independent readers assessed the age and growth periods of each captured and recaptured fish by using a Zeiss AXIOSKOP 2 compound microscope.

*Growth analyses.*— We calculated specific growth (SG) and absolute growth (AG) for recaptured juvenile Atlantic Sturgeon. Specific growth was calculated as

$$\mathrm{SG} = (\log_e Y_2 \ \log_e Y_1)/(T) \times 100,$$

where SG = specific growth rate in percent per day; $Y_2$ = FL at recapture; $Y_1$ = FL at original capture; and $T$ = number of days at large (Busacker et al. 1990). Absolute growth was calculated as

$$\mathrm{AG} = \left(M_f - M_i\right)/T,$$

where AG = absolute growth rate in length (mm) or weight (g) per day; $M_f$ = final length or weight measurement; $M_i$ = initial length or weight measurement; and $T$ = time between initial and final measurements (Hopkins 1992).

*Back-calculation of fork length from age.*— We used the Fraser–Lee method to back-calculate length at age,

$$L_i = [(L_c - a)/S_c]S_i + a,$$

where $L_i$ = the back-calculated FL of fish when the $i$th annulus was formed; $L_c$ = the FL of fish at capture; $S_c$ = the radius of the spine at capture; $S_i$ = the radius of the spine at the $i$th annulus; and $a$ = the $y$-intercept value from the regression of FL against the ventral or dorsal spine radius (DeVries and Frie 1996). The dorsal and ventral lobes from each "readable" pectoral spine were measured for annulus distance and total radius starting from the origin, which we identified as being adjacent to the principal blood vessel and in the center of the point of ossification. Measurements were taken by using a Zeiss STEMI SR dissecting microscope equipped with an ocular micrometer at 20× magnification. A paired two-sample $t$-test was used to detect differences in the ventral and dorsal lobe radius measurements between pooled sampling periods. We used a Kruskal–Wallis test to determine differences among all median FL-at-age groups, and we performed individual Mann–Whitney tests to compare actual median FLs with back-calculated median FLs at age based on examination of dorsal and ventral lobes.

## RESULTS

### Observed Growth Periodicity for Age Extrapolation

Three examiners unanimously agreed upon the presence of an OTC mark within each annually injected, hatchery-reared Atlantic Sturgeon and the absence of an OTC mark in each noninjected fish. Each annually derived OTC mark was located in the midst of a narrow, translucent growth band, subsequent to a wide, semi-opaque growth zone. The position of each OTC mark in conjunction with the seasonal timing of injection clearly supported the annual formation of a two-part growth zone (i.e., annulus) within hatchery-reared Atlantic Sturgeon (Figure 2). To further document annulus formation, pectoral spines from seven recaptured juvenile Atlantic Sturgeon were processed (Table 1). Two fish that were captured in fall 2003 and then recaptured in fall 2005 demonstrated the formation of two annuli. Two fish that were at large for 367 and 335 d formed one annulus while at liberty. One fish captured in fall 2003 increased in age by 2 years when captured 510 d later. Two recaptures were at large for 175 and 199 d, respectively; one of those fish added an annulus, but the other did not because growth occurred in the same year of its recapture. In summary, multiple year-classes of hatchery-reared and recaptured Atlantic Sturgeon exhibited the formation of an annulus—a two-part region—with each year of growth.

### Annulus Completion and Aging Precision for Captured Juveniles

We found that concluding annulus development was dissimilar between fall- and spring-collected juvenile Atlantic Sturgeon. At the time of capture, fish from the fall periods were still contributing to the summer's growth

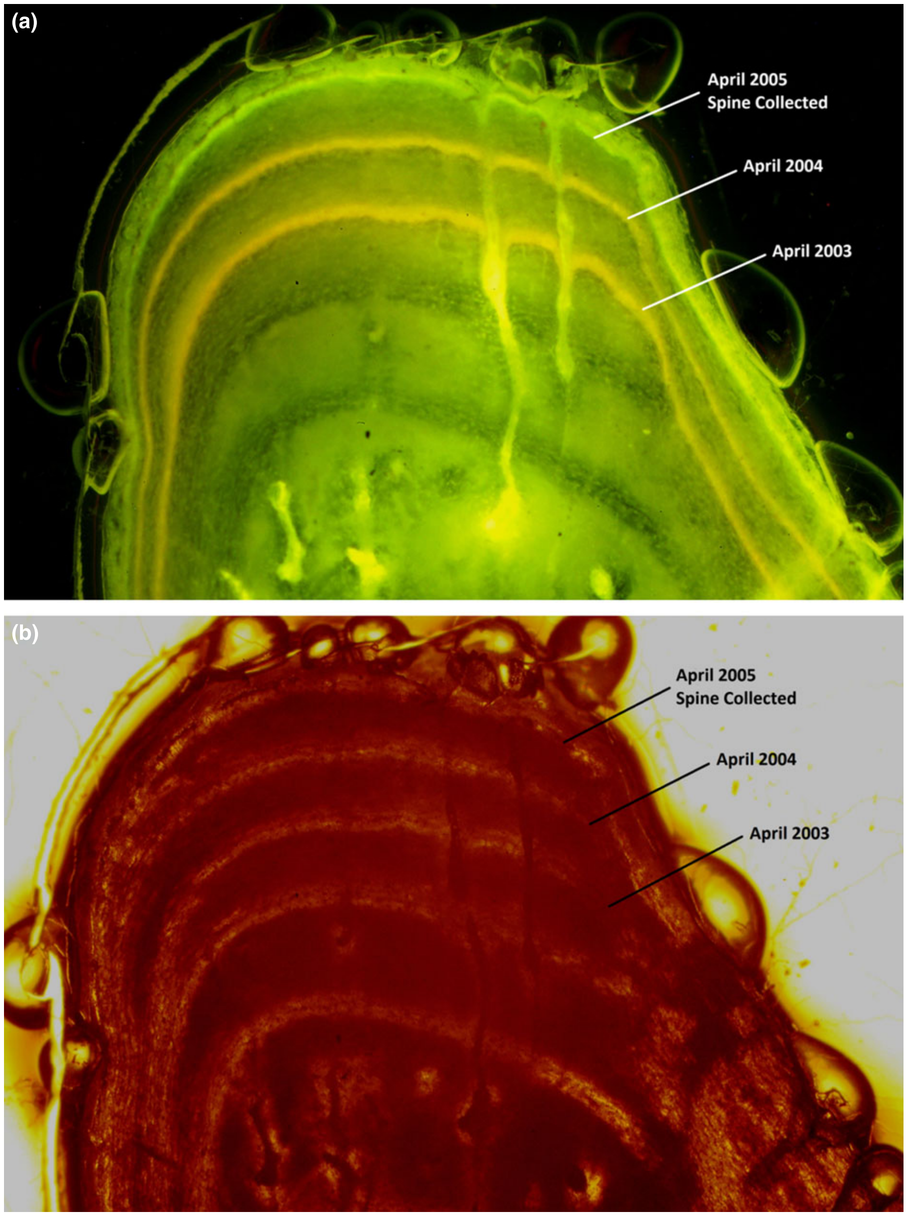


FIGURE 2. Transverse spine section from a hatchery-reared Atlantic Sturgeon that received oxytetracycline injections in April 2003 and April 2004: **(A)** the section shown under ultraviolet light and **(B)** the same section shown under transmitted white light. [Color figure can be viewed at afsjournals.org.]

formation in the newest (ending) annulus. In contrast, fish that were collected during the spring periods were found to be in the midst of the winter's growth formation. Of the 573 pectoral spines collected during this study, 90.8% ($n$ = 520) were used for age determination, and 9.2% ($n$ = 53) exhibited fractured, discontinuous, or severely compressed annuli, making them unreadable for aging. Readers agreed upon 91% ($n$ = 474) of the ages for juvenile Atlantic Sturgeon, establishing a CV of 1.7% (Figure 3). Between-reader agreement within 1 year was 8.5% ($n$ = 44), and agreement within 2 years was 0.5% ($n$ = 2). There was no statistical difference in age agreement and disagreement between analysts for pooled spring and fall sampling seasons ($\chi^2$ = 1.57, $P$ = 0.21).

## Length and Weight at Age of Captured Juveniles

Eight age-classes and eight year-classes of juvenile Atlantic Sturgeon were collected from fall 2003 to 2005 (Figure 4). Age-4 juveniles made up the largest age-class, with 39% of sampled fish ($n$ = 203), whereas age-1 fish constituted less than 1% of the sample ($n$ = 4). We determined that 82% of the total sample consisted of

TABLE 1. Description of juvenile Atlantic Sturgeon at initial capture and recapture from the Hudson River (asterisks indicate that the data were not available).

| Date at first capture | FL (mm) at first capture | Weight (kg) at first capture | Age (years) at first capture | Days at large | Age (years) at recapture | Absolute growth FL (mm/d) | Absolute growth Weight (g/d) | Specific growth FL (%/d) | Specific growth Weight (%/d) |
|---|---|---|---|---|---|---|---|---|---|
| Apr 20, 2003 | 486 | 0.79 | 3 | 183 | * | 0.551 | 3.33 | 0.1030 | 0.313 |
| Oct 23, 2003 | 424 | 0.53 | 3 | 362 | * | 0.354 | * | 0.0729 | * |
| Oct 30, 2003 | 553 | 1.15 | 4 | 708 | 6 | 0.227 | 2.52 | 0.0361 | 0.133 |
| Nov 3, 2003 | 452 | 0.61 | 3 | 367 | 4 | 0.381 | 2.04 | 0.0735 | 0.218 |
| Dec 4, 2003 | 535 | 1.15 | 4 | 510 | 6 | 0.265 | 2.10 | 0.0441 | 0.129 |
| Dec 4, 2003 | 561 | 1.25 | 4 | 672 | 6 | 0.277 | 3.05 | 0.0426 | 0.144 |
| Apr 20, 2004 | 460 | 0.66 | 4 | 216 | * | 0.514 | 2.96 | 0.1000 | 0.314 |
| Apr 22, 2004 | 458 | 1.32 | 6 | 186 | * | 0.892 | −0.54 | 0.1660 | −0.042 |
| Apr 22, 2004 | 396 | 0.37 | 3 | 335 | 4 | 0.37 | 1.82 | 0.0813 | 0.291 |
| Apr 27, 2004 | 405 | 0.75 | 3 | 163 | * | 0.883 | 2.70 | 0.1870 | 0.283 |
| Oct 25, 2004 | 558 | 0.56 | 4 | 175 | 5 | 0.108 | 4.69 | 0.0201 | 0.152 |
| Nov 4, 2004 | 550 | 1.19 | 4 | 18 | * | 0 | 0 | 0 | 0 |
| Apr 18, 2005 | 633 | 1.95 | 8 | 199 | 8 | 0.412 | 3.67 | 0.0612 | 0.160 |

individuals from the 1999 ($n$ = 128), 2000 ($n$ = 153), and 2001 ($n$ = 146) cohorts (Figure 4). Eight FL-at-age and weight-at-age classes of juvenile Atlantic Sturgeon were documented during this study (Figure 5). Median FLs of collected fish were 440 mm (interquartile range [IQR] = 424–452 mm) for age 1; 451 mm (IQR = 424–475 mm) for age 2; 464 mm (IQR = 432–543 mm) for age 3; 564 mm (IQR = 531–594 mm) for age 4; 595 mm (IQR = 564–652 mm) for age 5; 655 mm (IQR = 618–692 mm) for age 6; 656 mm (IQR = 587–694 mm) for age 7; and 730 mm (IQR = 702–776 mm) for age 8. Although there were significant differences in median FL among age-classes as a whole (Kruskal–Wallis test: $H = 364.4$, $P < 0.01$), Mann–Whitney tests indicated that median FL did not differ between ages 1 and 2 ($P = 0.54$) or between ages 6 and 7 ($P = 0.94$). The median weight for ages 1–8 increased consecutively from 0.59 kg (IQR = 0.55–1.01 kg) to 3.1 kg (IQR = 2.49–4.0 kg). Statistical differences were detected among the inclusive group of age-classes for median weight (Kruskal–Wallis test: $H = 269.1$, $P < 0.01$). Mann–Whitney tests revealed no difference in median weight between ages 1 and 2 ($P = 0.90$) or between ages 6 and 7 ($P = 0.54$). The weight–FL relationship was $y = (4.0 \times 10^{-10})\cdot x^{(3.0911)}$ ($r^2 = 0.91$; $n = 558$).

## Growth of Recaptured Juveniles

All but one recaptured Atlantic Sturgeon increased in FL and all but two increased in weight during their time at liberty (Table 1). Four of the recaptured fish were at liberty for at least 1 year. Those individuals were at large for 367, 510, 672, and 708 d, with $AG_{FL}$ values of 0.381, 0.265, 0.277, and 0.227 mm/d, respectively, and $AG_{weight}$ values of 2.04, 2.10, 3.05, and 2.52 g/d, respectively.

## Back-Calculation of Fork Length from Age

Radius lengths from both lobes of the sectioned pectoral spines were correlated with FL, revealing an $r^2$ value of 0.67 ($y = 5.7669x + 195.28$) for dorsal lobes and an $r^2$ of 0.63 ($y = 5.6674x + 201.28$) for ventral lobes. There were no statistical differences between dorsal and ventral radius measurements (Student's $t$-test: $P = 0.49$). Generally, dorsal and ventral lobes underestimated the median FL of all age-classes except ages 3 and 7, for which FLs were overestimated. We found statistical differences between actual median FLs and the median FLs that were back-calculated using dorsal and ventral lobes (Figure 6). Based on back-calculation using dorsal lobes, there were statistical differences at ages 2, 4, 5, and 6 (Mann–Whitney tests: $P < 0.01$, $P \leq 0.00$, $P < 0.04$, and $P = 0.05$, respectively), with actual median FLs being underestimated by 2.1–5.1%. Conversely, the use of ventral lobes for back-calculation produced no statistical difference in median FLs except at age 4 (Mann–Whitney test: $P \leq 0.00$), for which the actual median FL was underestimated by 4.5%.

## DISCUSSION

The ability to discern annual growth in aging studies is essential to understanding population dynamics, such as recruitment, longevity, and mortality (Campana 2001; Khan et al. 2013). One method of validating annual growth is by use of a chemical marking agent, such as

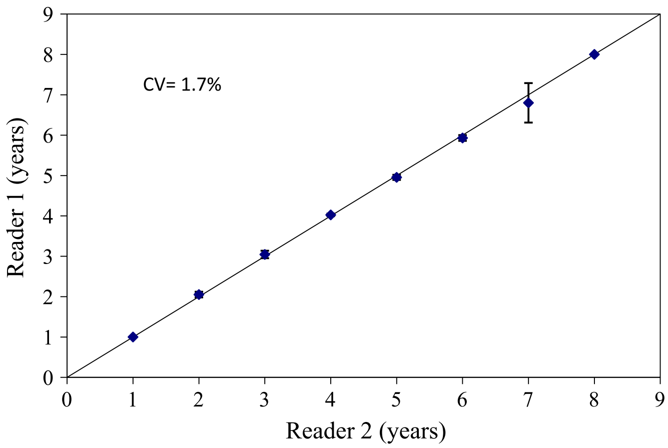


FIGURE 3. Age–bias plot showing differences in estimated ages produced by readers 1 and 2 based on examination of pectoral spines from juvenile Atlantic Sturgeon. [Color figure can be viewed at afsjournals.org.]

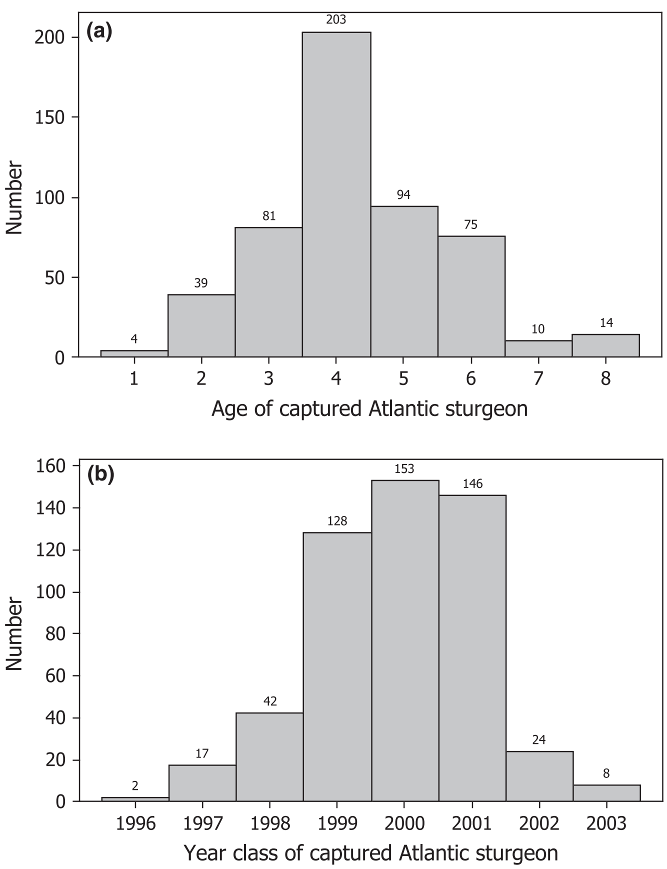


FIGURE 4. **(A)** Age-class and **(B)** year-class of captured juvenile Atlantic Sturgeon from the lower Hudson River, October 2003–November 2005. Sample size is shown above each bar.

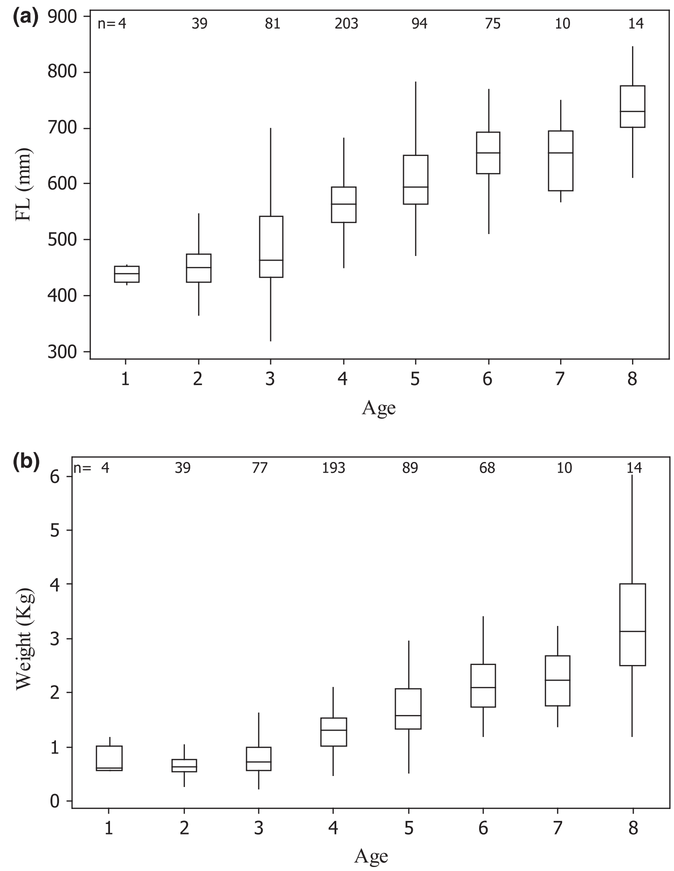


FIGURE 5. Box plots of **(A)** FL at age and **(B)** weight at age for juvenile Atlantic Sturgeon collected from the lower Hudson River during fall 2003 to 2005. Each box represents the interquartile range (IQR; first to third quartile values), with the median as a horizontal line. Vertical lines above and below each box represent the greatest and lowest datum within 1.5 times the IQR; sample sizes are presented at the top of each panel.

OTC (Nielson 1992). Injection of OTC into multiple cohorts of hatchery-reared Atlantic Sturgeon allowed us to confirm annulus formation within the pectoral spine for each year during our chemical marking study. Our findings concur with growth studies that have employed OTC as a marking agent for other sturgeon species. Rien and Beamesderfer (1994) injected 220 White Sturgeon from the Columbia River and identified annulus formation in pectoral spines from 98% of the recaptured fish. Rossiter et al. (1995) reported the formation of annuli in pectoral spine segments taken from OTC-injected Lake Sturgeon that were at large for 2 years. Moreover, our results agree with an Atlantic Sturgeon growth study by Stevenson and Secor (1999), who found the formation of an annulus in a pectoral spine collected from one hatchery-reared individual at 15 months after OTC injection. In our study, we were able to confirm annulus formation not only in multiple cohorts of hatchery-reared Atlantic Sturgeon but also within recaptured wild juveniles that were at liberty for 1 year or more, thus supporting the premise that a translucent zone and an opaque zone form for each year of growth in juvenile Atlantic Sturgeon (Dadswell et al. 2016).

The CV and age agreement (%) between readers serve as measures of precision in age determination studies. A low reported CV between readers correlates to greater precision (Murie et al. 2009). Although CV values should be species specific, the overall reporting of 5% signifies a high level of consistency in an aging method, but it does not necessarily reflect a high level of accuracy (Campana 2001). Age agreement between readers is influenced directly by species longevity—meaning that age agreement can decrease as the age of the fish increases (Campana et al. 1995). The reported CV from this study (1.7%) is comparable to the value of 1.8% reported by Balazik et al. (2012) and is under the 5% level, as has been observed in other Atlantic Sturgeon aging studies (4.8% in Stevenson and Secor 1999; 3;.78% in Dunton et al. 2016). Reported age agreement between readers varies among sturgeon species (Rien and Beamesderfer 1994; Morrow et al. 1998; Hurley et al. 2004). The age agreement of 91% from this study is similar to the 87% agreement reported by Kohlhorst et al. (1980) for 1,001 pectoral spines from age-0–9 White Sturgeon.

We suggest several reasons for the high agreement between our readers. First, the protocols used to determine age in our study were designed to facilitate discrimination between compressed annuli and false annuli. Compressed annuli (also known as banded annuli) were usually a product of embedded secondary fin rays in the spine section or slow-growth periods. Readers only counted the annulus as long as it was discernable throughout at least one of the two lobe regions of the pectoral spine section. In some cases, readers needed both lobes to

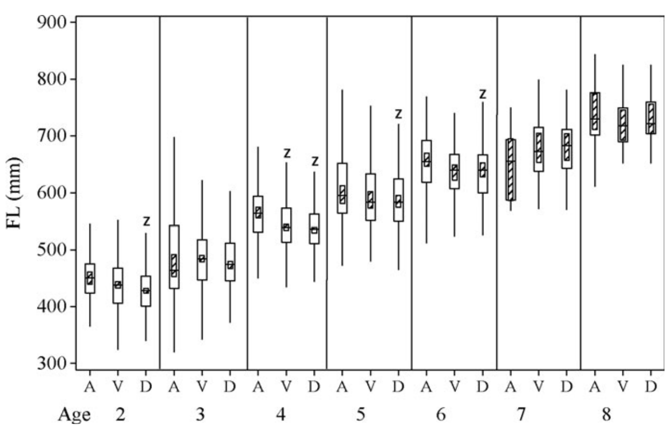


FIGURE 6. Box plots of actual FL at age (A) and back-calculated FLs at age estimated by using ventral (V) and dorsal (D) lobes of the pectoral spines from juvenile Atlantic Sturgeon of each age-class captured in the lower Hudson River. Each box represents the interquartile range (IQR; first to third quartile values), with the median as a horizontal line. Vertical lines above and below each box represent the greatest and lowest datum within 1.5 times the IQR; "z" signifies a statistically significant difference between the back-calculated FL and the actual FL.

distinguish all of the annuli. Incomplete or false annuli are well documented in sturgeon aging studies (Stevenson and Secor 1999; Whiteman et al. 2004). Slow or punctuated growth can affect annulus deposition in sturgeon (Rugg et al. 2014). Second, only juveniles (age $\leq$ 8) were examined in this study. Sometimes readers estimating the ages of sturgeon older than 20 years may rely on individual interpretation rather than preset guidelines for annulus determination (Wilson 1987). Dovel and Berggren (1983) reported that age estimation in Atlantic Sturgeon was easier when individuals were younger than 15 years than when they were older than 15 years, as the latter fish exhibited false annuli, re-absorption of calcified tissue, and unknown reasons for slow growth. Doroshov et al. (1997) estimated ages for Atlantic Sturgeon from 1.5 to 43 years and noted that fish over age 20 exhibited less-distinct annuli toward the outer spine edge, thus making adult fish harder to age. The guidelines implemented in our study were designed to standardize the aging method, not only for the present work but for future aging studies.

We documented eight year-classes among juvenile Atlantic Sturgeon captured in the lower Hudson River from all five sampling periods, with age-4 fish ($n$ = 203) being greatly represented and age-1 fish ($n$ = 4) being least represented. Sweka et al. (2007) described that the gill nets used in this study had the greatest probability of capturing Atlantic Sturgeon between 550 and 600 mm FL, which coincides with 10% of the age-4 fish and 10% of the total catch. Differences among seasonal age-classes may reflect in-river movement or juvenile emigration from the Hudson River. Dovel and Berggren (1983) reported that emigration of juvenile Atlantic Sturgeon began at age 1 and increased up to age 5. However, we collected 6- and 7-year-old individuals during each sampling season and 8-year-old fish during spring 2004 and fall 2005. The triggering mechanism behind the emigration of these juveniles is unclear. Since juvenile Atlantic Sturgeon emigrants congregate exclusively in the New York Bight (Dunton et al. 2016), periodic in-river movement may be a plausible assumption.

We found that median FL and weight at age increased consecutively for juvenile Atlantic Sturgeon, with no statistical differences in FL and weight between ages 1 and 2 or between ages 7 and 8. We attribute this to the small sample size, which ranged from 4 to 14. Dovel (1979) performed a comprehensive age and growth study of Atlantic Sturgeon in the Hudson River and reported mean TLs of 720 mm (SD = 58) at age 3, 739 mm (SD = 74) at age 4, and 799 mm (SD = 45) at age 5, with corresponding mean weights of 1.59 kg (SD = 0.42), 1.71 kg (SD = 0.55), and 2.44 kg (SD = 0.33), respectively. Our findings for the same age-classes identified consistently smaller means: TLs were 572 mm (SD = 88) at age 3, 657 mm (SD = 63) at age 4, and 708 mm (SD = 80) at age 5; and weights were 0.82 kg

(SD = 0.39) at age 3, 1.26 kg (SD = 0.34) at age 4, and 1.68 kg (SD = 0.60) at age 5. Dovel (1979) reported sample sizes of 30 age-3 Atlantic Sturgeon, 10 age-4 fish, and 4 age-5 fish; therefore, we suspect that the discrepancies in TL and weight at age between the two studies are an artifact of the earlier study's small sample sizes.

We documented juvenile Atlantic Sturgeon growth by individual recaptures. Four juveniles recaptured during our study were at liberty for between 367 and 708 d and exhibited mean growth rates of 0.3 mm/d and 2.4 g/d. These results are analogous to juvenile Atlantic Sturgeon growth reported by Dovel (1979) and Lazzari et al. (1986). Dovel (1979) described four recaptures from the Hudson River, with a mean growth rate of 0.3 mm/d after the fish were at liberty for at least 364 d. Eight recaptured juvenile Atlantic Sturgeon from the Delaware River, as reported by Lazzari et al. (1986), experienced mean growth rates of 0.385 mm/d and 2.5 g/d after being at liberty for 65–418 d.

Back-calculated lengths from age based on the use of pectoral spines have been reported for Shovelnose Sturgeon *Scaphirhynchus platorynchus* (Quist et al. 2002) and Pallid Sturgeon *Staphylococcus albus* (Koch et al. 2011), whereas similar estimates were not generated for Lake Sturgeon (Probst and Cooper 1955) or Gulf of Mexico Sturgeon *A. oxyrinchus desotoi* (Huff 1975) due to irregular spine shape or extreme banding. Moreover, we found no previous reported attempts at back-calculating lengths from age for Atlantic Sturgeon. The back-calculation of lengths by using annulus measurements derived from pectoral spines of juvenile Atlantic Sturgeon proved to be difficult. With no clear point of origin, we developed a starting point for annulus and radius measurements by using the principal blood vessel in conjunction with the center of ossification. Furthermore, the first annulus in each pectoral spine had a unique, tree-shaped appearance (i.e., the central star; Farr and Jones 2014; Stewart et al. 2015), but unlike subsequent measured annuli, this annulus was not concentric. Therefore, we could not back-calculate length from the start of life to the end of the first year of growth. Lastly, we discovered spine sections that contained compressed annuli due to inclusions or embedded secondary fin rays, making annulus measurements difficult or impossible in one or both lobes of some pectoral spines.

Radius measurements of annuli are essential for estimating length from age (DeVries and Frie 1996). There are limited reports of radius measurements for pectoral spine sections from sturgeon species. Brennan and Cailliet (1989) measured 122 spine sections from White Sturgeon and reported an $r^2$ value of 0.81. Our reported $r^2$ values for FL versus the lobe radius signified positive correlations, although they were weaker than that reported by Brennan and Cailliet (1989). The general morphology of sturgeon pectoral spines consists of two distinct lobes, but we could find no prior studies reporting a comparison of the lobes for estimating back-calculated lengths from age. We identified substantial differences between ventral and dorsal lobes when used in the back-calculation of median FL. When we compared the actual and back-calculated median FLs between lobes, over 50% of our collected age-classes exhibited statistically different lengths when dorsal lobes were used, whereas only 13% of age-classes had different lengths when ventral lobes were used. Although the differences between dorsal and ventral lobes were nominal (0–10 mm across ages), the fact remains that for most of the examined age-classes (ages 2, 4, 5, 6, and 8), the back-calculated FLs underestimated the actual median FLs. Since the difficulty of age interpretation increases with fish age, the difference between back-calculated and actual lengths is also likely to increase. This pattern of underestimation supports the occurrence of Lee's phenomenon, where back-calculated FL is smaller than the actual FL as fish age increases.

The successful management of Atlantic Sturgeon in the Hudson River necessitates the understanding of the growth and age structure of all resident year-classes, as they constitute the system's future spawning stocks. Accurate age determination is vital for distinguishing and predicting growth, longevity, mortality, and cohort presence. We documented eight consecutive cohorts (1996–2003) of juvenile Atlantic Sturgeon in the Hudson River from fall 2003 to 2005, thus providing evidence of eight consecutive years of spawning by adults in that system. Continuation of similar juvenile assessments would detect annual spawning trends and cohort strength to serve as benchmarks for evaluating adult stock status. Our results for annual growth periodicity through (1) annual OTC injections in multiple year-classes of Atlantic Sturgeon and (2) documented annulus formation in recaptured juveniles greatly add to the premise of distinguishable annulus formation in these fish—a necessary element for age determination. In addition, this study supports the use of pectoral spine aging as a nonlethal, minimally invasive method for application to endangered Atlantic Sturgeon. Our results indicate the ability to back-calculate Atlantic Sturgeon length from age based on examination of pectoral spines (albeit with a cautionary note regarding the morphological differences between lobe areas), which can be a useful fishery management tool for reconstructing past growth to evaluate environmental conditions. Impending research and management decisions for the future of Atlantic Sturgeon in the Hudson River hinge upon the accuracy of these population characteristics.

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