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ARTICLE

Population Characteristics of Adult Atlantic Sturgeon Captured by the Commercial Fishery in the Saint John River Estuary, New Brunswick

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Abstract
The commercial fishery for Atlantic Sturgeon *Acipenser oxyrinchus* in the Saint John River, New Brunswick, began in 1880. The early fishery was unregulated, and the adult stock was depleted by 1886 after landings of 712 metric tons. After a 10-year closure the fishery was reopened in 1897 with management regulations, and landings varied from 6 to 20 metric tons/year until 2010. In 2011 an annual quota of 350 adults was established and landings are now stable at 11.3 ± 1.7 (mean ± SD) metric tons/year. Since 2009, fishers have collected biological statistics from adults taken in the fishery and 14–60% of captured individuals have been marked and released each year. During 2009–2015, annual mean values of total length and dressed weight of landed adults were stable, the male : female sex ratio was 1.2:1.0, and mean age of males and females was 27.2 and 34.0 years, respectively. Estimates of instantaneous total mortality ranged from 0.08 to 0.11, and mean annual survival was 90.9%. Of 1,396 marked adults released, 147 were recaptured in the estuary in subsequent years. Tag returns indicated that the modal spawning periodicity of males was 2 years and that of females was 4 years. Valid, modified Schnabel and Jolly–Seber mean annual population estimates for 2013–2015 were 18,179 and 20,798 adults, respectively. The quota in relation to these estimated adult populations represented annual exploitation rates of 1.9% and 1.7%, which are below F_{50} and would maintain present stock size. The virgin adult population was determined using 1880–1886 total landings and a mean weight range for adults of 50–30 kg. Estimated range of the 1880 virgin population size was 14,240–23,733 adults. These data suggest that the fishery is sustainable at its current annual yield and that the population is near the carrying capacity of the Saint John River.

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The commercial fishery of Atlantic Sturgeon *Acipenser oxyrinchus* for meat, caviar, and oil was initiated in 1880 in the Saint John River (SJR), New Brunswick, by a group of itinerate fishers from Delaware Bay, Delaware–New Jersey. These fishers traveled along the Atlantic coast each year and exploited the sturgeon spawning runs in rivers from South Carolina to New Brunswick (Rogers 1936; Saffron 2004). This industrial fishery was persecuted at a time when natural resources were not managed effectively, and the Atlantic Sturgeon population on the eastern coast of North America was depleted by 1900 and the fishery collapsed (Cobb 1900; Secor 2002).

When the SJR commercial fishery began in 1880, there were no management regulations. In 1881, gill nets were restricted to a minimum size of 33.0-cm stretched mesh (DFO 2013b); however, by 1886 the adult stock was depleted after a total catch of 712 metric tons (Figure 1). In 1887, the fishery was closed for 10 years, and when reopened, a management regime was implemented that exists to the present and consists of (1) a season (closed during June), (2) gear restriction (minimum 33.0-cm-stretch-mesh gill net and number of nets allowed per license), and (3) a minimum (122 cm TL) size limit (DFO 2013a). The SJR stock recovered after initial overexploitation probably because this species has numerous juvenile cohorts in their natal estuary and at sea, which when recruited can restore spawning populations relatively quickly. In the case of the SJR, a northern stock, there are approximately 20 cohorts of juvenile males and 26 cohorts of juvenile females available for recruitment to the adult population as they mature (Dadswell 2006; Stewart et al. 2015).

After the commercial fishery reopened in 1897, it was pursued by local fishers only, but landings seldom exceeded 6 metric tons/year until 1980–1997 when catches ranged from 10 to 20 metric tons/year (Figure 1; DFO 2013b). During 1998–2008 the fishery was largely unexploited due to lack of processors and export markets to the United States, and average landings declined to 3 metric tons/year with no landings in some years (DFO 2013a). The fishery was reinitiated in 2009, and in 2011 an annual quota of 350 adults (175 males and 175 females) was implemented along with a system for documenting capture, tagging, and reporting (DFO 2013b). The annual quota and collection of biological characteristics of the catch was agreed upon between the fishers and the Department of Fisheries and Oceans Canada (DFO) in order to comply with the nondetrimental findings determined by the Convention on International Trade in Endangered Species (CITES; DFO 2013a).

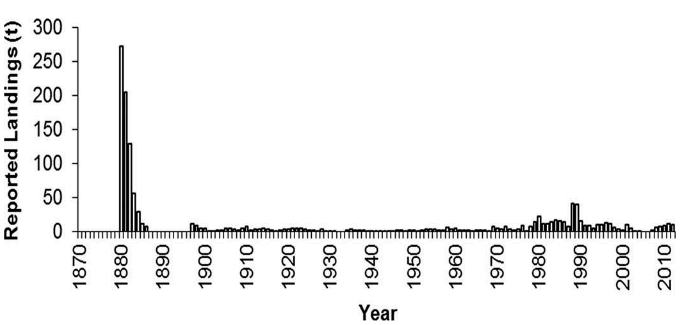

FIGURE 1. Annual reported landings (metric tons) for Atlantic Sturgeon during 1880–2012 from the Saint John River commercial fishery, New Brunswick (from Fisheries and Oceans Canada).

The current SJR Atlantic Sturgeon commercial fishery lands approximately 12 metric tons/year for meat, by-products, and caviar, and 66–99% of total weight of each fish is utilized depending on its sex and market demand. Fishers were trained by researchers to obtain biological data from the adults they caught. Fishers sampled all captured individuals for length and sex and processed fish for dressed weight and caviar weight. A subsample of the catch was aged by researchers using pectoral spines collected by the fishers, and 14–60% of adults captured annually were marked by fishers with uniquely numbered tags and released. Herein we analyzed the population characteristics of the SJR adult Atlantic Sturgeon captured in the estuary fishery and examine its sustainability. We present this study as an excellent example of cooperation between fishers and scientists in fisheries management.

METHODS

Study site.—The Saint John River empties into the Bay of Fundy (BoF) at the southeastern corner of New Brunswick (Figure 2). The river has the second largest watershed on the east coast of North America (55,045 km^2: Kidd et al. 2011). The estuary has an area of 500 km^2 and is divided into a complex series of channels, bays, and lakes that extend inland from the mouth on the BoF (at Reversing Falls) 120 km up the main stem to tide head at the city of Fredericton.

A combination of morphological and hydrographic features controls the occurrence and distribution of salinity in the estuary (Metcalfe et al. 1976). The Reversing Falls sill (Figure 2) restricts the circulation between the estuary and the BoF and dampens the mean tidal amplitude to 0.7 m in the estuary compared with 7.6 m in the BoF. There is partial mixing of the inflowing saline water with outflowing fresh or brackish water at Reversing Falls that creates a zone of lowered salinity in Long Reach, the lower 35 km of the estuary (Figure 2). Conversely the outflow of the large, annual freshet during spring is restricted by Reversing Falls causing an increase in the water level up to 7 m, and most of the estuary then becomes freshwater.

The current Atlantic Sturgeon fishery is situated in Long Reach on the main stem of the SJR (Figure 1). Long Reach has depths to 30 m where salinity fluctuates between freshwater during the spring flood in May–June to a salt wedge estuarine environment for the remainder of the year (Metcalfe et al. 1976). Salinities fluctuate between 0‰ and 10‰ in the top 8 m of the water column and 0–21‰ at the bottom. During

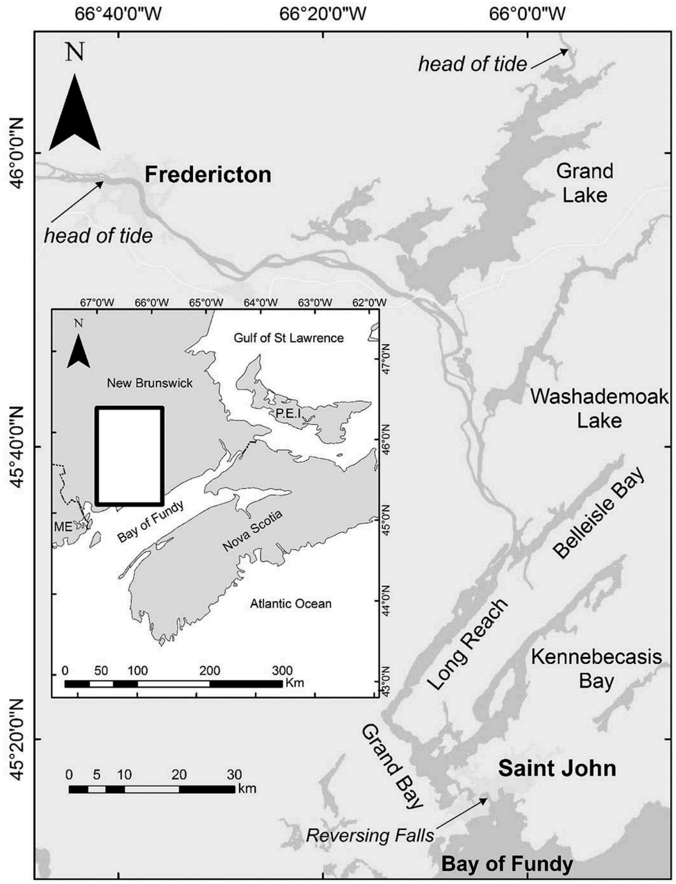

FIGURE 2. The Saint John River estuary, New Brunswick. The commercial fishery for Atlantic Sturgeon occurs throughout Long Reach in the lower estuary.

the fishing season (May and July–August) temperatures vary from 10°C to 22°C at the surface and 4–14°C at depths below 8 m. Surface and bottom currents vary from 1 to 2 m/s during the spring freshet to less than 0.5 m/s during July–August.

Sturgeon capture and sampling.—Atlantic Sturgeon were captured with multifilament, nylon gill nets of 33.0- and 38.7-cm stretched mesh. Nets were 55 m long and 6 m deep and were set on the bottom in depths of 5–20 m. Nets were set during May, July, and August and fished once or twice daily until the quota was landed, at which time fishing ceased. Sampling was performed by the fishers with technical assistance from DFO, University of New Brunswick (UNB), and Acadia University (AU).

Atlantic Sturgeon were removed from the net and either retained for harvest or sampled and released. Each fish was measured for TL and FL to the nearest 2.5 cm. Sex, maturity stage, and caviar suitability were determined using a biopsy probe passed through the abdominal wall. If a fish was not selected for harvest it was tagged with an external T-bar tag (Floy) on the right side at the base of the dorsal fin and a food-grade PIT tag under the skin between the dorsal and lateral scute rows immediately under the junction of the second and third dorsal scutes from the head. The external tag had either a UNB or DFO return address. Recaptured fish were sampled and/or harvested similarly. All captured fish were checked for PIT tags with a hand-held examining wand (Biomark Pocket Reader).

During 2011 and in subsequent years, Atlantic Sturgeon chosen for harvest were marked with a plastic, uniquely numbered, snap-closing, identification tag passed through one of the pectoral fins immediately after sampling. These tags were issued to the fishers before the season and were required to remain with the fish until processed. Fish were processed in the plant within 1–2 h of capture. In the processing plant fish were maintained below 10°C, each was bled by cutting the ventral artery, and the head, gills, fins, gut, and gonads removed. The dressed carcass was weighed to the nearest 0.1 kg on a Mettler Toledo balance, and retained female gonads (caviar) were weighed to the nearest 0.1 gm on a Uline balance. Both right and left pectoral fin spines were retained for aging and frozen until analyzed.

Data analysis.—Unfortunately the regulated use of minimum-mesh-size gill nets in the fishery and the use of larger mesh sizes by the fishers that optimized landings resulted in catches that would be biased to some degree in relation to the true composition of the adult spawning population (Ricker 1975). Gill-net selectivity curves using increments of 4 cm TL were developed to examine catch characteristics of males, females, and pooled adults from 2009 to 2015. Mean lengths of male and female catches were compared for statistical differences using the nonparametric Mann–Whitney test ($\alpha = 0.05$).

Total lengths were used in the data analysis because the minimum harvest size for the fishery is based on a TL of 48 in (122 cm). Mean, minimum, and maximum lengths of females and males were determined for each annual catch and compared for statistical differences (Kruskal–Wallis test, $\alpha = 0.05$). A linear regression between TL and FL was compiled using 1,396 Atlantic Sturgeon caught in the fishery for comparison with literature data where TL was not recorded. Mean, minimum, and maximum dressed weights (w_D) of females and males were determined for each annual catch during the period 2011–2015 and compared for statistical differences (Kruskal–Wallis test, $\alpha = 0.05$).

Annual landings in round weight (w_R) were estimated using the yearly number of harvested males and females and the mean w_R for each sex. To determine w_R, a total of 491 males and 257 females were weighed before processing and then reweighed when dressed after the removal of head, fins, gut, and gonads (DFO 2013a).

Weight–length relationships were determined for both males and females as

$$\text{Log}_{10}w_D \text{ males and } \log_{10}w_D \text{ females} = a + b\log_{10}\text{TL},$$

where w_D is dressed weight in kg, a and b are estimated parameters, and TL is the total length (cm) of males or females. Linear regressions were used to compare female gonad weight (caviar) to TL and w_D as

$$w_C = a + b\text{TL and } w_C = a + bw_D,$$

where w_C is the female gonad weight in kg, a and b are estimated parameters, TL is total length (cm) and w_D is dressed weight (kg).

Sex was determined using a 4-mm-diameter, hollow, biopsy probe passed through the abdominal wall into the gonad. The probe penetrated the body cavity and gonad to a depth of ~4 cm and retained a core of the gonad that was examined during sampling to determine which fish would be landed. Sex and maturity stage of harvested fish were confirmed during processing (DFO 2013a).

Pectoral fin spines used for aging were dried in an oven for 14 d at 24°C and cut into 5-mm sections with an Isomet low speed saw. Sections were immersed in 70% ethanol examined under a stereomicroscope at a magnification of 40× and photographed in reflected light. Digital photographs were enhanced with Adobe Photoshop and read off the screen of a laptop computer. In reflected light, opaque bands were considered as annuli. A blind reading of the sections to determine age was performed by two independent readers (M. J. Dadswell and N. D. Stewart) who did not know the fish length, and when they disagreed, the final age was decided by the two readers conferring over ages. Complete details on aging accuracy, reader bias, and precision are provided in Stewart et al. (2015).

Total instantaneous mortality (Z) for the adult population was estimated using a plot of $\log_e$-transformed number of individuals per year-class by age (Ricker (1975):

$$Z = -(log_e Nt_2 - log_e Nt_1)/t_2 - t_1,$$

where $\log_e Nt_2$ is the number fish at age t_2, $\log_e Nt_1$ is the number at age t_1, and $t_2 - t_1$ is the period in years between the two age-groups. A slope was generated by the analysis representing Z for the age distribution of 132 pooled adults that were age 28–51 years.

Because the number of aged samples was low compared with the total catch, a second estimate of Z was obtained by combining results from the Von Bertalanffy growth model for the SJR pooled adults (Stewart et al. 2015) with a Beverton–Holt instantaneous mortality equation to estimate Z (Gedamke and Hoenig 2006):

$$Z = [K(L_\infty - L_x)]/(L_x - -L_c),$$

where K is the Brody growth coefficient, L_∞ is the asymptotic length, L_c is the smallest average length when adults were vulnerable to fishing, and L_x is the mean length of the fish sampled that were larger than L_c. Annual survival rate (S) for pooled adults of the SJR population was acquired from the mean estimated Z from both methods using $S = e^{-Z}$ (Ricker 1975).

Estimates of the total SJR adult population of Atlantic Sturgeon were determined using both modified Schnabel and Jolly–Seber mark–recapture models. Catch and recapture data collections were extended to 2016 in this part of the study in order to obtain population estimates from the Jolly–Seber model for 2013–2015 that could be compared with the Schnabel model when number of sturgeon marked and number examined for marks were sufficient to obtain population estimates within 25% accuracy with 95% confidence limits (Robson and Regier 1964). The modified Schnabel model uses multiple censuses and was developed to assess closed populations (Ricker 1975). We considered a Schnabel estimate appropriate for this study because the SJR adult population is a closed, genetically distinct stock that returns to its natal river for spawning (Wirgin et al. 2000; Grunwald et al. 2008). The Jolly–Seber model was developed to examine open populations (Amstrup et al. 2005), and we used it as a means to compare with the modified Schnabel estimates.

Recaptures were not considered valid unless they had been at large for 1 year to allow random mixing into the total at-sea adult population. Recaptures that were processed were considered as removals from the population. Total known tag loss was 0.3% based on PIT tag retention when the external tag was lost or external tag retention when the PIT tag was lost. Since tag loss was minimal it was not applied to population calculations.

The modified Schnabel estimate is a very robust statistical method (Ricker 1975) and provides an estimate of population size (N_t) from

$$N_t = \Sigma(C_t M_t)/R_t + 1,$$

where C_t is the total number of individuals caught in sample t, M_t is the number of marks at large at sample t, and R_t is the number of recaptures caught in sample t. Since the fraction of the total population caught in each sample (C_t/N_t) and the fraction of the total population already marked (M_t/N_t) were always less than 0.1, modified Schnabel 95% confidence intervals (CIs) were calculated as

$$N_t = \pm \Sigma C_t M_t / df,$$

where df = Poisson value at t = 0.05 for the degrees of freedom (i.e., number of recaptures: Krebs 1989). The upper and lower CIs were not symmetrical around N until there were more than 50 recaptures.

The stochastic Jolly–Seber model uses mark and recapture of fish over four or more catches for an estimate of population size (N_t) from

$$\beta_t = R_t + \frac{(M_t + 1)K_t}{r_t + 1}$$

$$N_t = \frac{\beta_t (C_t + 1)}{R_t + 1},$$

where β_t is the marked population size just before year t, R_t is the number of individuals captured during year t that are marked (i.e. recaptures), M_t is the total number of individuals captured during sampling year t that are released, K_t is the number of individuals of the marked population not captured during a sampling year that are captured again later, r_t is the number of individuals of the M_t captured again later, N_t is the population size in year t, and C_t is the total number of individuals captured during sampling year t (notation as in Ricker 1975; equations as in Amstrup et al. 2005). The CI for the Jolly–Seber population estimate N_t was calculated using Manly (1984).

The exploitation rate (u) for the fishery with an annual quota of 350 adults was determined as u = 350 /(estimated annual mean adult population for 2013–2015). Total instantaneous fishing mortality (F) was obtained using $u = 1 - e^{-F}$ and total instantaneous natural mortality (M) from $M = Z - F$ (Ricker 1975).

Estimates of the 1880 virgin Atlantic Sturgeon adult population in the SJR were determined assuming that the catch of 712 metric tons during 1880–1886 represented the biomass of the total adult population (Figure 1). Based on the fact that fishers during 1880 were allowed to use any mesh size of gill net, had large catches (DFO 2013b), and would have probably caught all sizes of adult Atlantic Sturgeon, mean round weights of 50 and 30 kg were used to estimate the limits of possible range in the size of the virgin population.

RESULTS

Catch Characteristics

Because gill nets were used exclusively by the commercial fishery, all resulting data and subsequent conclusions from this study must be considered with respect to selectivity of the nets (Hamley 1975; Ricker 1975). An indirect estimate of selectivity for the combined mesh sizes of gill net used by the fishers indicated that they were most effective for catching Atlantic Sturgeon in the size range of 172–216 cm TL (Figure 3). Sex-segregated catch curves, however, suggested that there was a significant difference between lengths of males and females in the SJR spawning run, and captured males were significantly smaller than females (Figure 3; Mann–Whitney test: P < 0.001).

The annual, mean TL of female Atlantic Sturgeon was similar and varied little during the period 2009–2015 (Table 1). Only the female mean TL for 2009 differed significantly from the other annual means (Kruskal–Wallis test: H = 46.1, df = 7, P < 0.05). Annual means of male TL differed significantly from each other (Kruskal–Wallis test: H = 213.1, df = 7, P < 0.05) but exhibited no trend (Table 1). Overall TL

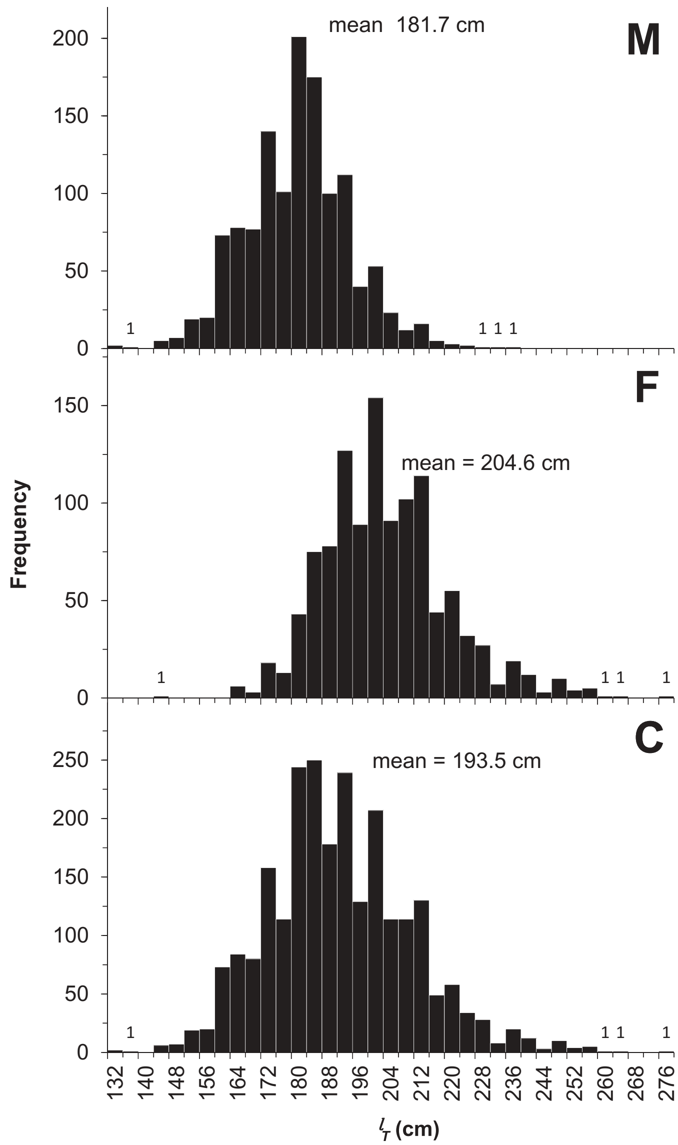

FIGURE 3. Indirect selectivity curves for gill nets having combined 33.0- and 38.7-cm stretched mesh for male (M), female (F), and pooled adult (C) Atlantic Sturgeon catches during 2009–2015 in the Saint John River commercial fishery, New Brunswick.

of females in the catch was 204.6 ± 16.3 cm (mean ± SD) and for males was 181.7 ± 13.8 cm. Maximum TL of females in the catch was 279.4 cm and for males was 236.2 cm. The minimum TL of captured males and females was 132.0 cm and 147.3 cm, respectively. The relationship between TL and FL for this Atlantic Sturgeon stock was TL = 1.07FL + 9.26 (r^2 = 0.93).

The dressed weight of 1,396 Atlantic Sturgeon processed during the period 2011–2015 was 31.4 ± 8.1 kg (mean ± SD) for females and 22.8 ± 4.9 kg for males. There was no significant difference in mean annual w_D for either sex among years

TABLE 1. Mean, SD, minimum (Min), and maximum (Max) TL (cm) and number (n) of Atlantic Sturgeon of each sex captured by the commercial fishery during 2009–2015 in the Saint John River estuary, New Brunswick.

	Females					Males				
Year	Mean	SD	Min	Max	n	Mean	SD	Min	Max	n
2009	199.5	13.9	164.0	253.0	197	176.0	13.6	132.0	227.0	423
2010	201.5	16.1	147.3	248.9	207	177.1	15.0	137.2	233.7	231
2011	206.7	13.5	175.3	256.5	237	188.2	11.8	160.0	215.9	224
2012	209.0	16.8	172.7	259.1	168	186.6	10.8	149.9	221.0	191
2013	205.3	17.0	167.6	264.2	235	188.1	12.4	160.0	228.6	248
2014	207.7	17.8	167.6	261.6	230	187.0	11.5	154.9	218.4	236
2015	205.9	16.6	175.3	279.4	225	184.6	10.3	162.6	236.2	199
All years	204.6	16.3	147.3	279.4	1,499	181.7	13.8	132.0	236.2	1,752

(Figure 4; Kruskal–Wallis test: $P > 0.05$). The largest female sturgeon captured was 81.9 kg w_D (110 kg w_R), and the largest male was 44.1 kg w_D (59.1 kg w_R). The relationship between w_R and w_D for both females and males was $w_R = 1.34w_D$. Based on the conversion of w_D to w_R, landings in w_R during 2009–2015 varied from 7.1 to 12.6 metric tons with a mean ± SD of 11.3 ± 1.7 metric tons (Table 2).

The dressed weight–TL relationships for female and male Atlantic Sturgeon were $\log_{10}w_D = 2.51(\log_{10}\text{TL}) - 4.44$ ($r^2 = 0.66$) and $\log_{10}w_D = 2.55(\log_{10}\text{TL}) - 4.70$ ($r^2 = 0.56$), respectively (Figure 5). The estimated round weight–TL relationship for pooled adults was $\log_{10}w_R = 2.72(\log_{10}\text{TL}) - 4.70$ ($r^2 = 0.74$).

Caviar weight from females varied from 0.5 to 18.0 kg, with the greatest w_C found among the largest fish (Figure 6). The female caviar weight–TL relationship was $w_C = 0.05\text{TL} - 8.42$ ($r^2 = 0.21$). The caviar weight–dressed weight relationship was $w_C = 0.10w_D - 0.35$ ($r^2 = 0.16$), indicating that the caviar weight obtained from a ripe female was approximately 10% of w_D.

Since the annual, landed quota for each sex was similar (175 fish), total catches (processed and released) were used to determine the sex ratio in the fishery. A total of 3,251 Atlantic Sturgeon were captured during the period 2009–2015: 1,752 males and 1,499 females for a sex ratio of 1.2:1.0.

Population Characteristics

A subsample of 132 (5.8%) of the processed Atlantic Sturgeon were aged (Figure 7). The subsample was selected so that the mean length of each sex in the age sample was approximately similar to the mean length for each sex in the catch. Mean TL ± SD of males in the sample was 186.4 ± 15.8 cm compared with to 181.7 ± 13.8 cm in the catch, and for females was 206.7 ± 18.6 cm compared with 204.6 ± 16.3 cm (Table 1). There was no significant difference between the age sample and the catch for females or males (Mann–Whitney test: $P > 0.05$). Age of males ranged from 18 to 41 years and females from 25 to 51 years. Mean age ± SD was 27.2 ± 4.3 years and 34.0 ± 5.6 years for males and females, respectively. The Von Bertalanffy length–age parameters for pooled adults were $L_\infty = 254$ cm TL, $K = 0.05$, and $t_0 = -0.86$ (Stewart et al. 2015).

Estimated total instantaneous mortality based on the frequency distribution of ages for pooled adults was $Z = 0.11$ ($r^2 = 0.65$; Figure 8). Using the Von Bertalanffy pooled adult L_∞ of 254 cm TL and $K = 0.05$ (Stewart et al. 2015), the minimum length for pooled adults from all years of 159 cm TL (Table 1), and the mean length for all Atlantic Sturgeon in the fishery of 193 cm TL, the Beverton–Holt model estimate of Z was 0.08. The mean of these two estimates was $Z = 0.095$, which resulted in an estimated annual survival rate (S) of 90.9%.

Between 2009 and 2016, a total of 3,837 Atlantic Sturgeon were caught, and of these, 1,396 (36%) were marked and 147 were recaptured after one or more years (Table 3). First recapture of returning males and females ranged from 1 to 6 years (Figure 9), but of the 147 recaptures, only eight (5.4%) were retaken after 1 year at large. The mode for first recapture of males was 2 years and for females was 4 years.

No tagged Atlantic Sturgeon at large for longer than 1 year were recovered before 2011 when 12 were recaptured (Table 3). Valid, annual population estimates during 2011–2016 ranged from 27,354 (95% CI, 16,944–57,917) to 16,890 (95% CI, 13,852–21,075) for the modified Schnabel model and 27,791 (95% CI, 21,428–118,667) to 12,591(95% CI, 10,560–44,864) for the Jolly–Seber model (Table 4).

The annual exploitation rate based on a quota of 350 adults/year and a mean 2013–2015 population of 18,179 adults for the Schnabel model or 20,798 adults for the Jolly–Seber model (Table 4) was 1.9% or 1.7%. The estimated total instantaneous fishing mortality for these exploitation rates was $F \approx 0.02$, and the total instantaneous natural mortality (M) would thus be ~0.075 (i.e., $Z - F$: Ricker 1975).

The estimated range of the 1880, virgin, Atlantic Sturgeon adult population size in the SJR was 14,240–23,733 fish. Although larger fish than now were undoubtedly captured during 1880–1886, fishers probably also took smaller adults among the large 1880 landings, which could result in the mean

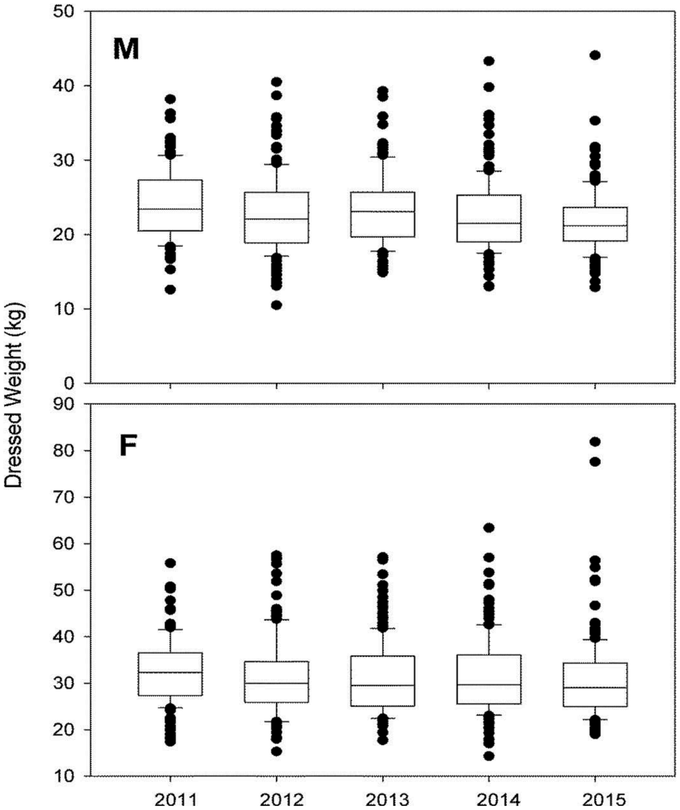

FIGURE 4. Boxplots for dressed weights (w_D) of male (M) and female (F) Atlantic Sturgeon landed in the Saint John River fishery, New Brunswick, during 2011–2015. Horizontal line represents the mean values, boxes are 25% to 75% quartiles, vertical lines represent the range, and solid circles are outliers.

weight per fish from the total 1880–1886 landings being somewhat similar to that found at present.

DISCUSSION

The Atlantic Sturgeon commercial fishery in the Saint John River has existed for 136 years. After initial overexploitation from 1880 to 1886 (Rogers 1936) and a 10-year closure until 1897 (DFO 2013b), the fishery has continued until the present with relatively low catches either because of the lack of local processors and reliable markets or because of the recently imposed quota (DFO 2013a). Low fishing mortality after 1897 combined with good habitat quality in the river and estuary (Cunjak et al. 2011), however, has probably led to the present existence of an exploitable population.

After a period of very low catches in the Saint John River between 1998 and 2008 caused by the closure of the U.S. Atlantic Sturgeon fishery and probibition of exports from Canada (DFO 2013a), the fishery entered a new phase with the opening of a modern processing plant on the river in 2009 and the involvement of fishers in the scientific management of the stock (DF0 2013b). The willingness of fishers to collect biological statistics from all captured individuals and the mark and release of undesired adults from their commercial catch since 2009 has made scientific assessment of the stock more reliable. Similarly, the ability of the fishery to reach the quota of 350 adults a year while good caviar was available in female fish has been possible (C. Ceapa, personal observation).

All biological statistics examined for adult Atlantic Sturgeon caught in the SJR fishery indicated the population has characteristics similar to other commercially exploited, northern Atlantic Sturgeon stocks. The mean TL for males and females captured in the fishery from 2009 to 2015 was 181.7 and 204.6 cm, respectively, which is similar to the Hudson River fishery where the mean TL of Atlantic Sturgeon from 1991 to 1995 was 183.9 cm for males and 220.4 cm for females (Kahnle et al. 2007). Similarly, the mean TL of adults in the St. Lawrence fishery before slot management regulations were imposed was 181.5 cm for males and 205.1 cm for females (Caron et al. 2002).

Because mean TL and w_D in the annual SJR catch have remained similar with little variation since 2009 and 2011, respectively, there appears to be no suggestion of overexploitation. Overexploitation typically leads to a decline in mean length and weight of an annual catch over time because too many larger fish are being removed (Ricker 1975).

TABLE 2. Annual harvest of male and female Atlantic Sturgeon from the Saint John River estuary commercial fishery and estimated total landings for 2009–2016. Mean round weight of males was 30.6 kg and that of females was 42.1 kg.

Year	Males (*n*)	Females (*n*)	Total catch (*n*)	Mean weight (kg)	Landed weight (metric tons)[a]
2009	148	137	285	36.1	10.3
2010	79	111	190	37.3	7.1
2011	164	176	340	36.5	12.4
2012	162	161	323	36.3	11.7
2013	163	175	328	37.7	12.3
2014	170	175	345	36.4	12.6
2015	172	174	346	36.4	12.6
2016	125	172	297	37.2	11.1

[a]Mean ± SD = 11.3 ± 1.7.

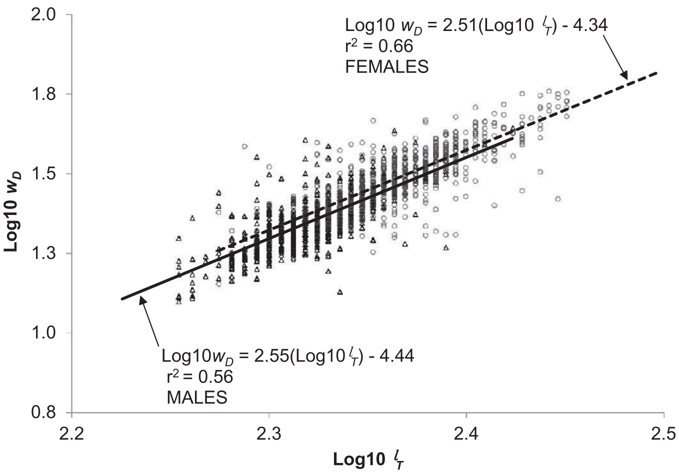

FIGURE 5. Dressed weight (w_D)–total length (TL) relationship for male (triangles; n = 655) and female (circles; n = 741) Atlantic Sturgeon from the Saint John River fishery, New Brunswick, during 2011–2015.

Weight–length relationships for Atlantic Sturgeon from the SJR fishery were based on total length and dressed weight and differed from weight–length relationships from other studies. The growth or condition parameter (b) for dressed SJR fish was 2.51 and 2.55 for males and females, respectively, which was lower than that found in other studies that were based on round weight. Verreault and Trencia (2011) reported that the growth parameter for Atlantic Sturgeon from the St. Lawrence estuary was 3.12. Similarly, the growth parameter for Atlantic Sturgeon feeding at sea in the inner BoF was 3.32 (Dadswell et al. 2016). The low growth parameter values for spawning SJR Atlantic Sturgeon were probably a result of using w_D to calculate the relationship. On the other hand, many sturgeon species fast for a year or more before spawning and shift somatic growth to gonad growth (Roussow 1957; Dadswell 1979). If Atlantic Sturgeon also fast for up to a year or more before spawning, a lower growth parameter could be expected and would be exaggerated by using the dressed carcass weight to calculate the relationship.

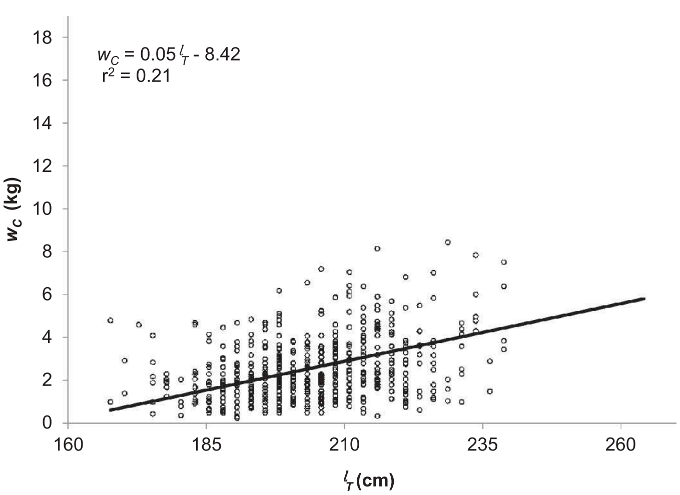

FIGURE 6. Caviar weight (w_C)–total length (TL) relationship for female (n = 608) Atlantic Sturgeon from the Saint John River commercial fishery, New Brunswick, during 2011–2015.

Caviar weight in females varied due to size and the ripeness stage of individual fish. Because caviar of the best quality is from females that are not quite ready to spawn, and these were the females selected to process (C.C., personal observation), the gonadosomatic index (GSI; w_C versus w_D) averaged 10%. Other studies have found that the GSI for this species ranged from 10% to 26% (mean, 13.8%), but these data included individuals that were in an advanced reproductive stage (Vladykov and Greeley 1963; Van Eenennaam et al. 1996; Van Eenennaam and Doroshov 1998).

The male : female sex ratio of Atlantic Sturgeon in the SJR commercial fishery was 1.2:1.0, which was different from that in most other documented *A. oxyrinchus* spawning runs. In the Hudson River fishery the male : female ratio from 1988 to 1995 was 4.0:1.0 (M. J. Dadswell and S. Nack, paper read at the 2012 annual meeting of the Atlantic States Marine Fisheries Commission). The difference in sex ratio between these two fisheries was probably because the minimum gill-net mesh size for the Hudson River was not regulated and fishers used mesh sizes as small as 20.3-cm stretched mesh (Kahnle et al. 2007). In the St. Lawrence River, Caron et al. (2002), using gangs of gill nets with mixed mesh sizes, found that the ratio of male to females on the spawning grounds was 4.9:1.0. In Florida, however, Huff (1975) reported that the male : female ratio in the Suwannee River Gulf Sturgeon *Acipenser oxyrinchus desotoi* commercial fishery during the spawning run was approximately 1:1. The latter observation was probably because fishers on the Suwanee River, similar to those on the SJR, were using larger-mesh gill nets to enhance selection of females for caviar.

The selectivity curve for combined 33.0- and 38.7-cm-stretched-mesh gill nets used in the SJR commercial fishery suggests that they are not effective for catching Atlantic Sturgeon less than 172 cm TL. Because mature males first occur in the SJR at 150 cm TL (Stewart et al. 2015), and the mean annual minimum length of males captured in the fishery was 159 cm TL while the overall mean length of males in the fishery was 181.7 cm TL, it is probable that smaller males were underrepresented in the SJR commercial catch. Also, we suggest that since the mean age of males captured in the SJR fishery was 27.2 years and male Atlantic Sturgeon in northern populations mature between 18 and 20 years (Magnin 1964; Stewart et al. 2015), younger males were probably evading capture because of gill-net selectivity.

The mean age of both males (27.2 years) and females (34.0 years) captured in the SJR fishery was considerably older than that of Atlantic Sturgeon captured in the Hudson River fishery but similar to that for fish captured in the St. Lawrence River fishery before recent management changes. Kahnle et al. (2007) found that mature males in the Hudson River were

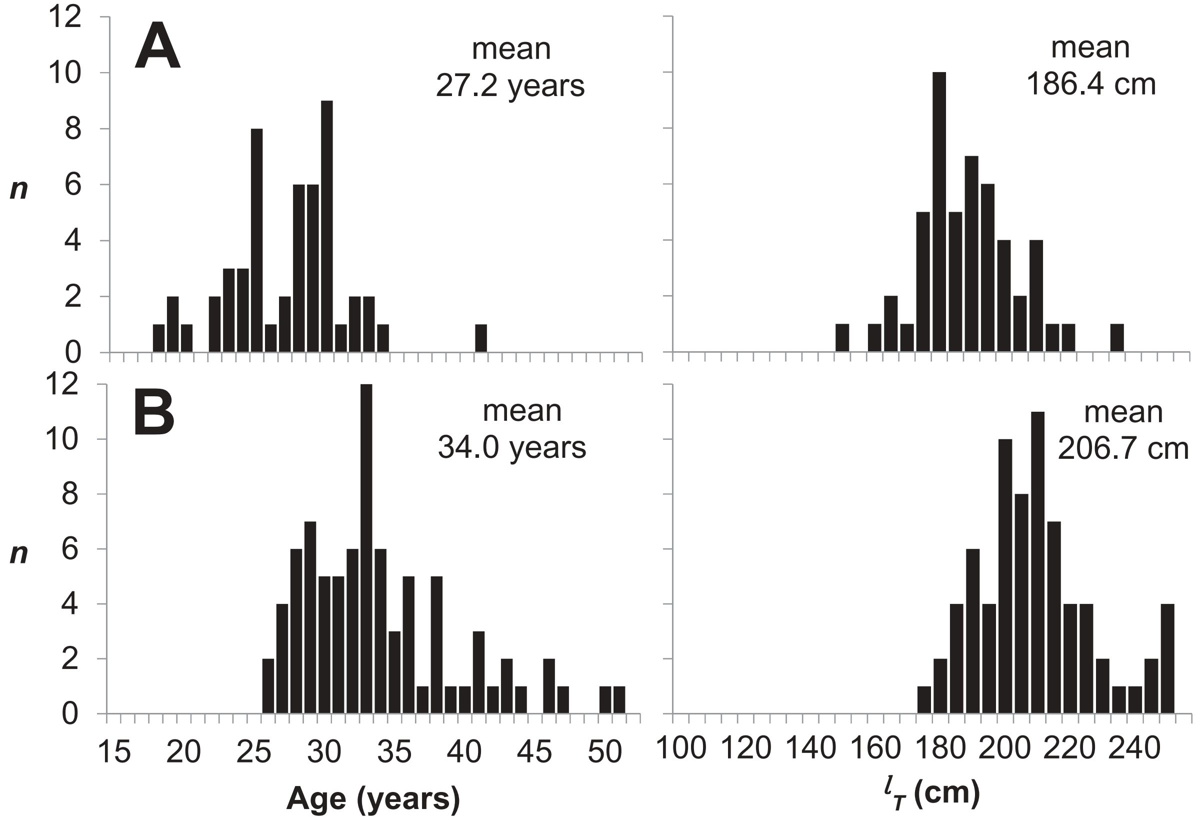

FIGURE 7. Frequency distribution of age and total length (TL) of (**A**) male (n = 51) and (**B**) female (n = 81) Atlantic Sturgeon sampled from the Saint John River commercial fishery, New Brunswick.

mostly 11–23 years of age with none older than 31 years, and mature females were 14–24 years with very few older than 30 years. Magnin (1964) found that mature males in the St. Lawrence River were older than 20 years and mature females older than 27 years. These findings, however, are probably also the manifestation of latitudinal effects of the spawning river on the growth rate and age of maturity of adults, as southern stocks grow faster and mature earlier than northern stocks (Dadswell 2006; Stewart et al. 2015).

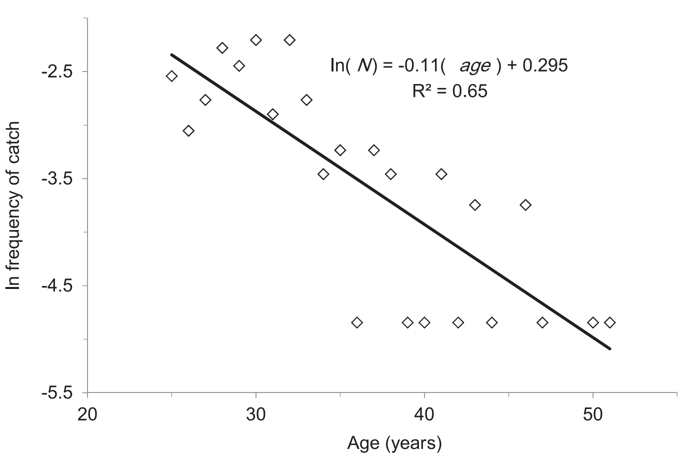

FIGURE 8. The $\log_e$-transformed (ln) number at age (years) for pooled Atlantic Sturgeon sampled from the Saint John River commercial fishery describing a total instantaneous mortality of Z = 0.11 for fish aged 28–51 years.

The mean total instantaneous mortality determined by two methods for the pooled SJR adult population was 0.095 and the estimated annual survival rate was 90.9%. The Z and S determined for other, individual Atlantic Sturgeon populations were in a similar range. Verreault and Trencia (2011) found that Z = 0.12 and S = 88.5% for the St. Lawrence River population. For the Hudson River sturgeon, a Z of 0.28 was determined for males and 0.08 for females (Kahnle et al. 2007).

Atlantic Sturgeon are iteroparous and, like most sturgeon species, do not spawn every year (Van Eenennaam et al. 1996; Dadswell 2006). Both male and female marked fish recovered in the SJR fishery were at large from 1 to 6 years before recapture, but males had a mode of 2 years before recapture and for females the mode was 4 years. Spawning periodicity in the SJR population appears to be somewhat similar to other sturgeon species. Shortnose Sturgeon *A. brevirostrum* males spawn every 2 years and females every 3 years (Dadswell 1979), and Green Sturgeon *A. medirostris* males spawn every 2.3 years and females every 2.7 years (Erickson and Webb 2007).

TABLE 3. Annual captures, recaptures, number marked, and removals of Atlantic Sturgeon for 2009–2016 from the Saint John River, New Brunswick. Removals are individuals processed in the year of their recapture.

Year	Captures (C_t)	Recaptures (R_t)	Number marked	Removals	At large (M_t)
2009	660	0	257	0	0
2010	439	0	264	0	257
2011	466	12	200	4	521
2012	357	12	109	2	717
2013	492	25	169	7	824
2014	476	38	136	15	986
2015	424	25	75	15	1,107
2016	523	35	186	26	1,156
Sum	3,837	147	1,396	69	

Valid, modified Schnabel and Jolly–Seber population estimates for the total SJR adult population of Atlantic Sturgeon ranged from 27,354 in 2011 to 16,891 in 2014 and from 27,791 in 2011 to 12,591 in 2014, respectively. Because some annual population estimates in 2011 and 2012 had confidence intervals of up to 327% of N_t, it is probable that the annual estimates from 2013 to 2016 were more reliable (Ricker 1975). By then, recaptures had increased to 0.6% of the total number of fish marked, and annual confidence intervals had declined to ±20% of the estimated population (except for some Jolly–Seber estimates).

We suggest that the Schnabel model is more reliable than the Jolly–Seber model for estimating total population sizes of adult Atlantic Sturgeon. Because of the intermittent return of adults to spawn (two or more years), the Jolly–Seber model has a wide fluctuation in estimates between years and very wide confidence intervals. These characteristics probably occur because the Jolly–Seber model assumes permanent emigration when recaptures are low in the sample immediately following marking (Amstrup et al. 2005). In all cases, adult sturgeon recaptures in this study were none to two fish in the year immediately following tagging, although 200 or more fish were marked during the previous sample. Also the Jolly–Seber model cannot provide an estimate for N_t for the last sampling period (Ricker 1975; Amstrup et al. 2005), whereas the Schnabel model can. This problem resulted in our having to extend the population estimate sampling for an extra year in order to obtain three Jolly–Seber estimates (2013–2015) to compare with similar-year Schnabel estimates once the number marked and number examined for marks were sufficient to provide statistically reliable estimates (Ricker 1975). By 2015 and 2016, when the number of fish marked and number of fish examined for marks were adequate to provide N_t to within 10% accuracy with a 95% CI, the annual, modified Schnabel estimates of N_t varied by only 0.04% (17,307 versus 17,299; Robson and Regier 1964).

When the commercial fishery began in 1880, there were no fisheries management restrictions and the experienced fishers from Delaware Bay (Saffron 2004) were able to exploit Atlantic Sturgeon in the SJR with any gill-net mesh size (DFO 2013b). During the first year of the fishery, 273 metric tons or 38% of the total catch taken up to 1886 was landed. Although a gill-net minimum size limit of 122–cm stretched mesh was introduced in 1881 (DFO 2013b), by the end of that year another 206 metric tons or, by then, 66% of the total to 1886 was landed because there were no restrictions on fishing effort or total catch.

We postulate that unrestricted use of gill nets in the first year and the high landings during the early fishery possibly resulted in a mean individual weight of landed sturgeon in the SJR during 1880–1886 that was somewhat similar to the current fishery (i.e., 36 kg). Secor (2002) used a mean weight per adult of 50 kg to estimate the population size of Atlantic Sturgeon in Delaware Bay during 1880–1900, but in that case the fishery used larger-mesh gill nets of 45.7-cm stretched mesh (Cobb 1900). Additionally, the introduction of a minimum gill-net mesh size for the SJR in 1881 suggests that managers thought too many younger sturgeon were being

TABLE 4. Valid, modified Schnabel and Jolly–Seber population estimates (N_t) and 95% confidence intervals for the total adult Atlantic Sturgeon population in the Saint John River, New Brunswick, for 2011–2016. Marked individuals must be at large for 1 year to be considered randomly mixed in the population. Confidence intervals for the modified Schnabel model are estimated using Ricker (1975), and for the Jolly–Seber model using Manly (1984). Population estimates from 2013 to 2015 have number marked and number examined for marks that are adequate to provide N_t within 25% accuracy with 95% confidence limits.

Year	Schnabel estimate	95% CI	Jolly–Seber estimate	95% CI
2011	27,354	16,944–57,917	27,791	21,428–118,667
2012	24,463	16,655–35,723	16,926	14,825–56,690
2013	20,340	15,493–26,623	24,914	20,496–91,735
2014	16,891	13,852–21,075	12,591	10,560–44,864
2015	17,307	14,407–20,785	24,888	11,558–218,544
2016	17,299	14,735–20,307		
Mean for 2013–2015	18,179		20,798	

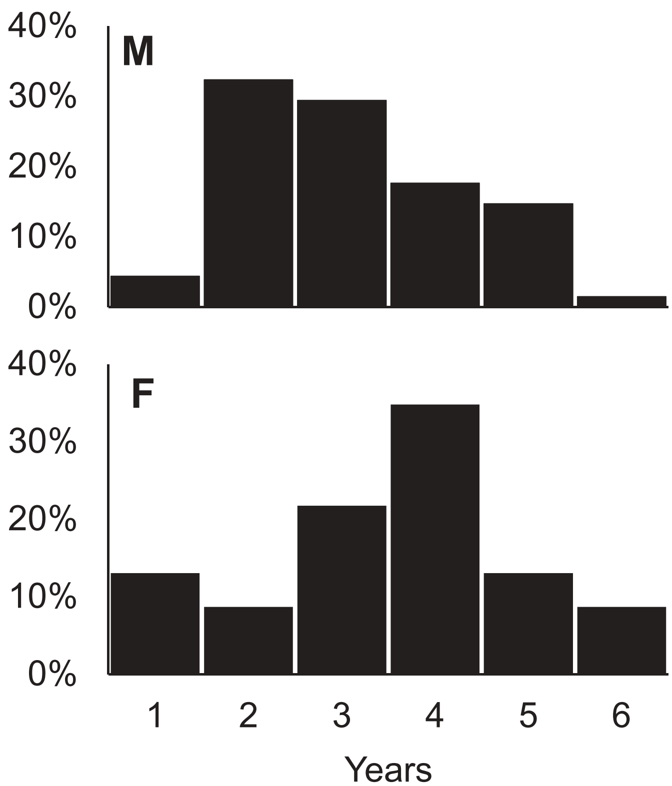

FIGURE 9. Percentage of total male (M) and female (F) Atlantic Sturgeon recaptured in the Saint John River commercial fishery, New Brunswick, in relation to the period at large (years) before first recapture.

exploited. For these reasons, as well as the fact that the minimum allowable gill-net mesh size is the same now as in 1881, we believe using a mean weight range for the early fishery of 50–30 kg per fish was justified, which led to an estimated range for the 1880 virgin adult population of 14,240–23,733 fish. Because the mean estimated annual population size for the current fishery during 2013–2015 using two mark–recapture models was approximately 18,200 or 20,800 adults, we contend that the present adult population of SJR Atlantic Sturgeon is near the same size as the virgin adult population was in 1880.

Earlier studies have suggested that the SJR Atlantic Sturgeon population had only 1,000–3,000 adults (DFO 2013b). These studies, however, were based on single-year, mark–recapture estimates made in the estuary and only determined the annual spawning run size. Similarly, Kahnle et al. (2007) in their study of Hudson River Atlantic Sturgeon estimated a population of 863 adults. Unfortunately, they also only determined the annual spawning run size, and the present Hudson River total adult population is probably three to four times larger (Dadswell and Nack, unpublished). Because spawning is not an annual event for individuals of this species, tagged fish may not return again until 2–4 years after tagging, and most of the adults are at sea in any given year; we suggest that a multiyear mark–recapture study over a period of at least 6 years in northern rivers would be required to effectively expose all fish to capture and recapture and provide the best estimate of the true population size.

With an annual quota of 350 fish from a total population of ~18,200–20,800 adults, the annual exploitation rate for the current SJR fishery would range from 1.9% to 1.7%. These exploitation rates represent a fishing mortality, F, of ~0.02, which means that the current quota is below the F_{50} for this species and near 75% of the lifetime maximum number of eggs per recruit and well within an acceptable maximum sustainable yield F (F_{MSY}) range (Boreman 1997). In addition, other fisheries management reference points appear to be satisfied, including (1) the mean age of first capture was above the age of maturity for both sexes (Froese et al. 2016), (2) the F_{MSY} was below the estimated M of 0.075 (Froese et al. 2016), and (3) there were more than 20 year-classes of females in the population (Ricker 1975).

Sturgeon populations are unable to sustain high levels of adult exploitation because of their slow growth, late age of maturity, and low, potential lifetime egg production per recruit (Boreman 1997). There are, however, a number of sustainable sturgeon fisheries in North America. The sport fishery for White Sturgeon *A. transmontanus* in the Columbia River has successfully used slot-retention management that prohibits the take of mature adults to sustain the fishery (Galbreath 1985). A similar management regime exists for the Atlantic Sturgeon commercial fishery in the St. Lawrence River where maximum retention length allowed is 150 cm FL, fishers choose to release individuals less than 100 cm FL because they are too small for their market, and there is an annual quota (Trencia et al. 2002). After 20 years with this management strategy the St. Lawrence fishery continues to sustain its annual quota of 60 metric tons (Verreault and Trencia 2011). Many sport and commercial fisheries for Lake Sturgeon *A. fulvescens* also continue to be sustainable because they have minimum length limits that allow adult spawning before permitted retention (Folz and Meyers 1985; Fortin et al. 1993).

Our analysis of the current Atlantic Sturgeon fishery in the Saint John River suggests that the fishery is sustainable at its present annual yield. Before 1880, SJR Atlantic Sturgeon were only exploited by North American natives for food (DFO 2013b), and the river and estuary were unencumbered by anthropogenic impacts such as industrial development and dams (Cunjak et al. 2011), which means the population was probably in equilibrium with its environment. Since our analysis indicated the current population size was within the range of the estimated virgin stock size of 1880, we suggest that the river and its estuary are now probably near the carrying capacity for this Atlantic Sturgeon population.

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