Seasonal distribution and movement of juvenile Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*) in the lower Saint John River Basin, New Brunswick, Canada

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Seasonal distribution and movement of juvenile Atlantic sturgeon 
(*Acipenser oxyrinchus oxyrinchus*) in the lower Saint John River Basin, 
New Brunswick, Canada

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**Keywords:** Acoustic telemetry, network analysis, Acipenseridae, movement ecology

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Abstract

Juvenile Atlantic sturgeon movement and distribution varies seasonally within the lower Saint John River Basin. We use acoustic telemetry to track coarse-scale movement and a network-based approach to develop metrics describing distribution and movement patterns of juvenile Atlantic sturgeon tagged in two rivers, the Saint John and Kennebecasis Rivers. We use principal component analysis to develop indices of movement and residency and test for differences among seasons and between fish from each river. Juvenile Atlantic sturgeon exhibit higher residency during summer months compared to winter and spring. Juveniles are primarily concentrated in the brackish waters of the lower river reaches but make movements as far upriver as rkm 88. There was high variation in distribution and movement patterns exhibited by fish tagged in the Kennebecasis River, ranging from single-location occupancy to wide distribution. Three fish left the system during the study, indicating juveniles embark on brief marine excursions. Identifying spatiotemporal distributions of juvenile Atlantic sturgeon in their natal river systems is a crucial step towards identifying critical habitat and informing management decisions for this species.

Introduction
Sturgeon (Acipenseridae) are among the most critically endangered fishes worldwide, with all 27 extant species listed on the International Union for Conservation of Nature (IUCN) Red List (IUCN 2006). Atlantic sturgeon (Acipenser oxyrinchus oxyrinchus) are listed as near threatened and are currently being considered for listing as threatened under the Species at Risk Act in Canada (IUCN 2006; COSEWIC 2015). Although the overall population trend in the United States is reported as increasing, there are mixed results for regional stocks (Patrick and Damon-Randall 2008). Despite uncertainty, there remains a small commercial fishery for Atlantic sturgeon meat and caviar in the Saint John River in New Brunswick, Canada in addition to an active recreational fishery that targets both shortnose and Atlantic sturgeon (DFO 2013).

Historically, there were five rivers in Canada that supported spawning populations (Dadswell 2006); however, the Saint John River is one of only two rivers in Canada known to support an active spawning population presently, the other being the St. Lawrence River. (Taylor and Litvak 2017).

Atlantic sturgeon are anadromous fish with a complex life history, making them difficult to study and especially vulnerable to anthropogenic change (Rochard et al. 1990; Gross et al. 2002). Adults overwinter in mixed stock aggregations in marine environments along the mid-Atlantic coast (Laney et al. 2012; Taylor et al. 2016) and spend spring, summer, and fall foraging in coastal waters (Wirgin et al. 2012; McLean et al. 2013). Pre-spawning adults are known to enter rivers in fall and overwinter downstream of spawning grounds (Dadswell 2006). In their northern range, adult Atlantic sturgeon make spawning migrations to their natal river from May to June depending on water temperature. Adults have an irregular spawning periodicity of between 1 and 5 years, with females spawning every 3 to 5 years and males spawning every 1 to 2 years (Smith 1985; Taylor and Litvak 2017). Juveniles are river-resident and remain in their
natal rivers for between 5 and 15 years, generally migrating to sea as subadults once they reach 80 to 120 cm (Dadswell 2006). Subadults remain in marine environments where they continue to grow until reaching maturity at an estimated size of 150-180 cm fork length, depending on sex (Smith 1985). Both subadult and adult fish are known to make long distance migrations along the Atlantic coast (Dadswell 2006; Erikson et al. 2011; Altenritter et al. 2017). Long lives, complex life history, irregular spawning intervals, and long-distance migrations are characteristic of sturgeon species and contribute to the difficulty of studying sturgeon and the persistence of ecological knowledge gaps.

There has been some investigation into the movement patterns of Atlantic sturgeon in the Bay of Fundy (MacLean et al. 2014; Taylor et al. 2016) but there has been no directed research into that of juveniles in the lower Saint John River basin. Investigations into distribution and movement of Atlantic sturgeon juveniles in the northern extent of their range suggest they prefer habitats near the salt wedge and typically remain within a small aggregation or foraging areas for extended periods in warm months (Hatin et al. 2007; Fernandes et al. 2010; Altenritter et al. 2017). Limited observations of juveniles during winter suggest they may form overwintering aggregations in the brackish waters of the lower basin (Bell 2011).

The goal of this project is to investigate distribution and movement patterns of juvenile Atlantic sturgeon in the lower Saint John River basin. The basin is comprised of two major rivers, the Saint John and Kennebecasis Rivers. We use acoustic telemetry to track coarse-scale movement throughout the basin and test for differences in patterns among seasons and between fish from each river. We also investigate the relationship between movement patterns and fish size. Social hierarchy has been observed in captive-reared Atlantic sturgeon, with larger fish exhibiting agonistic behavior and outcompeting smaller fish for forage (Kynard and Horgan
If this behavior influences movement patterns, it may manifest as a relationship between fish size and movement patterns even at coarser spatial scales. We hypothesized that there would be a positive relationship between fish size and frequency of movements as well as a negative relationship between size and residency. Juvenile Atlantic sturgeon in southern Atlantic states have been observed making more frequent movements during cold-weather months and exhibiting high residency during summer in brackish water near the saltwater interface (Moser and Ross 1995). Similarly, subadult Atlantic sturgeon in the Penobscot River exhibit high residency in mesohaline waters during summer months (Altenritter et al. 2017). We predicted that distribution and movement would be similar between fish tagged in the Sant John and Kennebecasis Rivers but different among seasons, with summer exhibiting the highest residencies and lowest movement frequency.

Materials and Methods

Study area

The Saint John River is one of North America’s longest rivers, stretching from its headwaters in Maine, through Quebec and New Brunswick, and draining into the Bay of Fundy. The lower Saint John River Basin is comprised of two major rivers, the Saint John and Kennebecasis Rivers (Figure 1). The salt wedge extends approximately to river kilometer (rkm) 45 in the Saint John River and in the Kennebecasis River brackish water can be detected as far upriver as the Hammond River confluence at approximately rkm 35 (Metcalf et al. 1976). The upriver portions of both rivers include dynamic channels, marshlands, and lakes. The Saint John River is blocked by the Mactaquac Dam at rkm 138 and this dam is the upriver boundary in this study. The upriver boundary in the Kennebecasis River is approximately at rkm 35; upstream of this point, the channel becomes shallow, marshy, and difficult to navigate.
Fish capture and tagging

We captured juvenile Atlantic sturgeon using 50-m bottom-set gill nets ranging in mesh size from 6 to 15 cm stretch. Soak times ranged from one to two hours depending on site. All sampling was conducted in May and June in both 2015 and 2016. Fishing effort was distributed throughout the river including extensive effort made near rkm 130 and rkm 20 in the Saint John River and rkm 20 in the Kennebecasis River; however, all fish used in this study were captured at three locations in the Saint John (rkm 20 and rkm 39) and Kennebecasis (rkm 32) Rivers (Figure 1). Upon capture, we transferred juvenile sturgeon directly from the net to an on-board holding tank and transported them to shore. We weighed all sturgeon and measured total length (TL), fork length (FL), and girth. We tagged each sturgeon with both a T-bar anchored floy tag and a passive integrated transponder (PIT) tag (Biomark HPT12) for future identification.

Juvenile Atlantic sturgeon that were less than 100 cm TL and in good condition were selected for acoustic tagging. Fish with regular opercular beats able to maintain orientation were determined to be in good condition. Fish were anesthetized with 80 mg/L methane sulfonate (MS-222) buffered 2:1 with sodium bicarbonate (NaHCO₃) in accordance with the Atlantic sturgeon research techniques outlined by NOAA (2010). We used the lowest recommended dosage for minimally invasive procedures to decrease recovery time. Loss of equilibrium typically occurred between 5 and 10 minutes. During the surgical procedure, we placed fish in a v-trough over a holding tank filled with river water and intubated fish using a recirculating system. A 3-cm incision was made ventrally between scutes four and five anterior to pelvic fin insertion to the left of the ventral line. Acoustic tags were sanitized using 90% ethanol, wiped clean, and inserted into the body cavity. The incision was closed with three to four interrupted sutures. When the body cavity wall was sufficiently thick, we used a single suture to secure the
tag internally following the surgical protocol outlined in Crossman et. al. (2013). The surgical procedure typically lasted between three and five minutes. Fish recovered in a holding tank before being released from shore, just downstream of the capture location. Recovery typically took between 10 and 15 minutes.

We tagged a total of 31 Atlantic sturgeon juveniles in 2015 and 2016 using Vemco coded acoustic tags (Table 1); 16 and 15 fish were tagged in the Saint John and Kennebecasis Rivers, respectively. Fish size ranged from 44 to 83 cm fork length (FL) (Figure 2). Tags emitted a signal at a random interval between nominal delay ± (1/2) nominal delay. Tag weight did not exceed the standard 2% of body weight (0.39 ± 0.12%, mean ± SD) (Winter 1983).

Acoustic telemetry

We used 21 Vemco VR2W receivers to passively track coarse-scale juvenile Atlantic sturgeon movement (Figure 1). Receivers were arranged longitudinally throughout the navigable channel and attached to navigational buoys for ease of access. Receiver positions were consistent across years in the Saint John River, with the exception of two receivers added to the Saint John River in 2016 due to a higher concentration of observed movements during active tracking in areas not previously covered. These two additional receivers were placed at rkm 39 and 44. Receivers were deployed as soon as navigational buoys were set and accessible by boat, typically in April. Most receivers were retrieved between mid-November and December, but in 2016 a small array of receivers was left attached to permanent navigational buoys in winter months.

To test detection efficiency, we used a Vemco dummy tag that emits a 69 kHz signal every 10 seconds. We deployed the dummy tag alongside a Vemco VR100 acoustic receiver at 200, 400, 500, 600, 700, 800, and 900 m from the VR2W receiver being tested. The dummy tag was deployed for five minutes at each distance and emitted 22 pings each deployment. The
proportion of pings received by the VR2W receiver was calculated for each distance. The proportion of detected pings was consistently between 75-80% for distances < 700 m and dropped below 50% thereafter. The detection envelope was therefore estimated as 700 m where receivers detected approximately 75% of all pings.

Data Analysis

Locational data were downloaded from receivers and filtered to remove false detections in two stages. First, we removed ghost detections isolated in time using Vemco Vue software. This is any detection without a sequential detection within a one-hour window before or after and does not distinguish between receiver locations. Next, we manually removed any detection isolated in space, or any single detection at a receiver with no sequential detections either before or after at that receiver. These are single detections at one receiver that are not removed by ghost detection filtering because there is a detection within one hour before or after at a different receiver. Given the distance between receivers, short ping intervals, and lack of sequential detections, it is highly likely that these are false detections. We also removed duplicate detections, or any single ping detected by two adjacent receivers. Duplicate detections can be identified by their occurrence at two different receivers within a time interval that is less than the nominal delay of the tag.

Frequently, duplicate detections are often isolated in space as well; however, duplicate detections also occur when a fish is moving between adjacent receivers, resulting in the first pings at a new receiver location being duplicate detections from the former receiver location that are not removed during the first two stages of filtering. In these instances, the earliest detection is retained as the closest approximation of location.

Filtered detection data were used to construct total and seasonal transition matrices for each individual fish. Transition matrices were then used to build directional networks for
individual fish using R Statistical software and package igraph (Csardi and Nepusz 2006; R Core Team 2013). These networks represented coarse-scale space use for individual fish throughout the lower Saint John River basin. For each individual fish, we calculated detection count, mean residence index (mean RI), total residence index (total RI), distribution (rkm), number of locations visited, and number of movements directly from filtered data (Table 2). Individual networks were used to calculate average path length (APL), degree centralization, and alpha centralization in summer, fall, winter, and spring as well as totaled values across seasons. Since winter receivers were only deployed in 2016-17, totaled network metrics for each fish were comprised of summer, fall, and spring data. Total RI is calculated as the ratio of total days a fish was detected to total days at large and is an indicator of time spent within the receiver array. Mean RI is the mean of residence indices calculated for each receiver location in an individual fish distribution and is an indicator of distribution of residency across the receiver array. High total RI indicates the receiver array is covering habitat selections well and high mean RI is indicative of high residency at one or few locations within the array. Distribution is the extent of movement of each fish, measured in river kilometers. APL is a network-scale metric measuring the likelihood of movement across a network (Jacoby et al. 2012). High APL values are indicative of large distributions throughout the basin with bidirectional movement between most locations; this describes a fish with a large distribution making regular, coarse-scale movements throughout its range. Low APL values are indicative of smaller distributions with limited bidirectional movement; this pattern describes a fish primarily moving between a small subset of locations within its range. Degree centrality is a measure of location importance calculated from the number of directed paths into and out of each node in the network of an individual fish, referred to as in-degree and out-degree; in this context, it is the number of paths to and from each
receiver in the distribution of an individual fish. Alpha centrality is a measure of location importance calculated from external and internal inputs, as well as directionality of movements between locations. Here, the number of movements between locations is the internal input weighting the transition matrix. The external input is the residence index at each location in the network of an individual fish. Thus, alpha centrality takes into consideration both frequency of movements and residency at each location in assigning importance to nodes. Measures of centrality are then centralized to create a single, network-scale metric that describe the distribution of importance across the entire network of an individual fish using the following formula:

$$\text{Centralization} = \sum (\text{node}_{\text{high}} - \text{node}_i)$$

Where $\text{node}_{\text{high}}$ is the highest centrality score among all nodes in an individual network and $\text{node}_i$ is the centrality score of every other node in turn. High centralization scores indicate high importance of one or few locations whereas low centralization scores indicate importance more evenly distributed across a network. Therefore, a high centralization score is indicative of a fish with a high concentration of movement or residency within a smaller subset of its range. In depth discussions of network metrics and applications to ecological data can be found in Jacoby et al. (2012) and Jacoby and Freeman (2016).

Ordinary least squares (OLS) regressions were used to determine relationships between distribution and movement metrics and fish size. Principal component analysis (PCA) was used to reduce the number of variables and test for differences in distribution and movement among seasons and between fish groups tagged in each river. A correlation matrix was used to account for differences in scale and magnitude between metrics and a varimax rotation to maximize variation explained by the components. One-way ANOVAs were used to test for differences
between rotated components by river origin and season. Pairwise comparisons with alpha-level corrections were made using a Tukey and Kramer Test where significant differences were found. A Kruskal-Wallace Test was used to investigate differences between rotated components by season where homogeneity of variance and normality assumptions could not be met.

Results

Juvenile Atlantic sturgeon were distributed throughout the lower reaches of the Saint John Basin but concentrated in the brackish waters of both the Saint John and Kennebecasis Rivers. No fish were detected upstream of rkm 88 in the Saint John River and only three fish were detected downstream of rkm 0 in the Saint John Harbor, indicating they left the system (Figure 3). All three fish that exited the system were tagged in the Kennebecasis River in 2016 and had distributions including portions of both the Kennebecasis and Saint John Rivers. These juveniles were at or above mean fish size for the basin (FL = 61, 63, and 71 cm) and were detected in June and November at 44 ± 13 (mean ± SE) minutes before high or low tide. All three fish returned and remained in the river system for the remainder of the study period. Detections between rkm 14 and 44 in the Saint John River accounted for 68% (n = 511) of all movements between locations; 34% (n = 254) of movements were made between rkm 29 and 39 in the Long Reach portion of the Saint John River (n = 751, total movements). Approximately 52% (n = 319, 438) of all detections occurred at rkm 32 in the Kennebecasis River and 22% (n = 135, 147) of all detections occurred at rkm 29 and rkm 39 in the Saint John River (n = 614, 303, total detections).

OLS regressions of movement and distribution metrics against fork length showed high variation and weak relationships. Number of movements and alpha centralization had significantly negative and positive slopes, respectively (OLS, p = 0.03, p = 0.01, respectively) but the R² values were low indicating little variation is explained by the regression (Table 3).
Alpha centralization values were heavily influenced by high location residency, with the highest values resulting from high residency in one or two locations within an individual fish distribution. Alpha centralization exhibited the highest $R^2$ value of the two significant slopes ($R^2 = 0.208$), indicating fish size accounts for roughly 21% of the variation in location importance in fish ranging from 44 to 83 cm FL.

The PCA of totaled movement and distribution metrics revealed two principal components with eigenvectors greater than one. Together, these components accounted for 70% of total variation. Only degree centralization had low loadings in both PC1 and PC2, indicating it was not an important factor in PC calculation and accounted for little variation. The highest loadings for RC1 were number of locations (0.97), APL (0.96), distribution (0.84), and number of movements (0.78). We interpreted the RC1 axis as a distribution and movement index that ranged from small distribution with few movements to large distribution with more frequent movements. The highest loadings for RC2 were days detected (0.94), total RI (0.92), mean RI (0.76), detection count (0.69), and alpha centralization (0.62). We interpreted RC2 as an index of residency and location importance that ranged from low residency with dispersed importance to high residency with importance concentrated in one or two locations in the array. RC1 was log transformed to meet normality assumptions prior to testing; however, RC2 passed both homogeneity of variance and normality tests without transformation. One-way ANOVAs revealed no significant differences in either RC1 ($p = 0.125$) or RC2 ($p = 0.465$) between fish tagged in the Kennebecasis and Saint John Rivers.

As with the totaled metrics, the PCA of seasonal movement and distribution metrics produced two PCs with eigenvectors greater than one. The two PCs accounted for 78% of total variation. Following varimax rotation, loadings were similar to those presented above with the
exception of degree centralization, which exhibited high loading in RC1. The highest loadings for RC1 were APL (0.98), number of locations (0.96), distribution (0.92), number of movements (0.83), and degree centralization (0.80). As above, this suggests RC1 is an index of distribution and frequency of movement ranging from small distribution with few movements to large distribution with more frequent movements. The highest loadings for RC2 were days detected (0.88), total RI (0.85), mean RI (0.84), alpha centralization (0.78), and detection count (0.76). Similarly, this suggests RC2 is an index of residency and location importance ranging from low residency with dispersed importance to high residency with importance concentrated within a small area. RC2 passed assumptions of both homogeneity of variance and normality; however, RC1 could not be made to pass either assumption. A Kruskal-Wallace non-parametric test of RC1 revealed no significant differences among seasons (p = 0.072). A one-way ANOVA of RC2 revealed significant differences among seasons (p = 0.012). Tukey’s post-hoc testing showed significantly higher RC2 values in summer than both spring (p = 0.042) and winter (p = 0.036).

Discussion

Juvenile Atlantic sturgeon were distributed throughout the Saint John Basin downstream from rkm 88 but were primarily concentrated in the brackish waters of the lower 40 river kilometers (Figure 3). Three fish left the system briefly over the two-year study period indicating it is largely a closed system for juveniles. All three fish were tagged in the Kennebecasis River but had distributions that included both the Kennebecasis and Saint John Rivers and were at or above average size. They were detected just downstream of rkm 0, in Saint John Harbor within a narrow window around high or low tide. The mouth of the Saint John River is a narrow reach with high flows and a set of rapids at rkm 0, which smaller juveniles may not be able to traverse successfully. This is consistent with previous findings documenting early juvenile Atlantic
sturgeon marine excursions as early as age-2 (Dovel and Berggren 1983; Hatin 2007) as well as laboratory experiments showing increases in swimming performance with increases in total length (Peake 1997). Juveniles may be timing marine excursions and re-entry with tidal cycle, when flows may be more favorable.

Distribution and movement do not appear to be strongly related to size within the Saint John River system. High variation in metrics across fish sizes suggests a diversity of movement patterns at the individual level (Table 4). A dominance hierarchy has been observed in Atlantic sturgeon whereby larger individuals will outcompete smaller individuals for foraging space by exhibiting agonistic behaviors such as charging or pushing (Kynard and Horgan 2002). If these interactions influence movement patterns at coarse scales, we would expect to see smaller juveniles making more frequent movements and exhibiting lower residency as they are outcompeted for forage and search for new foraging areas. This would have translated to lower detection counts, residence indices, and alpha centralization as well as higher movement frequency, number of locations, and APL.

We hypothesized there would be a positive relationship between size and frequency of movements as well as a negative relationship between size and residency. Although the observed slopes support our hypothesis, only two were significant and little variation was explained overall. Alpha centralization exhibited a significant, positive slope and fish size accounted for approximately 21% of the observed variation. Alpha centralization incorporates the number of locations visited, location residency, and number of movements between locations into a measure of location importance; however, the largest values resulted from fish with high residencies at one or two locations within their distribution. This suggests size may influence movement pattern at coarse scales but is not a strong predictor of observed patterns. Future
research should aim to include a larger sample size and focus on identifying additional biotic and abiotic variables driving distribution and movement patterns at coarse scales.

**Movement and distribution between rivers**

Differences in movement between fish tagged in the Saint John and Kennebecasis Rivers are driven by trade-offs between high residency and frequency of movements. Fish tagged in the Saint John River appear to make more frequent movements and are restricted to river reaches between rkm 14 and 88; Fish tagged in the Kennebecasis River appear to make fewer coarse-scale movements overall and exhibit either high single-receiver residency or wide distribution across both river systems (Figure 4). These differences were not significant, however. It is likely that the variation in movement patterns exhibited by Kennebecasis fish is masking differences between fish tagged in the two rivers. Overall, Kennebecasis fish display higher variation in movement pattern than Saint John River fish. Both rotated components passed homogeneity of variance testing between rivers, however p-values were relatively low and Kennebecasis fish clearly exhibited higher variation in both RC1 and RC2 (Bartlett Test, p = 0.26 and p = 0.21, respectively). As is often the case with movement ecology studies, the sample size (n = 31) was relatively low, decreasing the likelihood of statistical significance. Increasing the number of tagged fish increases the probability of signal interruption at frequently visited locations; however, pooling data from additional years of study in the future could yield significant results and confirm differences in movement and distribution patterns observed here.

Tagged juveniles exhibited diverse patterns of distribution in both rivers with the most heavily used areas being at or near the saltwater interface. Juvenile Atlantic sturgeon have been shown to have high variation in home range size as early as age-2 in the St. Lawrence River (Hatin 2007) as well as a tendency to use habitat near the saltwater interface more heavily.
(Lazzari et al. 1986; Moser and Ross 1995; Hatin 2007). As part of a related study, we identified two aggregation sites near the upriver extent of saltwater intrusion in each river (Whitmore and Litvak 2018), which likely accounts for high residencies in these locations. Potential drivers of distribution and movement pattern include social structure, resource distribution, and habitat characteristics such as salinity, flow, and substrate. Previous investigations of coarse-scale Atlantic sturgeon distribution have found that distribution pattern corresponds to that of high density prey (Fox et al. 2002; Stein et al. 2004; Hatin et al. 2007; Altenriter et al. 2017; Novak et al. 2017). Kynard and Horgan (2002) suggest social structure may be an important factor in Atlantic sturgeon migration, aggregation, and foraging behavior. Future research will focus on evaluating social structure, resource distribution, and habitat characteristics as drivers of river distribution.

Seasonal movement and distribution

Seasonal differences in residency and centralization were between summer and both spring and winter (Figure 5). This is driven by higher detection count, days detected, mean RI, total RI, and alpha centralization in summer compared with other seasons (Table 4). Higher total RI in summer indicates the receiver array is covering habitat selections well and suggests juveniles are remaining in areas of high activity for longer periods in summer compared with spring and winter. Alpha centralization is higher in summer compared to spring and winter indicating higher use of a smaller stretch of river in summer as well as a shift in overall pattern across seasons. This supports our hypothesis and suggests juveniles are moving in a narrow stretch of river between bouts of extended position-holding during summer months. The high summer residencies in small sections of brackish water is consistent with studies of juvenile and subadult Atlantic sturgeon throughout their range (Moser and Ross 1995; Hatin et al. 2007; Altenriter et
al. 2017). Previous work suggests adult Atlantic sturgeon form dense overwintering aggregations with very little or no movement (Bain 1997; Taylor et al. 2016), however, there has been little investigation into movement patterns of juveniles during cold months in their northern range. This is the first study to document coarse-scale movement of juveniles during winter months and indicates juveniles make regular, coarse-scale movements of up to 50 rkm.

The low detection counts and total RI observed in spring and winter could suggest the receiver array is not covering winter and spring habitat selection well. Seasonal shifts in habitat use in adult Atlantic sturgeon are well-documented and suggest increased use of deep water habitat in winter and early spring (Collins et al. 2000; Beardsall et al. 2016; Taylor et al. 2016; Wippelhauser et al. 2017). Receivers are attached to navigational buoys used to mark points and shallow inlets adjacent to navigable channel. It is possible that winter and spring habitat is in deeper channel habitats or between receiver positions and outside of range.

Investigations of Atlantic sturgeon movement in their northern range are largely focused on adult and subadult life stages. As a result, little is known of distribution and movement patterns of juveniles within their natal river systems. This is the first investigation into juvenile Atlantic sturgeon in the Saint John River Basin and establishes baseline data on seasonal distribution and movement patterns. These results can be used to inform investigations into population status and habitat use as well as aid in the identification of critical habitat. Future work should focus on increasing spatiotemporal resolution of locational data as well as characterizing habitat in areas of high residency.

Acknowledgements

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and Natural Science and Engineering Research Council of Canada Discovery and Research, Tools and Instruments grants to MKL. Clay Steell, Christine Gilroy, Matthew Brown, and Andrew Taylor were instrumental in conducting field work.
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Wirgin, I., Maceda, L., Waldman, J.R., Wehrell, S., Dadswell, M.J., and King, T. 2012. Stock origin of migratory Atlantic sturgeon in Minas Basin, inner Bay of Fundy, Canada,
Table 1. Summary of tag settings. Pressure tags used to measure fish depth are designated with a P; tag power is either high (H) or low (L). Tag settings were configured such that the nominal delay did not exceed 120 seconds and tag life was maximized.

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<th>Length (mm)</th>
<th>Weight in Water (g)</th>
<th>Nominal Delay (seconds)</th>
<th>Tag life (days)</th>
<th>Number of fish tagged</th>
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<td>2.9</td>
<td>90</td>
<td>365</td>
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Table 2. Summary of distribution and movement metrics used in statistical analysis. Metrics are calculated from movement data of individual fish.

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<th>Metric</th>
<th>Definition</th>
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<td>Days detected</td>
<td>The number of days a fish is detected across the study period</td>
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<tr>
<td>Detection count</td>
<td>The total number of detections across all receivers</td>
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<tr>
<td>Total residence index</td>
<td>The number of days a fish is detected within the receiver array divided by the number of days the fish is at large</td>
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<td>Mean residence index</td>
<td>Residence index calculated for each individual receiver and then averaged across the receivers visited by an individual fish</td>
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<tr>
<td>Distribution (rkm)</td>
<td>The size of the home range for each individual fish, measured in river kilometers</td>
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<tr>
<td>Number of movements</td>
<td>The total number of movements made between any pair of receivers</td>
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<tr>
<td>Number of locations</td>
<td>The total number of receivers visited by each fish</td>
</tr>
<tr>
<td>APL</td>
<td>Average Path Length. A measure of distribution that considers the number of receivers, directionality of movement, and the distribution of bidirectional movement across a network.</td>
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<tr>
<td>Degree centralization</td>
<td>Network-scale metric derived from individual degree centrality values for each receiver; measure of movements into and out of receiver range</td>
</tr>
<tr>
<td>Alpha centralization</td>
<td>Network-scale metric derived from individual alpha centrality</td>
</tr>
<tr>
<td>values for each receiver; measure of overall pattern that takes residency and number of movements into account equally</td>
<td></td>
</tr>
</tbody>
</table>
Table 3. Ordinary least squares regressions of movement and distribution metrics versus fish size, measured in fork length (cm). Metrics are calculated from spring, summer, and fall movement data of individual fish tagged in 2015 and 2016. Variables were log transformed to meet assumptions of normality as needed. Significant p-values are starred.

<table>
<thead>
<tr>
<th>Variable</th>
<th>df</th>
<th>F</th>
<th>Standardized coefficient</th>
<th>Slope</th>
<th>R²</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Log detection count</td>
<td>29</td>
<td>1.894</td>
<td>0.248</td>
<td>0.014</td>
<td>0.061</td>
<td>0.18</td>
</tr>
<tr>
<td>Log total RI</td>
<td>29</td>
<td>1.253</td>
<td>0.203</td>
<td>0.006</td>
<td>0.041</td>
<td>0.27</td>
</tr>
<tr>
<td>Log mean RI</td>
<td>29</td>
<td>1.898</td>
<td>0.248</td>
<td>0.009</td>
<td>0.061</td>
<td>0.18</td>
</tr>
<tr>
<td>Distribution (rkm)</td>
<td>29</td>
<td>0.313</td>
<td>0.103</td>
<td>0.274</td>
<td>0.011</td>
<td>0.58</td>
</tr>
<tr>
<td>Log number of movements</td>
<td>29</td>
<td>4.906</td>
<td>-0.380</td>
<td>-0.024</td>
<td>0.145</td>
<td>0.03 *</td>
</tr>
<tr>
<td>Log number of locations</td>
<td>29</td>
<td>0.046</td>
<td>-0.040</td>
<td>-0.001</td>
<td>0.002</td>
<td>0.83</td>
</tr>
<tr>
<td>Log APL</td>
<td>29</td>
<td>0.707</td>
<td>-0.154</td>
<td>-0.004</td>
<td>0.024</td>
<td>0.41</td>
</tr>
<tr>
<td>Log degree centralization</td>
<td>29</td>
<td>1.781</td>
<td>-0.241</td>
<td>-0.005</td>
<td>0.058</td>
<td>0.19</td>
</tr>
<tr>
<td>Alpha centralization</td>
<td>29</td>
<td>6.809</td>
<td>0.456</td>
<td>0.213</td>
<td>0.208</td>
<td>0.01 *</td>
</tr>
</tbody>
</table>
Table 4. Mean values of seasonal movement and distribution metrics calculated from individual tagged juvenile Atlantic sturgeon. Values are presented for summer, fall, winter, and spring (mean ± standard deviation). Summer, fall, and spring values are averaged across fish tagged in 2015 and 2016, winter values are averaged for 2016, the only year a winter receiver array was deployed.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Summer</th>
<th>Fall</th>
<th>Winter</th>
<th>Spring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection count</td>
<td>8549 ± 6993</td>
<td>6096 ± 9944</td>
<td>5460 ± 9346</td>
<td>2333 ± 6738</td>
</tr>
<tr>
<td>Days detected</td>
<td>50 ± 23</td>
<td>40 ± 26</td>
<td>21 ± 27</td>
<td>11 ± 13</td>
</tr>
<tr>
<td>Total RI</td>
<td>0.61 ± 0.28</td>
<td>0.38 ± 0.30</td>
<td>0.23 ± 0.29</td>
<td>0.15 ± 0.19</td>
</tr>
<tr>
<td>Mean RI</td>
<td>0.28 ± 0.31</td>
<td>0.15 ± 0.20</td>
<td>0.14 ± 0.17</td>
<td>0.07 ± 0.10</td>
</tr>
<tr>
<td>River distribution (rkm)</td>
<td>22 ± 19</td>
<td>19 ± 20</td>
<td>6 ± 10</td>
<td>11 ± 9</td>
</tr>
<tr>
<td>Number of movements</td>
<td>13.48 ± 18.88</td>
<td>8.74 ± 10.29</td>
<td>1.47 ± 2.82</td>
<td>1.42 ± 2.66</td>
</tr>
<tr>
<td>Number of receivers</td>
<td>4.12 ± 2.84</td>
<td>3.77 ± 3.23</td>
<td>1.32 ± 1.29</td>
<td>1.39 ± 1.43</td>
</tr>
<tr>
<td>APL</td>
<td>1.55 ± 1.13</td>
<td>1.35 ± 1.27</td>
<td>0.49 ± 0.61</td>
<td>0.52 ± 0.66</td>
</tr>
<tr>
<td>Degree centralization</td>
<td>28.45 ± 19.36</td>
<td>25.10 ± 20.66</td>
<td>12.00 ± 12.36</td>
<td>11.48 ± 15.90</td>
</tr>
<tr>
<td>Alpha centralization</td>
<td>7.66 ± 5.85</td>
<td>6.28 ± 8.13</td>
<td>3.67 ± 6.42</td>
<td>2.33 ± 3.57</td>
</tr>
</tbody>
</table>
Figure 1. Map of the lower Saint John River Basin with receiver locations. All receivers are deployed spring through fall (blue and green circles); a subset remains deployed through winter (blue circles). Receivers are labelled with the rkm occupied; receivers at rkm 39 and 44 were added in spring 2016 to provide additional coverage of an area of high activity. Map data: Google, DigitalGlobe.

Figure 2. Size distribution of juvenile Atlantic sturgeon tagged with acoustic transmitters in the Kennebecasis (pink) and Saint John (blue) Rivers. The dark blue shows overlap of the two distributions. The dashed line marks the mean fork length of fish captured from each river.

Figure 3. Network mapping juvenile Atlantic sturgeon distribution in spring, summer, and fall of 2015 and 2016. Color of network links indicates the number of movements made between each pair of receivers. Network nodes indicate locations of deployed receivers and are labeled with river kilometer occupied. Map data: Google, DigitalGlobe.

Figure 4. Network mapping distribution of juvenile Atlantic sturgeon tagged in the Kennebecasis (left) and Saint John (right) Rivers in 2015 and 2016. Color of network links indicates the number of movements made between each pair of receivers. Network nodes indicate locations of deployed receivers and are labeled with river kilometer occupied. Map data: Google, DigitalGlobe.

Figure 5. Network mapping distribution of juvenile Atlantic sturgeon tagged in the Kennebecasis and Saint John Rivers in summer (top left), fall (top right), winter (bottom left), and spring (bottom right). Spring, summer, and fall networks include data from fish tagged in 2015 and 2016; winter network includes data from 2016 only. Color of network links indicates the number
of movements made between each pair of receivers. Network nodes indicate locations of
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