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The annual marine feeding aggregation of Atlantic sturgeon *Acipenser oxyrinchus* in the inner Bay of Fundy: population characteristics and movement

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Atlantic sturgeon *Acipenser oxyrinchus* aggregate to feed from May to October in Minas Basin (45° N; 64° W), a large, cul-de-sac embayment of the inner Bay of Fundy. The aggregation consists mainly of migrants from the Saint John, NB and Kennebec Rivers, ME (99%). During 2004–2015, 4393 *A. oxyrinchus* were taken as by-catch by commercial fish trawlers or at intertidal fishing weirs, and 1453 were marked and/or sampled and released. Fork length (L_F) ranged from 458 to 2670 mm, but 72·5% were <1500 mm. Mass (M) ranged from 0·5 to 58·0 kg. The mass-length relationship for fish ≤50 kg was $\log_{10}M = 3{\cdot}32\log_{10}L_F - 5{\cdot}71$. Observed growth of unsexed *A. oxyrinchus* recaptured after 1–8 years indicated fish of 90–179 cm L_F grew *c.* 2–4 cm a year. Ages obtained from pectoral spines were from 4 to 54 years. The Von Bertalanffy growth model predicted $K = 0{\cdot}01$ and $L_\infty = 5209$ mm L_F. Estimated annual mortality was 9·5–10·9%. Aggregation sizes in 2008 and 2013 were 8804 and 9244 individuals, respectively. Fish exhibited high fidelity for yearly return to Minas Basin and population estimates indicated the total at-sea number utilizing the Basin increased from *c.* 10 700 in 2010 to *c.* 37 500 in 2015. Abundance in the Basin was greatest along the north shore in spring and along the south shore in summer, suggesting clockwise movement following the residual current structure. Marked individuals were recaptured in other bays of the inner Bay of Fundy, north to Gaspé, Quebec, and south to New Jersey, U.S.A., with 26 recoveries from the Saint John River, NB, spawning run. Fish marked at other Canadian and U.S. sites were also recovered in Minas Basin. Since all *A. oxyrinchus* migrate into and out of the Basin annually they will be at risk of mortality if planned tidal power turbines are installed in Minas Passage.

Key words: abundance; Acipenseridae; growth; Minas Basin; mortality; tidal power.

INTRODUCTION

The Atlantic sturgeon *Acipenser oxyrinchus* Mitchill 1814 is an anadromous fish which occurs in rivers, estuaries and on the continental shelf from Ungava Bay, Labrador, Canada, to the north coast of South America (Vladykov & Greeley, 1963; Dadswell, 2006) and formerly occurred in the Baltic Sea (Ludwig *et al.*, 2002).

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Once an important commercial fish, it supported large fisheries for meat and caviar until 1900 (Smith & Clugston, 1997). Unfortunately, stocks have been commercially depleted in many U.S. and some Canadian rivers (Rogers, 1936; Secor & Waldmen, 1999; Secor, 2002). Populations are now recovering in the U.S.A. (ASSRT 2007; Wippelhauser & Squires, 2015) or support small fisheries in Canada (Verreault & Trencia, 2011; DFO, 2013*a*).

Understanding all aspects of *A. oxyrinchus* biology is an important step in their management, but they can be an elusive research species. The majority of studies have been concentrated in rivers and estuaries, but the marine environment is essential to their life cycle (Dadswell, 2006) and while at sea they encounter many threats, including by-catch mortality in commercial fisheries (Stein *et al.*, 2004*a*), vessel strikes (Brown & Murphy, 2010; Balazik *et al.*, 2012*a*), tidal power development (Dadswell, 2006) and poor habitat quality (ASSRT, 2007). Distribution, habitat utilization and migration in the ocean, where they spend the majority of their life, is difficult to study and least understood. At sea *A. oxyrinchus* is found most often along the coastal shelf where depths of 10–50 m coincide with gravel and sand substrata (Collins *et al.*, 1996; Fox *et al.*, 2002; Savoy & Pacileo, 2003; Stein *et al.*, 2004*b*; Laney *et al.*, 2007; Dunton *et al.*, 2015), but they are also found offshore to a depth of 200 m (Scott & Scott, 1988; Stein *et al.*, 2004*a*; Erickson *et al.*, 2011). Researchers have identified key areas along the U.S. coastal shelf and within certain bays where they consistently aggregate (Collins *et al.*, 1996, Stein *et al.*, 2004*b*, Laney *et al.*, 2007, Dunton *et al.*, 2010, 2015) and have begun determining long distance migration patterns (Erickson *et al.*, 2011). Other than for the St Lawrence River population (Magnin & Beaulieu, 1960), information of this sort is sparse in Canada. Their current distribution range is similar to the historical range in both Canada and the U.S.A. (Stokesbury *et al.*, 2014), but the presence of the species is difficult to document and there may be more populations than currently recognized (Dadswell, 2006; ASSRT, 2007).

In Canada *A. oxyrinchus* is now abundant in the river and estuary of the Saint John and the St Lawrence Rivers, where they are commercially harvested (Trencia *et al.*, 2002; Verreault & Trencia, 2011; DFO, 2013*a*). A groundfish trawler survey in Minas Basin, inner Bay of Fundy (iBoF), during 2004–2005 reported it was the fifth most commonly caught fish species (Wehrell *et al.*, 2008) and intertidal weir fishers of Minas Basin report catches of up to 1000+ a year (A. Lewis, pers. comm.; W. Linkletter, pers. comm.; R. Wilcox, pers. comm.). In Chignecto Bay, iBoF, their feeding is considered the primary erosional and depositional agent on the intertidal mudflats during summer (Pearson *et al.*, 2007).

Long-term population monitoring is required to determine the true abundance of a long-lived and mobile species like *A. oxyrinchus* and to identify threats that could cause future problems for their survival. The impact that human development or environmental change could have on their populations cannot be determined without prior knowledge of the unperturbed condition (Bain *et al.*, 2000). Minas Passage leading into Minas Basin has been long regarded as one of the largest sources of tidal energy in the world and the development of in-stream tidal power in the region is under consideration (AECOM, 2009; Redden *et al.*, 2014). It is unknown if in-stream, hydro-kinetic machines will be a threat to migrants that arrive in Minas Basin *via* Minas Passage; but in the Annapolis River, Nova Scotia, where transit through an enclosed tidal turbine is necessary for the population, there have been strike mortalities during the spawning run (Dadswell & Rulifson, 1994; Dadswell, 2006). Other anadromous fishes such as American shad *Alosa sapidissima* (Wilson 1811) and striped bass *Morone saxatilis* (Walbaum 1792), which migrate through the iBoF during summer are a mix of stocks from numerous rivers in the U.S.A. and Canada (Dadswell *et al.*, 1987; Rulifson *et al.*, 2008; Waldman *et al.*, 2014); due to their extensive marine migration, the *A. oxyrinchus* which occur in Minas Basin are a mix of stocks as well. Genetic analysis of 433 *A. oxyrinchus* collected in the Basin during 2007–2014 assigned 61% to the Saint John River, NB, 38% to the Kennebec River, ME, and 1% to the Hudson River, NY (Wirgin *et al.*, 2012; I. Wirgin, unpubl. data). Should in-stream tidal turbines prove to be a threat to *A. oxyrinchus* they may not impact only local and nearby Canadian populations, but also U.S. populations that are recovering from past over exploitation and are now protected by fishery closures and status designation (ASSRT, 2007; NMFS, 2012). Previous studies in Minas Basin have described the occurrence of *A. oxyrinchus* in relation to other fishes (Dadswell *et al.*, 1984), assessed diversity of their ectoparasites (Munroe *et al.*, 2011), determined the stocks present in the Basin using genetic analysis (Wirgin *et al.*, 2012), examined impact of trawling capture on survival (Beardsall *et al.*, 2013), described their diet (McLean *et al.*, 2013) and intertidal feeding behaviour (McLean *et al.*, 2014). Known pre-turbine population characteristics and abundance will be important in any assessment of potential tidal power impacts on this aggregation (Stokesbury *et al.*, 2012).

In Atlantic Canada, commercial fishing for *A. oxyrinchus* is only allowed in the St Lawrence and Saint John Rivers and their estuaries (DFO, 2013*b)*. All individuals taken as by-catch in marine fisheries must be released. Fishers in Minas Basin provided the present study with captured *A. oxyrinchus* to sample, tag and release.

Based on preliminary work in 2004–2005, the seasonal occurrence, population characteristics and movement of the annual Minas Basin *A. oxyrinchus* feeding aggregation during 2007–2015 were examined. The questions posed were: (1) What was the seasonal occurrence of the aggregation in Minas Basin? (2) What were the biological characteristics and size of the aggregation? (3) What was the local and long distance movement pattern of individuals in the aggregation? Since marine aggregations of *A. oxyrinchus* are difficult to locate and study, their annual occurrence in an enclosed, relatively benign marine environment afforded a unique opportunity to expand knowledge of the life history of this species.

MATERIALS AND METHODS

STUDY REGION

The Bay of Fundy is located on the Atlantic Coast of Canada between the provinces of New Brunswick and Nova Scotia and is a large funnel-shaped embayment which is aligned south-west to north-east (Fig. 1). The outer Bay is a deep, undivided embayment connected to the Gulf of Maine while the inner Bay is shallow and divided between Chignecto Bay to the north and the Minas Basin to the east. Minas Basin (64° N; 45° W) is semi-enclosed by the province of Nova Scotia (Fig. 1). It is typically described in four sections: the entrance from the Bay of Fundy is Minas Passage, the middle, open water region is the Central Minas Basin, the lower embayment is the Southern Bight, and the most westerly embayment is Cobequid Bay. Combined, these four regions cover an area of *c.* 2000 km^2 (Parker *et al.*, 2007). A triangular cul-de-sac embayment *c.* 80 km long and 29 km wide at the base is formed by the Central Minas Basin, the Southern Bight and Cobequid Bay.

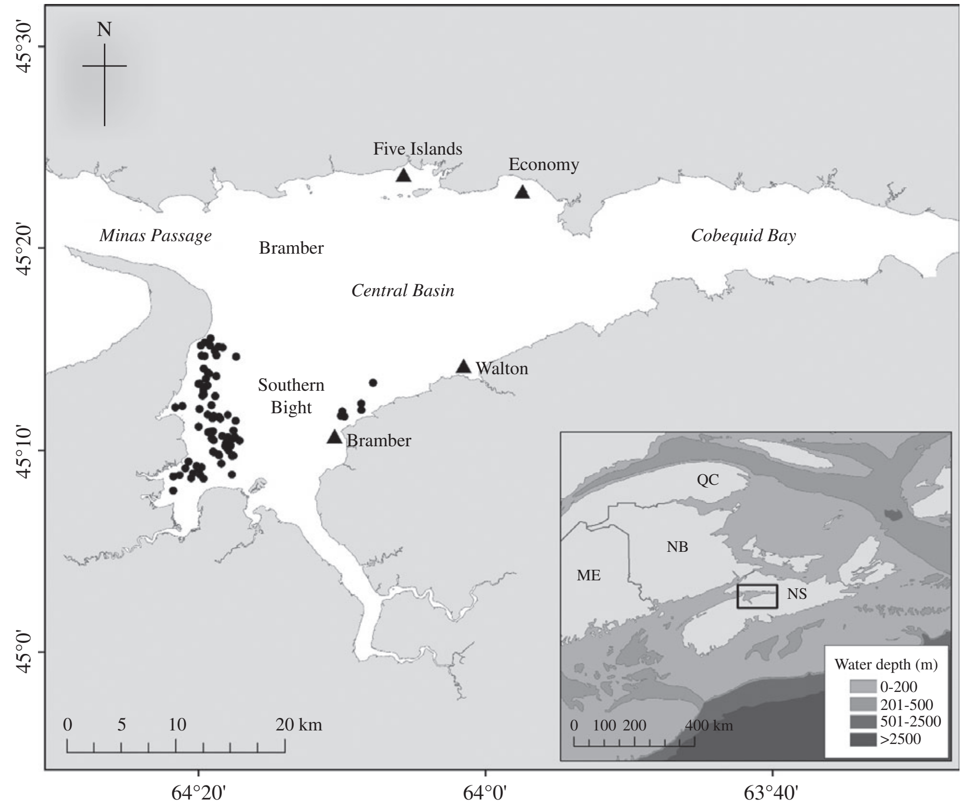

FIG. 1. Minas Basin, Nova Scotia, showing the four regions referred to in this study and sampling locations for *Acipenser oxyrinchus* using trawler (●) and intertidal fishing weirs (▲). Inset: location of Minas Basin, inner Bay of Fundy on the Atlantic coast of North America.

Tidal range in Minas Basin is *c.* 11 m with spring tides up to 16 m (Bousfield & Liem, 1959). At low tide roughly one third of the Basin area (670 km^2) is exposed as mud flats, sand and salt marshes and in places the water can recede as much as 5 km from the shoreline (Parker *et al.*, 2007). Low water depth of Minas Passage ranges from 35 to 115 m, but maximum depth of the Basin is only 17 m (Bousfield & Leim, 1959; Greenberg, 1984). The tidal regime is semi-diurnal and an estimated 3 x10^9 m^3 of water flows into and out of the Basin with each tide (Parker *et al.*, 2007). Owing to strong tidal forcing over shallow bathymetry, water exchange ratios with the Bay of Fundy vary from 0·39 to 0·60 a tidal cycle (Ketchum & Keen, 1953). The Basin is well mixed vertically with high turbidity and low primary production in the water column (Parker *et al.*, 2007). Inflow of fresh water to Minas Basin from its catchment is *c.* 239 m$^{\mathbf{3}}$ s^{-1} annually, but during July through September inflow decreases to *c.* 99 m^3 s^{-1} (Bousfield & Leim, 1959). The freshwater input does not greatly decrease the salinity of the majority of the Basin because of intense vertical mixing (Keizer, 1984). During summer, surface salinity levels are 30 in Minas Passage and the Central Basin, but decrease gradually in the Southern Bight and Cobequid Bay to below 25 (Bousfield & Leim, 1959; Wehrell *et al.*, 2008). Maximum summer, sea surface temperature (SST) of Minas Passage ranges from 13·0 to 15·0° C and the SST of the Central Basin is *c.* 17° C, but can be as high as 22° C in the Southern Bight and Cobequid Bay (Bousfield & Leim, 1959). During winter SST declines to −1·5° C and the Basin is covered by drifting ice pans up to 5 m thick (Gordon & Desplanque, 1983).

COLLECTION

The annual aggregation of *A. oxyrinchus* in Minas Basin was sampled during the months of June to August 2004–2005 and May to October 2007–2015. Individuals were collected from the by-catch of commercial fisheries, which use two fishing practices, trawler vessels and intertidal fishing weirs.

Collections were made from the 13 m trawler *Terri & Sandy*. The net used was a 24 m box trawl with a mesh size of 140 mm stretched, equipped with a tickle chain, 200 kg metal Bison doors and modified rock hopper equipment. The trawl was towed at 5·6 km h^{-1} (3 knots) when fishing. Tow times ranged between 15 and 120 min. Short tow times have been shown to be relatively benign to *A. oxyrinchus* (98% survival; Beardsall *et al.*, 2013). The vessel fished in the Southern Bight and along the southern shore near Walton (Fig. 1).

Fishing weirs are stationary, fence-like fish traps built on the intertidal flats of Minas Basin, a practice that has existed for many centuries (Gordon, 1993). The weirs are made of wooden posts spaced 1–1·5 m apart driven into the sediment of the intertidal zone until 2–3 m remain above the substratum and then covered for their length with netting (2·5 cm stretch). The structure resembles a V-shape, with the sharp end of the V pointing seaward and the wings spreading back towards the shore. From tip to tip of the V, weirs are *c.* 1–2 km in length. Weirs are tended at every low tide night and day during the fishing season, weather and tide range permitting. Four weirs were visited during the study: Five-Islands, Economy, Walton and Bramber (Fig. 1). Weirs are built each spring (April) and dismantled in late summer or autumn, since they can be destroyed by drifting ice during winter. At high tide, weirs are submerged, but become completely exposed at low tide. A pond of water is retained at the seaward end of the V at low tide. Fish are removed from the pond using a dip or seine.

Acipenser oxyrinchus were sampled when the trawl was hauled or the weir was fished at low tide. Each individual was out of water for examination only long enough to be tagged and measured and weighed (*c.* 5 min) and then released either off the side of the trawler or back into the weir pond. All individuals captured with the trawler were sampled since trawler catches seldom exceeded 10 fish. In weirs, on the other hand, time was sometimes limited by the return of the flood tide or the large size of the catch. If there was adequate time all were examined, if not a sub-sample was examined and tagged and the remainder tagged and counted.

Acipenser oxyrinchus sampling during this study was approved through Research Permit #322595 granted by the Canadian Department of Fisheries and Oceans. The sampling and tagging methods used were approved by the Acadia University Animal Care Committee protocol #05-07R#2.

SAMPLING

Acipenser oxyrinchus were measured for fork length (L_F) to the nearest mm. L_F only were used in the analysis because the top lobe of the fish's heterocercel tail was often worn or damaged. Individuals were placed in a mesh sling and weighed to the nearest 0·2 kg with a Chatillon spring balance (www.chatillon-scales.com). During 2007–2010 fish heavier than 50 kg could not be weighed because of the limit of the spring scale and because individuals greater than this mass could not be lifted safely by one person. Routine weighing of fish ceased after 2010 because with a sample size of 330 it was concluded that there were enough data to characterize the population. A 100 kg scale was acquired in 2013 when there were larger sampling crews, but it was only used to weigh larger individuals that were being acoustically tagged for subsidiary studies.

For ageing, a sub-sample of *A. oxyrinchus* were chosen from the catch and the leading pectoral fin ray (spine) was removed with a fine tooth hand saw and knife after the method of Cuerrier (1951). Individuals were chosen for spine removal based on their L_F and the number in each length increment of 10 cm, which had been previously sampled. The fin spine was cut 1·5 cm from the point of articulation on the side of the fish, a procedure known to be safe and do little harm (Collins & Smith, 1996; Nguyen *et al.*, 2016). The spines were dried in air for a month and returned to the laboratory for analysis. Removal of pectoral spines was terminated after 2009 when it was concluded that a sample of 299 fish was large enough to define age characteristics of the aggregation.

Individuals were tagged with a Floy dart tag (FT-1-94, 150 mm yellow, spaghetti; www.floytag.com) placed at the base on the right side of the dorsal fin. Tags were deeply embedded (one half their length) and snugged behind a pteriogyte bone to prevent loss. Tags had a unique identification number and an Acadia University return address printed on the spaghetti portion of the tag for future recognition. During 2009 to 2015 fish were also tagged with Passive Integrated Transponder (PIT) tags (www.biomark.com) implanted on the left side of the dorsal fin base for a secondary means of recognition if external tag loss occurred. Each PIT tag transmits a unique identification code to a hand-held examining wand (Biomark Pocket Reader; www.biomark.com). In addition, parallel acoustic tagging studies were conducted during 2010–2015 and 145 individuals were also implanted with VEMCO V-16 coded acoustic tags (http://vemco.com; Stokesbury *et al.* 2012; Beardsall *et al.* 2013; McLean *et al.* 2014).

AGE DETERMINATION

Fin spines were cleaned of excess epidermal tissue and five transverse sections of 0·25–0·5 mm in thickness were cut off the medial end using a fret-saw (6 teeth cm^{-1}) or a Buehler low-speed Isomet saw (www.buehler.com) with a 12·7 cm, diamond wafering blade. Spines sections were immersed in 95% ethanol, soaked for ≥10 min to clear, and then read with a Wild Stereo dissecting microscope using transmitted light under variable magnifications. Based on Cuerrier (1951), a pair of translucent and opaque rings indicates one year of growth and total age was based on the number of translucent annuli present in a transverse section. If the age ring at the edge of the spine section was only partially formed (samples were obtained during the season of growth) age was assigned to the next year.

The fin spine sections were read independently by two readers. If there were discrepancies between the assigned ages readers would confer until a consensus was reached. When fin rays were unreadable or an agreement could not be reached the data were not used. Age-frequency plots used a 1 year increment. Ages were pooled for analysis since sex of *A. oxyrinchus* cannot be distinguished accurately using external morphology (Dadswell, 2006).

GROWTH

The observed, annual growth increment for unsexed, tagged *A. oxyrinchus* was determined from the initial sampling L_F and recapture L_F for individuals recaptured in Minas Basin after at least 1 year at large. Minas Basin tagged individuals recovered in the Saint John River spawning run after one or more years at large were used to determine annual growth increments for sexed *A. oxyrinchus.*

A von Bertalanffy growth model (Ricker, 1975) was fitted to the Minas Basin pooled length-age data using: $L_t = L_\infty\ [1 - e^{-K(t-t_0)}]$, where L_t is the fork length of the fish in cm at time t, L_∞ is the asymptotic length, K is the Brody growth coefficient, t is the age in years and t_0 is the age in years at length equal to zero if the fish had always grown according to the von Bertalanffy model.

MORTALITY ESTIMATES

Total instantaneous mortality (Z) for the annual aggregation of *A. oxyrinchus* in Minas Basin was estimated using a plot of ln transformed number of individuals per year class by age (Ricker, 1975) where: $Z = -\ (\ln N_{t2} - \ln N_{t1})\,(t_2 - t_1)^{-1}$, where N_{t2} is the number of age t_2, N_{t1} is the number of age t_1 and $t_2 - t_1$ is the period in years between the two age groups. A slope was generated by this analysis representing Z for the age distribution of 21–54 years. Annual mortality rate (A) was acquired from estimated total instantaneous mortality using: $A = 1 - e^{-Z}$ (Ricker, 1975). For comparison a second mortality estimate was calculated by combining the results from the von Bertalanffy growth equation with a Beverton-Holt instantaneous mortality equation to estimate Z (Gedamke & Hoenig, 2006) as: $Z = K\ (L_\infty - L_x)\ (L_x - L_c)^{-1}$, where K is the Brody growth coefficient, L_∞ is the asymptotic length, L_c is the smallest size when *A. oxyrinchus* were vulnerable to fishing and L_x is the mean length of the fish sampled that were larger than L_c.

TABLE I. Annual and total numbers and percentages of *Acipenser oxyrinchus* marked in Minas Basin and recaptured in the basin during the same or subsequent years, 2004–2015. Recoveries include those from fishers where total catch is unknown, but those returns were not included in population estimates. For number of fish marked each year see Table III

Year marked	Year recaptured in Minas Basin												
	2004	2005	2007	2008	2009	2010	2011	2012	2013	2014	2015	Total	%
2004	0	0	0	1	0	0	0	0	0	0	0	1	4·2
2005		0	0	1	0	0	0	0	1	0	0	2	20·0
2007			2	6	1	0	0	0	0	0	1	10	8·3
2008				9	2	1	3	5	5	7	5	37	9·0
2009					0	0	2	1	1	1	1	6	14·6
2010						0	0	2	1	1	2	6	10·5
2011							0	0	5	2	2	9	10·5
2012								2	4	1	2	9	11·8
2013									5	12	14	31	8·3
2014										0	6	6	6·5
Total	0	0	2	17	3	1	5	10	22	24	33	117	8·0

POPULATION ESTIMATES

Population estimates for the *A. oxyrinchus* aggregation in Minas Basin were determined using two mark-recapture methods. The modified Schnabel method uses multiple censuses and was developed to assess closed populations (Ricker, 1975). The adjusted Peterson model uses a single census, but can group data over long sampling periods (Ricker, 1975). Recaptures of migrants were not considered valid unless they had been at large for 15 days to allow random mixing into the population.

The modified Schnabel estimate for a closed population is a very robust statistical method and provides an estimate of population size (N) from: $N = \Sigma(C_t M_t)(R_t + 1)^{-1}$, 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 fish already marked when caught in sample t. Since the fraction of the total population caught in each sample ($C_t N^{-1}$) and the fraction of the total population already marked ($M_t N^{-1}$) were always <0·1, modified Schnabel 95% C.I. were calculated as: $N = \pm\sum C_t M_t X^{-1}$, Where X = Poisson value at $t = 0{\cdot}05$ for the d.f. (*i.e.* number of recaptures; Krebs, 1989). The upper and lower confidence intervals were usually not symmetrical around N because there were < 50 recaptures except for the 2013 to 2015 estimates.

A Schnabel estimate was considered appropriate for this study based on external tag returns and acoustic tag information (M. J. W. Stokesbury & M. J. Dadswell, unpubl. data). When *A. oxyrinchus* enter Minas Basin each year they remain in the cul-de-sac from May to October (*i.e.* a closed population) and individual capture events over the sampling season from trawler or weir represented random censuses. The Schnabel model over multiple years was chosen since each year the aggregation consists largely of migrants from the Saint John and Kennebec River populations (99%; Wirgin *et al.*, 2012; I. Wirgin, unpubl. data) and because there was a high and consistent rate of annual returns for individuals externally (Table I) or acoustically tagged in the Basin in previous years (mean ± S.D. annual acoustic returns = 77 ± 12%; M. J. W. Stokesbury & M. J. Dadswell, unpubl. data). Observed tag losses and marked individuals that were taken in the Saint John commercial fishery and processed were subtracted from fish at large.

An adjusted Petersen model was used twice to estimate the aggregation size in 2014 and 2015 for comparison to the modified Schnabel estimates. There were enough recaptures of 2013 tags during 2014 and 2015 to obtain valid estimates. It was assumed that since mortality was low and there was a record of tagged fish removed in the commercial fishery in the Saint John River (no 2013 tagged fish) the estimate was justified. The adjusted Petersen model provides an estimate of population size:

$$N = (C + 1)(M + 1)(R + 1)^{-1},$$

where C is the total number caught in 2014 or 2015, M is the number tagged in 2013 and R is the number of 2013 marked individuals recaptured in 2014 or 2015. Confidence intervals were determined by treating R as a Poisson distribution and calculated directly using the Appendix II table from Ricker (1975).

RESULTS

COLLECTION

During 2004 and 2005 *A. oxyrinchus* were captured while researchers were deployed on board the fishing trawler *Terri and Sandy* to study the commercial fishing catches in Minas Basin. The directed study on *A .oxyrinchus* captured by fish weir and by trawler began in 2007 and continued annually until 2015. A total of 1674 sampling trips were made during 2007–2015 to four weirs (Fig. 1). The Five Islands weir was visited every year, the Economy weir during 2013–2015, the Walton weir during 2008 and 2009 and the Bramber weir during 2013–2015. A total of 3932 *A. oxyrinchus* were caught in the weirs (Table II). During 2004–2015 a total of 51 trips were made with the *Terri and Sandy* and 461 individuals were captured (Table II). Of *A. oxyrinchus* captured during 2004–2015, 1453 were tagged and sampled (Table III).

The earliest *A. oxyrinchus* were captured in Minas Basin weirs was generally late-May (Fig. 2) although the weirs were installed and fishing by mid-April. One individual was caught on 20 April 2008 (W. Linkletter, pers. comm.) and another on April 24, 2013, but these were rare occurrences. Migrants were abundant in the weirs until July or August depending on the year and in some years were captured until late October (Fig. 2). Fish were not taken with the trawler before 1 June since that was the start date of the trawler season. The latest fish were caught with the trawler was mid-September (Fig. 3).

Daily catches of *A. oxyrinchus* in the weirs ranged from one to 63 individuals (Fig. 2). Annual catches in weirs were highly variable among years and among weirs. Total catch in the Five Islands weir ranged from 29 in 2009 to 188 in 2014, in the Economy weir from 103 in 2013 to 1393 in 2015 and in the Walton weir from 694 in 2008 to 46 in 2009. During 2008 only 45 *A. oxyrinchus* were taken in the Five Islands weir and 133 at the Economy weir (W. Linkletter, pers. comm.), while 694 were taken at Walton (Fig 2). Catches with the trawler ranged from one to 16 a tow with total daily catches seldom exceeding 30 (Fig. 3).

LENGTH, MASS AND AGE

Acipenser oxyrinchus sampled in Minas Basin ranged from 458 to 2670 mm L_F (Fig. 4). Between 2007 and 2010 fish of 1000–1499 mm L_F made up the majority (57%), followed by fish of 1500–1799 mm L_F (30%). The smallest size class 400–999 mm L_F represented 9% of sampled fish and the largest size class (≥1800 mm) represented the least (4%). During 2011–2015 length distribution was: 400–999 mm, 10%, 1000–1499 mm, 69%, 1500–1799 mm, 17% and >1800, 4%.

TABLE II. Sampling effort, sampling periods and catches (n) of *Acipenser oxyrinchus* in intertidal fish weirs and by a trawler in Minas Basin 2004–2015

	Weir			Trawl			
Year	Trips	Period	Catch (n)	Trips	Period	Catch (n)	Total catch (n)
2004	0	–	–	12	1 June – 5 September	39	39
2005	0	–	–	4	5 July – 2 September	18	18
2007	144	7 June – 30 August	65	6	24 July – 28 August	79	144
2008	196	17 May – 30 August	739	3	22 July – 28 August	20	759
2009	148	25 May – 30 August	79	0	–	–	79
2010	90	15 May – 30 August	117	6	17 August – 7 September	30	147
2011	36	2 June – 19 June	16	6	22 June – 11 August	73	89
2012	38	29 May – 14 June	17	4	22 August – 16 September	77	94
2013	312	24 April – 31 October	322	7	18 June – 14 September	101	423
2014	348	15 May – 13 November	949	0	–	–	949
2015	362	8 May – 12 September	1628	3	8 June – 25 August	24	1652
Total	1674		3932	51		461	4393

Mean ± S.D. L_F of *A. oxyrinchus* captured during 2007–2010 by weirs was 1366 ± 263 mm and by trawler, 1326 ± 180 mm (Fig. 5). When compared there was no significant difference between L_F taken by the two collection methods (Z-test, $Z = 0{\cdot}068$, $P < 0{\cdot}05$). The range in L_F was greater among fish captured by weirs, 458–2670 mm, compared to 850–2140 mm for the trawler.

Mean ± S.D. L_F of *A. oxyrinchus* sampled in Minas Basin during 2007 was 1291 ± 278 mm, 2008 was 1405 ± 284 mm, 2009 was 1187 ± 205 mm and 2010

TABLE III. Annual captures (C_t), marked (M), marked at large (M_t) and recaptures (R_t) of *Acipenser oxyrinchus* in Minas Basin (2004–2015) and the modified Schnabel estimate for 2015. Individuals must be at large > 15 days after marking for random mixing in the population (Ricker, 1975). Removals were observed or from the Saint John River commercial fishery

Year	C_t	M	R_t	Removals	M_t	C_tM_t
2004	39	24	0	0	0	0
2005	18	10	0	0	24	432
2007	144	121	2	0	34	4896
2008	759	412	17	0	155	117 645
2009	79	41	2	2	567	44 793
2010	147	57	2	0	608	89 002
2011	89	86	3	1	665	59 007
2012	94	76	4	5	751	70 500
2013	423	374	21	6	822	347 283
2014	949	92	24	5	1190	1 128 361
2015	1652	160	30	3	1277	2 107 952
Sums	4393	1453	105	22	–	3 969 871

Modified Schnabel Estimate (2004–2015):
$N = \Sigma C_tM_t(\Sigma R_t + 1)^{-1} = 3\,969\,871(106)^{-1} = 37\,452$ (95% C.I. 31 259–45 789); valid.

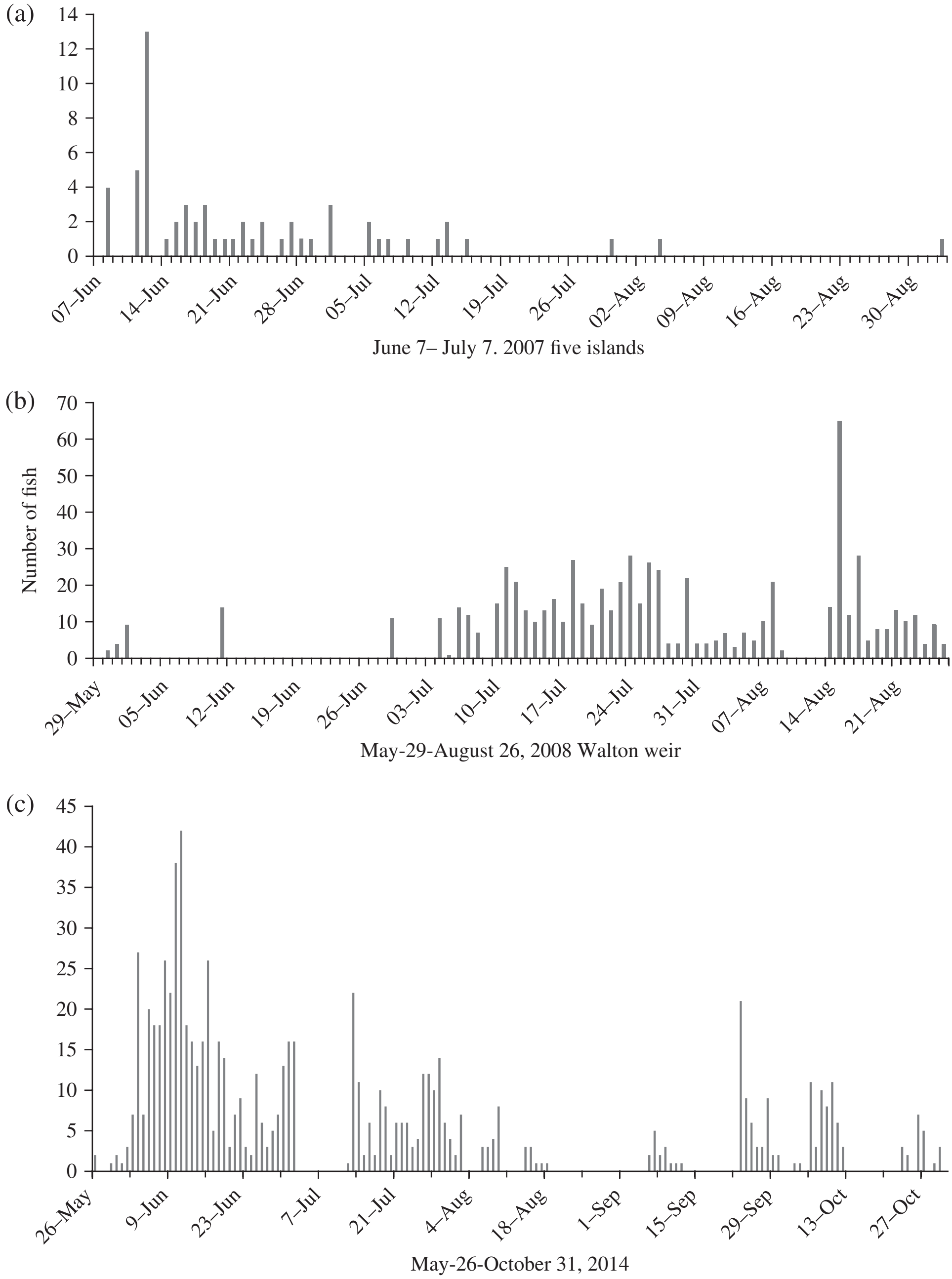

FIG. 2. Number of *Acipenser oxyrinchus* caught daily in Minas Basin, Nova Scotia, at (a) Five Islands weir during 2007 (*n* 45), (b) Walton weir during 2008 ($n = 694$) and (c) Economy weir during 2014 ($n = 791$). Note the different scales.

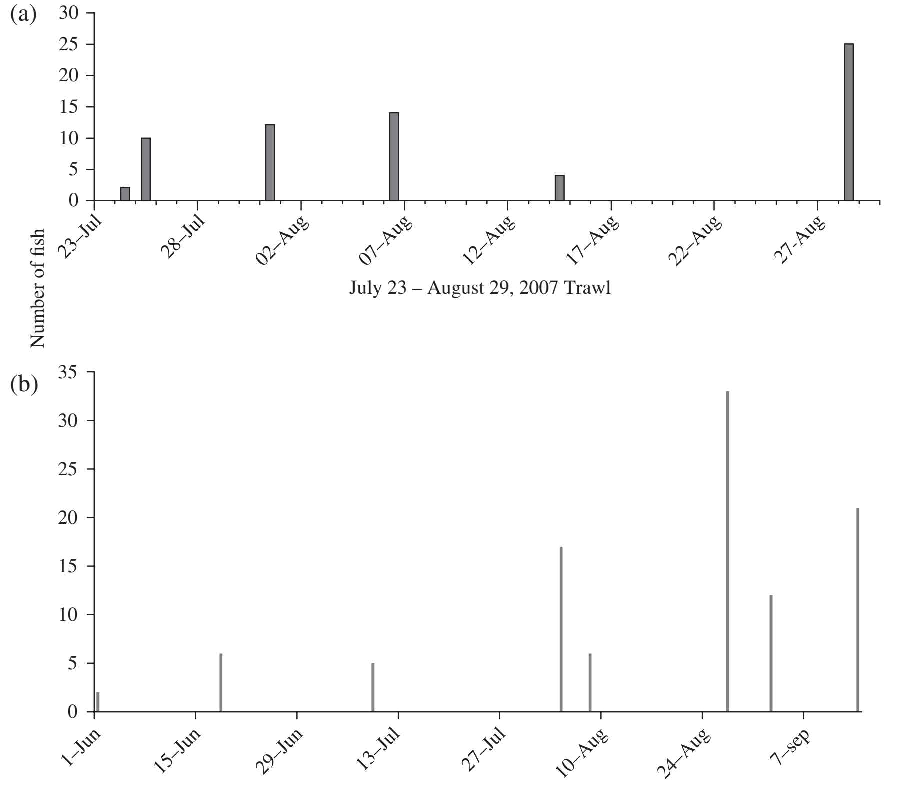

FIG. 3. Number of A*cipenser oxyrinchus* caught daily in Minas Basin, Nova Scotia, with the trawler (a) during 2007 ($n = 75$) and (b) during 2013 ($n = 92$).

was 1265 ± 267 mm (Fig. 6). When the annual mean L_F of sampled fish was compared among years (Tukey test with Holm's correction), those caught in 2008 were found to be significantly larger than those caught in 2007 ($T = -4{\cdot}01$, $P < 0{\cdot}001$), 2009 ($T = -4{\cdot}19$, $P < 0{\cdot}001$), and 2010 ($T = -4{\cdot}30$, $P < 0{\cdot}001$). There was no significant difference in L_F between the years 2007, 2009 and 2010 (ANOVA, $F_{3,218} = 2{\cdot}14$, $P > 0{\cdot}05$).

Mass (M) was obtained for 330 *A. oxyrinchus* captured during 2007–2010. The smallest fish weighed 0·5 kg, the largest, 50 kg. Mean ± S.D. M was 23·5 ± 6·1 kg. The resulting mass and length relationship for fish ≤ 50 kg was $\log_{10}M = 3{\cdot}32 \log_{10}L_F - 5{\cdot}71$ ($r^2 = 0{\cdot}949$). The spring scale used during this period had a maximum capacity of 50 kg and limited the L_F of individuals weighed to ≤1760 mm. The few larger individuals (>1800 mm) weighed during 2011–2015 were between 52 and 58 kg.

During 2005–2009 a total of 299 fin spines were collected and aged. The youngest *A. oxyrinchus* caught was aged 4 years and the oldest was estimated to be 54 years (Fig. 7). Of *A. oxyrinchus* sampled 85% were < 26 years.

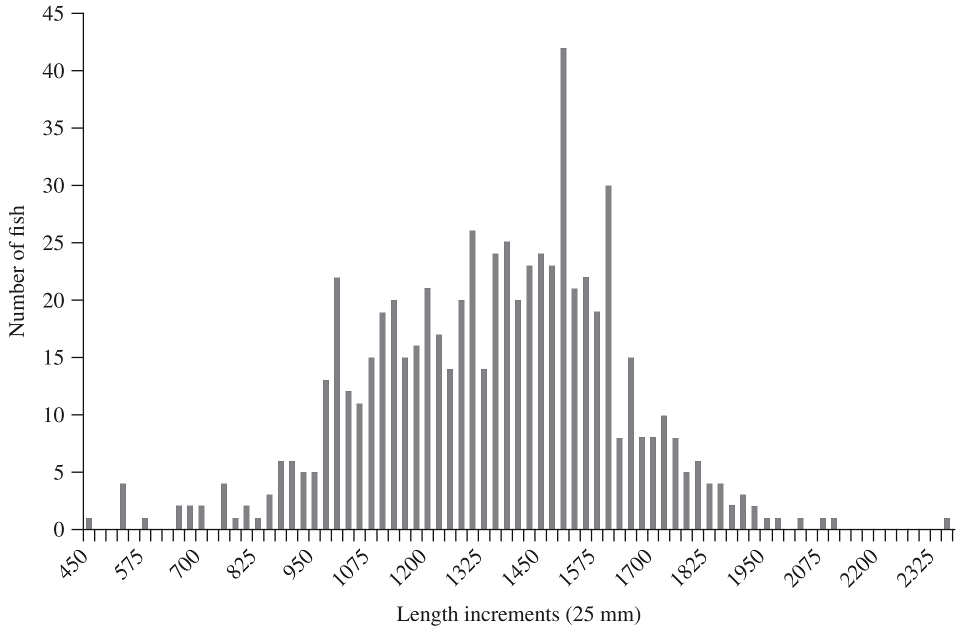

FIG. 4. Number of *Acipenser oxyrinchus* by 25 mm increments in fork length caught by trawler and weir in Minas Basin, Nova Scotia, during 2007–2010.

GROWTH

A total of 59 unsexed *A. oxyrinchus* sampled and tagged in Minas Basin were recaptured during 2007–2015 when researchers were present and fish re-measured. Since capture and measuring were done by numerous persons the length data were converted to cm to adjust for sampling inaccuracies. No fish at large <1 year were included in the analysis to avoid handling and tagging effects on growth (Ricker, 1975). Growth from size at release was analysed in 10 cm size classes (Table IV).

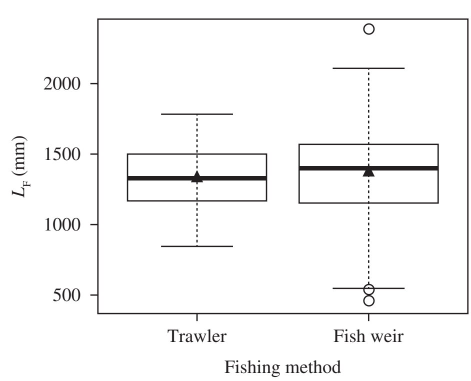

FIG. 5. Box plot of fork length (L_F) of *Acipenser oxyrinchus* caught in Minas Basin, Nova Scotia, by trawler and weir during 2007–2010. ▲, mean; ___, median; the boxes are the 25% to 75% quartile; ¦, range; ○, outliers.

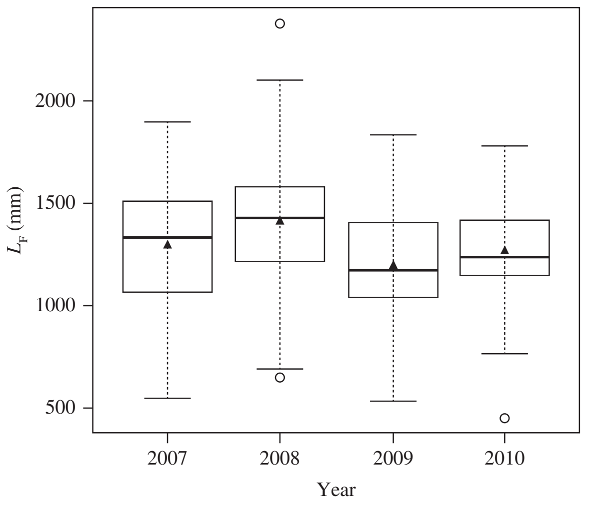

FIG. 6. Annual box plots of fork length (L_F) of *Acipenser oxyrinchus* caught in Minas Basin, Nova Scotia, by trawler and weir during 2007–2010. ▲, mean; ___, median; the boxes are the 25% to 75% quartile; ⁞, range; ○, outliers.

Greatest observed growth was for one *A. oxyrinchus*, 148 cm L_F at release, which grew 22 cm after 8 years at large. Mean ± S.D. growth between release and recapture varied with size class from 13·4 ± 5·9 cm among 90–99 cm L_F fish to *c.* 9 cm in the 130–170 cm size classes (Table IV). Mean ± S.D. time at large for the 10 cm size classes varied between 2·3 ± 1·7 and 5·1 ± 1·9 years and mean ± S.D. for annual growth increment from 2·07 ± 0·63 to 3·94 ± 2·35 cm. In general individuals in smaller size classes had a greater annual increment than larger size classes (Table IV).

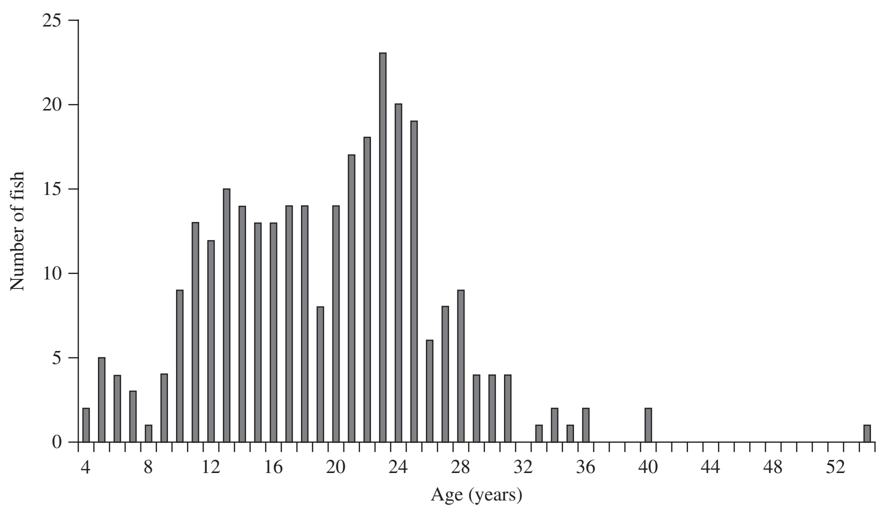

FIG. 7. Number of sampled *Acipenser oxyrinchus* in each age class that were caught by trawler and weir in Minas Basin, Nova Scotia, during 2005–2009.

TABLE IV. Mean ± S.D. for fork length (L_F) at release and recapture, growth, time at large and annual growth by 10 cm size classes of *Acipenser oxyrinchus* tagged and recaptured in Minas Basin (2004–2015). Sex is unknown. Individuals at large < 1 year were not included to avoid handling and tagging effects on growth (Ricker, 1975)

Size class L_F (cm)	n	Release L_F (cm)	Recapture L_F (cm)	Growth (cm)	At large (years)	Mean growth (cm year^{-1})
90–99	9	94·4 ± 3·1	107·8 ± 7·5	13·4 ± 5·9	3·4 ± 1·9	3·94 ± 2·35
100–109	5	105·8 ± 4·1	116·8 ± 6·1	11·0 ± 6·5	3·8 ± 1·9	2·89 ± 0·44
110–119	8	112·4 ± 2·5	120·2 ± 3·9	7·8 ± 2·5	3·3 ± 1·0	2·36 ± 0·51
120–129	7	124·3 ± 2·7	130·5 ± 6·1	6·2 ± 4·6	2·3 ± 1·7	2·69 ± 1·97
130–139	2	135·0 ± 4·2	141·5 ± 2·1	6·5 ± 2·1	4·8 ± 0·2	2·32 ± 0·60
140–149	9	145·6 ± 2·5	157·3 ± 7·5	11·7 ± 6·7	5·1 ± 1·9	2·25 ± 1·01
150–159	10	153·4 ± 2·0	163·9 ± 4·6	10·5 ± 5·5	4·6 ± 1·7	2·28 ± 1·21
160–169	4	166·0 ± 3·5	174·7 ± 6·7	8·7 ± 3·2	4·2 ± 1·3	2·07 ± 0·63
170–179	5	173·7 ± 2·1	182·8 ± 4·4	9·1 ± 3·4	3·9 ± 1·7	2·33 ± 0·85

A total of 26 *A. oxyrinchus* tagged in Minas Basin were recaptured in the Saint John River and measured after 2–8 years at large. These fish were ripe adults and their sex was determined by biopsy probe or when they were processed (16 males and 10 females; Table V). Mean ± S.D. male L_F was 151·6 ± 9·9 cm when tagged and released in Minas Basin and 159·7 ± 8·6 cm when recaptured in the Saint John. Mean ± S.D. female L_F was 167·9 ± 11·7 cm when tagged and 181·1 ± 7·3 cm when captured during their spawning run. Mean ± S.D. growth of males between release and recapture was 8·1 ± 5·6 cm and for females 13·2 ± 4·9 cm. Mean ± S.D. time-at-large for males was 4·6 ± 1·6 years and for females, 5·2 ± 1·6 years. Mean ± S.D. annual growth rate for males was 1·76 ± 0·78 cm and for females, 2·53 ± 0·49 cm. Mature females grew significantly faster than mature males (t-test, $P < 0·05$). The Von Bertalanffy growth model for Minas Basin fish calculated using L_F (cm) at age (years) was $L_t = 520·9$ $[1 - e^{-0·010(t-9·76)}]$. The asymptotic L_F was 520·9 cm and the Brody growth coefficient was 0·010.

MORTALITY

Since year classes appeared to be recruiting to the aggregation of *A. oxyrinchus* in Minas Basin until 20 years of age (Fig. 7) a mortality estimate was confined to older fish. For *A. oxyrinchus* 21–54 years old, total instantaneous mortality was 0·115 ($r^2 = 0·68$; Fig. 8) and annual mortality 10·9%. The Berverton-Holt model produced $Z = 0·100$, with $A = 9·5\%$.

POPULATION ESTIMATES

Acipenser oxyrinchus marked from 2004 to 2015 were recaptured during the same and following years (Table I). Two recaptured individuals had retained their dart tag for 8 years, six for 7 years and nine others for 6 years. Tag retention appeared to be excellent since only two fish with a tag wound from a lost tag and one which retained only its PIT tag were observed (0·2% loss). Four tags were removed by fishers and returned. Three

TABLE V. Mean ± S.D. for fork length (L_F) at release and recapture, growth, years at large and annual growth increment for male ($n = 16$) and female ($n = 10$) *Acipenser oxyrinchus* tagged in Minas Basin and recaptured in the Saint John River, New Brunswick during the annual spawning run

	Release L_F (cm)	Recapture L_F (cm)	Growth (cm)	At large (years)	Mean increment (cm year^{-1})
Male	151·6 ± 9·9	159·7 ± 8·6	8·1 ± 5·6	4·6 ± 1·6	1·76 ± 0·78
Range	125–161	145–175	2–19	3–7	0·25–3·60
Female	167·9 ± 11·7	181·1 ± 7·3	13·2 ± 4·9	5·2 ± 1·6	2·54 ± 0·49
Range	148–184	168–188	7–22	2–8	1·62–2·75

recaptured fish had broken tags and their numbers lost. Of 26 *A. oxyrinchus* marked in Minas Basin and captured in the Saint John commercial fishery 12 were processed and the remainder released alive. All removed, broken and harvested tags were considered as removals (Table III).

In total, 105 *A. oxyrinchus* were recaptured during 2007–2015 after being at large > 15 days and when total catch data were available and could be used in population estimates (Table III). A modified Schnabel, single-year estimate for the 2008 aggregation in Minas Basin was 8804 (95% C.I. 4 108–15 443) and for 2013, 9244 (95% C.I. 4962–28 154; Table VI). Both estimates were valid (Ricker, 1975).

Valid, multi-year modified Schnabel estimates for at-sea *A. oxyrinchus* that utilized Minas Basin ranged from 10 699 in 2010 to 37 452 in 2015 (Table VII). A valid, adjusted Petersen population estimate for 2014 using fish marked in 2013 and recaptured in 2014 was 27 403 (95% C.I. 15 975–51 630). For fish marked in 2013 and recaptured in 2015 the valid estimate was 41 325 (95% C.I. 26 366–74 415).

Although year-to-year weir catches tended to be variable a considerable increase in the number of *A. oxyrinchus* caught in weirs over the period of the study was also apparent (Table II). During 2007–2010 the mean ± S.D. annual weir catch was 250·0 ± 326·7, whereas during 2013–2015 the mean ± S.D. annual catch increased to 966·5 ± 653·2.

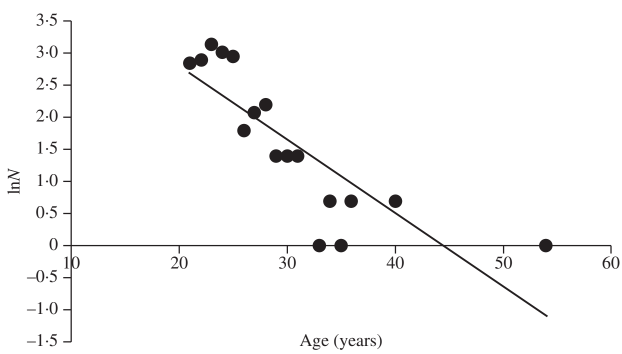

FIG. 8. Plot of the ln number (ln*N*) of *Acipenser oxyrinchus* at age sampled from Minas Basin, Nova Scotia. The slope describes a total instantaneous mortality of $Z = 0·115$ for ages 21–54 years: $y = -0·1149x + 5·0949$ ($r^2 = 0·6820$, $P < 0·05$).

TABLE VI. Single year, modified Schnabel estimates for the Minas Basin aggregation of *Acipenser oxyrinchus* during 2008 and 2013, following Ricker (1975): C_t, catch at time t, R_t, recaptures at time t, M, marked at time t and M_t, marked and at large at time t. N is the population estimate, L and U represent the 95% C.I. Individuals must be at large greater than 15 days to be considered randomly mixed in the population

Month	C_t	R_t	M	M_t	C_tM_t	N	L	U
2008								
May	8	0	8	0	0			
June	33	1	33	8	264			
July	461	5	227	41	18 901			
August	257	3	144	268	68 876			
Sum	759	9	412		88 041	8804	4108	15 443
2013								
May	69	0	52	0	0			
June	157	2	130	52	8164			
July	102	1	99	182	18 564			
August	61	1	60	281	17 141			
September	34	1	33	341	11 594			
Sum	423	5	374	–	55 463	9244	4962	28 154

MOVEMENT

Acipenser oxyrinchus tagged in the Five Islands weir were recaptured later in the same year at either Economy, Walton or Bramber weirs or in the Southern Bight by trawler. Migrants tagged in the Economy weir were recaptured later in the same year in the Bramber weir or by trawler. Migrants tagged in the Walton and Bramber weirs were recaptured later in the same year by trawler. During the 12 years of this study no *A. oxyrinchus* tagged along the southern shore of Minas Basin were recaptured along the northern shore in the same year as marking.

Four *A. oxyrinchus* tagged at the Five Islands weir were recaptured at Economy weir during the same year, a mean ± S.D. of 12·0 ± 1·3 days after release and movement along

TABLE VII. Multi-year modified Schnabel estimates for the at-sea population of *Acipenser oxyrinchus* contributing to the annual Minas Basin aggregation (2010–2015) and adjusted Petersen estimates for 2014 and 2015. All estimates were valid

Year	Captures $\sum C_t$	Marked $\sum M$	Recaptures $\sum R_t$	N	95% C.I.
Schnabel					
2010	1186	665	23	10 699	7393–16 982
2013	1665	1199	51	14 106	10 940–18 930
2014	2741	1293	75	24 498	19 808–31 149
2015	4393	1453	105	37 452	31 259–45 789
Petersen					
2014	949	374	12	27 403	15 975–51 360
2015	1652	374	14	41 325	26 366–74 415

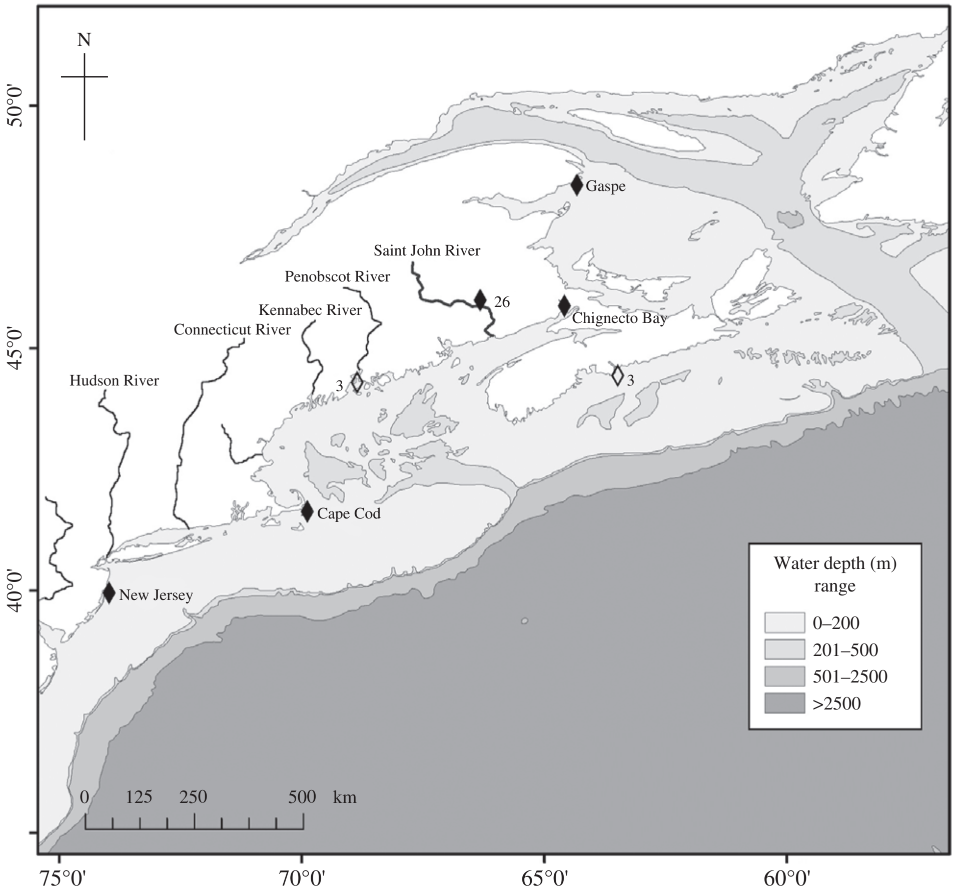

FIG. 9. Long distance recovery locations off the east coast of North America for *Acipenser oxyrinchus* that were marked in Minas Basin, Nova Scotia, during 2004–2015. ◆, external Floy tag returns; ◇, acoustic tag detections. Numbers beside the symbols represent the number of returns from that site if there was more than one.

the north shore of the Basin was *c.* 1·2 km day^{-1}. Similarly, four migrants tagged at Walton or Bramber weirs on the southern shore were recaptured by trawler during the same year in the Southern Bight after a mean ± S.D. of 32·0 ± 4·6 days and had again moved *c.* 1·2 km day^{-1}. Three fish tagged at Five Islands weir were recaptured by trawler in the Southern Bight during the same year after a mean ± S.D. of 63·0 ± 15·4 days. The longest period between marking and recapture during the same year was 108 days.

In general, movement of *A. oxyrinchus* in Minas Basin was in a clockwise direction from north to south then west. Conversely, in some years, individuals appeared to remain in the Central Basin for extended periods. During 2008 seven individuals tagged in the Walton weir were recaptured at Walton after 10–49 days at large and during 2014 fish remained around the Economy weir until late October (Fig. 2).

Marked *A. oxyrinchus* were reported from outside Minas Basin (Fig. 9). One was recaptured in Chignecto Bay, iBoF. Three were acoustically detected off eastern Nova Scotia and three off Penobscot Bay, ME (M.J.W. Stokesbury & M. J. Dadswell, unpubl.

data). The most southern recapture was 13 km offshore of Seaside, NJ, 5 years after tagging and an at-sea straight line distance (SLD) of 1300 km. The most northern, off Grande Rivière, Gaspé, Quebec, after 4 years at large and an at-sea SLD of 1440 km. As of 2015, 26 *A. oxyrinchus* tagged in the Minas Basin were caught in the Saint John River commercial fishery.

Recovery of marked *A. oxyrinchus* in Minas Basin from other locations indicated numerous stocks contributed to the annual aggregation. These included one each from the Connecticut and Merrimac Rivers, three from the Penobscot River, three from the Hudson River, 22 from the Saint John River and nine with acoustic tags from the Kennebec River, which were detected by acoustic receivers in Minas Basin (G. Wippelhauser, pers. com.). A female that was tagged on the spawning grounds in the Hudson River during 1994 was recaptured in a basin weir during 2015 after 21 years at large (M. Mangold, pers. comm.).

DISCUSSION

Over the course of 12 years 1453 *A. oxyrinchus* were marked and sampled. Annual effort and the number of fish marked each year fluctuated with 2008 and 412 tagged, the most successful season. That year an unusually large number of migrants (694) were caught in the Walton weir, an occurrence never before experienced by the weir fisher (R. Wilcox, pers. comm.). It is unclear why *A. oxyrinchus* were so abundant at Walton during 2008, but even larger catches of 791 and 1393 individuals occurred in the Economy weir during 2014 and 2015, respectively. Migrants occurred in the Basin from May to October, but in some years a few were observed as early as April and as late as November. Peak abundance was from June to September.

The method of sampling *A. oxyrinchus* in fishing weirs and by trawler was different from the gillnets used in other studies (Kahnle *et al.*, 2007; Balazik *et al.*, 2012*b*). Weir fishing is a passive method, relying on the fishes being caught behind the weir on the receding tide. Weirs were not size selective for *A. oxrinchus*, since none could pass through the 2·5 cm weir mesh. During this study, weirs captured the smallest and largest individuals. Alternatively, the 140 mm trawl net mesh was probably large enough to allow small individuals to escape and very large individuals were powerful enough to break through the twine (G. Travis, pers. comm.). Because of the non-selective nature of the weirs, and the similarity of length between weir and trawl catches, however, the characterization of the length and age of *A. oxyrinchus* from the aggregation in Minas Basin is probably unbiased.

Acipenser oxyrinchus sampled in the Minas Basin aggregation had a relatively extensive length and age distribution ranging from 458 to 2670 mm L_F and 4 to 54 years. In Canadian rivers, *A. oxyrinchus* tend to mature at larger size and older age than those from southern stocks, 150 cm L_F and 16–24 years of age for males and 180 cm L_F and 27–28 years of age for females (Magnin, 1964; Dadswell, 2006), which means the Basin aggregation was predominately juvenile fish, but also contained maturing adults and adults. Age of sampled *A. oxyrinchus* confirms this conclusion since 85·0% were ≤ 26 years old, and 36·1% were ≤ 16 years. Both the length and age frequency of *A. oxyrinchus* in the Minas Basin aggregation exhibited a steep decline among larger and older fish, which was probably due to mature individuals returning to their natal rivers to spawn and adults utilizing other marine regions. After spawning some adult fish eventually do return to the Basin because there were 22 returns from Minas Basin out of 1106 *A. oxyrinchus* tagged in the Saint John River spawning run since 2009 (C. Ceapa, unpubl. data). Since, however, 90% of the spawning run in the Saint John River consists of *A. oxyrinchus* > 25 years old and 180 cm L_F (DFO, 2013*a*), low abundance of adults in Minas Basin suggests that they probably go elsewhere when at sea. Explanation for this observation may include a change in ocean migration caused by selection of cooler temperatures among older individuals, which is common among fishes (McCauley & Huggins, 1979). It may also be because of prey preferences. *Acipenser oxyrinchus* captured on the Scotian Shelf were often feeding on sand lance *Ammodytes* sp. (Scott & Scott, 1988), a prey item never reported in *A. oxyrinchus* stomachs from Minas Basin (McLean *et al.*, 2013).

Northern populations of *A. oxyrinchus* are known to migrate to sea from estuaries at sizes of 80 cm - 120 cm L_F and an age of *c.* 10 years (Bain, 1997; Smith & Clugston, 1997; Dadswell, 2006). During the present study, however, 33 individuals were caught in Minas Basin that were ≤ 80 cm L_F and 28 aged from 4 to 10 years. It is unlikely that these small juveniles emigrated from the nearest documented spawning rivers, the Saint John and Annapolis Rivers (Dadswell, 2006), which are both an at-sea SLD of *c.* 150 km away. Possibly after exiting nearby rivers these small juveniles were utilizing the Basin as a nursery. Wirgin *et al.* (2012) proposed that the smaller *A. oxyrinchus* (<100 cm L_F, $n = 10$) in their study, which they genetically assigned to the Saint John, may have had an origin in the inner Bay of Fundy rivers, but they did not have necessary genetic samples to make the comparisons.

The mass and length relationship determined for *A. oxyrinchus* from Minas Basin that were ≤ 50 kg was $\log_{10}M = 3{\cdot}32 \log_{10}L_F - 5{\cdot}71$ and was similar to relationships found in studies of other northern populations (Caron *et al.*, 2002; DFO, 2013*a*). The condition factor ($b = 3{\cdot}32$) suggests that *A. oxyrinchus* in the Basin aggregation were in excellent health.

Observed growth of *A. oxyrinchus* in Minas Basin indicated larger juveniles (>100 cm) and maturing fish (>140 cm) were growing at *c.* 2–4 cm year^{-1}. These growth rates validated the ageing determinations since calculated growth between ages 10 (*c.* 100 cm L_F) and 25 (*c.* 140 cm L_F) years was *c.* 37·5 cm and observed length difference between these two size classes was 40·8 cm. On the other hand, observed mean ± S.D. growth rates of sexed adults recaptured in the Saint John River indicated that once mature, females continued to grow at $2{\cdot}54 \pm 0{\cdot}49$ cm year^{-1}, but male growth slowed significantly to $1{\cdot}76 \pm 0{\cdot}78$ cm year^{-1}.

When compared to length at age data for *A. oxyrinchus* over its distribution range, fish sampled in Minas Basin clearly exhibited characteristics of northern stocks; since as the river of origin increases with latitude, the growth rate of this species declines (Bain, 1997; Sulak & Clugston, 1999; Stewart *et al.*, 2015). Calculated Von Bertalanffy growth characteristics for Minas Basin *A. oxyrinchus* included L_∞ of 520·9 cm L_F, and K of 0·01. The asymptotic L_F was greater than found in other studies (254–315 cm; Stevenson & Secor, 1999; Johnson *et al.*, 2005; Stewart *et al.*, 2015), but comes close to the largest *A. oxyrinchus* reported from the St Lawrence River ($L_{F\,=}$ 5·3 m; Magnin, 1964), and encompasses the largest caught in the Saint John River ($L_F = 4{\cdot}6$ m; Scott & Scott, 1988). The Brody coefficient for mixed sexes of *A. oxyrinchus* from Minas Basin compares best with growth rates from the St Lawrence ($K = 0{\cdot}3$; Magnin, 1964) and the Saint John Rivers ($K = 0{\cdot}5$; Stewart *et al.*, 2015), but was less than those determined for southern locations (0·09–0·24; Johnson *et al.*, 2005; Kahnle *et al.*, 2007; Balazik *et al.*, 2012*b*).

Instantaneous total mortality of *A. oxyrinchus* from the Minas Basin aggregation for ages 21–54 was 0·115 using the age-class size model and 0·100 using the Beverton-Holt model. The two estimates are similar although they use different sources of data from the Basin aggregation. Both compare reasonably well with estimates obtained in other studies ($Z = 0·08–0·24$, Hudson River; Kahnle *et al.*, 2007; $Z = 0·12$, St Lawrence River; Verreault & Trencia, 2011). The annual mortality estimate of 9·5–10·9% was among the lower range of reported values for *A. oxyrinchus* and other sturgeon species (Dadswell, 1979; Beamesderfer *et al.*, 2007; Kahnle *et al.*, 2007). Research on Gulf sturgeon (also *A. oxyrinchus*) predicted that an annual mortality rate of 15–21% for some sturgeon stocks would lead to a stable, high density population (Morrow *et al.*, 1998; Pine *et al.*, 2003). Although from southern populations which grow faster and mature earlier, these values for annual mortality are nearly twice those for *A. oxyrinchus* found in Minas Basin, which suggests the Basin aggregation is from healthy, stable populations.

Evidence that individual *A. oxyrinchus* in the annual feeding aggregation use the Basin for >1 year came from recapture of 117 marked fish in subsequent years over the period of the study. Number of recaptures, as would be expected, relied on the number of migrants marked each year and capture effort in subsequent years. During 2008 and 2013, the largest number of *A. oxyrinchus* was tagged and in turn these fish were the most frequently recaptured during following years. The longest period between tagging and recapture was 8 years. One individual was tagged in 2005 and recaptured twice in Minas Basin weirs during 2013, another was tagged in 2007 and recaptured in a weir during 2015.

Valid, modified Schnabel and adjusted Petersen population estimates were calculated for the aggregation of *A. oxyrinchus* in Minas Basin. The single-year Schnabel estimate for 2008 was 8840 fish and was similar to the 2013 estimate of 9244 fish. These population estimates would reflect only the number of migrants that were in the Basin cul-de-sac during a given year. In comparison, the valid, multi-year estimates from the modified Schnabel method for the period 2010–2015 increased from *c.* 10 700 to *c.* 37 500.

Based on tag returns, acoustic detections (Taylor *et al.*, 2016; G. Wipplehauser, pers. comm.) and genetic stock discrimination (Wirgin *et al.,* 2012) it is proposed that multi-year population estimates represent the total number of at-sea juveniles and maturing adults from both the Saint John and Kennebec populations, some of which may be at other marine locations in other years, as well as mature adults that returned to those rivers to spawn during the present study and which may or may not have returned to Minas Basin. The Saint John is known to have an annual spawning run of up to 3000 adults, which are in the river during May–September (DFO, 2013*a*), the same time of year that the aggregation forms in Minas Basin. The multi-year estimates would be larger than single-year estimates since they include all at-sea fish that were available to utilize Minas Basin over the 12 year study period. The multi-year Schnabel estimates were supported by the adjusted Petersen estimates for 2014 and 2015, which gave slightly greater, but similar results to the 2014 and 2015 multi-year Schnabel estimates, a characteristic of the Petersen model noted by Ricker (1975). Additionally, the observed increase in the total at-sea population of *A. oxyrinchus* utilizing Minas

Basin was further confirmed by increasing, annual numbers of individuals captured in weirs during the study period.

Why the *A. oxyrinchus* at-sea population utilizing Minas Basin increased in abundance approximately three-fold between 2010 and 2015 is unclear, but three factors may have played a role. First, the *A. oxyrinchus* stock in the Saint John River was virtually unexploited between 1998 and 2008 because of the lack of a processor (DFO, 2013*a*), which probably led to increased escapement and recruitment. Second, all landing of *A. oxyrinchus* from Canadian, marine waters was prohibited after 2002 (DFO, 2013*b*). And third, the closure of all U.S. fisheries for *A. oxyrinchus* by 1998 (ASSRT, 2007) probably resulted in an increase in recruitment and escapement from U.S. rivers. Since *c.* 39% of *A. oxyrinchus* in Minas Basin are of U.S. origin (Wirgin *et al.*, 2012), increased abundance of U.S. fish in the Basin could be expected after the intervening 17 years. The fact that the proportion of 100–150 cm L_F fish (large juveniles) in the Basin aggregation increased from 57% in 2007–2010 to 69% in 2011–2015 also suggests that increased recruitment was occurring. Over the last 30 years the increase in abundance of *A. oxyrinchus* in Minas Basin has been dramatic. During intensive fish sampling in the same weirs along the north shore of the Basin from 1982 to 1985 (Dadswell *et al.*, 1984; Rulifson *et al.*, 2008), seldom more than one *A. oxyrinchus* was caught a day.

Abundance of *A. oxyrinchus* was greatest along the northern shore of the Basin in spring, then along the southern shore during summer, suggesting the annual run enters predominately along the northern shore during May-June and departs the Basin through the Southern Bight during August to October. A few migrants were captured with the trawler each year in the Southern Bight during June, but catches seldom exceeded four a day whereas catches increased to 30+ a day in August. The annual migration apparently follows the residual current structure in the Basin, where inflow is along the northern shore and outflow along the southern (Greenburg, 1984). In some years, however, migrants appear to remain for an extended period in the Central Basin (2008 and 2014).

Tag recoveries of *A. oxyrinchus* marked in both Minas Basin and the Saint John River indicate there is considerable annual exchange between the two locations. Juvenile and maturing fish appear to utilize the Basin for repeated summers then leave for the Saint John (and probably the Kennebec; Wippelhauser & Squires, 2015) to spawn, sometimes returning to the Basin after a year or more (22 tag returns; C. Ceapa, unpubl. data). One male tagged in Minas Basin during 2005 was recaptured in the Basin again during 2008, and was then captured and released in the Saint John during the 2013 spawning run. Also, a female tagged in Minas Basin during 2013 was recaptured in the Basin in 2014 and harvested from the Saint John during 2015. Additionally, adult *A. oxyrinchus* that were acoustically tagged in the Saint John River during the 2010 spawning run were detected in Minas Basin annually during 2011, 2012 and 2013 (Taylor *et al.,* 2016).

Recoveries of *A. oxyrinchus* marked in Minas Basin again demonstrated the ability of this species to make long distance migrations while at sea (Dadswell 2006). One fish tagged in Minas Basin was recaptured an at-sea SLD of 1300 km off New Jersey, which was similar to the distance moved by the individual marked in the Hudson River during 1994 and recovered in Minas Basin during 2015. Erickson *et al.* (2011) marked an *A. oxyrinchus* on the spawning grounds in the Hudson River with a satellite tag that popped off in Cobequid Bay a year later. Another fish tagged in Minas Basin was recovered from at-sea SLD of 1440 km off Gaspé, Quebec, which was similar to the individual marked in the Saint John River and acoustically detected off Riviere Saint-Jean, Quebec, an at-sea SLD of 1500 km (Taylor *et al.,* 2016). Since *A. oxyrinchus* are able to migrate from Minas Basin or the Saint John River into the Gulf of St Lawrence then they could also migrate in the other direction. Four such *A. oxyrinchus* were marked in the St Lawrence River and later recovered off St Margaret's Bay on the Atlantic side of Nova Scotia (Magnin & Beaulieu, 1960).

The number and source of *A. oxyrinchus* caught in Minas Basin indicate the importance of the inner Bay of Fundy to stocks from north-eastern North America some of which are designated as at risk (NMFS, 2012). Since the present study demonstrated that large *A. oxyrinchus* (>1 m) from these populations utilize Minas Basin as a summer feeding ground and individuals do so for numerous years, their size would make them susceptible to mechanical strikes from in-stream turbines if they are installed in Minas Passage in the future (Dadswell & Rulifson, 1994; Redden *et al.*, 2014). Unfortunately, the potential threat of turbine encounter will repeat with each pass made into or out of the Basin and would extend over many years. Such a situation would probably increase the total mortality for *A. oxyrinchus* on the north-east coast of North America.

In conclusion the present study has established that the annual, feeding aggregation of *A. oxyrinchus* occurs in Minas Basin from May to October and has biological characteristics similar to the northern populations which make up the majority of migrants each year. The single-year population estimates for Minas Basin indicate there is an annual aggregation of *c.* 9000 juvenile, maturing and adult *A. oxyrinchus* in the Basin, the largest marine aggregation known, and multi-year population estimates suggest the size of the at-sea population contributing to the aggregation has been increasing. Finally, returns of tagged *A. oxyrinchus* marked or recovered in Minas Basin confirm earlier genetic analysis that the annual aggregation consists of north-eastern Atlantic coast stocks. New information gained from the present study of the annual feeding aggregation of *A. oxyrinchus* in Minas Basin has substantially increased the knowledge concerning the marine portion of the life-history for this species.

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